Assessing Responses of Fish to Habitat Enhancement in Barrenlands Streams, N.W.T., Canada

by

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Abstract

The development of the Diavik diamond mine destroyed pristine lakes and streams in Barrenlands region of northern Canada. Subsequently, several fish habitat compensation projects were undertaken to offset these losses. The M-Lakes project was intended to enhance the productive capacity of a pristine headwater lake-stream system through improved stream channel connectivity among three small (<5 ha), isolated lakes and with the much larger (>57,000 ha) Lac de Gras. Three fishpasses (two gabion-style pool-weir and one nature-like choke-pool) were constructed to enhance inter-lake connectivity in the M-Lakes system. My objectives were to determine if (1) fish ≥ 150 mm were attracted to and passed through fishpasses, (2) fish use of fishpasses was comparable to reference streams before and after construction and to manipulated streams before construction, and to (3) identify environmental correlates to fish passage events when fishpasses allowed for fish movement. I used passive integrated transponder telemetry, and visual and electrofishing surveys to address my objectives for one year before (2011) and two years after fishpass construction (2012-2013). The gabion-style fishpasses limited fish movement and use, while the nature-like fishpass allowed for fish movement and use comparable to reference streams and the stream prior to manipulation. Few consistent correlates with hydraulic conditions and date were identified for passage events of Arctic Grayling (*Thymallus arcticus*) in the nature-like fishpass, relative to the conditions available. However, I observed strong diel periodicity in Arctic Grayling passage activity as most (95%; 137/144) passage events occurred during evening or early morning (18:00-5:59). My findings provide evidence against using gabion-style pool-weir fishpasses in low-gradient headwater Barrenlands streams, and demonstrate that nature-like fishpasses can be effective tools for enhancing connectivity in these systems. Additionally, this thesis documents the first case of clear diel periodicity in passage activity for Arctic Grayling, which may be a response to avian predation given the shallow depth of the fishpass.

Preface

This thesis is an original work by Christopher L. Cahill. The research project, of which this thesis is a part, received research ethics approval from the Animal Care and use Committee under: "Improving habitat connectivity to enhance productive capacity of Arctic freshwater ecosystems" No. 688/03/12 on 1 May 2011. The project was renewed as No. 688/03/13 on 1 April 2012, and also renewed under "Enhancing productive capacity and understanding biodiversity of arctic freshwater ecosystems" No. 764/03/13 on 1 April 2012. This project was subsequently renewed as AUP00000034 on 19 March 2013.

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Chapter I: General Introduction

Anthropogenic activities increasingly damage fish habitat. When this occurred in Canada prior to 2013, the federal Fisheries Act (hereafter, “the Act”) and Policy for the Management of Fish Habitat (hereafter, “the Policy”) provided legal authority and outlined a management framework intended to sustain fish productivity. The Policy required there be “No Net Loss” (NNL) to the productive capacity of aquatic habitats. If unavoidable Harmful Alteration, Disruption, or Destruction (HADDs) to fish habitat occurred, fish habitat compensation projects were required to offset the HADD to ensure NNL (DFO 1986). Controversial changes to the Act in 2013 (e.g., Hutchings and Post 2013) no longer mention NNL or HADDs per se. Instead, the goal of the revised Act is to “maintain or enhance the ongoing productivity and sustainability of commercial, recreational, and Aboriginal fisheries” through the prohibition of activities that cause “serious harm to fish that are part of a commercial, recreational, or Aboriginal fishery, or to fish that support such a fishery” (Fisheries Act 2013). Projects that cause unavoidable serious harm to fish are now required to perform fish habitat offsetting projects to maintain or enhance the productivity of the fishery (DFO 2013).

Such changes shift the focus of the Act away from protecting general fish habitat (e.g., Brouha 1993), and raise important questions as to what qualifies as a commercial, recreational, or Aboriginal fishery (Hutchings and Post 2013). However, the tools with which fisheries managers compensated HADDs or now offset serious harm remain largely unchanged. For instance, the restoration of damaged habitat, the enhancement of existing, and the creation of entirely new aquatic habitats were all viable options for compensating aquatic habitat losses under the former Act (DFO 1986), and remain viable options for managers looking to offset serious harm to fish under the revised Act (DFO 2013).

Resource managers, ecologists, and engineers face substantial uncertainty when designing and implementing fish habitat compensation projects (Minns and Moore 2003). As a result, our collective ability to create or restore the productive capacity of natural habitats is often inadequate. A review by Quigley and Harper (2006) suggests nearly two-thirds of evaluated compensation projects failed to achieve NNL, even when compensation ratios (area gain: area lost) were >2:1. Knowledge of fish-habitat relationships and aquatic ecosystem function increases the probability that a habitat manipulation will result in a desirable outcome (Bradshaw 1996), but sufficient information is often lacking for the systems or species in question. For instance, industrial development that harms fish and/or fish habitat has occurred and is projected to increase throughout the Canadian Arctic (Schindler 2001; Gavrilchuck and Lesage 2014), but fish ecology throughout this region remains understudied (Power 1997). Achieving NNL in these situations may require increasing connectivity between natural habitats (DFO 1986). Such projects by-pass issues related to our incomplete knowledge of aquatic ecosystems, and instead take advantage of the productive capacity of natural systems by linking previously isolated fish habitats. Moreover, projects that increase or restore connectivity between isolated, but otherwise usable aquatic habitats often achieve management goals (Roni et al. 2002).

Fish dispersal is normally limited to direct waterways between lakes (Olden et al. 2001), and many styles of fishpasses have been used to increase connectivity for fishes between isolated aquatic ecosystems (Larinier 2001). Of particular interest to this thesis are pool-weir and nature-like fishpasses. Pool-weir fishpasses have traditionally been used to increase connectivity for salmonids and other strong-swimming and leaping fishes (Larinier 1998). These fishpasses feature weirs that span the width of the fishpass to create a series of step-pools, and fish swim through pools and over weirs to ascend (Clay 1995). Pool-weir fishpasses can be used to overcome slopes >10% (Katopodis et al. 2001). Nature-like fishpasses attempt to mimic the characteristics of a natural stream (Jungwirth 1996). In doing so, they are thought to provide heterogeneous hydraulic conditions usable by a range of species and life stages (Katopodis et al. 2001). Nature-like fishpasses have been developed for slopes of 5% or less (Larinier 2001). However, little information is available on the suitability of these designs for enhancing aquatic connectivity in northern Canada.

Fish habitat was destroyed during the development of the Diavik diamond mine in the Barrenlands region of northern Canada. Consequently, Fisheries Act Authorization required several fish habitat compensation projects from Diavik Diamond Mines Inc. (DDMI) to offset all HADDs and achieve NNL. One of these projects, the M-Lakes fish habitat compensation project, was required to offset the destruction of headwater lake-stream systems. In August 2011, three fishpasses (two gabion-style pool-weir and one nature-like choke-pool fishpass) were constructed to eliminate dispersal barriers between three small (<5 ha), isolated lakes and the much larger (>57 000 ha) Lac de Gras to increase the productive capacity of the pristine M-Lakes system (Golder Associates 2001). The rationale behind improving connectivity to enhance the productive capacity of the pristine M-Lakes system stemmed largely from the hypothesis that fishpasses would facilitate movement of fish into a fishless, but otherwise habitable lake (Golder 2001). Thus, this compensation plan assumed that connectivity was a main factor limiting the productivity of the system during the design of the M-Lakes project, and assumed that other important unknowns (e.g., ecological carrying capacities of lakes) were not primarily limiting the productive capacity of the system at that time. My M.Sc. research objectives were to determine if the M-Lakes fishpasses provided connections suitable for fish passage, and to describe correlates to fish passage events when fishpasses allowed for fish movement. It is important to note that this thesis did not explicitly evaluate whether NNL was achieved, but instead evaluated the efficacy of the constructed fishpasses at M-Lakes.

My thesis contains two data chapters, each of which is prepared as an independent manuscript intended for primary publication. Chapter 2 evaluates the M-Lakes fish habitat compensation project from a fish-passage perspective for the first two post-compensation years (2012-2013). Chapter 3 examines Arctic Grayling *Thymallus arcticus* passages through the M-Lakes nature-like fishpass in detail during the same period. I conclude my thesis by discussing the implications and applications of my research, and make recommendations for future studies.

References

Bradshaw, A. D. 1996. Underlying Principles of Restoration. Canadian Journal of Fisheries and Aquatic Sciences 53:3-9.

Brouha, P. 1993. Emulating Canada: Recognizing Existing Aquatic and Fish Habitat Area as Invaluable. 18(10):4.

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

Department of Fisheries and Oceans (DFO). 1986. The Department of Fisheries and Oceans Policy for the Management of Fish Habitat. Communications Directorate, Fisheries and Oceans, Ottawa, Ontario, Canada.

Department of Fisheries and Oceans (DFO). 2013. The Deparment of Fisheries and Oceans Fisheries Productivity Investment Policy. 2013. Available: http://www.dfo-mpo.gc.ca/pnw-ppe/offsetting-guide-compensation/index-eng.html (June 2014).

Fisheries Act. R.S.C. 1985. c. F-14. 2013. Available: http://www.dfo-mpo.gc.ca/habitat/changes-changements/index-eng.htm (June 2014).

Gavrilchuk, K., and V. Lesage. 2014. Large-scale marine development projects (mineral, oil and gas, infrastructure) proposed for Canada’s North. Can. Tech. Rep. Fish. Aquat. Sci. 3069:viii + 84 pp.

Golder Associates. 2001. West Island Stream Fish Habitat Compensation Works Proposed Design. Diavik Diamond Mines Inc., NWT. Technical Memorandum.

Hutchings, J. A., and J. R. Post. 2013. Gutting Canada's Fisheries Act: No Fishery, No Fish Habitat Protection. Fisheries 38(11):497-501.

Jungwirth, M. 1996. Bypass Channels at Weirs as Appropriate Aids for Fish Migration in Rhithral Rivers. Regulated Rivers-Research & Management 12(4-5):483-492.

Katopodis, C., J. Kells, and M. Acharya. 2001. Nature-Like and Conventional Fishways: Alternative Concepts? Canadian Water Resources Journal 26(2):211-232.

Larinier, M. 1998. Upstream and Downstream Fish Passage Experience in France. In: Jungwirth, M., Schumtz, S. and Weiss, S., eds. Fish Migration and Fish Bypasses. Oxford: Fishing News Books, Blackwell Science Ltd, pp. 127-145.

Larinier, M. 2001. Environmental Issues, Dams and Fish Migration. FAO Fisheries Technical Paper (419):45-89.

Minns, C. K., and J. E. Moore. 2003. Assessment of Net Change of Productive Capacity of Fish Habitats: The Role of Uncertainty and Complexity in Decision Making. Canadian Journal of Fisheries and Aquatic Sciences 60(1):100-116.

