University of Alberta

Stream Modifications to Enhance Fish Habitat in Arctic Headwater Systems

by

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Abstract

Disruptions to Canada's pristine northern regions have been steadily increasing due to industrial activities. Many of these impacts lead to destruction or harmful alteration of aquatic ecosystems. Recently, efforts have been made to reduce and offset aquatic habitat impacts through habitat compensation projects. This thesis investigated two habitat compensation projects in the Barrenlands region of Canada to explore the hydraulic responses to stream modifications and determine the efficacy of constructing these works in remote locations with a limited understanding of site characteristics.

First, an investigation was conducted to explore various stream modification efforts to enhance ecosystem connectivity of an isolated system of three small lakes by enhancing system connectivity. The lakes' ephemeral outlet streams were modified, intending to create conditions favorable for fish passage and thereby promote movement among the lakes and the large lake into which they drain. Variation of lake levels and duration, variability, and depth of stream flow indicated that outlet geometry and lake catchment area should be important considerations when enhancing connectivity for fish in ephemeral systems. A narrow, rectangular outlet cross-section was deemed effective for increasing flow depth while decreasing discharge, resulting in increased duration of flows. Catchment area was an effective indicator of a headwater lake's potential response to connectivity enhancements. Smaller catchments may provide inadequate runoff to sustain minimum storage requirements for enhanced connectivity.

Second, we investigated efforts to enhance spawning habitat and connectivity to a headwater stream. An on-site, field engineering approach at the time of construction was developed for design of these modifications. This approach addressed challenges associated with remote construction and limited information on site characteristics, focusing on communicating to the construction crew the intent of the designs, rather than a detailed design, to facilitate modification and optimization of structures when confronted with unforeseen challenges. Primary design considerations included (1) controlling flows in periods of high and low discharges; (2) minimizing drop heights; (3) improving flow variability for enhanced stream habitat; and (4) salvaging and incorporating vegetation disturbed from construction activities into riparian and in-stream habitat structures. Preliminary observations showed suitable depths for fish passage were present over the entire stream during the study period indicating discharges were controlled effectively at all stream gradients. These findings should advance the knowledge of headwater system hydraulics in the Barrenlands and assist in designing future fish habitat compensation projects on similar Arctic systems.

To mom and dad,

thank you for giving me the support to find myself.

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Chapter 1

General Introduction

1.1 Research Background

With growing Canadian and global economies, there are increased societal demands for expanding resource exploitation, which have been challenged by the public's desire to ensure the environment is protected. To achieve the former, Canada's scarcely understood northern regions are being developed at an ever increasing rate, leading to impacts on the affected landscapes, watersheds, and ecological systems. Many of these developments fragment or destroy aquatic habitats. In 1986, the Canadian government mandated a policy of no net loss (NNL) in the productive capacity of fish habitat due to human activities (DFO 1986, Quigley and Harper 2006). This policy has traditionally been fulfilled through habitat compensation projects by restoring, enhancing, or developing new habitat.

Traditionally, habitat fragmentation (e.g. development of dams and weirs) is offset by structures such as pool and weir, vertical slot, Denil, and culvert fishways (Katapodis et al. 2001), however these structures may not be suitable when considering the project location and compensation objectives. Most recent resource exploitation developments are found in remote settings where construction conditions are variable and readily available construction materials are limited. Conventional building methods and materials (e.g. wood, metal, and concrete) may not be cost-effective. When considering fish habitat enhancement, many projects have incorporated nature-like fishway designs (e.g., Schmutz et al. 1998, Harris et al. 1998, Stephan et al. 2007, Baki et al. 2014). Native materials found on site may be used to construct structures that emulate natural stream characteristics suitable for a variety of fish species (Katapodis et al. 2001). Nature-like fishways may sacrifice the predictability of traditional designs due to the site-specific variability of available materials, especially in remote settings. Nevertheless, such low-impact solutions are favoured in pristine systems to promote ecological productivity.

Diavik Diamond Mines, Inc. (DDMI) initiated two habitat compensation projects in provision of NNL triggered under Canada's Fisheries Act. The first project (M-Lakes, constructed fall 2011) intended to increase connectivity among three small (<6 ha), isolated lakes and with the larger (>57,000 ha) Lac de Gras to provide connections suitable for fish passage, thus enhancing productive capacity of the system (Golder 2001). The second project (West Island, constructed fall 2012) intended to enhance spawning habitat in an ephemeral stream and connectivity between a small (13.65 ha) headwater lake and Lac de Gras (Dillon 2004).

1.2 Motivation for Research

The primary motivation of this study is to explore hydraulic responses to various modifications within Arctic headwater systems and to investigate the efficacy of design and construction of in-stream structures in a remote location with limited understanding of site characteristics. Few previous studies have been conducted on the characteristics of Barrenlands streams and aquatic habitat (Baki et al. 2012a/b; Jones et al. 2003a/b). Therefore, little is known about the efficacy of manipulating these pristine systems. Further study will allow us to design more effective habitat enhancement projects on Arctic headwater systems.

Designing appropriate fish habitat compensation projects are only as effective as our ability to successfully implement the design on site. Working in remote locations with a limited understanding of site characteristics pose challenges when assumptions used in the design process are not valid for site-specific conditions. Understanding these challenges will help us develop methods to improve the likelihood that projects will meet the intended habitat compensation objectives.

This thesis explores the effectiveness of various in-stream structures to control varying discharges throughout the entire open-water season on several small, ephemeral Arctic headwater streams. Stream discharges vary over several orders of magnitude, creating a unique design challenge. Results from this study will improve our ability to assess feasibility and optimize design for future Arctic stream modification projects.

1.3 Research Objectives

The overall objective of this thesis is to investigate hydraulic characteristics and responses of Arctic headwater lake-stream systems to stream modifications to enhance fish habitat. The thesis is organized around the following objectives:

1 – To investigate connectivity enhancements of various outlet modifications to a system of multiple small, previously isolated lakes and streams and assess the corresponding impacts on the likelihood of success as fish habitat enhancement.

2 – To develop a field engineering approach for remote in-stream habitat structure construction and investigate responses in hydraulic characteristics to these habitat enhancement modifications in a natural headwater stream.

1.4 Significance of Research

Findings from this study will increase our understanding of designing effective stream modification to Arctic headwater systems in the Barrenlands region of Canada. The developed field engineering approach for remote sites will serve to increase the likelihood of successfully implementing designs of future stream modification projects.

1.5 Organization of Thesis

This thesis is written in paper format and comprises 4 chapters including an introduction, two field studies, and conclusions and recommendations.

Chapter 1 consists of a general introduction, providing a background and context to the research along with research motivation and objectives.

In Chapter 2, connectivity enhancements to a pristine headwater system (M-Lakes) of three pairs of small (< 6 ha) lakes and outlet streams were investigated to explore hydraulic responses to modifications and the likelihood of fish habitat enhancements. Various lake outlet geometries and in-stream structure characteristics were examined and compared.

In Chapter 3, hydraulic responses to stream modifications in a 420 m long headwater stream were explored to examine the likelihood of fish habitat enhancement and improved connectivity for fish passage between Lac de Gras and one of its headwater lakes. A field engineering approach was developed and evaluated to address challenges associated with remote construction and uncertain site characteristics.

Chapter 4 presents the conclusions and recommendations for future work.

Chapter 2

Stream modifications to enhance system connectivity for fish habitat compensation: a case study in the Barrenlands region of Canada[1]

2.1 Introduction

In ephemeral headwater systems, outlet elevation and geometry play important roles in governing lake storage thresholds and stream discharge. Modifying outlet characteristics will impact discharge, water storage, and aquatic habitat. When considering manipulations to a system of multiple lake-stream connections, this hydraulic response becomes more complex. Outlets of one lake will affect subsequent downstream lake storage and stream discharges. Investigating the dynamic relationship between storage and runoff, Spence (2007) concluded that lake storage thresholds directly influence the ability of a catchment to move water to its outlet. This effect is prevalent in small systems where discharge periods are short and sensitive to snowmelt and precipitation. A strong relationship exists between snowmelt-governing spring temperatures and freshet date in headwater systems (Burn 2008). Additional factors contributing to the duration of freshet include precipitation and evaporation. Even relatively minor changes to an outlet may cause a large impact to lake storage and discharge, e.g., wider outlets will create large peaks in discharge that drop off quickly whereas narrow outlets will restrict discharge, preserving lake storage. Enhancing hydraulic connectivity within small lake-stream

[1]The content of this chapter has been published as: Courtice et al. 2014: "Stream modifications to enhance system connectivity for fish habitat compensation: a case study in the Barrenlands region of Canada" Canadian Journal of Civil Engineering, 41(7): 650-659.

systems requires a balance between increased outlet discharges and water storage retention.

Design considerations to enhance connectivity for fish migration further complicate the process of modifying connections. Traditionally, fish impediments are bypassed by structures such as pool and weir, vertical slot, Denil, and culvert fishways (Katapodis et al. 2001). These structures are generally constructed with wood, steel, and concrete components. In remote settings where construction conditions are variable and available resources are limited, conventional building methods and materials may not be cost-effective. Recently, many projects have elected to incorporate nature-like fishway designs (e.g., Schmutz et al. 1998, Harris et al. 1998, Stephan et al. 2007, Baki et al. 2014). Materials available on site are used to construct structures that simulate natural stream characteristics suitable for a variety of fish species (Katapodis et al. 2001). Such low-impact solutions are also favoured in pristine systems to promote ecological productivity. Although usually more economical in remote settings, these nature-like fishways may sacrifice the predictability of traditional designs, as structure design and construction are dependent upon resources available and logistical considerations. For certain projects, a combination of traditional and nature-like structures may be beneficial to make use of the structural consistency and reliability of traditional designs while promoting ecological productivity from the nature-like designs.

Diavik Diamond Mines Inc. (DDMI) initiated the Mainland Lakes (M-Lakes) fish habitat compensation project in the Barrenlands region of northern Canada to offset mining-based aquatic impacts. In autumn 2011, outlet streams of three small (<6 hectares) lakes were modified with in-stream structures to improve connectivity among the lakes and with a much larger lake (Lac de Gras) and thus facilitate fish migration and system production. DDMI constructed gabion step-pool structures in two of the outlet streams and a choke-and-pool structure in the third. Gabions were chosen over boulder structures due to available resources and construction logistics. Following a preliminary hydraulic evaluation (June 2012), in conjunction with a fish monitoring program, the two gabion-based structures were subsequently retrofitted (September 2012) by modifying geometries and dressing with boulders to improve performance.

We investigated storage and discharge variability within M-Lakes and their streams beforeand after outlet modifications to determine important factors for ensuring suitable connectivity for fish migration. Quantifying the responses should further our understanding of hydraulic characteristics related to habitat enhancement in ephemeral headwater systems.

2.2 Background

DDMI is located approximately 320 km northeast of Yellowknife, NWT in the Barrenlands region of Canada (Figure 2.1). The mine is approximately 100km north of the tree-line and falls within the Southern Arctic Ecozone (Environment Canada 1991). The Barrenlands feature relatively low topographical relief (<50 m) and 21% of the area is covered with interconnecting chains of lakes and streams (Jones et al. 2003a). The region receives approximately 200-300mm of precipitation annually (ca. half as snow) and the mean annual temperature is -12°C (Environment Canada 1991). The permafrost layer is continuous. Spring freshet in streams begins around

June 1, after which evaporation gradually lowers lake levels and stream flows diminish or cease altogether (Baki et al. 2012). Streams freeze solid by the end of October and remain frozen until spring (Jones et al. 2003b).

M-Lakes are located approximately 5 km east of the DDMI mine site. Prior to modification, M-Lakes featured three headwater lakes (M1L, M2L, and M3L) in the greater Lac de Gras (LDG) watershed (Figure 2.2; Table 2-1). M2L and M3L connected ephemerally to M1L during the 2-3 week freshet and M1L connected to LDG. Streams were short with moderate to steep gradients (Table 2-1); impassable cascades and undefined channel reaches prevented fish from navigating these natural lake outlets.

M-Lakes compensation objectives were to improve connections between lakes, creating conditions favourable for fish passage, by modifying channels, reducing channel slopes, and installing hydraulic structures. A gabion berm was installed between M1L and LDG, increasing the former's water storage capacity to lengthen durations of flow in M1S during high return period events. Six gabion weirs, numbered one (upstream) to six (downstream), were installed in both M1S and M3S to create step-pool structures (Figures 2.3-2.5). The design drop height for these structures coincided with a suggested jump height of 20 cm for Arctic Grayling, *Thymallus arcticus,* reputed to be a species of limited jumping ability (Dillon 2004). Data regarding the downstream water level elevation in M3S was uncertain; M3S weirs five and six were installed to ensure drop heights throughout the stream were no greater than 20 cm. In M2S, one pool was constructed immediately downstream of a single choke-point (Figure 2.6).

Following hydraulic evaluation conducted during the first post-construction freshet period, the gabion weirs of M1S and M3S were retrofit in autumn 2012. Our observations of the M-Lakes system before and after construction suggested that depth and drop heights were the primary criteria limiting the potential for fish migration; velocities in these streams were much lower than maximum burst speed for Arctic Grayling (Stewart et al. 2007). Therefore, weirs were modified to eliminate sudden drops and dressed with boulders, available on site, to improve flow characteristics for fish passage (Figures 2.3-2.5). In contrast, the choke-and-pool structure in M2S remained unmodified (Figure 2.6).

The M1S and M3S structure modifications were designed to create narrow controls, restricting large discharges at the lake outlets during freshet and increasing flow depths throughout the streams during low flow periods. Structures were retrofit with rectangular 'slot' geometries to maximize flow depths at all discharges over each weir. For the upstream most weirs in M1S and M3S, i.e. M1L and M3L lake outlets, structures were modified to create a deeper structure slot while maintaining the crest elevation by raising the structure elevations on either side of the slot. This modification intended to reduce outlet discharges and increase lake storage retention, prolonging discharges sufficient for fish migration.

2.3 Freshet Stages and Characteristics

Understanding the unique characteristics of freshet for Barrenlands lake-outlet streams is critical to ensure suitable connectivity. Qualitative observations of these lake-stream systems revealed several stages during the transition from winter to summer. The period of potential connectivity may not align with peak flows depending on factors such as stream characteristics and winter snowpack distribution. Further study would be required to quantify specific details; nevertheless, the following freshet stages give context to the system's sensitivity and decisions supporting structure modifications.

(1) *Warming of Snow Pack*: This stage begins around the end of April and continues through mid-May. Cold content is reduced, warming the snow pack to a point at which melt begins where depth is shallow.

(2) *Visible Reduction of Snow Pack*: This stage develops between early May and early June, initially dependent on spring temperatures. Once patches of land become exposed, local melting proceeds more rapidly due to a reduced snowpack depth and decreased albedo, which further increases local temperatures. As this stage progresses, snowpack disappears except in low lying areas with less exposure, including lakeshores and in the vicinity of stream channels. Water levels in headwater lakes increase due to subnivean runoff from direct catchments while outlet stream channels remain filled with snow and ice. Disparities in freshet progression between adjacent lake systems become evident during this stage; individual site features begin to dominate over larger scale climate characteristics. These differences are mainly governed by characteristics such as winter snowpack distribution and exposure to sun and wind. Timing of subsequent stages may vary by as much as 15 days between nearby systems.

(3) *Peak Stream Discharge and Overland Flooding*: This stage begins early-to-mid-June and lasts up to 10 days. Once the snowpack becomes unstable at an outlet, heightened lake levels cause a steep hydraulic gradient that quickly clears this snow. Peak

discharge begins that may last less than 12 hours or several days, depending on outlet characteristics and lake size. In some cases, downstream sections of the outlet channel may still have a considerable snow pack, diverting water out of the channel and creating unconfined surface runoff. In these situations, fish passage within channel flow would remain unavailable until all snow and ice has melted in the channel.

(4) *Decline of Lake Levels and Stream Discharge*: This stage extends from early to late June, depending on progression of previous stages. Stage duration may be as short as a few days or as long as a few weeks, depending on catchment size and lake storage. During this stage, stream channels are free of snow and ice, the majority of unconfined surface runoff has finished, and stream discharge dominates the water balance. Up to this point, the heightened levels of smaller lakes and stream discharges have preceded any increase in storage of larger lakes, but only now do the latter begin to show a response to freshet. In this system, the M-Lakes discharges may decrease considerably before connectivity is established with LDG.

(5) *End of Freshet*: This final stage begins in late June and continues throughout the summer months, or until surface flow in the outlet stream ceases. Lake levels decrease due to evaporation, stream discharge becomes quite small and in many cases channels become dry.

Based on the characteristics of these stages, the following considerations are important when considering channel modifications to ensure sufficient connectivity among lakes that is suitable for fish passage. (a) Connectivity enhancement needs to focus on discharge and storage available through Stage 4. (b) Because of the processes described in Stage 3, controlling initial discharge should decrease peak flows and maintain upstream lake storage, allowing for higher discharges once stream channels are clear and open to migration. (c) The delayed seasonal response of larger lakes relative to smaller lakes is important to consider if connectivity is to be established or enhanced between different-sized systems. Without improving outlet channel characteristics and duration of freshet discharge, suitable connectivity between different-sized systems may be very brief or non-existent. (d) In-stream structure design may require some attention to Stage 5 to reduce the possibility of fish becoming trapped in a small stream channel during low summer discharges, unable to migrate to their overwintering habitat.

2.4 Methodology

In addition to visual observations on the M-lakes and their outlet streams, hydraulics data were collected during freshet, including discharge, flow depth, structure drop height, and continuous lake and stream water levels. Meteorological data, including temperature, solar radiation, and precipitation, were collected from the DDMI meteorological station. We collected baseline data in 2010 and 2011; in addition, one year of post-construction data with gabion structures (2012) and one year with retrofitted structures (2013) were collected.

We monitored water levels at 15 minute intervals with SWS Mini-Diver pressure data loggers (Schlumberger Water Services). Divers were tied to boulders and placed in each stream and lake. An SWS Baro was placed on shore adjacent to lakes to account for atmospheric pressure. Locations within streams were chosen based on a uniform section where flow was developed and backwater effects were absent. Lake locations were chosen where depth was sufficient for expected lake level decline over the summer months. Once collected, we calculated daily averages to smooth trends. Where large rainfall events occurred, we calculated independent storage trends before and after the event to reduce skew; these independent trends were given a weighted averaged to obtain a single trend for each lake.

Discharge was measured at one cross section in each stream using the area-velocity method (Linsley et al. 1982). Water surface width was measured using a surveyor's tape stretched perpendicular to the flow. At each cross section, we measured flow depth using a meter stick at ten or more equally spaced locations along the width of the cross section. Velocity measurements were taken at 0.6 of depth from surface using a Marsh-McBirney (Model 2000 Flo-Mate) current meter for > 20 seconds at each cell. We calculated discharge for each cell by multiplying depth by cell width by velocity. Total stream discharge was then calculated as the sum of discharges of each cell. We took measurements as many times as possible during the open-water period of each year (6 or more measurements) to document discharge variability within the system. The measured discharge was correlated with water level data to obtain a rating curve from which continuous discharge could be extrapolated. Rating curves had R^2 values of 0.83 - 0.99. We collected relative elevation data in 2013 for M1L, M2L, and M3L using a laser level (model AGL EAGL 3000S), as well as water levels immediately upstream and downstream of each retrofitted weir structure. Water depth on top of each weir (M1S and M3S), and the corresponding drop height, were measured directly in 2012 and with the laser level in 2013 to determine flow variation over structures; measurements were then averaged over each stream. We measured bed level on the crest of each weir to determine water depths and drop heights. A bed measurement was also taken at the M1S velocity cross-section (M1 VXS) and used as a benchmark and site datum to compare each set of laser level measurements.

Finally, standardized visual and electrofishing surveys were performed to enumerate the number and species of fish using fishways. We also tagged > 200 fish (123 Arctic Grayling, 20 Burbot *Lota lota*, 10 Lake Trout *Salvelinus namaycush,* and 56 Round Whitefish *Prosopium cylindraceum)* in the M-Lakes using Passive Integrated Transponder (PIT) tags. Movements into and/or through the outlet streams were recorded with tracking antennae (C. Cahill et al. *in prep.*) and video cameras over the two years post-construction.

2.5 Results

Study periods during 2010 and 2013 began with partial or full ice and snow cover in M1S and M3S, whereas 2011 and 2012 seasons began shortly after snow had melted from streams. M2S was snow free at the start of all four study periods. Upon probing the snow pack in 2013, no flow was present in M3S whereas flow in M1S was present but obstructed, causing flow to be diverted from the stream channel.

2.5.1 Stream Discharges

M-Lakes stream discharges were limited to water available from heightened lake levels during freshet; groundwater contribution to stream discharge was negligible due to permafrost and short stream lengths (G. Courtice pers. obs.). Documenting lake level changes in M-Lakes is thus useful for predicting stream discharge and duration of freshet, indicating the system's suitability for fish migration. Visual observations during 2012 freshet indicated that M1L was approximately 20-30cm higher than baseline study years, consistent with changes to the outlet at M1S. Consequently, by 12 June, M1L and M2L water elevations were approximately equal.

Outlet elevations were not modified during the autumn 2012 retrofit process. In 2013, M2L water elevation remained higher than M1L through the freshet evaluation period; change in storage from 2012 resulted from differences in annual snowpack. On 3 June 2013, ice cover was still present over (downstream) weirs five and six in M1S and all weirs in M3S. Freshet stages in M3L were delayed by several days relative to M1L and M2L. Visual observations indicated that M3L storage continued to increase early in the study period because the outlet remained closed due to snow pack. M1L and M2L showed consistent declines in lake storage whereas stream discharges declined steeply at first and became more gradual subsequently (Figure 2.7). This effect was due to less confined outlet discharges at high storage levels, which became confined within narrow outlets only when levels dropped.

Baseline measurements from 2010 and 2011 showed maximum freshet flow in M1S at 0.071m^3/s; flows in M2S and M3S were negligible (Figure 2.7). After construction, flows in M1S, M2S, and M3S were 0.005-0.030 m^3/s, 0.003-0.020 m^3/s, and 0-0.003 m^3/s, respectively, in 2012 and 0.015-0.045 m^3/s, 0.010-0.037 m^3/s, and 0.002-0.008 m^3/s in 2013. In 2012, discharge in all streams declined to negligible levels by Julian Day 164 (12 June; Figure 2.7). In 2013, following retrofitting of M1S and M3S, only M3S discharge became negligible within the first two weeks of June (Figure 2.7).

2.5.2 Hydraulic Performance of M1S and M3S

Flow and structure observations were collected at gabions, inlets, and outlets throughout M1S and M3S to determine the likelihood of successful fish migration. Gabion materials proved difficult to manipulate during construction due to workability of materials and inconsistent soil characteristics. As a result, the transverse profile of each gabion was inconsistent, leading to difficulties concentrating flows toward the channel centreline. In most cases, angles were close to horizontal near the center of the channel and only inclined near the banks causing flows to be quite shallow over structures and drop heights to be unnecessarily large. Because water surface elevation of LDG increases over the summer months, excavation of the M1S-LDG connection during autumn 2011 was limited. Consequently, in spring 2012, the lowermost section of M1S widened out into a braided, divergent, and undefined channel spanning several meters. During this period, water depths over this section were <5 cm before entering Lac de Gras.

The downstream section of M3S also faced challenges in spring 2012. The six weirs in M3S were built based on the surface elevations of the upstream and downstream lakes (M3L and M1L) at the time of construction (autumn 2011). Because outlet changes at M1L subsequently increased its water levels, the two downstream-most weirs (five and six) were submerged during freshet the following spring (2012). Therefore only four weirs were available to overcome the M3S gross slope of 2.5%.

On 12 June 2012, weir two of M3S critically failed and no longer retained water. Consequently, new sediment was observed immediately downstream of the gabion. This indicated that failure likely resulted initially from a large pressure differential above and below the weir. An investigation of the structure during autumn 2012 determined that an adjacent boulder was forced against the gabion, likely caused by winter frost heave, and pierced through the bituminous liner.

In 2013, following retrofitting, M1S and M3S maintained lower drop heights than in 2012 (Figure 2.8), although the final structure in M1S (weir six) ended the freshet period at 20cm. Retrofitted structures in M1S also controlled water depths over the weirs more effectively than the original weirs (Figure 2.8). Weir six again became problematic during late freshet, with negligible water depth due to lack of subsequent downstream structures. Water depths in the retrofitted M3S were found to be only slightly greater than in 2012 and again declined to negligible levels within the study period (Figure 2.8).

2.5.3 Nature-Like Choke-and-Pool Structure Performance (M2S)

The lower gross slope of M2S allowed for a less intrusive construction than gabion weirs. The increase in M1L storage further reduced the gross slope to < 1%, creating more desirable flow conditions during freshet. The gross slope, and hence discharge, of M2S became negligible by 12 June 2012 due to increased water retention in M1L (Figure 2.7). Nevertheless, M2S continued to connect the two lakes until late July, when evaporation caused lake levels to decline below the shallowest point in M2S. This point in M2S was approximately 10cm deep at the time discharge functionally ceased. Performance in 2013 was similar, although discharge continued through the entire freshet study period (Figure 2.7), likely due to differences in snowpack and timing of freshet.

2.5.4 Water Level Monitoring

Datalogger installation during freshet was highly dependent on snow pack, weather, and logistics of travelling to site, resulting in variable study periods. Water storage trends ranged from 0.04 to 0.46 cm/day through the common study period from mid-June to the end of July (Figure 2.9). Annual rainfall was comparable in 2010, 2012, and 2013, ranging from 72.5 mm to 95.8 mm whereas 2011 was much greater with 187.0 mm (Table 2-2). Water level elevations were measured on 10 June 2012 and 6 June 2013 to correlate with continuous water level data. Lake levels in 2012 appeared to decline at independent rates whereas in 2013 elevation differences between lakes remained similar through the study period (Figure 2.10).

Direct discharge measurements depict a sharp decline in M1S and M2S discharge through freshet in 2010, 2012, and 2013, whereas the 2011 study period appears to begin at a later freshet stage (Figure 2.11).

2.5.5 Fish Movement Results

Data from fish sampling (C. Cahill et al. *in prep.*) supported hydraulic measurements and observations during 2012. No fish were observed (visual surveys), captured (electrofishing surveys), or detected (PIT antennae and video cameras) between gabion weirs one and six in either M1S or M3S. However, in M1S we observed Arctic Grayling, Ninespine Stickleback *Pungitis pungitis*, and Slimy Sculpin *Cottus cognatus* upstream of weir one (approximately 10 total fish). We also captured Arctic Grayling (n=2), Lake Trout (n=3), Ninespine Stickleback (n=8), and Slimy Sculpin (n=1) immediately downstream of weir six. Similarly, in M3S we captured Ninespine Stickleback (n=2) immediately below weir five (i.e., the lowest unsubmerged weir). Conversely, in M2S we documented fish throughout the fishpass; we observed

Ninespine Stickleback (n=2) during visual surveys, and captured young-of-year Burbot (n=4) and Slimy Sculpin (n=1) during electrofishing surveys. PIT antennae in M2S detected Arctic Grayling (n=20) making a total of 140 passage events (74 upstream passage events vs. 66 downstream passage events). Similarly, Arctic Grayling were observed spawning in this fishpass using video cameras.

During 2013, fish surveys in the fishpasses once again supported hydraulic observations. In M1S, visual surveys detected Arctic Grayling (approximately 5) spawning immediately upstream of weir one in M1L, and subsequent visual surveys detected young-of-year Arctic Grayling (>500) passively migrating downstream through this fishpass and into Lac de Gras. Electrofishing surveys in this fishpass captured young-of-year Arctic Grayling (n=22) and Ninespine Stickleback (n=7). However, no tagged fish were detected migrating through this stream using PIT antennae. In M3S, one Slimy Sculpin was observed between weirs two and three during visual surveys and was subsequently captured during electrofishing surveys. No tagged fish were detected migrating through this stream using PIT antennae. Visual surveys in M2S detected young-of-year Arctic Grayling (approximately 30), and electrofishing surveys captured young-of-year Arctic Grayling (n=1) and Ninespine Stickleback (n=1). PIT antennae in the M2S fishpass detected Arctic Grayling (n=22) making a total of 64 passage events (32 upstream passage events vs. 32 downstream passage events).

2.6 Discussion

Variations in M-Lakes storages were sensitive to yearly hydrological variability. Spring runoff and summer evaporation dominated the water balance. An overestimation in M1L storage decline due to evaporation during June 2012 indicated the presence of additional, unaccounted infiltration and/or surface runoff. M1L and M3L water levels both showed baseline trends of -0.33 cm/day and -0.14 cm/day for 2010 and 2011, respectively. After construction, trends between the two lakes were less comparable. M1L declined faster than M3L in 2012, at rates of -0.42 cm/day and -0.36 cm/day, respectively, suggesting improved hydraulic connectivity from M1L to LDG. Given the storage trends of M3L over the same period, the change in M1L appeared due to a larger fraction of available water storage leaving M1L in outlet discharge than in baseline years. In 2013, while the decline in M2L was similar to 2012, the M1L and M3L declines slowed to rates of -0.18 cm/day and -0.23 cm/day, respectively, following the retrofit process. This suggests M1L and M3L retrofitted outlets restricted discharge more effectively, prolonging duration of flows. Retrofitted M1S and M3S provided improved connectivity due to the re-sloped gabions that created an unimpeded hydraulic connection rather than a sudden drop. Greater variability in M2L trends through baseline years suggests more sensitivity to hydrological variation. The small and inconsistent elevation difference between M1L and M2L in 2012 was attributed to the increase storage retention in M1L, causing imbalances in the system. After this initial stabilization period, the larger and more consistent elevation difference in 2013 was attributed to an undisturbed hydraulic connection, allowing for the M1L water level to impact M2L.

Stream discharges were correspondingly variable, as they are governed by lake water levels. In 2012, M1S discharge was not yet controlled effectively, therefore discharge dropped quickly after freshet. This effect was mitigated with a change in outlet geometry for the 2013 freshet. Peak storage levels remained higher than the outlet control, and even after a slight drop in lake level, the outlet was able to control flows effectively. To optimize performance, this type of outlet could be elevated while creating a deeper rectangular notch to eliminate the initial unconfined peak discharge and maximize lake storage retention. It is important to consider notch depth, as this governs the minimum lake storage that will contribute stream discharge. Creating a notch that is deeper than the natural outlet elevation would decrease lake storage and impact adjacent habitat.

M3S discharge was inconsistent after construction and difficulties were found when designing for an increased discharge. Natural M3S discharges were very low, therefore creating and sustaining discharges comparable to M1S and M2S would have produced a more drastic effect on M3L storage, which its smaller direct catchment area could not sustain. There was very little response to outlet changes, indicating an enhanced connectivity objective may not be appropriate for a lake and catchment of this size.