Olden, J. D., D. A. Jackson, and P. R. Peres-Neto. 2001. Spatial Isolation and Fish Communities in Drainage Lakes. Oecologia 127(4):572-585.

Power, G. 1997. A Review of Fish Ecology in Arctic North America. In: Reynolds, J. (Ed.), Fish Ecology in Arctic North America, American Fisheries Society, Symposium vol. 19. American Fisheries Society, Bethesda, Maryland, pp. 13 – 39.

Quigley, J. T., and D. J. Harper. 2006. Effectiveness of Fish Habitat Compensation in Canada in Achieving No Net Loss. Environmental Management 37(3):351-366.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A Review of Stream Restoration Techniques and a Hierarchical Strategy for Prioritizing Restoration in Pacific Northwest Watersheds. North American Journal of Fisheries Management 22(1):1-20.

Schindler, D. W. 2001. The Cumulative Effects of Climate Warming and Other Human Stresses on Canadian Freshwaters in the New Millennium. Canadian Journal of Fisheries and Aquatic Sciences 58(1):18-29.

Chapter II: Assessing Responses of Fish to Habitat Enhancement in Barrenlands Streams, N.W.T., Canada

Abstract.—I examined the effectiveness of three fishpasses (two gabion-style pool-weir and one nature-like choke-and-pool) at enhancing connectivity between three small, largely isolated headwater lakes as part of a fish habitat compensation project in the Barrenlands region of the Northwest Territories, Canada. I quantified fish attraction and passage efficiency of fishpasses using passive integrated transponder (PIT) antennae, and compared fish use of fishpasses to reference streams using visual and electrofishing surveys for one year before and two years after construction. I did not detect, observe, or capture any fish in either gabion-style pool-weir fishpass during the first year post-construction, and these two fishpasses were subsequently retrofitted to improve performance. After retrofits were completed, I did not detect any tagged fish (≥150 mm) migrating through the two fishpasses using PIT telemetry, but identified some small fish moving downstream in these fishpasses through visual and electrofishing surveys. Conversely, I detected tagged Arctic Grayling *Thymallus arcticus* migrating up-and downstream through the nature-like choke-pool fishpass during both years post-enhancement, and also encountered fish throughout this fishpass during visual and electrofishing surveys. My results suggest gabion-weir fishpasses limited fish movement and use even after modification, whereas the nature-like fishpass successfully facilitated fish movement and use when compared to reference streams. I recommend against using gabion-style pool-weir fishpasses in Arctic headwater lake-stream systems, particularly when stream flow is limited, and also suggest future projects aimed at enhancing lake-stream connectivity explore nature-like fishpass designs in an experimental management framework.

Introduction

Increasingly, anthropogenic activities are damaging aquatic habitats and threatening the sustainability of aquatic resources. The prevention of Harmful Alteration, Disruption, and Destruction (HADD) of fish habitat should be the focus of management whenever possible. However, in situations where HADDs are inevitable, many jurisdictions, including Canada, have required habitat compensation to restore damaged, enhance existing, or develop entirely new aquatic habitats to achieve No Net Loss (NNL), if not an actual gain, in fish habitat (DFO 1986; Brouha 1993). While HADDs are no longer prohibited in Canada (Fisheries Act 2013; Hutchings and Post 2013), it is nevertheless illegal to cause "serious harm to fish that are part of a commercial, recreational, or Aboriginal fishery, or to fish that support such a fishery" (Fisheries Act 2013). When unavoidable "serious harm" occurs, habitat restoration, enhancement, and creation can still be used to offset any incurred losses (DFO 2013).

Fish habitat management must often proceed without full scientific understanding of the habitat needs of target species and the functioning of ecosystems that support these needs; this is particularly true in the Arctic, where knowledge of aquatic ecosystems and fish-habitat relationships is limited (Power 1997). Arctic regions have undergone increasing development over the past 50 years, and projections indicate this trend will continue in the future (Schindler 2001; Gavrilchuck and Lesage 2014). However, few published studies have assessed habitat compensation in high latitude systems despite the importance of NNL to fisheries management (but see Jones et al. 2003a,b,c, 2008; Jones and Tonn 2004a,b; Scrimgeour et al. 2013,2014). Scientists should treat habitat compensation case studies as ecological experiments, with appropriately defensible study designs, to help advance our understanding and guide future management (Walters and Hilborn 1978; Walters and Holling 1990). Case studies documenting both failures and successes are therefore important (Bradshaw 1996).

A review of habitat compensation in Canada found only 37% of projects actually resulted in NNL, and even projects with compensation ratios (area gain: area loss) >2:1 did not guarantee NNL (Quigley and Harper 2006). This suggests a limited ability to successfully create or restore habitat. However, projects that enhance or create connections to previously isolated natural habitats are frequently successful (Roni et al. 2002). These types of manipulations take advantage of the productive capacity of natural ecosystems, and may circumvent issues related to our incomplete knowledge of ecosystem function. Thus, attainment of NNL through habitat compensation may require greater emphasis on increasing connectivity to naturally existing ecosystems (DFO 1986).

A variety of fishpasses have been used to promote fish migration and increase connectivity in aquatic ecosystems. In particular, pool-weir style fishpasses use weirs to create a series of step pools, and fish must swim over weirs to move between pools (Clay 1995). Pool-weir fishpasses typically represent ‘hard’ approaches to fishpass construction as concrete, metal, or wood are often used during construction (Breton et al. 2013). Pool-weir fishpasses can be used to overcome slopes of 10% or greater (Katopodis et al. 1997), at least for certain target species. Nature-like fishpasses have been developed for lower slopes (< 5%; Larinier 2001), and are designed to emulate the substrate, hydraulics, and channel morphology of a natural stream (Jungwirth 1996). These fishpasses represent ‘soft’ engineering approaches by using natural materials found onsite for construction, and can provide passage conditions suitable for a variety of fish species and other aquatic organisms (Katopodis et al. 2001). A meta-analysis by Noonan et al. (2012) suggests both pool-weir and nature-like fishpasses have similarly high upstream passage efficiencies, particularly for salmonids; however, these fishpass types have not been formally evaluated in northern Canada.

In autumn 2011, Diavik Diamond Mines Inc. (DDMI) completed a Mainland Lakes (M-Lakes) fish habitat compensation project to offset habitat losses due to mining in the Barrenlands Region of northern Canada. A Fisheries Act Authorization required increasing stream channel connectivity among three small (< 6 ha), isolated lakes and with the larger (> 57,000 ha) Lac de Gras to provide stream connections suitable for fish passage and, in turn, enhance the productive capacity of this pristine system (Golder Associates 2001). This was addressed with the construction of three fishpasses. My objectives were to determine if (1) fish ≥ 150 mm were attracted to and migrated through fishpasses, and (2) fish use of fishpasses was comparable to reference streams before and after construction and to manipulated streams before construction.

Methods

Study area.—The study was conducted near Lac de Gras, ca. 64°29' N, 110°16' W, 320 km northeast of Yellowknife, Northwest Territories (Figure 2.1). This area falls within the Southern Arctic Ecozone, and is ca. 75 km north of the tree line in a region known as the Barrenlands (Environment Canada 1991; Krajick 2001). The Barrenlands is cold (mean annual temperature is ca. -12°C), semi-arid (200-300 mm of precipitation yearly), and the permafrost layer is continuous (Environment Canada 1991). Numerous lakes and streams in this region form the headwaters of the Coppermine River, which flows north to the Arctic Ocean (Jones and Tonn 2004b). Stream water in the study area is acidic (5.37 – 6.17 pH) and features low conductivity (Jones et al. 2004b; Table 1). Freshet typically begins in early June, and stream flows decline or stop toward the end of summer (Jul-Aug) as evaporation lowers lake levels (Jones et al. 2003b; Baki et al. 2012). Streams freeze solid by October (Jones and Tonn 2004b).

The M-lakes compensation site featured two headwater lakes (M3L and M2L) that flowed into a third lake (M1L) via two separate streams (M3S and M2S); M1L then flowed into Lac de Gras via the M1S stream (Figure 2.1). All connecting streams were originally ephemeral and/or featured diffuse channels or cascades, making fish passage under pre-construction conditions limited or unlikely (Golder Associates 2001). Streams were short with shallow overall gradients, and had small catchments (Table 2.1).

Two reference streams were selected based on their hydraulic similarity to the M-lakes system, and on logistic feasibility (Figure 2.1; Table 2.1). Reference streams (R6S1 and R6S2) were ephemeral and featured diffuse channels. Reference sites and the pre-construction M-lakes were assumed to represent undisturbed conditions based on their remote Arctic location.

Fish communities in the smaller lakes comprised nine species (one to eight species per lake), with Lac de Gras (10 species) containing one additional species (Appendix). Although M3L was believed fishless during the design of the habitat compensation project (Golder Associates 2001), we captured Lake Trout, Burbot, and Slimy Sculpin (Hulsman 2012; see Appendix for scientific names). Except for a lack of coregonids, stream fish communities were similar to those of the lakes, but were numerically dominated by Arctic Grayling, Burbot, Ninespine Stickleback, and Slimy Sculpin.

M-Lakes Manipulations & Retrofit.—In autumn 2011, DDMI constructed three fishpasses to enhance stream connections among the M-Lakes and with Lac de Gras. Gabion-style pool-weir fishpasses were constructed in both M1S and M3S because of their steeper slopes (≥ 2.0%). Both fishpasses featured six gabion-weirs, numbered one (upstream) to six (downstream), that spanned the fishpass channel and created a series of step-pools (Figure 2.1). Gabion-weirs were constructed by filling wire baskets with crushed rock (< 20 cm diameter; Figure 2.2), and were covered with geotextile lining. A nature-like choke-pool fishpass was constructed in M2S because of the lower slope in this stream. This fishpass had no hydraulic structures spanning the fishpass channel, and instead featured a constricting "choke" immediately above a wider "pool" (Figure 2.3). The banks of the nature-like fishpass were lined with crushed rock.

Following a preliminary evaluation after the 2012 freshet, both gabion-weir fishpasses (M1S and M3S) were retrofitted in autumn 2012 to improve their as-built hydraulic performance. All gabion-weirs were notched in the center to minimize sudden drops over weir structures, and to concentrate flows and increase flow depth over gabion structures during low flows (Figures 2.2 and 2.4). The downstream end of M1S was also channelized and extended by approximately 10 m into Lac de Gras to minimize diffuse, shallow flows observed during the initial period. Lack of baseline engineering data during the design and construction phase rendered the lowermost gabion-weir in M3S (weir six) completely submerged during both years. Initial construction of the gabion-weir fishpasses (2011) used heavy machinery (e.g., excavator and loader), whereas retrofits (2012) were performed by a small field crew using hand tools. The nature-like fishpass of M2S was not modified during 2012, and reference streams remained unmanipulated throughout the study.