Maximum unit yield is an indicator of the efficiency in which a catchment moves water to its outlet. Compared to other lake-outlet systems in the Barrenlands region, the M-Lakes and most systems studied by Baki et al. (2012) have much smaller catchment areas but much larger maximum unit yields than those nearby systems from Jones et al. (2003a and 2003b) (Table 2-3). The former sites thus have larger effective catchments relative to their catchment area. This may result in larger discharge variability, as available runoff will move through the system faster, creating relatively higher peaks that decline more rapidly. Hence, issues associated with enhancing connectivity in systems with smaller catchments, such as limited water availability, are exacerbated by the higher unit yields. The outlet modifications also indicated that larger catchment areas will respond to outlet changes more effectively than smaller catchments, which therefore may be more difficult to enhance.

It is important to identify characteristics of sites that can benefit from enhanced connectivity to achieve habitat compensation objectives. For headwater systems similar to this study, we suggest that candidate lakes need minimum catchment areas of 20 ha when outlet streams have slopes > 1% and 10 ha when outlet slopes are < 1% to ensure positive hydraulic responses, based on the responses observed at M-Lakes. Further study on various headwater lake sizes could refine these minimum areas. Effective in-stream structures for headwater systems may be possible for slopes greater than 2%, but are not recommended for remote settings such as the Barrenlands due to uncertainty of site characteristics and availability of appropriate materials. If connectivity is deemed important for streams with higher slopes, we would suggest first increasing stream length to create slopes of 1-1.5% to ensure reliable connectivity while minimizing the number of required in-stream structures. Constructing these in-stream structures in remote sites inherently poses difficulties in aligning as-built structures with the proposed design. There is less risk involved in reducing the channel slope for improved connectivity intended for fish migration however this strategy requires re-purposing nearby land which may not be possible. We recommend detailed assessments of candidate systems for future aquatic habitat compensation projects to investigate the viability of all compensation strategies from ecological, hydraulic, and constructability standpoints.

The life history characteristics and swimming abilities of Arctic fishes are diverse and generally understudied (Power 1997). However, we expected Arctic Grayling to use the M-Lakes fishpasses given they are strong swimming salmonids (adult fish have burst speeds from 162 to 213 cm/s) that often spawn in streams during freshet (Stewart et al. 2007; Northcote 1995). Moreover, the fishpasses at the M-Lakes compensation site were designed specifically for Arctic Grayling (Golder Associates 2001). Although they occurred in 89% of Barrenlands streams surveyed by Jones et al. (2003a), little information is available on Burbot ecology in Arctic streams (Birtwell et al. 2006). Adfluvial populations, which migrate from lakes to rivers to spawn, are known for the Arctic (Evans et al. 2002), however. With few exceptions, Lake Trout is a lacustrine species (Scott and Crossman 1973), but adfluvial populations exist that migrate up to 3 km to reach spawning areas (Loftus 1958). Ninespine Stickleback and Round Whitefish are typically found in shallow water habitats of lakes and slow flowing rivers and streams (McPhail and Lindsey 1970). Slimy Sculpin inhabit both lacustrine and riverine habitats (McPhail and Lindsey 1970; Scott and Crossman 1973). We are unaware of studies examining the burst swimming abilities of these fishes. However, generally speaking, Burbot, Ninespine Stickleback, and Slimy Sculpin are typically thought of as "weak swimmers" (Lucas and Baras 2001); their benthic habits would suggest that jumping over a 20-cm weir would be quite challenging. Additionally, young-of-year fishes are generally thought of as passive (i.e., downstream) migrants (Lucas and Baras 2001), owing to their small size (< 50 mm).

Unobstructed flows appeared to be an important factor in promoting fish migration. In M1S, re-sloping gabion geometries to a more gradual drop, which allowed for unobstructed flows in 2013 while maintaining sufficient water levels in pool sections, permitted at least downstream migration of young-of-year Arctic Grayling throughout M1S. In M3S, where hydraulic responses to structure modifications were less apparent, response in fish activity was correspondingly limited. Fish activity in M2S was similar in 2012 and 2013, suggesting that the differential responses in fish activity in M1S and M3S could be attributed to the structure modifications of the gabion weirs.

2.7 Summary and Conclusions

The M-Lakes system, three small Barrenlands lakes and their outlet streams, were modified to enhance connectivity suitable for fish migration. Gabion structures were found to be an ineffective design due to sudden drops and difficulty in sustaining suitable flow depths. Re-sloping gabion structures and dressing with boulders was more effective as flows became unobstructed and suitable flow depths were maintained through freshet. A nature-like choke-and-pool structure added to a lower-gradient stream proved most effective. A fish movement study supported the hydraulics findings.

Primary water balance mechanisms for M-Lakes were spring snowmelt through freshet followed by summer evaporation. As such, the capacity of headwater Barrenlands lakes to support additional loss of water via enhanced connectivity through outlet discharge during freshet will be based on catchment area; smaller systems convey water more efficiently, creating larger runoff peaks with shorter durations that are less desirable for migrating fish. To increase storage retention of freshet runoff for enhanced connectivity, outlet geometry must be considered. A narrow rectangular notch was effective for this application; discharges were decreased while flow depth and storage retention were increased, creating flows suitable for fish migration for longer periods.

Table 2-1: Summary of the characteristics of M-Lakes and associated streams.

Lake	Direct Catchment Area (ha)	Lake Area (ha)	Stream	Length (m)	Unmodified Slope (%)	Modified Slope[1] (%)
M1L	9.4	5.68	M1S	50.0	2.0	2.0
M2L	9.1	4.65	M2S	27.5	1.5	0.7
M3L	5.3	3	M3S	40.0	3.0	2.5

[1]Gross slopes of streams were altered through changes in lake storage and installed structures.

Table 2-2: Summary of lake level changes and annual rainfall.

	M1L (cm/day)	M2L (cm/day)	M3L (cm/day)	Annual Rainfall (mm)
2010	-0.33	-0.46	-0.33	72.5
2011	-0.14	-0.04	-0.14	187.0
2012	-0.42	-0.21	-0.36	75.8
2013	-0.23	-0.20	-0.14	95.8

Table 2-3: Maximum discharge and unit yield for M-Lakes and nearby study sites.

Site	Total Catchment Area (ha)	Maximum Discharge (m^3/s)	Maximum Unit Yield ($L/s/km^2$)
M1S	23.8	0.087	362.5
M2S	9.1	0.037	408.4
M3S	5.3	0.009	168.5
WIS[1]	32.0	0.158	492.5
R2S[1]	48.0	0.013	26.9
R6S1[1]	16.0	0.061	385.1
R6S2[1]	8.0	0.041	486.9
WGS-14[2]	717.0	0.235	32.7
WGS-39[2]	213.0	1.189	55.8
WGS-24[2]	1850.0	5.816	31.4
WGL-46[2]	290.0	0.064	22.1
WGS-35[2]	425.0	0.093	21.8

1. Baki et al. (2012)
2. Jones et al. (2003a and 2003b)

Figure 2.1: DDMI mine site is located 320 km northeast of Yellowknife, NWT in the Barrenlands region. The two open pits located in the image foreground were constructed over the Lac de Gras lake bed through the installation of dyke systems to allow for de-watering. The mine footprint caused extensive fish habitat loss, triggering habitat compensation projects to help offset environmental impacts. Photo courtesy Diavik Diamond Mines, Inc.

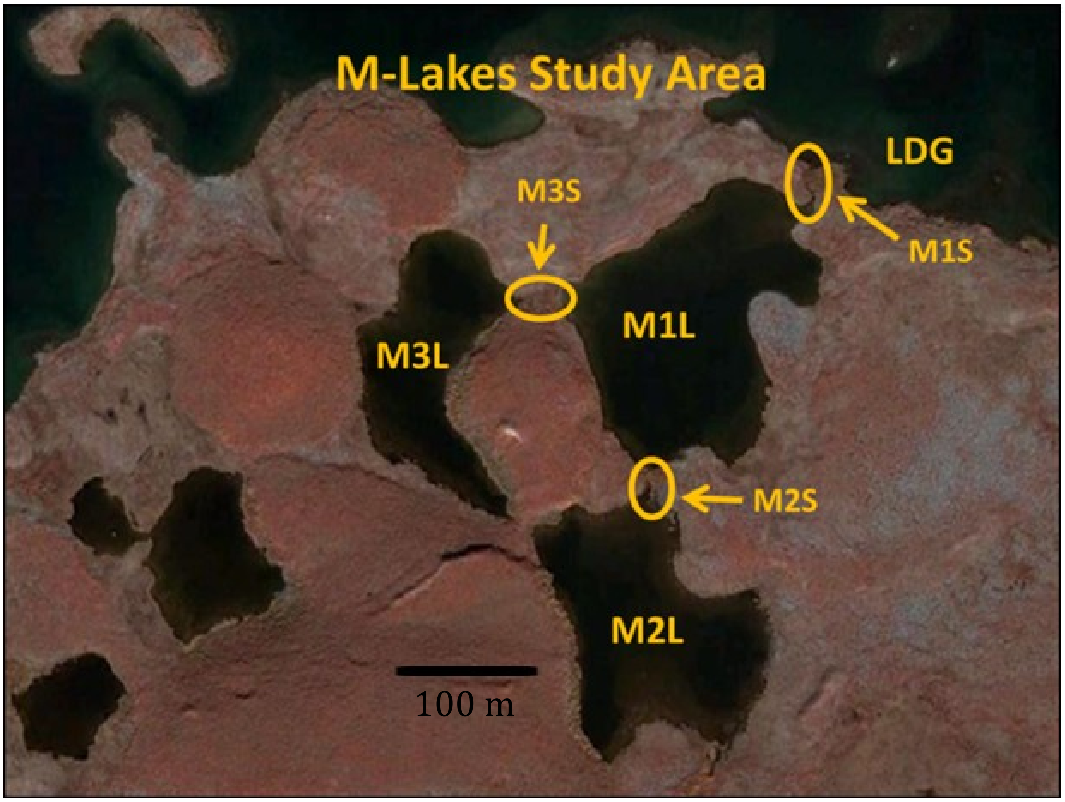

Figure 2.2: The M-Lakes system consists of two headwater lakes (M2L and M3L) that flow into a third lake (M1L) via two separate ephemeral streams (M2S and M3S); water then flows into Lac de Gras (LDG) via a third stream (M1S). Image adapted from Google Earth™.

Figure 2.3: Comparison photos of the original gabion structures (left) and retrofitted boulder structures intending to enhance lake-stream connectivity suitable for fish migration. The original gabion structures were found to be ineffective through a preliminary ecohydraulic evaluation during 2012 freshet and were retrofitted fall 2012. The structures shown include the three most upstream structures (weirs 1, 2, 3) of M1S, with M1L shown in the background; photos taken 2 June 2012 and 15 June 2013, respectively. The hoop-like structure in 2013 is a PIT-tag antenna to monitor fish movement. Weirs 1, 2, and 3 are shown.

Figure 2.4: Aerial photo of M1S with original gabion structures. Overlaid images depict the location and details of various retrofitted structures including weir one (left), weir two (bottom), weir five (right), and the channelized M1S-LDG connection (top). Aerial photo courtesy of Praetorian Construction Management.

Figure 2.5: Image of M3S with original gabion structures at weirs four (left) and five (right); image is facing upstream towards M3L. Overlaid images depict the location and details of various retrofitted structures including weirs four and five (bottom left overlay) and weir two with additional minor boulder structures (top right overlay). Top right overlay image is located behind the bank in the main image and is not visible.

Figure 2.6: M2S choke-and-pool structure, facing downstream towards M1L. Preliminary evaluations indicated project goals were successful for this structure. A retrofit was not necessary unlike M1S and M3S. Fish were documented using M2S in 2012 and 2013.

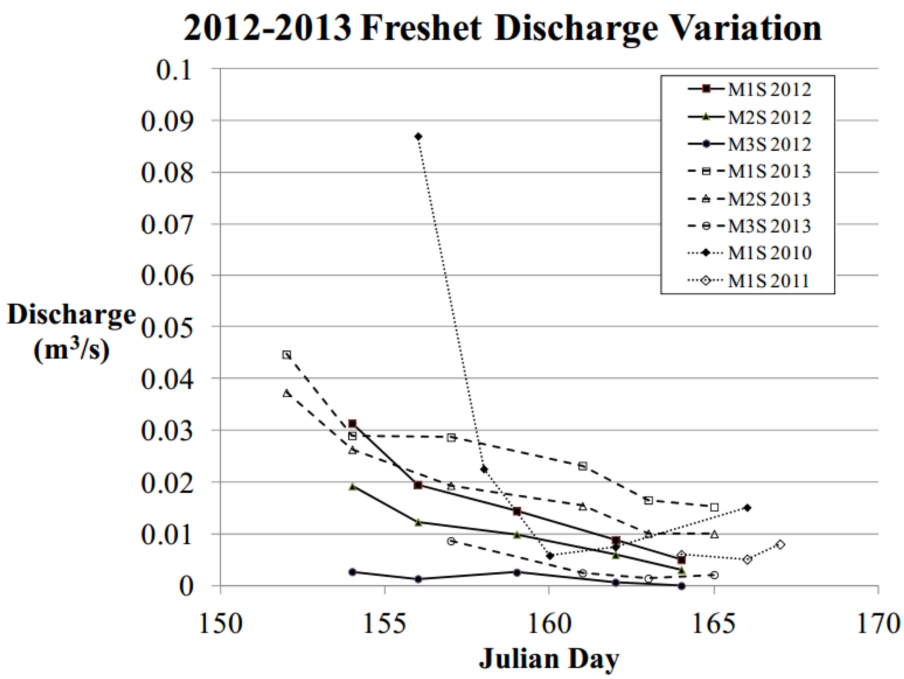

Figure 2.7: Post-construction (2012-2013) freshet direct discharge measurements from the three M-Lakes outlet streams; also shown are 2010-2011 baseline discharge measurements from M1S. Measurement dates were dependent upon logistics of travelling to site.