Field sampling.—During 2011-2013, fish in M1L, M2L, and M3L were captured using angling, seining, long-lines, trap nets, and short (15 minute) sets of gillnets (24.8 m x 1.8 m, with 3.1 m panels of 38, 51, 64, 76, 89, 102, 114, and 127 mm stretched mesh). Captured fish were identified, enumerated, and measured (FL±1 mm for Arctic Grayling, Lake Trout, and Round Whitefish; TL±1 mm for Burbot). Fish ≥ 150 mm were anaesthetized using tricaine methanesulfonate (MS-222; Western Chemical Inc., Ferndale, Washington) and marked using Passive Integrated Transponder (PIT) and anchor tags, as this size requirement ensured low total tag weight/body mass ratios (i.e., approximately 1%, C.L. Cahill unpublished data; Winter 1996). Individual half-duplex PIT tags (23 mm long, 3.5 mm diameter, 0.3 g) were inserted into fish via a small incision in the peritoneal cavity along the mid-ventral line (Jepsen et al. 2002). Anchor tags (25mm long, 0.2g) were inserted at the posterior base of the dorsal fin using a 16 gauge injection gun. Scalpels and injection gun were sterilized between fish in 90% ethanol to reduce the potential for infection and horizontal disease transmission (CBFWA 1999). After tagging, fish were allowed to recover for approximately 15 minutes before being released at point of capture. I tagged 158 fish (107 Arctic Grayling, 16 Burbot, 2 Lake Trout, and 33 Round Whitefish) prior to fishpass construction in autumn 2011. During summer 2012, I tagged an additional 19 fish (six Arctic Grayling, one Lake Trout, and 12 Round Whitefish) in M1L, and one Round Whitefish in M2L. In winter 2013, I tagged another 32 fish (13 Arctic Grayling, three Burbot, 10 Lake Trout, and six Round Whitefish) throughout M1L via ice angling.

In 2012 and 2013, one OregonRFID™ PIT reader and two in-stream swim-through antennae were placed in each fishpass to monitor movement of PIT tagged fish at each fishpass. Antennae (approximately 75 cm diameter) were constructed using three consecutive wraps of eight gauge wire. Each reader system was powered using one 30W solar panel and a 90A·h ceramic plate 12V battery. Antennae were placed at weirs one and six in M1S, and at weirs one and five in M3S (Figure 1). In M2S, antennae were placed 1.0 m upstream of the choke structure and 3 m downstream of the pool. Individual antenna efficiency was tested *in situ* by floating a standardized, PIT-tagged drone through each antenna 10 times and recording detection events. Drone floating and detection distance testing were performed twice yearly for each antenna, and all drone floats were detected by all antennae for both years. The longitudinal detection range of each antenna was tested by measuring the distance (m) a PIT tag was detected from each antenna. Longitudinal detection distances ranged from 1.25 to 1.42 m, which gave a total read range of 2.5-2.84 m. All antennae were installed during freshet (ca. 1 June), and were removed by mid-July (or sooner if a stream stopped flowing). Logger tags were placed near the downstream antenna in each stream to document PIT reader function every 31 minutes.

All streams were surveyed visually for fish during 2011-2013. Block nets (3-mm mesh openings) were placed at both ends of each stream to minimize fish movement into and out of streams during surveys (Thompson 2003). Two individuals wearing polarized sunglasses performed independent visual surveys by scanning each stream from opposite banks. Both individuals started at the downstream block net and scanned the stream channel to the upstream block net. Surveyors then switched stream banks and scanned the stream channel back to the downstream block net. Observed fish were identified to species, enumerated, and location within each stream was recorded. In 2011, baseline stream surveys were only performed once (2-15 July). In 2012 and 2013, streams were surveyed twice (5-16 June and 2-15 July).

Immediately after completing each visual survey, each stream was electrofished with three depletion passes (Zippin 1956). In situations where the first two passes yielded no fish, no further passes were made. A backpack electrofisher (Smith-Root LR-24) with one circular anode was used by a crew of two to make depletion passes between block nets. All depletion surveys were performed at 600 V DC. Captured fish were identified, enumerated, and measured (FL±1 mm for salmonids; TL±1 mm for all others), and fish location within streams was recorded. Fish were released at point of capture when all depletion surveys for a particular stream were completed.

Data analysis.—Data from PIT readers were examined to ensure antennae systems remained operational, and records of tagged fish were enumerated. I quantified upstream and downstream attraction and passage efficiency. Attraction efficiency was defined as the number of individual fish tagged and released within a species in a given lake that were then detected at an adjacent PIT antenna in a fishpass (Aarestrup et al. 2003). Passage efficiency was calculated as the number of fish able to exit a given fishpass (i.e., to have been subsequently detected at the second antenna within a given fishpass) divided by the number detected at the entrance to that fishpass (Bunt et al. 1999). I could estimate only downstream attraction and passage efficiency estimates for M1S (I did not tag fish in LDG), and was limited to upstream efficiency estimates for M3S (few fish were captured and tagged in M3L). I used chi-square goodness-of-fit and contingency table analyses to test whether attraction and passage efficiency estimates differed among fishpasses. Differences were considered significant at $P \leq 0.05$.

I analyzed visual and electrofishing survey data in a Before-After Control-Impact (BACI) framework (Underwood 1991, 1994). Visual survey counts in each stream were averaged for each year, and this average was then divided by the total length of the stream to determine the number of fish observed per meter. Low catch rates for electrofishing surveys precluded the possibility of abundance estimates, so the cumulative catch for all passes during a particular survey divided by the length of stream sampled was used as a measure of relative fish abundance. Because my sampling unit was the whole stream, replication was low (gabion-weir and reference streams, n=2) or absent (nature-like fishpass, n=1); therefore, I assessed visual and electrofishing surveys qualitatively in the BACI framework.

Results

With the exception of a 14-hour period (2-3 June 2012) at M1S, logger-tag records indicated PIT antennae systems operated continuously while installed. PIT antennae only detected Arctic Grayling. During 2012, upstream attraction efficiencies were similar in M2S (41%; 11/27) and M3S (52%; 14/27; $\chi^2 = 0.36$, df = 1, $P = 0.55$), whereas upstream passage efficiency was significantly higher in M2S (91%; 10/11) than M3S (0%; 0/14; $\chi^2 = 21.21$, df = 1, $P < 0.01$). Downstream attraction efficiencies in 2012 were similar in M2S (14/80; 18%) and M1S (17%; 4/27; $\chi^2 = 0.10$, df = 1, $P = 0.75$), however, although half (7/14) of the fish attracted to M2S successfully passed downstream, none of the fish attracted to M1S passed successfully. In 2013, upstream attraction efficiency was significantly higher in M2S (38%; 18/48) than in M3S (0%; 0/48; $\chi^2 = 18.00$, df = 1, $P < 0.01$). Similarly, downstream attraction efficiency was significantly higher at M2S (18%; 14/78) than M1S (0%; 0/48; $\chi^2 = 9.69$, df = 1, $P < 0.01$). Up- and down- stream passage efficiencies in M2S remained high at 83% (15/18) and 50% (7/14), respectively, whereas passage efficiencies could not be estimated for M1S and M3S because no tagged fish were attracted to these gabion-weir fishpasses during 2013.

Visual surveys detected four species (Arctic Grayling, Burbot, Ninespine Stickleback, and Slimy Sculpin) in the M-Streams; only Burbot was not observed in reference streams. When fish were observed, they were typically small (<150 mm) and few in number (Figure 2.5). Visual survey data showed that mean observations/ meter in both the gabion-weir and nature-like fishpasses increased in a manner similar to reference streams before and after construction (Figure 2.5).

However, a closer examination of the visual survey data suggested that fish were unable to use large portions of the gabion-weir fishpasses prior to stream retrofits. For example, during 2012, after fishpasses were first constructed, surveys in M1S detected Arctic Grayling, Ninespine Stickleback, and Slimy Sculpin (approximately 20 total fish), but no fish were observed between the upper and lower gabion-weirs. Similarly, in M3S, no fish were observed between the upper and lower weirs in 2012, although I observed approximately 20 Ninespine Stickleback immediately below weir five (i.e., on the downstream, lake side of the first unsubmerged gabion-weir). In June 2013, following the gabion-weir retrofitting, I observed several adult Arctic Grayling spawning in M1L immediately above M1S weir one. Subsequently (July 2013), my visual survey detected relatively large numbers of young-of-year (YOY) Arctic Grayling in M1S between weirs one and two. At M3S, I again observed numerous Ninespine Stickleback immediately below weir five, but in this post-retrofit year I also observed one Slimy Sculpin between the upper and lower gabion-weirs. During July 2013, relatively large numbers of YOY Arctic Grayling were observed in M2S, R6S1, and R6S2 (Figure 2.5), but unlike M1S, YOY were observed throughout M2S, R6S1, and R6S2.

Electrofishing surveys also suggested that fish were unable to use large portions of the gabion-weir fishpasses prior to stream retrofits, although catch rates were low and variable. Surveys during 2011-2013 captured fish throughout each reference stream (Figure 2.5). With few exceptions, electrofishing surveys in the M-Lakes streams captured only small fish (<150 mm), similar to visual surveys. In 2011, electrofishing captured Arctic Grayling, Burbot, Ninespine Stickleback, and Slimy Sculpin in M1S, but no fish were captured in M3S or M2S. After fishpasses were constructed, surveys in 2012 failed to detect fish in either gabion-weir fishpass, but Burbot and Slimy Sculpin were captured throughout the nature-like fishpass (Figure 2.5); additionally, Slimy Sculpin was also caught in the nature-like fishpass in 2013. After retrofits to the gabion-weir fishpasses occurred (2013), I captured Arctic Grayling and Ninespine Stickleback in M1S (Figure 2.5). Most of the former were young-of-year fish, presumably coming down from the observed lake spawning, adjacent to the top weir, but two fish were larger. I also caught a single Slimy Sculpin in M3S.

Discussion

Migratory characteristics of fish are important factors contributing to fishway efficacy (Bunt et al. 2012). Arctic Grayling typically undergo potamodromous spawning migrations to small tributaries or streams during freshet (Northcote 1995). None of the other species I PIT tagged (Burbot, Lake Trout, Round Whitefish) undergo similar spring spawning migrations (Scott and Crossman 1973). These life history characteristics suggest tagged Arctic Grayling are vulnerable to detection by antennae during freshet, and likely why I only detected Arctic Grayling using PIT antennae. However, I also tagged more Arctic Grayling in the M-Lakes than any other fish species. PIT antennae detected no Arctic Grayling ≥150 mm migrating through the gabion-weir fishpasses (before or after retrofits), but showed that these fish migrated through the nature-like fishpass during both years post-stream enhancement.