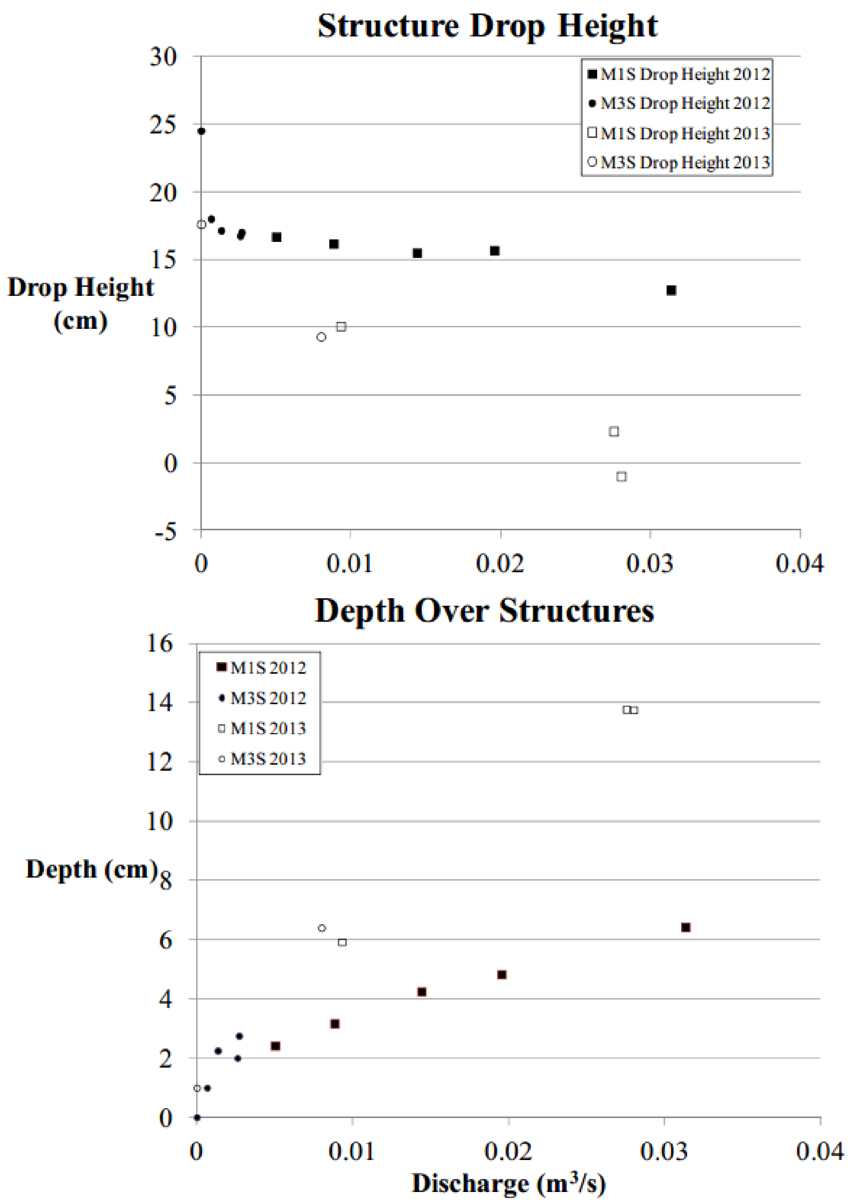

Figure 2.8: Mean drop height and mean depth over structures for M1S and M3S during freshet, before and after gabion retrofitting (2012 and 2013, respectively). Negative drop height indicates submergence relative to adjacent downstream water level.

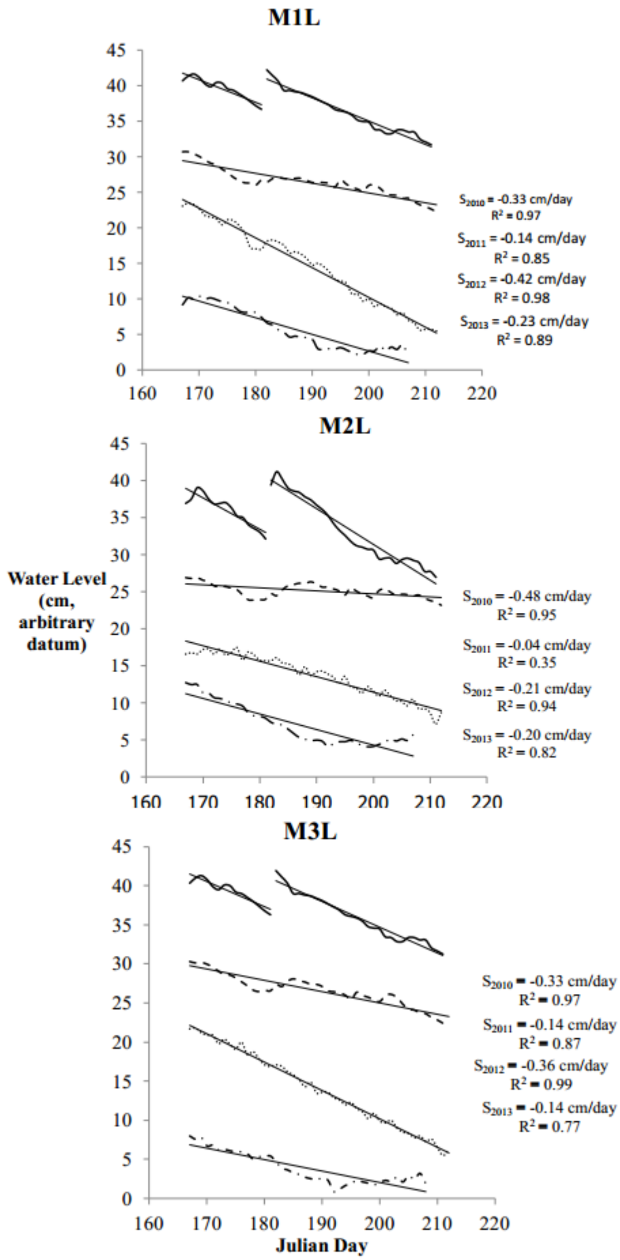

Figure 2.9: Comparison of daily averaged M-Lakes water storage trends. Water level datum is arbitrary for each lake and year. A significant rainfall event in 2010 required independent storage trends to be calculated before and after to reduce skew. These trends were then given a weighted averaged to obtain a single 2010 trend for each lake.

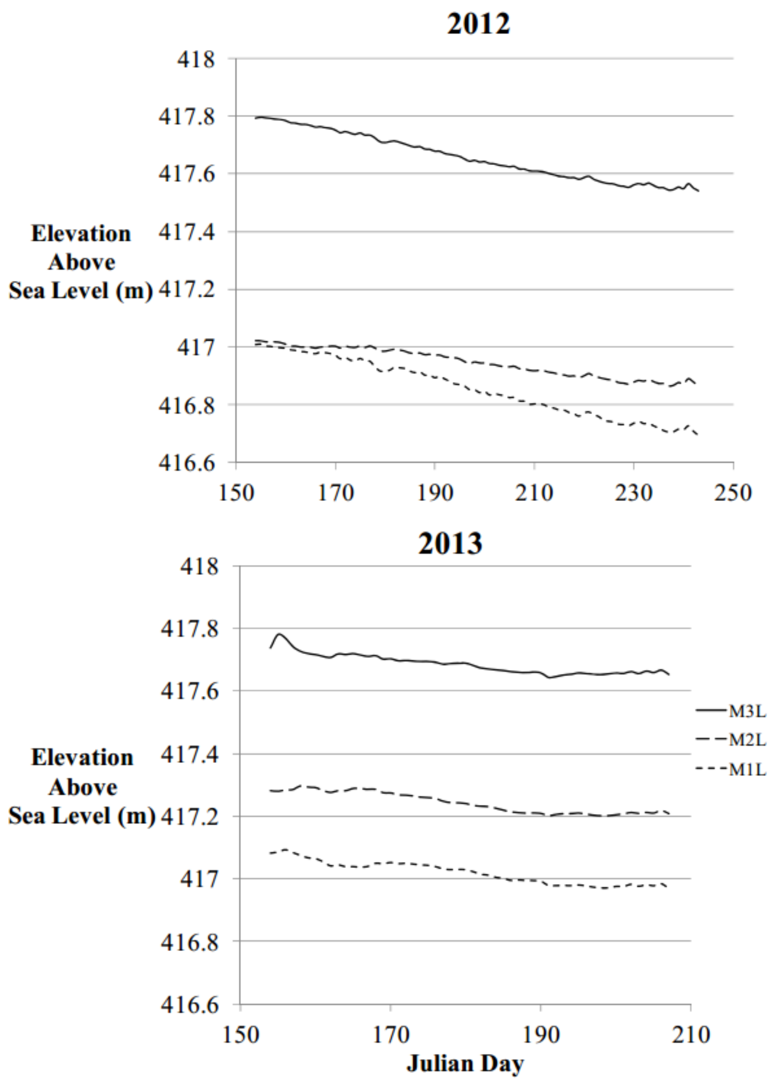

Figure 2.10: M-lakes elevations above sea level for 2012 and 2013. We attribute the less uniform 2012 lake elevations to the introduction of structures into the system, causing changes in available lake storage.

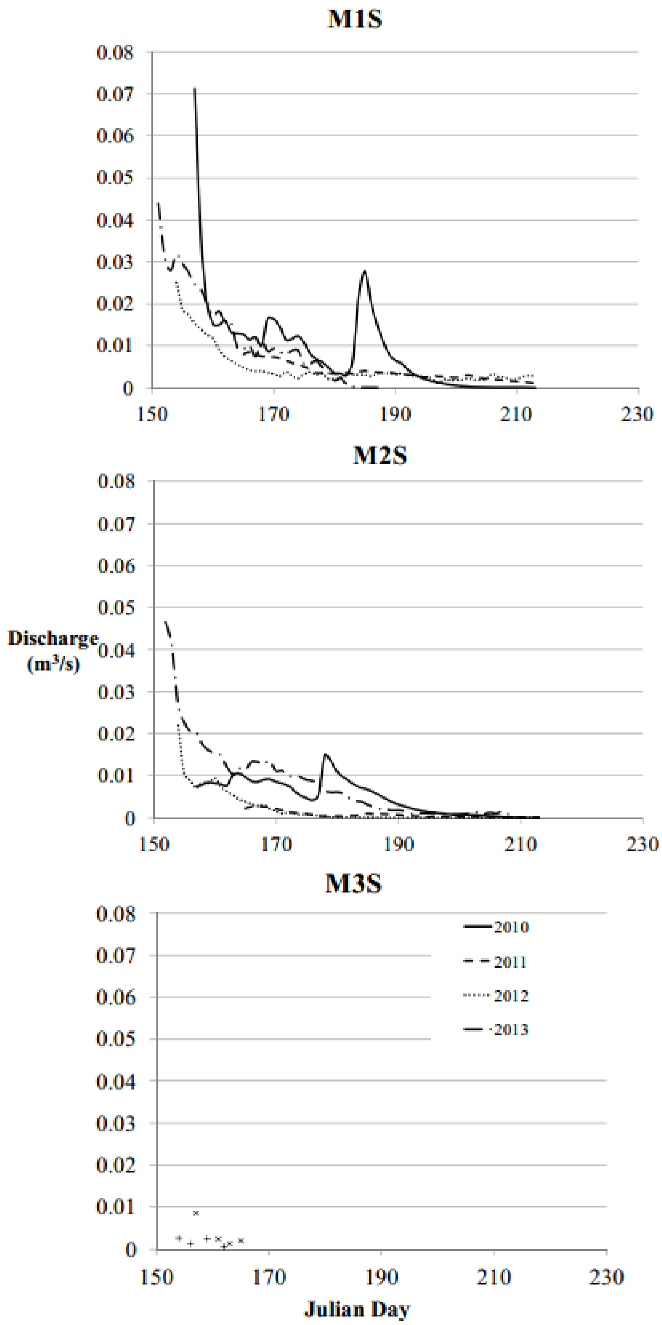

Figure 2.11: Comparison of discharges of M-lakes outlet streams, 2010-2013. Direct discharge measurements are presented where depth-discharge correlations were poor (M3S); pre-construction M3S discharges were omitted as flows were negligible.

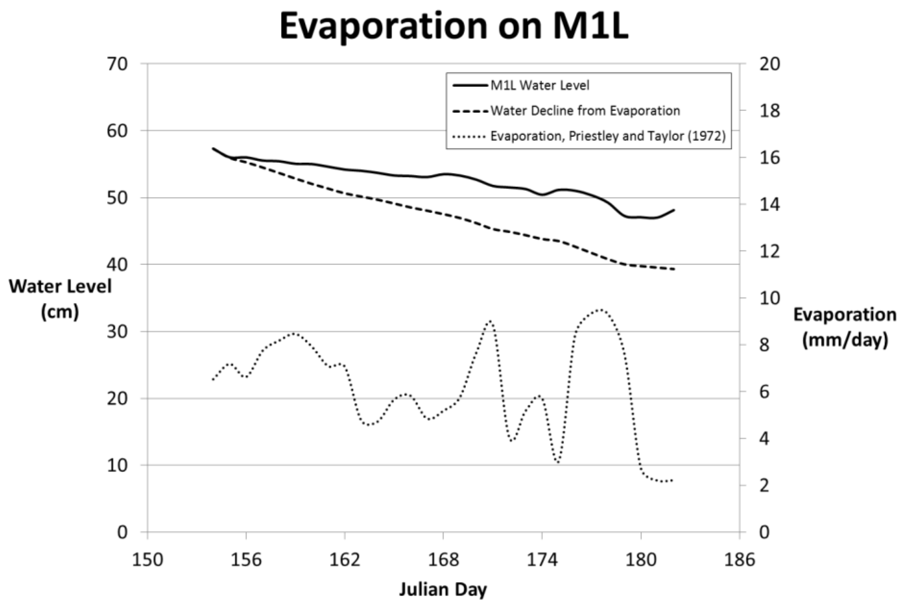

Figure 2.12: Contribution of evaporation to M1L storage during 2012 study period. Water level decline due to evaporation was calculated by the Priestley and Taylor (1972) method. An overestimation of M1L water declines indicate additional, unaccounted for infiltration and/or surface runoff.

Chapter 3

Design and preliminary hydraulic evaluation of modifications to a natural stream for fish passage and habitat enhancement in the Barrenlands region of Canada

3.1 Introduction

In systems where stream hydraulics are unsuitable for fish habitat, channel modifications may be possible to enhance the existing aquatic environment. If stream gradients are too steep, hydraulic structures may be installed to dissipate energy and maintain sufficient water depth. Conversely, if gradients are lower but unconfined, fish habitat may be improved by creating a more defined channel resulting in structured habitat with greater flow variability (Wesche 1985). Designing hydraulic structures to enhance aquatic habitat requires an understanding of the major hydrologic and hydraulic mechanisms governing stream flow at a specific site. For example, in small ephemeral headwater systems where flows are very sensitive to available upstream storage and direct catchment areas, channelization of a stream causes a greater portion of the water balance to be conveyed as stream flow, which in turn increases the potential for enhancing habitat characteristics; however, the stream will convey this water more efficiently, increasing velocities and decreasing the duration of flow, necessitating the installation of hydraulic structures. Thus, describing and quantifying hydraulic responses is important to understand impacts of stream modifications for successful enhancement of fish habitat within an ephemeral headwater lake-stream system.

Few case studies have been published investigating the efficacy of hydraulic structures within natural stream channels for fish passage. Weibel and Peter (2012) determined passage efficiency in block ramp type NLFs was impacted by size selectivity, indicating smaller fish had more difficulties navigating; they also suggested that vertical drops may inhibit upstream passage efficiency, especially in small-sized species with low leaping potential. Our concurrent study (Courtice et al. 2014, Cahill et al. *in review*) also found that vertical drops using gabion weirs were ineffective in promoting fish passage for Arctic Grayling and other native Barrenlands fishes. Retrofitting these structures with a centre notch to create an unimpeded flow path was found to pass some fish downstream. Wang and Hartlieb (2011) found water depth was a more important indicator of NLF performance than velocity, especially under low flow conditions; they suggest a detailed hydraulic investigation be conducted to identify important site-specific criteria for the assessment of fish passage in NLFs. Wang and Hartlieb (2011) also found through various laboratory and field observations that the arrangement of boulders was considered important for passage efficiency; creating gaps between boulders was found to be preferential over one opening above flat boulders, hence multiple slot openings is preferred. Franklin et al. (2012) suggested natural substrates are more acceptable for success in low gradient fishways indicating use of natural materials on site is beneficial when designing NLFs. However, due to minimal published studies it is difficult to determine if this is always the case. Nevertheless, Calles and Greenberg (2007) found that NLFs were effective in providing passage for a wide range of fish species, indicating more suitable flows for species of different swimming abilities. Calles and Greenberg (2005) also found on the same study sites that anadromous Brown Trout *Salmo trutta* yearling densities upstream of NLFs were noticeably improved compared to control sites, indicating NLFs reduced impact on Brown Trout life stages due to impediments within the river systems. The lack of definitive results presented among these studies and site-specific variability inherent to each NLF design suggest detailed hydraulic analysis on as-built NLF structures is necessary to more fully understand hydraulic responses and their habitat impacts to NLF designs.