Examining 101 fishpass evaluations, Bunt et al. (2012) found that upstream attraction efficiencies for pool-weir fishpasses ranged from 29 to 100% (mean = 77%), while nature-like fishpasses ranged from zero to 100% (mean = 48%). Noonan et al. (2012) also found that pool-weir fishpasses often exhibit relatively high upstream passage efficiencies. My upstream attraction efficiency estimates for Arctic Grayling were lower than the Bunt et al. (2012) mean values for both the gabion pool-weir and nature-like fishpasses, but several studies have also reported poor fishpass performance, at least for certain fish species (Laine et al. 1998; Bunt et al. 2000; Mallen-Cooper and Brand 2007; Mallen-Cooper and Stuart 2007). I suggest that my below-average attractions were due to the relatively small catchment sizes of the headwater M-Lakes, which ultimately resulted in inadequate water flows for pool-weir style fishpasses with >2% slope (Courtice et al. 2014).

I found a general paucity of published information discussing downstream attraction efficiencies, and it is unclear to me why downstream attraction efficiency decreased in the gabion-style pool-weir fishpass (M1S) after retrofits to this stream took place. Noonan et al. (2012) found that downstream passage efficiency was often slightly higher than upstream passage efficiency, but my data from the nature-like fishpass showed, somewhat surprisingly, the opposite pattern. Lucas and Baras (2000) suggested targets for passage efficiency of 90-100%, and my upstream passage efficiency estimates for Arctic Grayling in the nature-like fishpass fell within (2012) or close to (2013) this range. At 0%, however, upstream passage efficiency in the gabion-weir fishpass fell far short of this target during both post-enhancement years. Downstream passage efficiencies in both the gabion-weir and nature-like choke-pool fishpasses were far less than the 90% target.

Capture methods, anesthesia technique, and antennae design all influence efficiency estimates determined using electronic tagging (Cooke and Hinch 2013), but it seems unlikely that such factors caused the differences I observed between fishpass types, given that I used the same methods and the same antennae designs. Although fish passage typically decreases as fishpass slope increases (Mallen-Cooper and Stuart 2007), none of the fishpass slopes or water velocities approached maximum values used by Arctic Grayling (4%, 60 cm/sec, Vincent 1962). Rather, I suggest that Arctic Grayling failed to navigate the gabion-style pool-weir fishpasses because fish were unable to cross 5-6 gabion-weirs with shallow, diffuse flows and ~20 cm drop heights (C. Cahill, pers. obs.). Lastly, although I could not estimate upstream attraction and passage efficiencies for M1S or downstream estimates for M3S, the two gabion-weir fishpasses had the same design, so my observed estimates are likely representative of the unestimated values. Upstream migration from Lac de Gras into M1S would have been extremely unlikely given the extremely shallow (< 3 cm), braided entrance to this fishpass during 2012, but may have been more likely during 2013 after retrofits. Although I captured two larger Arctic Grayling in this fishpass during 2013 electrofishing surveys, these fish most likely migrated downstream from M1L given that large Arctic Grayling were observed immediately above the first weir during visual surveys. Overall, my data indicate that Arctic Grayling (and other fish) were unable to ascend the gabion-weir fishpasses.

My visual survey data indicated that the gabion-weir fishpasses limited fish use, whereas the nature-like fishpass successfully facilitated fish use when compared to reference streams. For example, in M1S or M3S I never observed any fish between the upper and lower gabion-weirs during the first year post enhancement, but did observe small fish (Ninespine Stickleback, Slimy Sculpin) congregating immediately downstream of the lowermost and/or immediately upstream of the uppermost gabion weirs. In contrast, I never observed fish congregating at apparent barriers in the M2S nature-like choke-pool fishpass or any of the reference streams. This suggests that in addition to migrating adult grayling, small fish (<150 mm) were unable to use large portions of the gabion-style pool-weir fishpasses during 2012, and concurs with studies documenting fishpasses as unusable for non-salmonid fishes (Mallen-Cooper and Brand 2007; Foulds and Lucas 2013). Retrofits did result in some improvement, e.g., I witnessed large numbers of young-of-year Arctic Grayling moving downstream through the M1S fishpass in 2013. Newly emerged Arctic Grayling are small (< 15 mm), weak swimmers (Stuart and Chislett 1979; Northcote 1995), so it would be virtually impossible for these fish to be ascending from Lac de Gras. I also observed many young-of-year Arctic Grayling in the M2S nature-like choke-pool fishpass and in the reference streams during 2013, a year in which the highly variable hydrology of ephemeral Barrenlands streams (Jones et al. 2003b) apparently contributed to successful reproductive conditions.

My electrofishing data also showed fish use of fishpasses was not always comparable to reference streams. Again, important differences in the spatial distribution of catches in the gabion-weir vs. the nature-like fishpasses and reference streams suggest to me that fish did not use gabion-weir fishpasses during the first post-enhancement year. Catches increased in M1S only after retrofits took place, but these increases were overwhelmingly due to the young-of-year Arctic Grayling migrating downstream. I captured one Slimy Sculpin between weirs in M3S after fishpass retrofits occurred, likely the result of downstream passage from M3L, given the poor upstream passage of small cottids through pool-weir fishpasses (Knaepkens et al. 2006). Conversely, small fish were captured throughout the nature-like fishpass, similar to reference streams. As a result, these electrofishing survey data support the conclusion that the gabion-weir fishpasses limited fish use, but the nature-like fishpass facilitated fish use when compared to its pre-construction condition and to reference streams.

Management Implications—I recommend against using gabion-style pool-weir fishpasses for increasing connectivity in Arctic headwater lake-stream systems, particularly where stream flow is limited. Tagged Arctic grayling did not ascend or descend gabion-weir fishpasses, and information from visual and electrofishing surveys suggested that small fish could only drift downstream rather than ascend from lakes below, and only after retrofitting. Conversely, the nature-like fishpass allowed both upstream and downstream passage of tagged Arctic Grayling, and functioned similarly to reference streams for small fishes. I further recommend that fish habitat managers investigate similar and other nature-like fishpass designs in an experimental framework, paying careful attention to hydraulic considerations such as catchment size and stream slope (see also Courtice et al. 2014). This study represents an important step toward understanding Barrenlands stream enhancement and provides fish habitat managers a defensible case study upon which to base future stream enhancement objectives. Such projects can increase the likelihood of achieving NNL, and can inform future fish habitat offsetting objectives.

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References

Aarestrup, K., M. C. Lucas, and J. A. Hansen. 2003. Efficiency of a Nature-Like Bypass Channel for Sea Trout (Salmo Trutta) Ascending a Small Danish Stream Studied by Pit Telemetry. Ecology of Freshwater Fish 12(3):160-168.

Baki, A. B. M., D. Z. Zhu, M. F. Hulsman, B. D. Lunn, and W. M. Tonn. 2012. The Hydrological Characteristics of a Stream within an Integrated Framework of Lake-Stream Connectivity in the Lac De Gras Watershed, Northwest Territories, Canada. Canadian Journal of Civil Engineering 39(3):279-292.

Bradshaw, A. D. 1996. Underlying Principles of Restoration. Canadian Journal of Fisheries and Aquatic Sciences 53:3-9.

Breton, F., A. B. M. Baki, O. Link, D. Z. Zhu, and N. Rajaratnam. 2013. Flow in Nature-Like Fishway and Its Relation to Fish Behaviour. Canadian Journal of Civil Engineering 40:567-573.

Brouha, P. 1993. Emulating Canada: Recognizing Existing Aquatic and Fish Habitat Area as Invaluable. Fisheries 18(10):4.

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

Bunt, C. M., S. J. Cooke, and R. S. McKinley. 2000. Assessment of the Dunnville Fishway for Passage of Walleyes from Lake Erie to the Grand River, Ontario. Journal of Great Lakes Research 26(4):482-488.

Bunt, C. M., T. Castro-Santos, and A. Haro. 2012. Performance of Fish Passage Structures at Upstream Barriers to Migration. River Research and Applications 28(4):457-478.

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

Columbia Basin Fish and Wildlife Authority. 1999. PIT Tag Marking Procedures Manual. Portland, OR.

Cooke, S. J., and S. G. Hinch. 2013. Improving the Reliability of Fishway Attraction and Passage Efficiency Estimates to Inform Fishway Engineering, Science, and Practice. Ecological Engineering 58:123-132.

Courtice, G., A. B. Baki, D. Zhu, C. L. Cahill, and W. M. Tonn. 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.

Department of Fisheries and Oceans (DFO). 1986. The Department of Fisheries and Oceans Policy for the Management of Fish Habitat. Communications Directorate, Fisheries and Oceans, Ottawa, Ontario, Canada.

Department of Fisheries and Oceans (DFO). 2013. Fisheries Productivity Investment Policy. Available: http://www.dfo-mpo.gc.ca/pnw-ppe/offsetting-guide-compensation/index-eng.html (June 2014).

Environment Canada. 1991. Canadian Climate Normals 1961-1990. Environment Canada, Ottawa, Ont. http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html (June 2014).

Fisheries Act. R.S.C. 1985. c. F-14. 2013. Available: http://www.dfo-mpo.gc.ca/habitat/changes-changements/index-eng.htm (June 2014).

Foulds, W. L., and M. C. Lucas. 2013. Extreme Inefficiency of Two Conventional, Technical Fishways Used by European River Lamprey (Lampetra Fluviatilis). Ecological Engineering 58:423-433.

Gavrilchuk, K., and V. Lesage. 2014. Large-scale marine development projects (mineral, oil and gas, infrastructure) proposed for Canada's North. Can. Tech. Rep. Fish. Aquat. Sci. 3069:viii + 84 pp.

Golder Associates. 2001. West Island Stream Fish Habitat Compensation Works Proposed Design. Diavik Diamond Mines Inc., NWT. Technical Memorandum.

Hulsman, M.F. 2012. Influence of Fish Competitors on Lake Trout Tropic Ecology in Sub-Arctic Lakes. M.Sc. Thesis. University of Alberta. 108 pp.

Hutchings, J. A., and J. R. Post. 2013. Gutting Canada's Fisheries Act: No Fishery, No Fish Habitat Protection. Fisheries 38(11):497-501.

Jepsen, N., A. Koed, E. B. Thorstad, and E. Baras. 2002. Surgical Implantation of Telemetry Transmitters in Fish: How Much Have We Learned? Hydrobiologia 483(1-3):239-248.

Jones, N. E., W. M. Tonn, and G. J. Scrimgeour. 2003a. Selective Feeding of Age-0 Arctic Grayling in Lake-Outlet Streams of the Northwest Territories, Canada. Environmental Biology of Fishes 67(2):169-178.

Jones, N. E., W. M. Tonn, G. J. Scrimgeour, and C. Katopodis. 2003b. Ecological Characteristics of Streams in the Barrenlands near Lac De Gras, Nwt, Canada. Arctic 56(3):249-261.

Jones, N. E., W. M. Tonn, G. J. Scrimgeour, and C. Katopodis. 2003c. Productive Capacity of an Artificial Stream in the Canadian Arctic: Assessing the Effectiveness of Fish Habitat Compensation. Canadian Journal of Fisheries and Aquatic Sciences 60(7):849-863.