In 2012, Diavik Diamond Mines, Inc. (DDMI) initiated the West Island habitat compensation project to help offset aquatic impacts due to mining activities. DDMI is located 320 km northeast of Yellowknife, NWT, in the Barrenlands region of Canada. The Barrenlands consists of interconnecting lake-stream systems with relatively low topographical relief (<50m). Lakes range in size from small headwater lakes (<5 ha) to much larger lakes (ca. 57 000 ha) such as Lac de Gras. The climate is characterized by long, cold winters, quick and extreme spring flooding, and cool arid summers (Gibson et al. 1994). The water balance is governed primarily by spring snowmelt and summer evaporation. The West Island study site is located approximately 5 km west of DDMI within the Lac de Gras watershed (Figures 3.1 and 3.2).

The West Island compensation project intended to enhance fish spawning habitat and connectivity between a small headwater lake, West Island Lake (WIL), and Lac de Gras (LDG). WIL is 13.65 ha in area with a direct catchment area of 30.08 ha. Changes in water storage within WIL are governed by spring snowmelt from its direct catchment, summer evaporation, and outlet discharges from a single stream (WIS) connecting WIL to LDG (Baki et al. 2012a). WIS is an ephemeral stream with an overall gross slope of 1.88%; a cascade section that impeded fish passage was present near the downstream end, while several poorly defined floodplain reaches were also present throughout the stream (Baki et al. 2012a).

Currently, there is little understanding of the impact of manipulating Arctic headwater systems for fish habitat enhancement (Courtice et al. 2014; Baki et al. 2012 a/b; Jones et al. 2003a/b/2004). Baki et al. (2012 a/b) conducted studies on WIS to characterize hydrology and hydraulic characteristics prior to habitat enhancement efforts, and provided important baseline information on natural stream characteristics prior to modification. We investigated various connectivity enhancements of a nearby habitat compensation project (M-Lakes) consisting of a set of three small headwater lakes and ephemeral streams in a concurrent study (Courtice et al. 2014). Courtice et al. (2014) showed that catchment size and stream gradient were indicative of a system's fish habitat enhancement potential in headwater lake-stream Barrenlands systems. We suggested that when a similar system has a catchment area >20 ha, fish habitat enhancement may be possible and recommended an optimum stream gradient of 1-1.5% (Courtice et al. 2014). Therefore, potential existed to enhance stream habitat at the West Island compensation site (catchment area of 30.08 ha and gross stream slope of 1.88%) by reducing the stream slope where possible and installing in-stream structures. Constructing effective in-stream structures in WIS is a more critical aspect in the project's success as there are a much larger number of impediments (>25 structures) than in M-Lakes (≤6 structures per stream).

We investigated changes to the hydraulic characteristics of WIS in response to a field engineering approach developed to design and construct modifications of a remote headwater stream. Impacts of modifications to hydraulic characteristics before and after modifications were quantified by analyzing hydraulic responses to installed structures, in addition to monitoring changes to the stream's hydraulic gradient, discharge hydrograph, and at-a-station hydraulic geometry. Our objectives were to (1) develop a successful field engineering approach to the design and construction of NLF structures in a remote environment, (2) determine if there was a noticeable response in the stream's hydraulic characteristics after modifications, and (3) characterize and evaluate the hydraulic performance of these structures based on fish habitat enhancement goals.

3.2 Methods

Baseline hydraulics data were collected spring and summer 2010 and 2011 while post-construction hydraulics data were collected spring and summer 2013. Data included discharge, local maximum flow depth, relative water level elevation, continuous water level at a downstream cross-section, and visual observations.

Water levels were monitored continuously at 15 minute intervals with SWS Mini-Diver pressure data loggers. Data loggers were installed during freshet. Divers were tied to boulders and placed in streams where direct discharge measurements were collected to develop depth-discharge rating curves. Locations were chosen based on areas of uniform channel geometry where flow was developed and backwater effects were not present. As such, post-construction measurement cross-sections were altered from pre-construction locations to ensure suitable flow locations. An SWS Baro was placed on shore adjacent to the stream to account for atmospheric pressure variability.

Water surface elevations and local maximum depths were measured every 10 m. Leveling was done using a laser level (model AGL EAGL 3000S) while depths were measured with a metre stick. The leveling rod was placed at the water surface, resting on an adjacent bank or boulder at the appropriate elevation to stabilize the rod prior to reading the elevation. The most downstream measurement was set to an elevation of 0 m. Local maximum depth measurements were taken at the same time as leveling allowing us to simultaneously obtain streambed elevations; depths were measured at the deepest point in all measurement cross sections.

A channel was constructed to bypass the cascade section and various nature-like fishpass (NLF) structures were installed within all reaches of WIS using natural materials (e.g. cobbles, boulders, and vegetation) found on site. Gravel sourced off-site was placed on the bed of the excavated channel to provide spawning substrate and minimize sediment transport. Willows were harvested from the disturbed tundra and transplanted into the newly excavated channel to stabilize banks, improve cover, and create large woody debris structures to further enhance aquatic habitat. Willows were mainly transplanted in the upper two-thirds of the fishpass.

Detailed design was developed in an adaptive, field engineered approach during construction to ensure proper connectivity to address the remote and uncertain nature of the site environment. Our primary design considerations included (1) controlling flows in periods of high (spring) and low (summer) discharges; (2) minimizing drop heights and creating unimpeded flow paths to minimize the potential for young-of-the-year (YOY) fish to get trapped during extremely low discharges; (3) increase flow variability to enhance stream habitat; and (4) salvage and incorporate vegetation disturbed from construction activities into riparian and in-stream habitat structures when possible.

3.3 Structure Designs and Stream Modifications

The primary challenge associated with using materials available on site is to ensure the as-built structures align with their intended purpose. Variability in materials (e.g. quantity, size, and shape of boulders) will impact how each structure performs, therefore it is important to have a comprehensive understanding of the intentions behind the design when installing structures. This understanding aids in overcoming unforeseen circumstances that require modifications to the original design. We created several unique stream reaches, each featuring various structures to provide suitable connectivity and habitat primarily for Arctic Grayling *Thymallus arcticus*, however other native species (Burbot *Lota lota,* Lake Trout *Salvelinus namaycush,* Longnose Sucker *Catostomus catostomus,* Ninespine Stickleback *Pungitius pungitius*, Round Whitefish *Prosopium cylindraceumi,* and Slimy Sculpin *Cottus cognatus)* were also given consideration in the designs. Once preliminary structure installation was completed, pumps were used to manipulate stream discharge to investigate hydraulic responses to our modifications. We focused on optimizing structure alignment to appropriately control low flows, which we deemed a more difficult consideration for our designs than controlling high flows. We then addressed the four main design considerations discussed previously, prior to construction crews leaving site.

Construction began fall 2012 when very low flows were naturally present in the stream. A multi stage process was used to field engineer stream modifications to optimize stream suitability for fish migration and habitat enhancements. First, the channel was excavated to create a more defined channel which eliminated undefined floodplain reaches and bypassed a steep cascade section to reduce the stream gradient in this reach (Figure 3.2). Second, we assessed each excavated stream reach to determine the most appropriate use of the limited materials available on site based on various channel characteristics such as gradient, geometry, and natural substrate. Finally, we constructed and optimized our designs by artificially increasing discharges with pumps to fine-tune the structures, ensuring high and low flows were properly controlled.

Stage 1 – Channel Excavation: Prior to excavation, there was considerable uncertainty to the characteristics of the soil underneath the excavation alignment. We based the excavation on a proposed preliminary alignment, however, the as-built channel was modified in the field based on site conditions. For example, certain sections consisted of very large boulders that were too difficult to move with the equipment available on site; thus, we incorporated immovable boulders into the stream design.

Stage 2 – Assessment of Stream Reaches: We identified unique characteristics within each individual stream reach. Three primary gradient categories, defined as high (2.5-5%), medium (1.5-2.5%), and low (<1.5%), were found to require different approaches to effectively enhance fish habitat. After an initial assessment, various design intentions and applicable structures were chosen for enhancing each reach based on identified challenges (Table 1). For all reaches, increased flow variability was required to enhance the variety of habitats available for fish to use. For steep gradient reaches, more obstructive structures, such as boulder weirs, were required to effectively reduce velocities and increase flow depths. We found these more obstructive structures provided improved cover, flow variability, and created resting zones for fish. For medium gradient reaches, controlling velocity and depth was still necessary in some cases, but to a lesser extent. Less obstructive structures, such as rock ramps and boulder chokes, were used to ensure suitable flow depths while increasing flow variability and creating resting zones. These structures do not provide as much cover as boulder weir structures, so riparian vegetation (i.e. transplanted willows) was incorporated into the banks to improve cover. For mild gradient reaches, hydraulic structures were not necessary to control flows. Riparian vegetation and in-stream woody debris were installed to increase cover and flow variability. Woody debris was used to a lesser extent throughout the entire stream to promote growth of benthic communities.

Stage 3 – Construction and Optimization of Structure Designs

The three primary structure designs developed were boulder weirs, boulder chokes, and rock ramps. All boulders were obtained on site from excavated material or found nearby. Priority for boulders was given to highest gradient sections to ensure effective hydraulic controls were constructed. A well-graded mixture of cobbles and gravel was placed around the structures to ensure interfaces between boulders were properly sealed. Boulders were also used to armour the stream banks; more extensive armouring was constructed adjacent to hydraulic structures to ensure flows could not outflank structures. Gravel was used to line the newly excavated channel to improve habitat and reduce sediment transport. There was a limited supply of gravel so priority was given to the steeper and more downstream reaches as we deemed these locations more likely for fish to use for spawning.

After initial structure installation was complete, water was briefly pumped into the stream to simulate flow rates varying from 1 to 15 lps allowing us to optimize structures for high and low flow periods. Water was pumped from WIL into WIS and subsequently pumped out near the outlet onto the tundra to ensure sediment did not enter LDG. We did not want to adversely impact water storage in WIL therefore we only pumped a total of approximately 10 000 litres over 30 minutes, equivalent to a lake level decline <0.1mm (G. Courtice, unpublished data). We assessed structures while flow was being manipulated to address our four primary design considerations: (1) control high and low flows, (2) create unimpeded flows to prevent fish isolations, (3) optimize flow variability, and (4) incorporate vegetation to further enhance fish habitat. We did not always incorporate all four considerations within a single reach if the proposed design intentions were already being met using fewer. For example, many boulder weir structures were providing suitable cover and flow variability without incorporating vegetation. Structures were monitored through the entire flow manipulation process to observe how flows around structures responded to the discharge changes.

3.3.1 Boulder Weir Design

Weir structures were constructed in steep gradient reaches. Our primary concern was impeding fish migration, especially during low flow conditions, while ensuring structures were large and stable enough to control high spring flows. Boulders were oriented in a configuration to convey low flows through several small sloped channels, while larger flows are controlled with major weir structures. In several cases where this was deemed insufficient for minimizing the drop height, we placed a deflection boulder against the bank, protruding into the channel immediately downstream of the main flow channel (Figures 3.3-3.6). In the most difficult cases where manipulating water levels was not effective, we lowered the weir crest height within the low flow paths while ensuring the adjacent upstream water level was not adversely impacted. This was accomplished by narrowing the primary low flow path and restricting discharge in secondary low flow paths, allowing a similar level of discharge to pass the structure.

3.3.2 Boulder Choke Design

Choke structures were constructed in medium gradient reaches where flow depth was deemed problematic or in sections adjacent to weir structures where subsequent downstream weirs were spread too far apart to provide suitable backwater effects to minimize drop heights. Small boulders (10-20 cm) were placed in the channel to control the minimum water level during low flows. These boulders were buried to create a control that was less than 10 cm above the stream bed to prevent connectivity issues. The choke width varied from 30-50 cm and functioned as a hydraulic control point during higher flow events (Figures 3.3-3.6).

3.3.3 Rock Ramp Design

A staggered arrangement of boulders was constructed in medium gradient reaches to control velocity and depth while maintaining continuous flow paths for fish migration. Flow variability is quite substantial in this boulder configuration, breaking up faster riffle sections with resting zones behind boulders. Boulder sizes were selected to not take up more than one-third of the channel width; no more than two-thirds of the channel width was impeded by boulders in a given cross-section (Figure 3.7).

3.3.4 Riparian Vegetation and Woody Debris Habitat Structures

We installed riparian vegetation into the stream banks to increase cover over the stream and to stabilize the bank. Willows *Salix spp.* were salvaged from the areas disturbed by construction activities and transplanted within the stream bank armouring along all reaches that could benefit from improved cover. The willow root systems remained intact throughout construction and installation, increasing the likelihood of root systems developing upon transplantation.

In-stream woody debris structures were installed along the stream to increase flow variability and promote benthic community growth. These submerged structures were keyed-in to the banks between boulders and protruded into the channel. Woody debris structures do not have intact root systems therefore are not expected to be permanent once degradation occurs. Instead, they are intended to promote initial growth of benthic communities and help accumulate additional woody debris for dynamically changing habitats.

3.3.5 Stream Modifications

Seven reaches (A through G) were identified within WIS based on channel geometry and stream gradient. These reaches were constructed to create combinations of unique structures and substrate based off the design process discussed previously.

A - Inlet (Figure 3.8): This reach is adjacent to WIL and consists of a silted bottom with large interspersed boulders. Slope is less than half a percent and channel width varies from 1 to 3 m. The channel splits into multiple sub-channels halfway down the reach; during construction, all channels but the main channel were blocked off to concentrate flows into WIS by placing large boulders into the sub-channel inlets.

During freshet, the region is an active floodplain therefore these hydraulic controls are only effective once water levels begin to decline. The constructed channel begins halfway down this reach after a natural choke point, ensuring discharges remain similar to baseline levels. Beginning at the excavated section, a more defined channel was created, consisting of gravel and cobble substrates to cover portions of the bed, improving fish habitat use potential and reducing sediment transport; no defined structures are present. Both pre- and post-construction upstream velocity measurement cross sections (VXS1-Pre and VXS1-Post) are located in this reach (Figure 3.2).

B - Pool and Weir One (Figure 3.9): Prior to construction, this section consisted of a wide, braided and unconfined section with very low velocities. Much of the unconfined surface runoff within this reach was eliminated due to the blocking of sub-channels in reach A. The constructed channel consists of boulder weir and choke structures with a slope of approximately 3% and is 1-2 m wide. The streambed is lined with gravel and cobble; we installed riparian vegetation and in-stream woody debris structures to enhance fish habitat.

C - Riffle One (Figure 3.10): This section was similar to reach B pre-construction. The constructed channel is 1-1.5 m wide, consists of a silt bed with few boulders and 1% slope. No boulder structures were required to control flows. We harvested willows and transplanted them into banks to provide additional cover; large woody debris was fixed in stream to improve benthic habitat and increase flow variability.

D- Rocky Ramp (Figure 3.11): Prior to construction, the unconfined flows found in reaches B and C began to concentrate in this reach. The constructed channel is 1 m wide and consists of a staggered arrangement of boulders ranging from 0.3 to 0.7 m in diameter with a 2% slope. The larger boulders are partially buried into the stream bank to reduce channel obstruction while improving flow variability.

E- Riffle Two (Figure 3.12): The pre- and post-construction channels are in similar locations throughout this reach. The constructed channel is 1-1.5 m wide. Slope is approximately 1.5% and similar in characteristic to Reach C, however the bed is comprised of more sand than silt and less vegetation cover. Pre- and Post-construction downstream velocity measurement cross sections (VXS3-Pre and VXS2-Post) are located in this reach.

F- Pool and Weir Two (Figure 3.13): The constructed channel is 1-2 m wide, slope is approximately 5% and similar in characteristics to Reach B. This is the steepest section; the channel was diverted and lengthened from the original stream reach which consisted of a cascade section with 13% slope, impassable by fish. Excavation was slightly altered from the proposed alignment as very large boulders imbedded in the ground could not be moved with the equipment available on site. In-stream woody debris was installed along this reach to improve flow variability and cover.

G- Outlet (Figure 3.14): The channel is 1-1.5 m wide and slope is 5%. This reach reconnects the diverted channel to the natural stream below the cascade section and then enters Lac de Gras. Gravels were placed over the excavated bed to improve fish habitat and minimize sediment transport. The last half of this reach is unmodified as we deemed its characteristics suitable for fish passage. Silt screens were installed after construction to reduce silt transport into LDG.

3.4 Results

Study periods during 2010 and 2013 began near the peak of freshet whereas 2011 began after much of the snowpack had melted; 2010 and 2013 study periods depict freshet characteristics more completely than 2011. In the beginning of the 2013 study period, there was a large snowpack present on Reach F (Figure 3.13). This snowpack caused some backwater effects however did not appear to impact the stream flow characteristics substantially during the study period as the high spring discharges had already created a subnivean channel. Spring discharges contained a substantial amount of silt due to the recently excavated channel which caused changes to the bed characteristics in riffle reaches C and E, where the slope becomes less steep (Figures 3.10 and 3.12). Deeper channels had substantial deposition which resulted in riffle sections forming. After approximately one week, sediment transport had declined noticeably.

3.4.1 Stream Discharges

Stream discharges during freshet are governed by the heightened upstream lake level, overland flooding, and groundwater contribution. Documenting upstream and downstream discharges is important to investigate stream modification impacts and the viability of creating and improving fish habitat and connectivity. Visual observations indicated less unconfined surface runoff post-construction.

Baseline measurements indicated maximum freshet flow at the upstream and downstream velocity cross sections (VXS1 and VXS3) of 0.03 m^3/s on day 159 (6 June) and 0.15 m^3/s on day 157 (5 June) for 2010, and 0.02 m^3/s and 0.01 m^3/s on day 165 (13 June) for 2011, respectively. Maximum freshet flow post-modification indicated maximum freshet flow in 2013 at the upstream and downstream velocity cross sections (VXS1 and VXS2) were 0.07 m^3/s and 0.10 m^3/s on day 153 (1 June), respectively (Figure 3.15). We documented near-peak freshet discharges in 2010 at VXS1 and in 2013 at both VXS1 and VXS2. It was not possible to obtain near-peak discharge measurements for 2010 VXS3 and for both cross sections in 2011 due to logistical constraints.

Stream flow contributions in addition to WIL outlet discharge (e.g. unconfined surface runoff and groundwater) may be approximated by assessing the difference in upstream and downstream discharges. Baseline years show variable contributions whereas post construction discharge measurements appear to show a uniform convergence of upstream and downstream discharges. Discharges in 2013 converge uniformly from day 153 (June 1) to 164 (June 12) where they remain approximately equal to day 167 (June 15). Trends between upstream and downstream discharges in baseline years are comparable, however do not appear to show a similar uniform convergence as in 2013 based on direct measurements and on-site observations.

In 2013, we were only able to collect the VXS2 datalogger for continuous discharge monitoring, therefore only pre-construction downstream (VXS3) continuous discharges are presented (Figure 3.16). Downstream measurements are indicative of all sources of water entering the stream and therefore are most representative of the discharge characteristics of the stream as a whole. Discharge was more variable in 2010 than in 2011 or 2013. Data collection in 2011 began after the high freshet discharges ceased and therefore a low, consistent discharge is present through the entire study period. Post construction discharge in 2013 indicated a less steep decline in initial freshet discharges, however near the end of freshet discharges were more comparable to 2011.

3.4.2 Water Level and Stream Bed Elevation Measurements

Maximum water depth measurements give indication to the hydraulic characteristics and suitability for fish migration within small headwater streams. The structures and substrate characteristics in a stream will cause flows to exhibit varying depth responses to differing slopes. It is important from a fish habitat and connectivity context to determine the suitability and threshold at which the stream will allow for sufficient flow depths. We surveyed the hydraulic grade line on 8 June 2013. The WIS bed elevation was calculated from direct depth measurements taken in conjunction with leveling measurements to determine the response of depth to hydraulic gradient (Figure 3.17). We found no apparent relationship between depth and gradient. We observed a greater variability in maximum depth where more extensive structures were installed, such as sections B and F. Section A and G where no defined structures were installed, were found to have the least variable maximum depth, however were also found to have the smallest maximum depths. Most of the smallest local maximum depths (~10 cm) within the entirety of WIS were located near the structures, indicating suitable controls were present to allow larger depths to be maintained elsewhere in the channel; these smaller depths were still deemed suitable for fish passage.

3.5 Discussion

Responses to modification in WIS may take more than one year to stabilize as substrates were quite mobile through the first post-modification study period.

Additional study years will be required to assess long-term responses. Nonetheless, it is important to investigate these initial results to elucidate immediate responses to system changes.

The range of discharges in WIS does not appear to be impacted due to modifications, however flows may be more consistent as the channel is better defined (Figures 3.15 and 3.16). For example, the relationship of upstream and downstream discharges during freshet is more consistent after modifications, converging throughout freshet to a comparable level once the snowpack has melted (Figure 3.15). Baseline measurements do not show as predictable of a relationship indicating a visible response to modifications has taken place (Figure 3.15). We speculate this observation may be attributed to the unconfined reaches of the pre-construction channel altering in characteristic as the snow pack melts and ground thaws, creating unpredictable hydrologic and hydraulic changes. One year of post construction data does not give us a definitive response to the long term impacts of our modifications as the channel is still quite dynamic and may take multiple seasons to stabilize.

At-a-station hydraulic geometry relationships were developed for post-construction velocity cross sections to compare with relationships developed by Baki et al. (2012) for pre-construction velocity cross sections and other nearby streams of similar size and characteristics. These relationships describe the response of cross-sectionally averaged depth, water surface width, and cross-sectionally average velocity to a change in discharge. The post-construction at-a-station coefficients and exponents are within the same range found prior to modifications and on the nearby natural streams, indicating hydraulic geometry relationships have not been considerably altered due to modifications (Table 3-2).

According to the pre and post modification discharge hydrographs, no visible changes have occurred to available stream flows in WIS during the first year post-modifications. We can expect these modifications will not impact flow duration as the headwater outlet was not modified therefore the primary catchment feeding WIS has not changed. Flows may be expected to stabilize to summer discharge levels (1-10 lps) towards the end of June (days 170-180). The success of stream modifications then becomes a function of in-stream structure performance and how effective flows may be controlled to ensure usable habitat.

The NLF structures were found to effectively control discharges in WIS on 8 June 2014 at 30 lps. A relationship between local maximum depth and hydraulic gradient was not apparent. This lack of relationship indicates the boulder structures controlled stream flows at all gradients found within the modified stream reaches (i.e. 1-5%). However as no other set of depth data was available from the post construction study period, we must determine structure responses and effectiveness through an assessment of the visible hydraulic responses during the optimization phase of construction (i.e. when discharges were manipulated) in conjunction with the preliminary hydraulic analysis.

3.5.1 Hydraulic Performance of Structures

Throughout freshet, high flows transition to low flows where various reaches of the stream exhibit unique characteristics as structure performance responds to changes in discharge. Low flows will persist through majority of the summer until flows nearly dry up by end of August or early September (Courtice et al. 2014).

During high flow periods where discharges inundate majority of the channel width, flows submerge the entirety of boulder weirs and are controlled primarily by choke sections rather than variations in streambed elevation. No substantial drops are present at boulder weirs therefore upstream water levels are noticeably impacted by subsequent downstream water levels. The low-flow paths constructed through weirs are deeply submerged. These narrow channels exhibit higher flow resistance than main channel flow, creating preferential low-velocity pathways for smaller fish where main channel flows may be too fast or turbulent to overcome. We observed less obstructive structures such as chokes and deflection boulders to have limited impact as hydraulic controls during very high flows as they are completely submerged, but still remain useful as habitat structures. A large portion of bank armouring is submerged, increasing flow variability which creates small resting pools near the banks. During the 2013 freshet period, these aspects of high flow conditions were apparent and structures controlled flows effectively in all reaches of WIS.

As high flows decline, water level drops over weirs become apparent and individual low flow paths begin to develop. Water levels upstream of weirs begin to decline at a decreasing rate as flows concentrate in low flow paths, restricting the channel width at weirs which in turn maximizes flow depths. Bank-side flow variability begins to develop less from bank armouring and more from woody debris structures.

Boulder weir structures exhibit zones of heightened velocity where flows concentrate in low flow paths and water level drops are present. We were unable to collect detailed velocity measurements at these sections due to difficulty collecting this data with equipment available on site. However, we can approximate maximum velocities by determining the corresponding head loss over the structures. These theoretical velocities indicate the level of difficulty fish may encounter when overcoming these structures. At the time of measurement on 8 June 2013 with a flow rate of 30 lps, drop heights were found to be 10-18 cm, which corresponds to maximum velocities of 1.4-1.9 m/s over distances of 10-30 cm. These velocities may pose challenges for fish, however the relatively short distances indicate these more challenging sections may be passable as burst swimming speeds do not have to be sustained for prolonged durations. In addition, these heightened velocities will provide enhanced attraction flows improving the likelihood for attempted fish passage.

Once low flows begin late June or early July, discharges are controlled primarily by low flow paths through boulder weirs and also by the channel gradient where weirs are not present. Flow depths through weir structures are governed by substrate characteristics, i.e. rougher substrates cause higher flow resistance and larger depths. The base elevations of choke structures govern upstream water levels which may determine upstream weir drop heights if a weir is nearby. Major habitat characteristics and flow variability are governed by in-stream woody debris structures and any remaining submerged boulders. During the optimization phase of construction, structure responses to low flows (1-5 lps) were observed. We deemed all structures to meet or exceed our intended designs, indicating fish passage was likely possible. These levels of flows were maintained through most of the summer according to the three years of discharge data presented. Therefore, we feel it is likely WIS may support suitable fish habitat extending through most of the summer, though additional study is needed to confirm our observations.

Designing site-specific structures based on challenges identified through construction was found to be an effective approach for successfully modifying WIS. Using materials found on site inherently creates highly variable structures that may be very sensitive to slight, yet unavoidable design adjustments. Therefore, it is important to understand the intentions behind the designs to properly adjust structures to incorporate the unforeseen challenges presented during construction. For example, boulder geometries are an important aspect of proper in-stream placement when constructing a weir structure. A slight change in the primary low-flow path of a weir to accommodate less preferable boulder shapes may cause drastic changes to the adjacent hydraulic grade line or unimpeded flow through the structure. Additionally, the as-built weir design must be robust enough to ensure that once the structure is deemed suitable, it will not be shifted in the future due to natural processes such as ice breakup or high flows in the spring. Conversely, incorporating complex configurations into less obstructive structures such as boulder chokes and rock ramps allows for natural processes to slightly alter boulder placement while maintaining its intended purpose. This dynamic aspect of these structures align more closely to similar processes inherent to natural streams, which may indicate further enhancement of the aquatic habitat over time.

3.5.2 Stream Suitability for Fish Habitat

Suitable fish habitat may be characterized in part by using hydraulic criteria such as substrate size, velocity, and depth (Wesche 1985). In natural systems, stream substrate size distribution correlates with velocity; high velocity reaches are associated with larger substrate such as cobbles and boulders whereas low velocity sections are associated with smaller substrate such as gravels, sands, or fines (Wesche 1985). According to the habitat suitability index graph for Arctic Grayling, maximal stream habitat usage will occur when substrates are 1-20 cm in diameter (Hubert et al. 1988). Prior to modifications, WIS substrate varied from gravel to boulders where D_{84} = 22 cm and D_{50} = 2.6 cm which may be considered suitable for Arctic Grayling habitat. Post modification substrate size distribution did not vary greatly from pre modification conditions, however due to the excavated channel, gravels were placed within the channel to simulate natural streambed substrate characteristics according to the preferential habitat criteria, i.e. substrate 1-20 cm in diameter. These gravels were placed mostly in the steeper reaches as would naturally occur. Finer substrate (sand/silt) were exposed due to the newly excavated channel and subsequently deposited in the lower gradient reaches (C and E) during the first freshet period. These reaches are less suitable habitat however they consist of less than 25% of the entire stream length and have suitable flow depth to allow fish to migrate to the preferred habitats. Furthermore, there is no evidence to support that intermittent sections of less suitable habitat is in any way detrimental to the productivity of the stream as a whole.

Jones and Tonn (2004) developed resource selection curves for small and large YOY Arctic Grayling in nearby Barrenlands study sites. Response shapes indicate that maximal habitat usage probabilities occurred at 13 cm depth and 2 cm/s velocity for small YOY Arctic Grayling, and 58 cm depth and 10 cm/s velocity for large YOY Arctic Grayling. Prior to construction, there were several cross sections that had average maximum depths lower than 10 cm, indicating sub-optimal conditions for both small and large YOY Arctic Grayling (Baki et al. 2012). After modifications, similar depths were found, however these depths were located near the installed structures, allowing majority of the stream to maintain depths greater than 10 cm for the entire study period.

3.6 Conclusion

We developed a field engineering approach and designs to modify a 420 m long stream using nature-like fishpass structures in the Barrenlands region of Canada. This project intended to offset aquatic impacts near Diavik Diamond Mines, Inc. An ephemeral headwater stream was modified to bypass a steep cascade section impassable by fish, create and enhance stream spawning habitat, and enhance connectivity between Lac de Gras and one of its headwater lakes, West Island Lake. Nature-like fishpass structures were constructed using boulders and vegetation available on site to create various structures such as weirs, chokes, rock ramps, riparian vegetation, and in-stream woody debris habitat structures. We developed designs on-site to overcome challenges such as high velocities, low depths, minimal cover for fish, and minimal flow variability, and thereby enhance aquatic habitat. These challenges varied in all seven stream reaches, defined primarily on stream gradient. Preliminary hydraulic results, in conjunction with initial observations, suggested these structures were effective in addressing all challenges presented. Preliminary responses to modifications after one year of post-construction data showed no apparent relationship existed between stream gradient and depth. Other hydraulic characteristics, such as at-a-station hydraulic geometry, exhibited similar characteristics comparable to other natural streams nearby. Preliminary observations showed structures promoted beneficial habitat characteristics such as a large flow variability, improved cover, and sufficient flow depths at a wide range of discharges. Findings may assist in the design and construction of future headwater stream modification projects to help ensure they provide their intended functions, especially in remote locations where resources and stream flows are limited.

Table 3-1: Challenges, design intentions, and applicable structure designs for enhancement modifications of various stream gradients.

Stream Gradient	Challenges	Design Intention	Applicable Structure Designs
2.5-5% (High)	High Velocity, Low Depth, Uniform Flow, No Cover	Reduce Velocity, Increase Depth, Create Resting Zones	Boulder Weirs, Boulder Chokes, Deflection Boulders
1.5-2.5% (Medium)	Possible High Velocity Possible Low Depth, Uniform Flow, No Cover	Increase Flow Variability, Increase Cover, Create Resting Zones	Rock Ramp, Boulder Chokes, Deflection Boulders, Riparian Vegetation
<1.5% (Low)	Uniform Flow, No Cover	Increase Flow Variability, Increase Cover	Riparian Vegetation, In-Stream Woody Debris

Table 3-2: Pre and post modification at-a-station hydraulic geometry relationships from WIS compared to the range of values found at nearby study sites. Post-construction velocity cross sections VXS1 and VXS2 correspond to pre-construction velocity cross sections VXS1 and VXS3, respectively.