Jones, N. E., and W. M. Tonn. 2004a. Enhancing Productive Capacity in the Canadian Arctic: Assessing the Effectiveness of Instream Habitat Structures in Habitat Compensation. Transactions of the American Fisheries Society 133(6):1356-1365.

Jones, N. E., and W. M. Tonn. 2004b. Resource Selection Functions for Age-0 Arctic Grayling (Thymallus Arcticus) and Their Application to Stream Habitat Compensation. Canadian Journal of Fisheries and Aquatic Sciences 61(9):1736-1746.

Jones, N. E., G. J. Scrimgeour, and W. M. Tonn. 2008. Assessing the Effectiveness of a Constructed Arctic Stream Using Multiple Biological Attributes. Environmental Management 42(6):1064-1076.

Jungwirth, M. 1996. Bypass Channels at Weirs as Appropriate Aids for Fish Migration in Rhithral Rivers. Regulated Rivers-Research & Management 12(4-5):483-492.

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

Katopodis, C., J. Kells, and M. Acharya. 2001. Nature-Like and Conventional Fishways: Alternative Concepts? Canadian Water Resources Journal 26(2):211-232.

Knaepkens, G., K. Baekelandt, and M. Eens. 2006. Fish Pass Effectiveness for Bullhead (Cottus Gobio), Perch (Perca Fluviatilis) and Roach (Rutilus Rutilus) in a Regulated Lowland River. Ecology of Freshwater Fish 15(1):20-29.

Krajick, K. 2001. Barren Lands: An Epic Search for Diamonds in the North American Arctic.

Laine, A., R. Kamula, and J. Hooli. 1998. Fish and Lamprey Passage in a Combined Denil and Vertical Slot Fishway. Fisheries Management and Ecology 5(1):31-44.

Larinier, M. 2001. Environmental Issues, Dams and Fish Migration. FAO Fisheries Technical Paper (419):45-89.

Lucas, M. C., and E. Baras. 2001. Migration of Freshwater Fishes. Blackwell Scientific Press, Oxford.

Mallen-Cooper, M., and D. A. Brand. 2007. Non-Salmonids in a Salmonid Fishway: What Do 50 Years of Data Tell Us About Past and Future Fish Passage? Fisheries Management and Ecology 14(5):319-332.

Mallen-Cooper, M., and I. G. Stuart. 2007. Optimising Denil Fishways for Passage of Small and Large Fishes. Fisheries Management and Ecology 14(1):61-71.

Noonan, M. J., J. W. A. Grant, and C. D. Jackson. 2012. A Quantitative Assessment of Fish Passage Efficiency. Fish and Fisheries 13(4):450-464.

Northcote, T. G. 1995. Comparative biology and management of Arctic and European Grayling (Salmonidae, Thymallus). Reviews in Fish Biology and Fisheries 13(4):450-464.

Power, G. 1997. A Review of Fish Ecology in Arctic North America. In: Reynolds, J. (Ed.), Fish Ecology in Arctic North America, American Fisheries Society, Symposium vol. 19. American Fisheries Society, Bethesda, Maryland, pp. 13 – 39.

Quigley, J. T., and D. J. Harper. 2006. Effectiveness of Fish Habitat Compensation in Canada in Achieving No Net Loss. Environmental Management 37(3):351-366.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A Review of Stream Restoration Techniques and a Hierarchical Strategy for Prioritizing Restoration in Pacific Northwest Watersheds. North American Journal of Fisheries Management 22(1):1-20.

Schindler, D. W. 2001. The Cumulative Effects of Climate Warming and Other Human Stresses on Canadian Freshwaters in the New Millennium. Canadian Journal of Fisheries and Aquatic Sciences 58(1):18-29.

Scott, W. B., and E. J. Crossman. 1973. Freshwater fishes of Canada. Bulletin of the Fisheries Research Board of Canada, 184.

Scrimgeour, G., N. Jones, and W. M. Tonn. 2013. Benthic Macroinvertebrate Response to Habitat Restoration in a Constructed Arctic Stream. River Research and Applications 29(3):352-365.

Scrimgeour, G. J., W. M. Tonn, and N. E. Jones. 2014. Quantifying Effective Restoration: Reassessing the Productive Capacity of a Constructed Stream 14 Years after Construction. Canadian Journal of Fisheries and Aquatic Sciences 71(4): 589-601.

Stuart, K.M., and G.R. Chislett. 1979. Aspects of the life history of the Arctic grayling in the Sukunka drainage. British Columbia Fish and Wildlife Branch, Prince George. 111 pp.

Thompson, W. L. 2003. Hankin and Reeves' Approach to Estimating Fish Abundance in Small Streams: Limitations and Alternatives. Transactions of the American Fisheries Society 132(1):69-75.

Underwood, A. 1991. Beyond Baci: Experimental Designs for Detecting Human Environmental Impacts on Temporal Variations in Natural Populations. Marine and Freshwater Research 42(5):569-587.

Underwood, A. 1994. On Beyond BACI: Sampling Designs That Might Reliably Detect Environmental Disturbances. Ecological applications 4(1):3-15.

Walters, C. J., and R. Hilborn. 1978. Ecological Optimization and Adaptive Management. Annual Review of Ecology and Systematics 9:157-188.

Walters, C. J., and C. S. Holling. 1990. Large-Scale Management Experiments and Learning by Doing. Ecology 71(6):2060-2068.

Winter, J.D. 1996. Advances in Underwater Biotelemetry. *In* Murphy, B.R. and Willis, D.W. eds. *Fisheries Techniques.* 2nd edition. 555-590 pp. Bethesda, Maryland. American Fisheries Society.

TABLE 2.1— Attributes of fishpasses and reference streams in the Barrenlands region of the Northwest Territories, Canada during 2011-2013. M1S and M3S were gabion-style pool-weir fishpasses, while M2S was a nature-like choke-pool fishpass. Parentheses designate standard errors.

Location	pH	Conductivity (µS/cm)	Length (m)	Slope (%)	Mean Bankfull Width (m)	Total Catchment Area (ha)
M1S	5.81 (0.06)	21.2 (1.1)	50.0	2.0	1.0	23.8
M3S	5.39 (0.22)	22.8 (6.1)	40.0	2.5	0.5	5.3
M2S	6.17 (0.13)	21.4 (1.9)	27.5	0.7	1.0	9.1
R6S1	5.56 (0.25)	15.4 (0.9)	108.0	1.5	2.7	16.0
R6S2	5.37 (0.07)	14.5 (1.8)	177.0	2.2	2.6	8.0

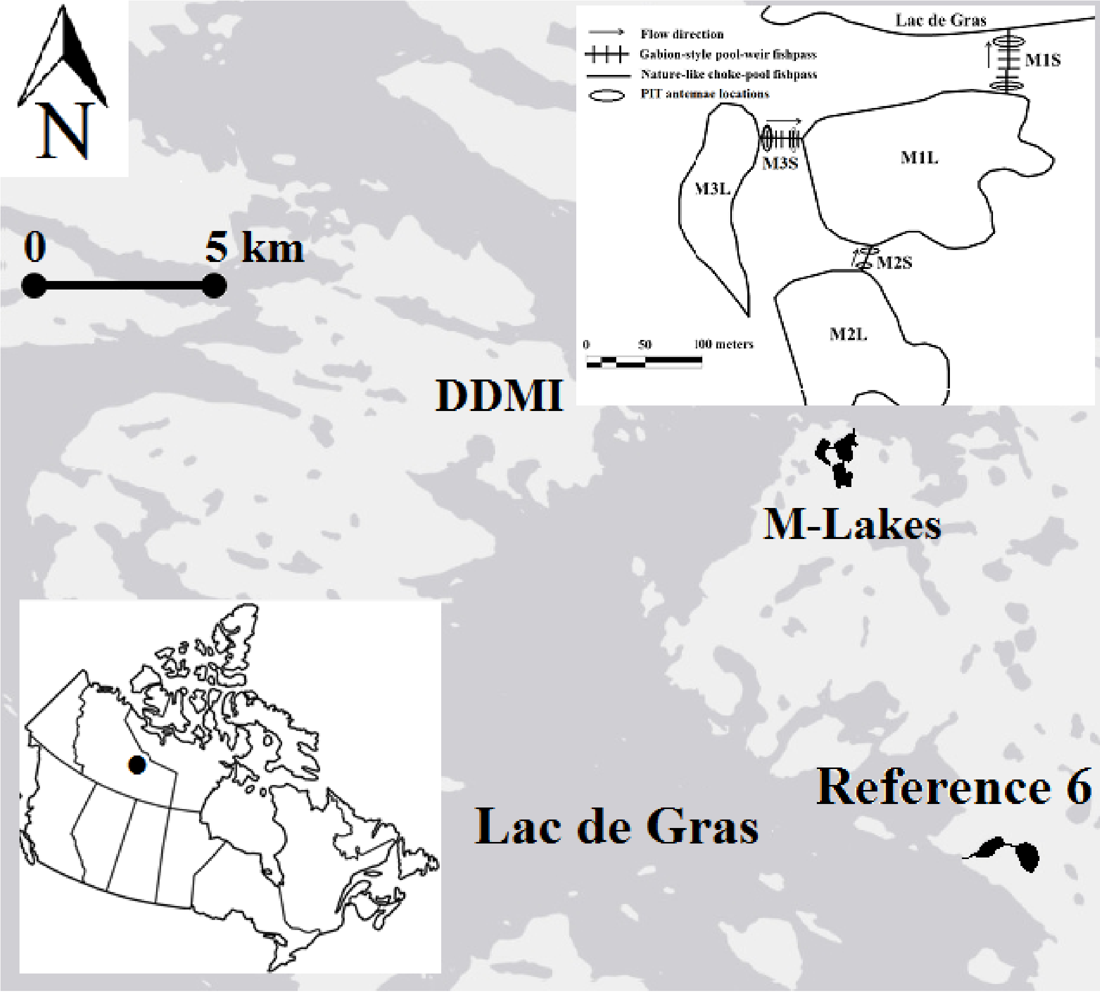

FIGURE 2.1.—Map showing the location of the M-Lakes fish habitat compensation site (three lakes and associated streams), two reference sites (two lakes and associated streams), and Diavik Diamond Mine (DDMI) in the Lac de Gras watershed. Lower insert: location of study area in the Northwest Territories, Canada. Upper insert: Schematic showing the M-Lakes fish habitat compensation site. In autumn 2011, gabion-style pool-weir fishpasses were constructed in M1S and M3S and a nature-like choke-pool fishpass was built in M2S to enhance connectivity among the M-Lakes and with Lac de Gras. Also shown are the locations of PIT antennae in each fishpass.