Stream Name	Cross Section	No. of Observations	Water surface width $w = aQ^b$			Mean Depth $d = cQ^h$			Mean Velocity $v = kQ^l$		
			a	b	R^2	c	h	R^2	k	l	R^2
WIS (Post)	VXS1	6	1.37	0.08	0.92	0.84	0.5	0.99	1.25	0.55	0.92
	VXS2	5	2.44	0.22	0.93	0.63	0.43	0.91	1.17	0.49	0.94
WIS (Pre)[1]	VXS1	8	4.63	0.08	0.88	0.61	0.21	0.94	0.36	0.71	0.99
	VXS3	6	3	0.11	0.9	0.47	0.27	0.92	0.71	0.62	0.99
Nearby Unmodified Study Site Ranges[1]			1.32-4.63	0-0.4	0.35-0.94	0.16 to 0.61	0.1 to 0.27	0.46 to 0.96	0.36 to 1.55	0.43 to 0.85	0.89 to 1

[1] Baki et al. 2012 b

Figure 3.1: DDMI mine site is located 320 km northeast of Yellowknife, NWT in the Barrenlands region. The two open pits located in the image foreground were constructed over the Lac de Gras lake bed through the installation of dyke systems to allow for de-watering. The mine footprint caused extensive fish habitat loss, triggering habitat compensation projects to help offset environmental impacts. Photo courtesy Diavik Diamond Mines, Inc.

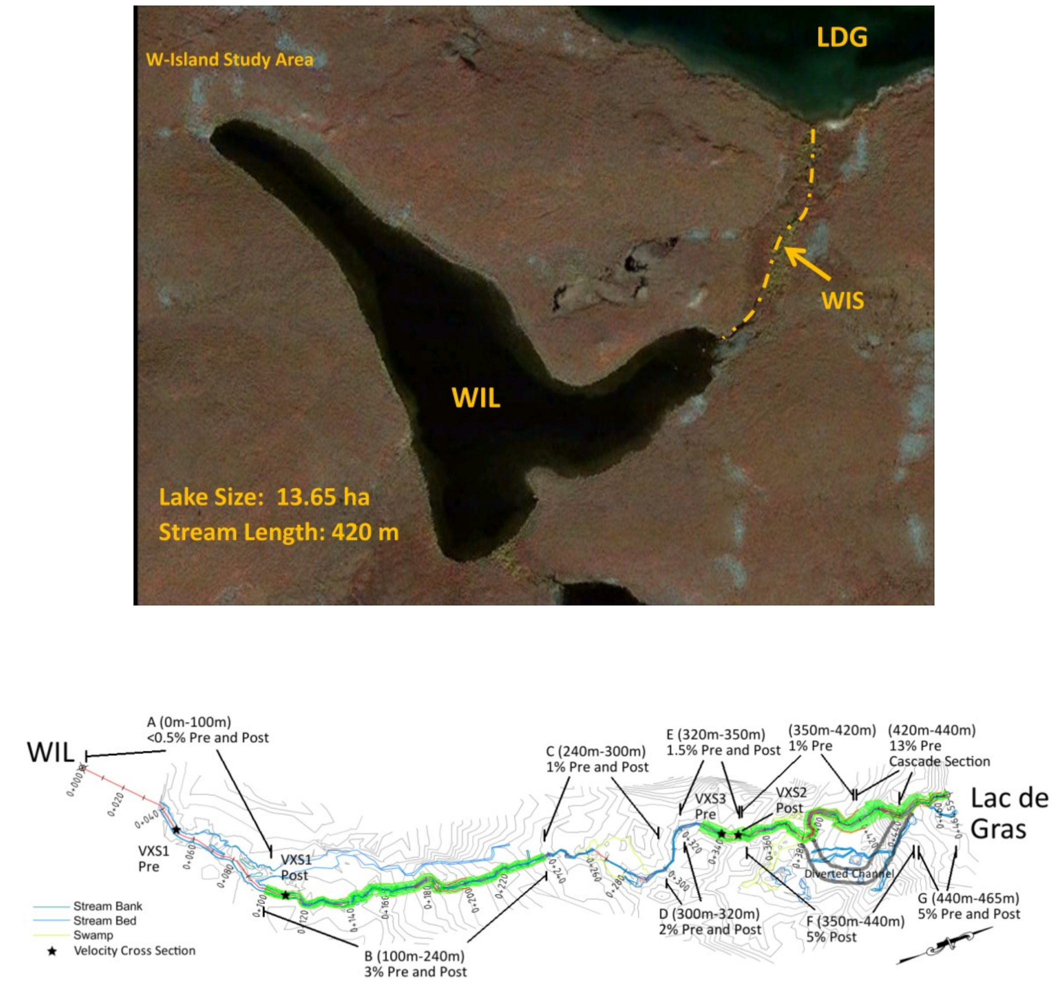

Figure 3.2: West Island study area (top) and stream alignment indicating unique reaches A through G. Diverted channel in reach F is identified from station 0+380m to 0+440m where a meander was created to the east of the original channel to bypass the cascade section. Locations of velocity measurement cross sections are also shown. Aerial image adapted from Google Earth™. Survey data and topographical drawing courtesy DDMI and Praetorian Construction Management.

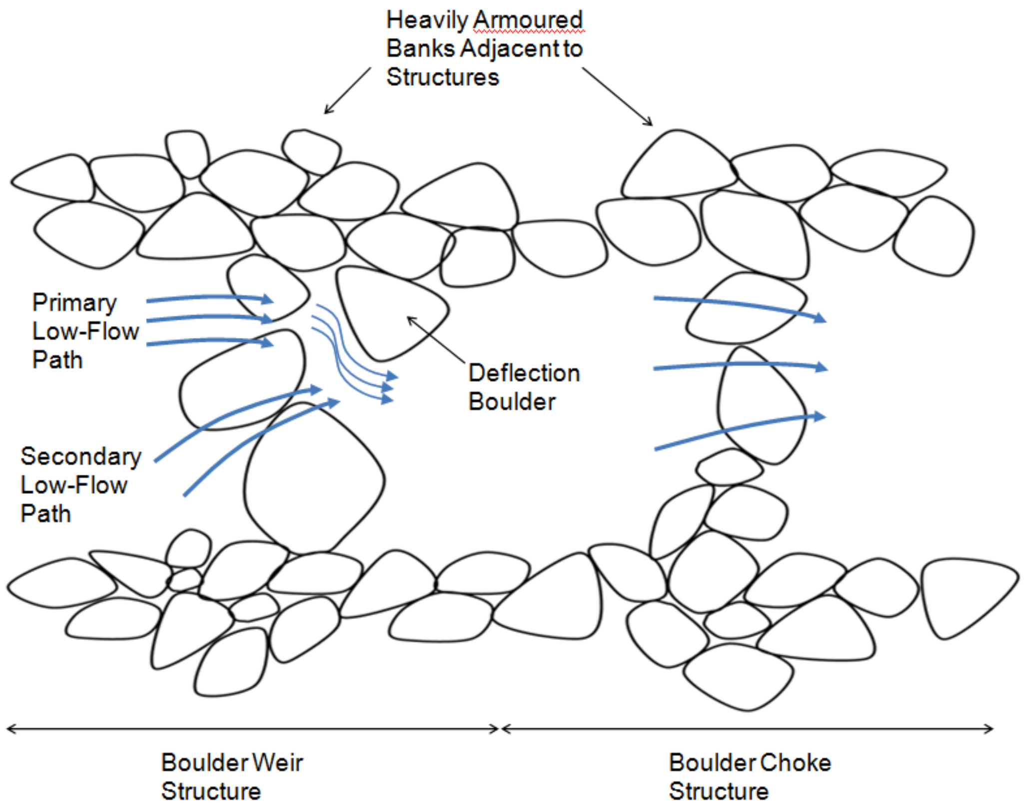

Figure 3.3: Plan view of boulder weir and choke structures installed in reaches B and F. As-built structures varied from single weir structures for lower gradient sections while higher gradient sections incorporated weirs with deflection boulders and in some cases choke structures when deemed necessary to reduce drop heights. Not to scale.

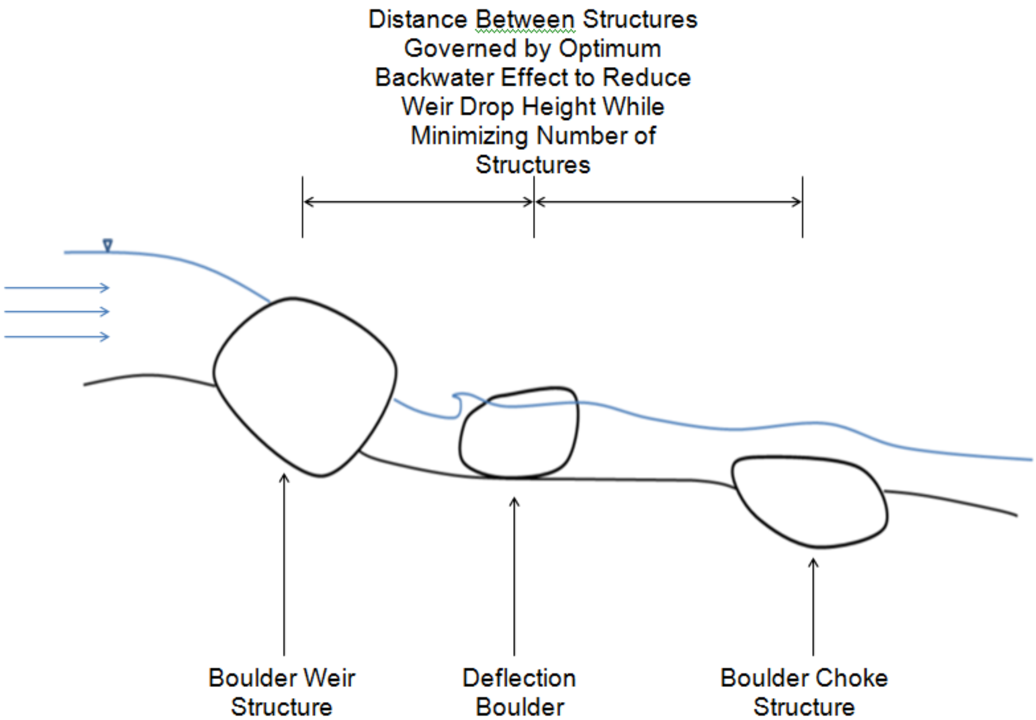

Figure 3.4: Profile view of boulder structures. If deemed necessary, we reduced the boulder weir drop height by placing a deflection boulder downstream and also a choke structure in higher gradient sections. The distance between each structure was governed by creating an appropriate backwater effect to reduce the upstream drop height while minimizing the number of structures required. Not to scale.

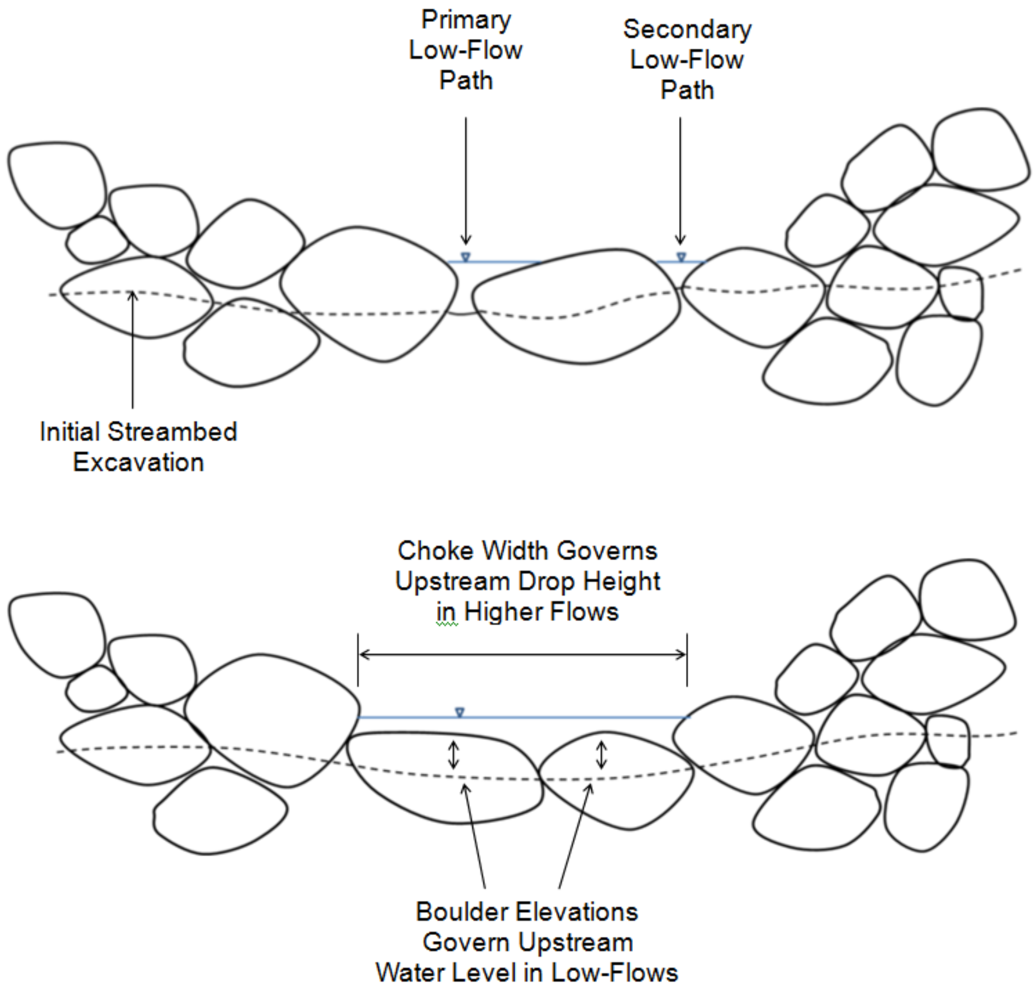

Figure 3.5: Cross-sectional view of boulder weir (top) and choke structures. Boulders were imbedded into the initial streambed excavation to obtain appropriate structure elevations. The boulder weir structure consists of one primary low-flow path and a secondary low-flow path. When higher flows are present, the larger scale structure controls the flow. The boulder choke structure consists of a narrowing of the channel. In low flows, the centre boulder elevation governs upstream water level whereas the width of the choke shall govern in higher flows. Not to scale.

Figure 3.6: Various as-built structures during construction in fall 2012. Boulder choke (top left) shown after construction with no flow; boulder weir (top right) with a very rough primary low-flow path to increase flow depth during very low flows is shown after construction with now flow; and boulder weir (bottom) with deflection boulder during optimization phase of construction with approximately 5 lps discharge. This level of discharge exhibits low flow characteristics as flows are concentrated in the primary low-flow path; the deflection boulder is noticeably increasing water levels immediately downstream of the boulder weir, reducing the drop height.

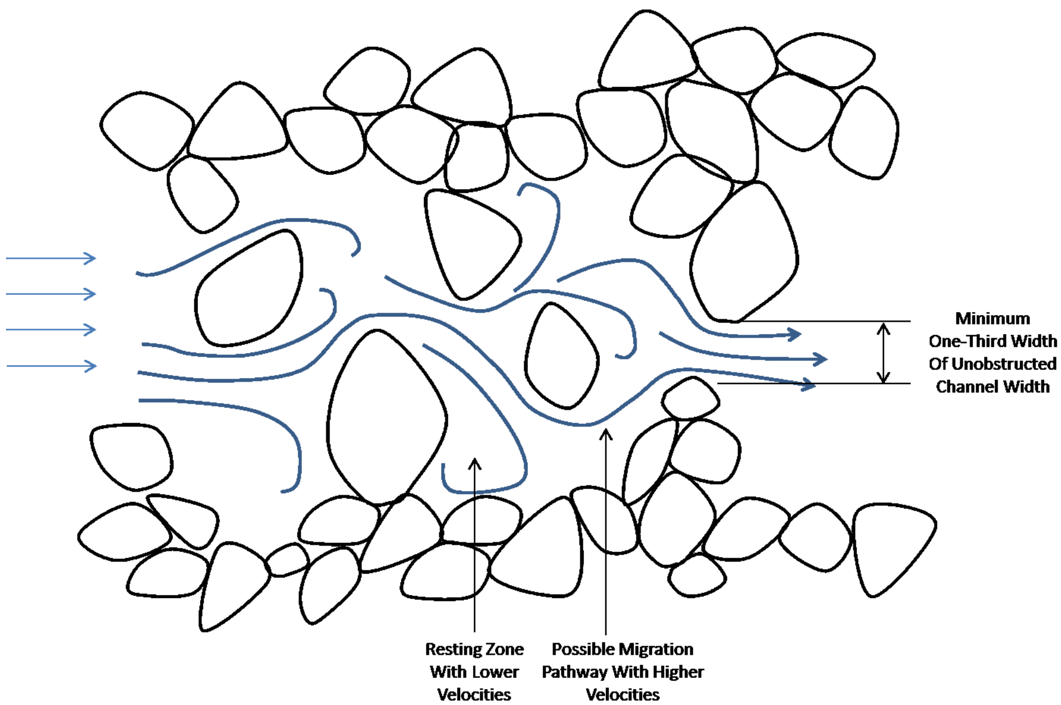

Figure 3.7: Plan view of rock ramp boulder configuration. Various flow path characteristics are depicted indicating resting zones and a possible migration pathway. This configuration is intended to maintain an unimpeded flow path by ensuring one-third of the unimpeded channel width is open at any given cross section. Not to scale.

Figure 3.8: WIS Region A - Inlet - The upstream extent of construction is shown. A natural choke-point is located in the centre of the photograph. Upstream of the choke are several sub-channels which were blocked off with larger boulders to allow more flow into the main channel. This provides minimal hydraulic control during peak freshet as the reach functions as an active flood plain.

Figure 3.9: WIS Region B - Pool and Weir One - Looking upstream, the channel consists of boulders configured into weir and choke structures. The bed is lined with gravel and cobbles with willow vegetation on the banks to improve cover for fish habitat.

Figure 3.10: WIS Region C - Riffle One - Looking upstream, this section consists of a silt bed with a few larger boulders and willow vegetation on the banks to improve cover for fish habitat. During the first freshet period, additional silt was deposited in this reach due to the freshly excavated channel causing increased sediment transport.

Figure 3.11: WIS Region D - Rock Ramp - Looking upstream, this section consists of a series of staggered boulders of various sizes with several choke structures in the foreground. Boulders optimize fish habitat suitability by creating additional flow variability, breaking up faster riffle flows with slower resting zones.

Figure 3.12: WIS Region E - Riffle Two - Looking downstream, this region is similar to Region C, consisting of a silt bed with a few large boulders. Substantial silt deposition occurred in this reach, altering the bed characteristics from the as-built channel. Photograph was taken several days after silt deposition declined. Channel characteristics changed over the first freshet period from variable and rocky to a more uniform and silted bed.

Figure 3.13: WIS Region F - Pool and Weir Two - Looking upstream, this region is similar to Region B, consisting of boulders arranged in weir and choke structures. This is the steepest section and was diverted around the original cascade which impeded fish migration. The top photo was taken 1 June 2013 at the beginning of the study period while there was still a considerable snow pack present; stream flows created a subnivean channel underneath the snow pack, causing minimal hydraulic impact. The bottom photo was taken on 22 June 2013 at the end of freshet.

Figure 3.14: WIS Region G - Outlet - Looking downstream, Lac de Gras is shown in the background. This section was not modified from the natural channel as it was deemed suitable habitat and passable by fish. Silt fences are installed in the channel to reduce silt discharges into Lac de Gras from the disturbed sediment on the upper reaches of the newly excavated channel.

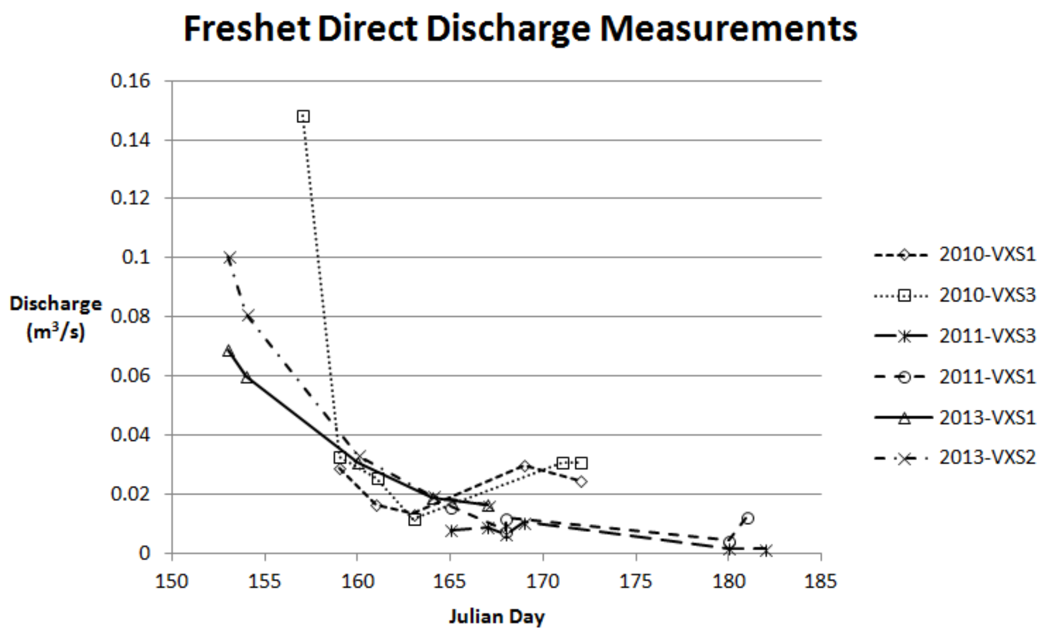

Figure 3.15: Direct discharge measurement for WIS upstream (VXS1) and downstream (VXS3-pre construction and VXS2-post construction) velocity cross sections during freshet. Accessing streams during peak discharges were difficult logistically therefore we only documented near-peak discharge in 2010 at VXS1 and 2013 at both VXS1 and VXS2.

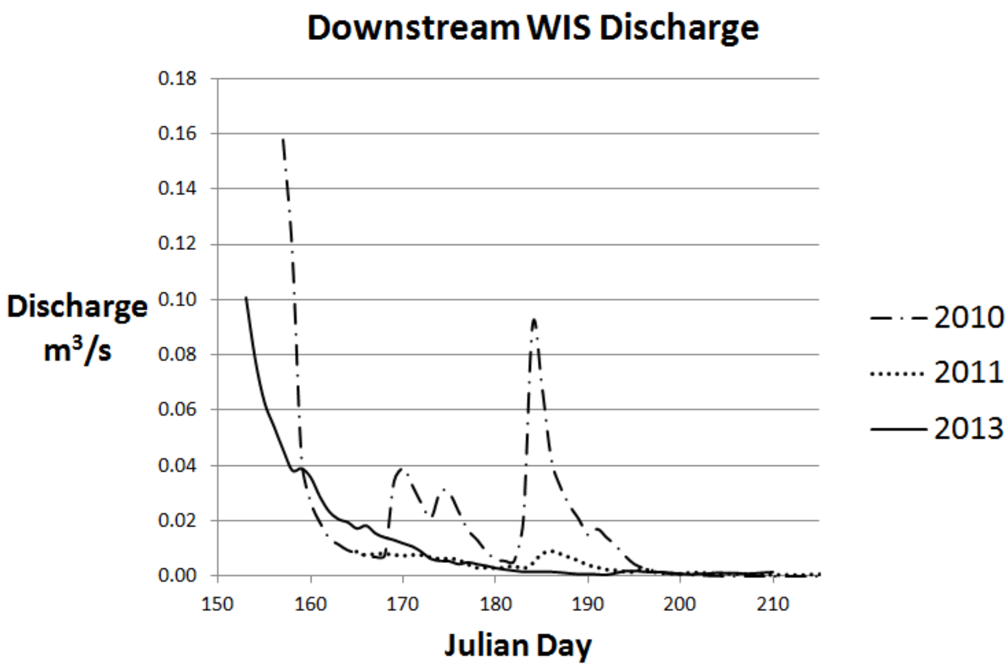

Figure 3.16: Daily-averaged continuous discharge data for 2010, 2011, and 2013. Discharge decline in 2010 was more rapid than 2013. Measurements in 2011 began near the end of freshet therefore it is not apparent how freshet 2011 compared with the other two study periods. Post freshet discharge decline in 2011 is comparable with 2013.

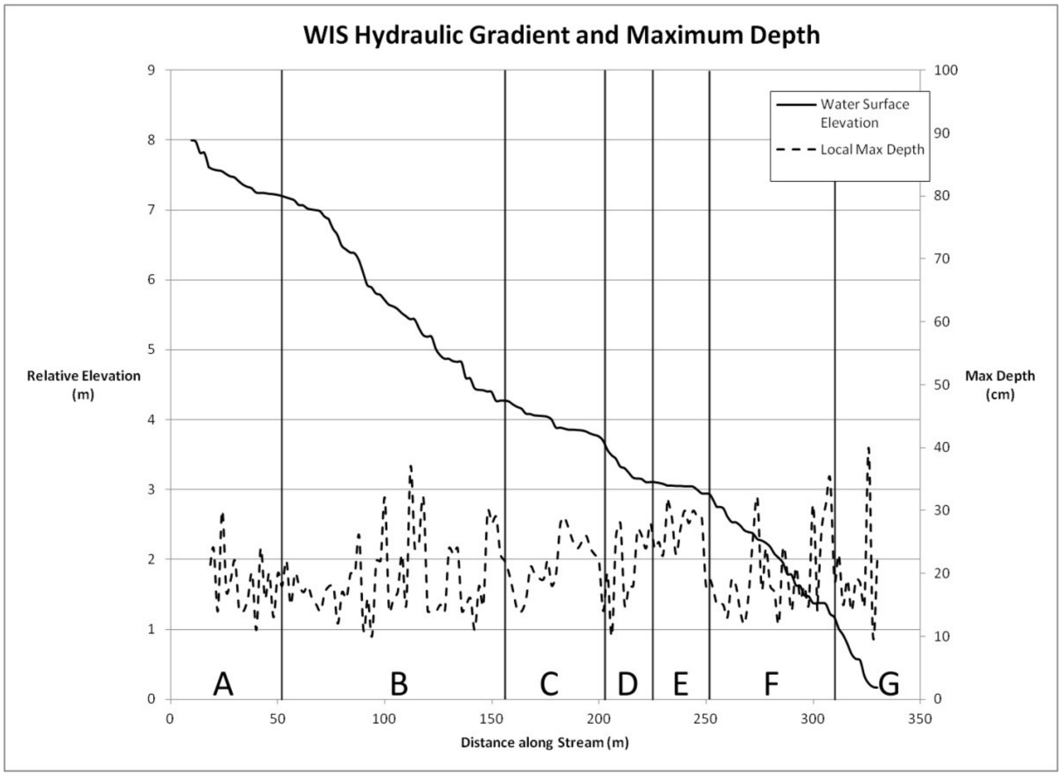

Figure 3.17: Water surface elevation and local maximum depth, separated by stream reach. Measurements were taken on 8 June 2013 at a discharge of 30 lps. Stream gradient ranges from <1% to 5%. Variability in local maximum depth is greatest in reaches B and F which consist of the pool and weir structures to overcome the steepest slopes. Reaches A and G have the lowest maximum depths and do not consist of any boulder structures.

Chapter 4

Conclusions and Recommendations

4.1 General Conclusions

This paper based thesis investigated various modifications to Arctic headwater systems in the Barrenlands region of Canada. The following conclusions have been made:

In Chapter 2, I assessed the hydrology and hydraulics of three small lakes and their outlet streams that were modified to enhance connectivity suitable for fish migration. Traditional construction materials (i.e. gabions) were found to have limited workability, causing difficulties aligning as-built structures with the proposed designs. Maintaining suitable flow depths for fish migration was challenging using these structures. Modifying structures with a centre notch and dressing with native materials (i.e. boulders) to create unimpeded flows was found to be somewhat successful. A choke-and-pool structure installed in the lowest gradient stream proved most effective. Catchment area was found to be an important indicator of a small lake's ability to support enhanced connectivity in the Barrenlands. Outlet geometry must be considered when intending to lengthen periods of discharge, which may be accomplished by restricting outlet discharge, increasing lake storage retention; a narrow rectangular notch was effective for this application.

In Chapter 3, we developed a field engineering approach and design to modify a 420 m long stream using nature-like fishpass structures in the Barrenlands region of Canada. This approach focused on communicating, to the construction crew, the intent of the designs to more easily modify and optimize structures when confronted with unforeseen challenges during construction. These challenges included high velocities, low depths, minimal cover for fish, and minimal flow variability to enhance aquatic habitat. Structures were constructed using boulders and vegetation available on site to create various structures, such as weirs, chokes, rock ramps, riparian vegetation, and in-stream woody debris habitat. Preliminary hydraulic results in conjunction with visual observations suggested that these structures were effective in addressing all challenges presented. Modifications show no apparent relationship between stream gradient and depth, indicating structures effectively controlled discharges. Other hydraulic characteristics such as at-a-station hydraulic geometry were found to exhibit similar characteristics to other natural streams nearby. Observations showed structures promoted beneficial habitat characteristics such as a large flow variability in each reach, improved cover, and provided sufficient flow depths at a wide range of discharges.

4.2 Recommendations

Arctic headwater systems are not yet well understood, therefore designing stream modifications and quantifying their impacts remains quite uncertain. We currently do not have data on the long term impacts of these projects to determine if the modifications have successfully enhanced fish habitat and connectivity to the extent for which they were intended. The two compensation projects investigated in this thesis should benefit from long term studies to find to what extent, if any, there exists a hydraulic stabilization period impacting stream hydraulics after modifications are made. Such studies would give us a better understanding of the number of seasons required to evaluate future stream habitat enhancement projects.

My research suggested a relationship between catchment area and habitat enhancement potential in small Arctic lake-stream systems. Although based on limited data, I propose guidelines that candidate sites for future projects should have a catchment area >20 ha and a stream gradient ≤1.5%. There is great potential to refine the suggested minimum catchment areas while augmenting the number of criteria used to indicate preferable enhancement sites. These criteria may be explored by investigating the broader relationships between catchment area, outlet geometries, outlet stream gradient, in-stream structure geometries, period of suitable discharges for fish migration, and the robustness of enhancements when faced with variable hydrologic conditions. A much larger database of enhancement projects would be required to reveal statistically meaningful relationships. Developing more refined relationships among these characteristics would help to ensure suitable candidate sites are chosen and appropriate designs are proposed to increase the likelihood of successful enhancement in small Arctic lake-stream systems. If we are to be manipulating pristine systems, we should be confident there is a high probability of success involved.

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