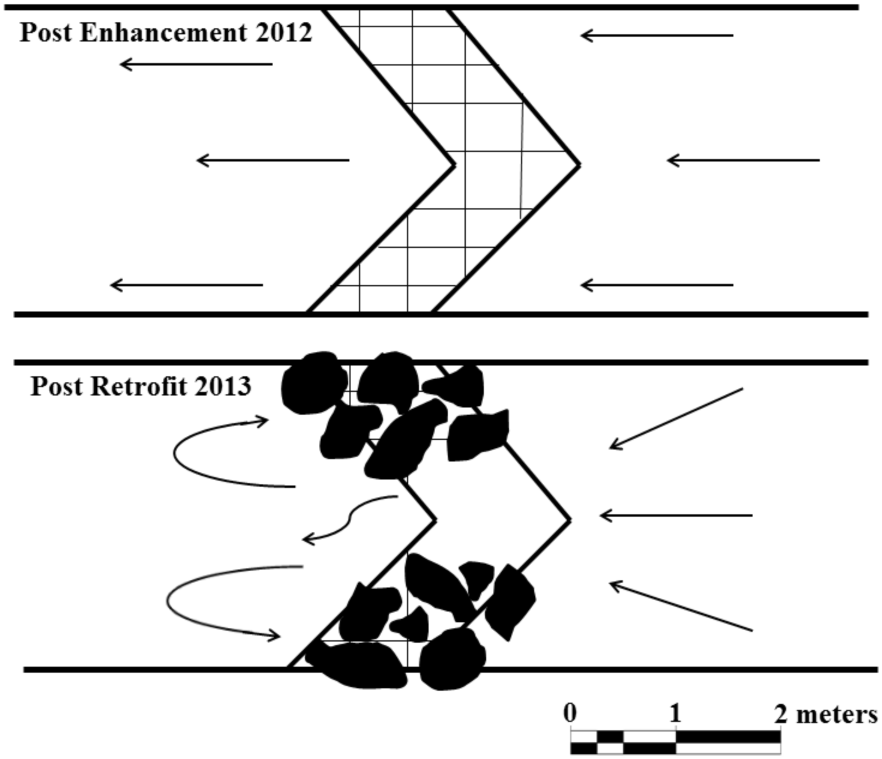

FIGURE 2.2.—Planar view of gabion weir structures used in M1S and M3S to enhance inter-lake connectivity on the Barrenlands, Northwest Territories, Canada (upper panel). Gabion weirs were retrofitted for 2013 by notching out the center of each weir (lower panel). Retrofitted weirs were also armored with boulders. Arrows indicate general flow direction.

FIGURE 2.3.—Nature-like choke-pool fishpass (M2S), facing downstream, 4 June 2013. The black hoop is the upstream PIT antenna, the constricting "choke" is immediately behind this antennae, and the relatively wide "pool" is immediately downstream of the choke. This fishpass was not retrofitted for 2013. Photo by Fred Noddin.

FIGURE 2.4.—A. M3S weir one (of six), facing upstream, 2 June 2012. This structure featured a 20 cm drop height and shallow (< 3 cm) diffuse flows during the spring freshet, similar to other gabion-weirs during 2012. B. The same M3S structure, 5 June 2013. All gabion weirs were retrofitted for 2013 by notching their center to reduce sudden drops over weir structures, and to increase flow depths during low flows. The black hoop is the upstream PIT antenna. Photos by Fred Noddin

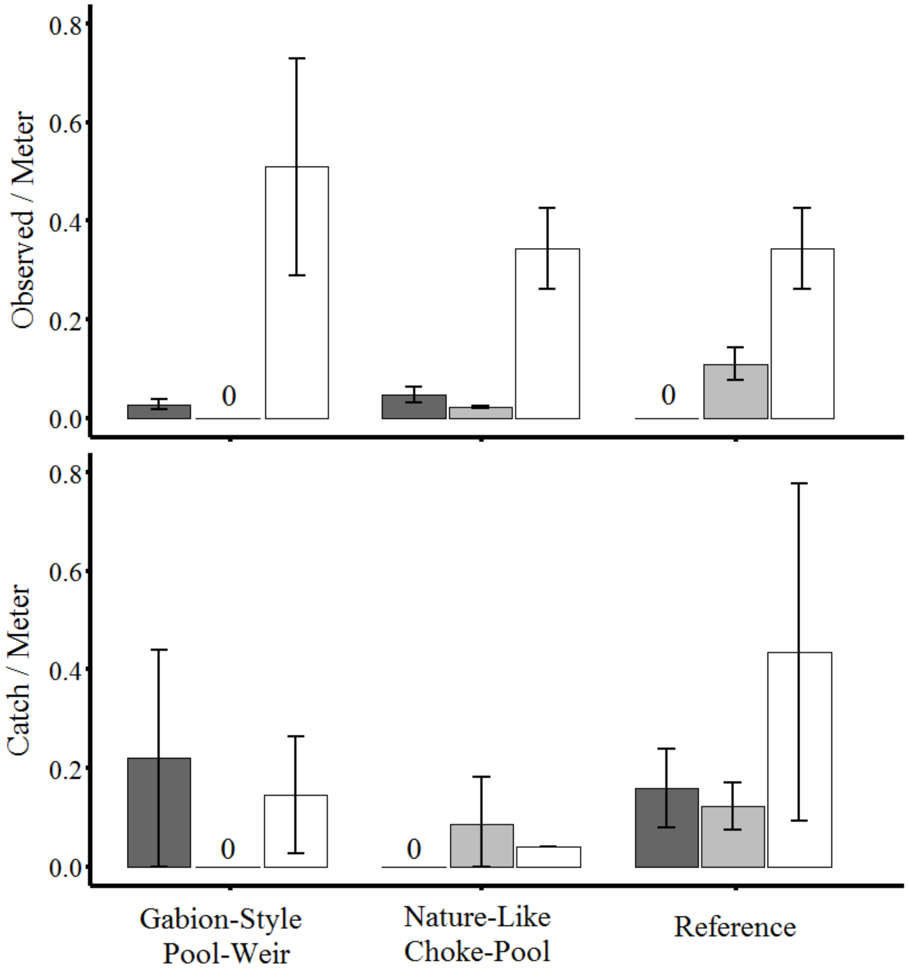

Figure 2.5. —Mean ± SE fish/meter as determined during visual (upper panel) and electrofishing (lower panel) surveys before (2011; dark bars) and after (2012; light bars, 2013; white bars) fishpass construction at the M-Lakes fish habitat compensation site in the Barrenlands, Northwest Territories, Canada. Gabion-weir (M1S, M3S) and nature-like (M2S) fishpasses were constructed in autumn 2011; the former were retrofitted in autumn 2012. Reference streams (R6S1, R6S2) remained unmanipulated throughout the study.

Chapter III: Arctic Grayling *Thymallus arcticus* Passage through a Nature-like Fishpass

Abstract.—I examined Arctic Grayling (*Thymallus arcticus*) passages through a nature-like choke-pool fishpass in the Barrenlands region of northern Canada for two seasons. Arctic Grayling were captured in lakes adjacent to the fishpass, marked with passive integrated transponder (PIT) tags, and passage through the fishpass was monitored using an automated PIT-tag logging station. The fishpass was not size-selective for Arctic Grayling ≥150mm, and I observed few consistent patterns when comparing velocity, discharge, depth, temperature, and date during passage events to the conditions available for Arctic Grayling selection. However, I observed strong diel periodicity in passage related activity as most (95%; 137/144) passage events occurred during evening or early morning (18:00-5:59). My results suggest nature-like fishpasses can be effective tools for increasing connectivity for Arctic Grayling in low-gradient Barrenlands systems. Similarly, this study documents the first case of clear diel periodicity in passage activity for this species, and I suggest this pattern represents a response to avian predation given the shallow depth of the fishpass.

Introduction

Understanding relationships between fish and their habitats is a central issue in fisheries ecology and management. Habitat selection patterns influence dynamic population rates such as survival and reproduction (Southwood 1977), and thus ultimately reflect the evolutionary consequences of natural selection (Boyce and McDonald 1999). In an applied sense, knowledge of fish-habitat relationships improves the odds that a particular habitat manipulation will result in a desirable ecological outcome (Bradshaw 1996; Bond and Lake 2003). Unfortunately, a paucity of information regarding fish habitat ecology exists for Arctic North America (Power 1997), where continued and increasing resource development and extraction activities often threaten the sustainability of aquatic habitats (Schindler 2001; Angell and Parkins 2011). Consequently, fish habitat managers in high-latitude regions face considerable challenges as habitat management projects often proceed based on limited ecological knowledge.

In Canada, the federal Fisheries Act provides the legal framework outlining the protection of aquatic habitats. Prior to changes to the Fisheries Act in 2012 (Hutchings and Post 2013), the Act prohibited "Harmful Alteration, Disruption, or Destruction" (HADD) of fish habitat if avoidable. If unavoidable, the Policy for the Management of Fish Habitat required habitat compensation achieve "No Net Loss (NNL) to the productive capacity of aquatic ecosystems," and defined productive capacity as the "maximum natural capability of habitats to produce healthy fish…or to support or produce aquatic organisms upon which fish depend" (DFO 1986). Habitat compensation projects were designed to offset losses incurred during a HADD by enhancing existing, restoring degraded, or creating new aquatic habitats. However, a review on the effectiveness of habitat compensation in Canada found only 37% of projects actually achieved NNL (Quigley and Harper 2006), which suggests shortcomings in our collective ability to reproduce functioning aquatic ecosystems. Achieving NNL through habitat compensation, particularly in poorly known or pristine ecosystems, may require enhancing connectivity to naturally existing ecosystems (DFO 1986). This approach may help circumvent issues resulting from our incomplete understanding of ecosystem function. Roni et al. (2002) have also suggested stream habitat improvement projects that eliminate dispersal barriers between isolated, but otherwise high-quality habitats frequently prove effective.

A variety of fishpass structures have been designed to increase fish migration between isolated habitats (DVWK 2002). Technical fishpasses (i.e., Denil, Alaska steep-pass, and pool-weir) have been developed to deal with slopes greater than 10% (Katopodis et al. 1997), and are usually constructed of concrete, metal, or wood (Breton et al. 2013). Historically, technical fishpasses have been developed for strong swimming and leaping fishes (e.g., most species of Atlantic and Pacific salmon; Larinier 1998), and likely act as barriers to the majority of fish species present (Lucas et al. 2001). In response to this, nature-like fishpasses have been developed for milder slopes (< 5%; Larinier 2002), and are intended to provide suitable passage conditions for a variety of species and life stages (Katopodis et al. 2001). These fishpasses emulate the substrate, hydraulics, and channel morphology of a natural stream, and are constructed using natural materials located onsite (Jungwirth 1996). Although nature-like fishpasses are used worldwide, few assessments of these structures have occurred (but see Aarestrup et al. 2003; Calles and Greenberg 2005). Moreover, no published studies have examined fish passage in an Arctic nature-like fishpass, even though this information would help develop biologically optimal fishpasses (Katopodis et al. 2001).

In 1994, diamonds were discovered in Lac de Gras in the Barrenlands region of northern Canada. The subsequent development of Diavik Diamond Mines Inc. (DDMI) resulted in

HADDs, and a federal fisheries authorization mandated DDMI offset these habitat losses to achieve NNL. One component of DDMI's fisheries authorization, the Mainland Lakes (M-Lakes) fish habitat compensation project, was required to offset the elimination of headwater lakes and streams during mine development (DDMI 1998). The M-Lakes project was designed to enhance the productive capacity of three pristine, headwater lakes through the elimination of dispersal barriers among the M-Lakes and with Lac de Gras (Golder Associates 2001). In 2011, three fishpasses (two gabion-style pool-weir and one nature-like choke-pool fishpass) were constructed to enhance stream connectivity in this system. Hydraulic (Courtice et al. 2014) and fish passage (Cahill et al., chapter one) evaluations showed gabion-style pool-weir fishpasses at M-Lakes performed poorly, whereas the nature-like choke-pool fishpass allowed for passage of Arctic Grayling *Thymallus arcticus* Pallus (Northcote 1995). In the present paper, my objective was to document the habitat selection patterns of the grayling migrating through this nature-like fishpass. Specifically, I examined fish length in relation to passage events, compared the environmental conditions during passage events to available environmental conditions, and quantified the timing of Arctic Grayling passage events through this successful fishpass.

Methods

Study area.—The study was conducted within the Lac de Gras watershed in a region known as the Barrenlands, approximately 320 km northeast of Yellowknife, Northwest Territories (ca. 64°29' N, 110°16' W; Figure 3.1). The Lac de Gras watershed lies ca. 75 km north of the tree line within the Southern Arctic Ecozone, which is characterized by a semi-arid, low Arctic climate (200-300 mm precipitation yearly; mean annual temperature is -12°C, mean June min(max) temperature is 9(18)°C; Environment Canada 1991). Interconnected chains of shallow lakes and small (bankfull width 2-50 m), short (80-2900 m) outlet streams dominate the landscape (Jones et al. 2003c). Spring freshet typically begins in early June, after which stream flows decline and occasionally stop altogether by mid-late summer (Jones et al. 2003c; Baki et al. 2012). Streams are acidic (5.37-6.17 pH), and are frozen solid from October to May (Jones et al. 2003c).

The M-Lakes fish habitat compensation site is located 5 km east of the DDMI mine site on the eastern shore of Lac de Gras (Figure 3.1). The site features two headwater lakes (M3L and M2L) that flow separately into another lake (M1L), which, in turn, flows into Lac de Gras (Figure 3.2). All three connecting streams (M1S, M2S, and M3S) were ephemeral, and featured cascades and/or diffuse channels impassable to fish (Golder Associates 2001). Unmodified stream channel slopes were steeper in M1S and M3S (≥ 2.0%) than in M2S (1.5%). Accordingly, DDMI constructed gabion-style pool-weir fishpasses in both M1S and M3S, and a nature-like choke-pool fishpass in M2S. The M2S fishpass was built by a small field crew using hand tools, and featured a single constriction point upstream of a wider and deeper "pool" (Figure 3.3). After construction, the M2S fishpass was small (average bankfull width = 1.0 m), short (length = 27.5 m), and had a low gradient (slope = 0.7%).

Study species.—Few stream habitat restoration projects have specifically focused on Arctic Grayling, although exceptions to this have occurred in the remote Barrenlands region where grayling dominate stream fish communities (Jones et al. 2003a; b; c; Jones and Tonn 2004a; b; Scrimgeour et al 2014). Although there is some variation in their life history, Arctic Grayling are spring spawners that commonly move into streams from lakes during freshet to spawn (Rawson 1950; Beauchamp 1990). Spawning migrations typically occur when stream water temperatures are 5ºC - 10ºC (Armstrong 1986; Nelson and Paetz 1992; Northcote 1995; Stewart et al. 2007). Adult grayling leave small streams after spawning to return to lakes

(Lawrence and Davies 1979; Jones et al. 2003c). Arctic Grayling are visual predators, and typically feed on a variety of drifting aquatic and terrestrial invertebrates (Armstrong 1986; Nelson and Paetz 1992; Northcote 1995).

Tagging.— Arctic Grayling were captured by angling, seining, and short-set gillnets (15 minute sets, with nets measuring 24.8 m x 1.8 m, with 3.1 m panels of 38, 51, 64, 76, 89, 102, 114, and 127 mm stretched mesh) during 2011-2013. Captured Arctic Grayling were enumerated and measured (Fork Length (FL) ±1 mm). Grayling $\geq$ 150 mm FL were anaesthetized using tricaine methanesulfonate (MS-222; 25-50 mg/L; Western Chemical Inc., Ferndale, Washington), and marked using a half-duplex Passive Integrated Transponder (PIT) tag (23 mm long, 3.5 mm diameter, 0.3 g) and an anchor tag (25mm long, 0.2g). This minimum size requirement ensured low total tag weight/body mass ratios (i.e., approximately 1%, C.L. Cahill unpublished data; Winter 1996). A small scalpel incision was made in the peritoneal cavity to insert PIT tags (Jepsen et al. 2002), while anchor tags were inserted near the dorsal fin using a 16 gauge injection gun. Tools were sterilized in 90% ethanol to minimize the potential for infection and disease transmission between fish (CBFWA 1999). Grayling were released at point of capture after a 15-minute recovery period. We tagged 104 Arctic Grayling (28 in M1L and 76 in M2L) prior to fishpass construction, and an additional 19 in M1L during 2012 and winter 2013, after fishpass construction.

One OregonRFID™ PIT reader and two swim-through antennae were used to monitor movement of tagged fish at the M2S fishpass during 2012-2013. Each antenna (ca. 75 cm diam.) used three wraps of eight gauge Wirez™ high current capacity audio cable, and antenna inductance was approximately 15 μH. One antenna was placed directly upstream of the "choke" section, and the lower antenna was placed near the stream mouth, ca. 15 m downstream (Figure

3.3). Antennae were placed in the same locations during both 2012 and 2013. I installed the PIT antennae systems during freshet, and removed them in July when the M2S fishpass stopped flowing. In 2012, the PIT antennae system was installed on 2 June and removed on 8 July, while in 2013 the system was installed on 31 May and removed on 1 July. The PIT tracking system was powered by a single 90A·h ceramic plate 12V battery, and charged by one 30W solar panel. The tracking system recorded the time, alphanumeric PIT tag identifier, and antenna (upstream or downstream) for each detection event.

I conducted two antennae efficiency and detection range evaluations each year. On each occasion, a PIT-tagged drone was drifted through the entire fishpass ten consecutive times, and antenna detection events were recorded. Both antennae detected the drone in every drift for both years. I also measured the maximum distance (m) the tagged drone could be detected from each antenna. This maximum read range was 2.84 m for the upstream antenna, while this distance was 2.64 m for the downstream antenna. I documented PIT antennae system function by placing a logger tag near the lower antenna. The logger tag created detection event records at consecutive 31-minute intervals and allowed me to determine when the tracking system was operational.

Hydraulics data.—Information on water depth (cm) and temperature (˚C) was collected in the M2S fishpass at 15-minute intervals using one SWS Mini-Diver pressure data logger (Schlumberger Water Services). This was attached to a boulder at the bottom of the fishpass, 10 m upstream of the M2S choke where flow was approximately uniform and backwater effects were negligible. An additional SWS Baro logger was placed on shore to account for variation in atmospheric pressure.

The area-velocity method (Linsley et al. 1982) was used to measure discharge (m^3/sec) at a single cross section in M2S. For each discharge measurement, a surveyor's tape was stretched perpendicular to the flow, and this cross section was divided into eleven evenly spaced cells. Flow depth at each cell was measured using a meter stick, and velocity (m/sec) was measured for 20 seconds at 0.6 of depth using a Marsh-McBirney (Model 2000 Flo-Mate) current meter. Discharge was then calculated for each cell by multiplying depth, cell width, and velocity. The sum of these discharges was then used as a measure of total stream discharge. Total discharge was measured five times in 2012 and six times in 2013 to account for hydraulic variability in the M2S fishpass. These velocity and discharge measurements were correlated to water level data obtained using the SWS Mini-Diver to create average discharge and velocity rating curves for each year. Rating curves assumed an exponential relationship between depth and average discharge or velocity, and had R^2 values of 0.81 - 0.94. These rating curves were then used to extrapolate continuous discharge and velocity measurements to the depth measurements recorded by the SWS Mini-Diver in the M2S fishpass.

Data analysis.—Logger-tag detection records were inspected to confirm the PIT antennae system operated continuously, and Arctic Grayling detection events were enumerated. Passage events occurred when an individual Arctic Grayling was first detected at one antenna and subsequently at the opposite antenna. Fisher's exact tests were used to compare the length-frequency distribution of fish detected passing through the fishpass and the length-frequency distribution of tagged fish. I used 20 cm bins, and considered distributions significantly different at $P \leq 0.05$.

I created a database to link detected passage events to the nearest SWS Mini-Diver depth and temperature record, and then to the extrapolated average discharge and velocity measurements from the rating curves. I standardized the domain of temporal stream habitat availability between years. For each year, this standardized period began after I recorded the first two consecutive days with a passage event, and ended after I recorded four consecutive days without a passage event. I considered the effects of velocity, discharge, depth, temperature, ordinal date, and time of day on Arctic Grayling passage. For each year, I examined passage both during the entire period of stream habitat availability and during the spawning period, which I defined as the first ten days of the available period based on Arctic Grayling life history (i.e., Arctic Grayling in northern regions spawn during spring freshet at temperatures <10˚C; McPhail and Lindsey 1970; Scott and Crossman 1973). High collinearity among explanatory variables (i.e., >0.8, C. Cahill unpublished data) led to numerical estimation problems with resource selection function models. Thus, I instead used pairwise permutation tests with 1 000 000 randomizations to determine whether median conditions during passage events differed from median conditions available in the fishpass, and from median ordinal date during the available period. I used the difference in medians between the used and available conditions as my permutation test statistic to compare the central tendencies of non-normal distributions (Ernst 2004). I originally analyzed upstream, downstream, and both up- and downstream oriented passages separately. However, the patterns I observed among all three categories were generally similar (C.L. Cahill, unpublished data), so I have chosen to instead report only the combined up- and downstream passage category. I used chi-square tests to determine if passage events were more likely during 06:00-17:59 vs. 18:00-05:59 to examine the effect of time of day on Arctic Grayling passage. Statistical tests were considered significant at $P \leq 0.05$. I performed all analyses using R Statistical Computing Software (2012), and used the ‘ggplot2’ package (Wickham 2009).

Results

The logger-tag was detected at all 31-minute intervals throughout the 2012 and 2013 field seasons, indicating the PIT antennae computer operated without interruption. PIT antennae in the M2S fishpass detected 144 passage events, representing 31 individual Arctic Grayling, during 2012-2013. Mean length of tagged Arctic Grayling was 222±7 mm (FL±SE) vs. 234±11 mm for grayling detected passing through the fishpass (Figure 3.4). Length-frequencies of tagged and detected Arctic Grayling were similar for each year (C.L. Cahill, unpublished data) and when pooled together (P=0.271).

The spawning periods were 5-15 June in 2012 and 6-16 June in 2013, and the full passage season was also similar between years (ending 29 June and 1 July in 2012 and 2013, respectively; Figure 3.5). In 2012, most (74%; 14/19) Arctic Grayling were detected during the spawning period, and these fish accounted for 83% (74/89; 42 upstream passages vs. 32 downstream passages) of the total number of passage events for that year. I detected 1.7 ± 0.50 (mean ± S.E.) passage events per day during the spawning period compared to 1.2 ± 0.27 during the non-spawning season in 2012 (Figure 3.5). Passage events were split nearly equally between upstream and downstream directions, with 52% (46/89) upstream. During 2013, most (70%;14/20) Arctic Grayling were similarly detected during the spawning period, but this period only accounted for 35% (19/55; 13 upstream vs. 6 downstream) of the total number of passage events for that year. I detected 1.6 ± 0.75 (mean ± S.E.) passage events per day during the spawning period vs. 1.5 ± 0.38 (mean ± S.E.) during the non-spawning season in 2013 (Figure 3.5). For 2013, 49% (27/55) of the passages were upstream movements.

Passage events occurred at median velocities, discharges, and depths similar to the median available hydraulic conditions in the M2S fishpass during the 2012 spawning period (velocity (*P*=0.352), discharge (*P*=0.350), and depth (*P*=0.077)), but generally occurred at lower than median available temperatures (*P*=0.001; Figure 3.6). Arctic Grayling were also more likely to pass through the M2S fishpass earlier than the median ordinal date during this period (*P*<0.001; Figure 3.5).

Conversely, when analyzed throughout the entire available 2012 season, median velocities during passage events were significantly higher than the median available velocity (*P*<0.001; Figure 3.7). Similarly, median discharge (*P*<0.001; Figure 3.7) during passage events was significantly higher than median available discharge. Median temperatures during passage events were all significantly lower than median available temperature, and passages occurred at dates significantly earlier than the available dates (all *P*<0.001).

Environmental conditions associated with passage in 2013 differed from those in 2012. During the 2013 spawning period, passages again occurred at earlier than median available dates (*P*<0.001; Figure 3.5). However, median velocity, discharge, and depth during passage events were usually higher than the median available conditions (all *P*<0.001; Figure 3.8). Conversely, median temperatures during passage events were similar to the available median temperature (*P*=0.790; Figure 3.8). When analyzed throughout the entire 2013 season, permutation tests indicated no differences existed between median available conditions and median velocity, discharge, depth, temperature, or ordinal date during Arctic Grayling passage events (Velocity *P*=0.167; Discharge *P*=0.167; Depth *P*=0.151; Temperature *P*=0.152; Ordinal *P*=0.775, Figures 3.5,3.9).

During 2012 and 2013, 97% (86/89) and 93% (51/55) of Arctic Grayling passed through the nature-like choke-pool fishpass between 18:00-05:59, respectively (Figure 3.10). As a result, passage during this period was significantly more likely than passage during the middle of the day ($\chi^2 = 83.20$, df = 18, $P<0.001$ and $\chi^2 = 40.16$; df = 19, $P=0.003$, for 2012 and 2013, respectively). In 2012, the three daytime passage events were made by the same individual, but this individual still made most (73%; 8/11) passages during the evening and early morning period). Of the four daytime passage events in 2013, all occurred after 17:00 (Figure 3.10).

Diel fluctuations in hydraulic conditions were evident during both years. During both the 2012 and 2013 spawning periods, velocity, discharge, depth, and temperature peaked during 15:00-18:00, and were lowest in early morning (04:00-07:00; Figures 3.11 and 3.12).

Discussion

My length frequency analyses indicated that for Arctic Grayling ≥150 mm, ability to pass through this nature-like choke-pool fishpass was not size-selective. This coincides with other studies that show nature-like fishpasses can be effective tools for increasing stream channel connectivity for salmonids (Noonan et al. 2012), and suggests enhancing stream connectivity in low gradient Barrenlands streams may be a realistic fisheries management objective, at least for Arctic Grayling ≥150 mm. Clearly, however, more species and more nature-like fishpasses should be examined for their passage efficacy.

With the exception of time of day and ordinal date during the spawning periods, environmental correlates with passage events differed between 2012 and 2013, and between the spawning season and the full summer passage season. During the 2012 spawning period, Arctic Grayling showed no selection for median velocity, discharge, or depth, but generally selected below-median temperatures for passage through the fishway, whereas considering the full 2012 passage season, fish selected higher than median velocities, discharges, and depths (but continued their preference for lower temperatures). I suggest this discrepancy occurred because most passages in 2012 were concentrated in the spawning season (Figure 3.5), when velocities, discharges, and depths were generally higher and temperatures were lower than the passage season as a whole.

In many respects, my results showed nearly opposite patterns during 2013, as Arctic Grayling generally selected higher than median velocities, discharges, and depths for passage during the spawning period, but not during the full season. As well, passage events occurred when temperatures were similar to the median, during both the spawning and full passage season. Passage events occurred at earlier than median available dates during the spawning period (similar to 2012 spawning period), but then at dates similar to the median available dates during the full season. Given the similar diel patterns of environmental fluctuations during both years (Figures 3.11 and 3.12), I suggest the patterns during the 2013 spawning period occurred because the available conditions during that period were more variable than the conditions during the 2012 spawning period, which may have decreased my ability to detect a significant difference. Additionally, whereas most (83%) passage events throughout 2012 occurred during the spawning season, passages were far more evenly distributed throughout the whole season in 2013, with only 35% occurring during the cooler, higher discharge spawning season.

Although evaluations of fishpasses are typically location specific (Jungwirth et al. 1998), my results are concordant with published literature on Arctic Grayling biology and general habitat requirements. My finding that most passage events occurred on earlier than median available dates during both the 2012 and 2013 spawning periods was expected given grayling undergo potadromous spawning migrations during freshet throughout their geographic range (Armstrong 1986; Northcote 1995; AESRD 2005). While habitat selection patterns can change seasonally and/or among years due to changes in resource availability (Boyce et al. 2002), the apparently inconsistent selection patterns I observed between years, coupled with basic information on Arctic Grayling life history, suggests to me that velocity, discharge, and depth were not overwhelmingly important correlates of fish passage over the range of the values observed. For example, the highest water velocity measured during this study was 13 cm/sec, but Arctic Grayling regularly use streams with water velocities up to 60 cm/sec (Vincent 1962). Moreover, while recruitment of young-of-year Arctic Grayling has been negatively correlated to stream discharge (Clark 1992), it seems unlikely that any of the extremely low (i.e., < 0.025 m^3/sec) discharges measured during this study would be detrimental to a strong swimming salmonid ≥150mm. Additionally, Arctic Grayling often use shallow streams (< 1 m; McPhail and Lindsey 1970; Northcote 1995; Stewart et al. 2007), so the shallow depth of M2S was likely not a limiting factor. However, Arctic grayling are known to occasionally forgo spawning events (i.e., non-annual spawning) similar to other northern fishes (Scott and Crossman 1973, Northcote 1995); consequently, it is possible that this life history characteristic resulted in the inconsistent patterns we observed. For instance, grayling may select stream habitat resources differently during spawning vs. non-spawning years. Moreover, it is possible that behavioral plasticity among individual grayling influenced my results.

Temperature was also an inconsistently selected ecological resource throughout this study. Wojcik (1955) suggested adult Arctic Grayling in Alaska avoid water temperatures above 20˚C. Water temperature in the M2S fishpass surpassed this level during both years, and I only recorded one passage event when stream temperature was above 20˚C (C.L. Cahill, unpublished data). However, as such temperatures were uncommon, it seems unlikely temperature was an important factor limiting grayling passages throughout most of this study; the selection of lower-than median temperatures in 2012 largely reflects the high concentration of passages during the (early) spawning season.

In contrast to the inconsistency with the other environmental correlates, I observed striking consistency in diel-related passage activity in this nature-like choke-pool fishpass over both years. While many fishes exhibit clear diel periodicity in activity levels (Helfman 1993), I am unaware of studies that have documented this with regard to Arctic Grayling movements. Most observations of Arctic Grayling spawning behavior suggest spawning occurs throughout the day (Bishop 1971; Beauchamp 1990), but at least one study has observed spawning into late evening and at night (Van Wyhe 1961). Similarly, Bass et al. (2014) recently showed that some European Grayling *Thymallus thymallus* Linnaeus exhibited clear circadian rhythms, and suggested that these patterns were a consequence of changing light levels. Others have suggested diel activity and movement patterns, similar to what I observed, are generally the result of responses to predation, improved foraging opportunities, or both (Lucas et al. 2001). Northcote (1995) suggested European Grayling in the River Frome, England, showed strong diel periodicity in feeding, and that this behavior was likely driven by increases in invertebrate drift relative to prey visibility. Similarly, Arctic Grayling have been documented feeding on a 24-hour basis during mid-summer in the Delta Clearwater River, Alaska (Reed 1964). However, it seems unlikely to me that Arctic Grayling passed through the M2S fishpass in the evening and early morning for improved foraging opportunities alone, given its short length. Rather, fish can be vulnerable to avian predators in shallow water (Miller 1946; Power 1987), and I observed avian predation events on Arctic Grayling in the M-Lakes system. Thus, I suggest that lower light levels in the evening and early morning provide grayling a refuge from avian predation as fish venture into the shallow habitats within and bordering the M2S fishpass. Clearly, further study is needed to elucidate the ecological mechanisms behind this and the other patterns I observed.

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References

Aarestrup, K., M. C. Lucas, and J. A. Hansen. 2003. Efficiency of a Nature-Like Bypass Channel for Sea Trout (Salmo Trutta) Ascending a Small Danish Stream Studied by Pit Telemetry. Ecology of Freshwater Fish 12(3):160-168.

Alberta Environment and Sustainable Resource Development and Alberta Conservation Association. 2005. Status of Arctic Grayling (*Thymallus Arcticus)* in Alberta. Edmonton, AB.

Angell, A. C., and J. R. Parkins. 2011. Resource Development and Aboriginal Culture in the Canadian North. Polar Record 47(01):67-79.

Armstrong, R. H. 1986. A Review of Arctic Grayling Studies in Alaska, 1952-1982. University of Alaska. Institute of Arctic Biology, 0568-8604.

Baki, A. B. M., D. Z. Zhu, M. F. Hulsman, B. D. Lunn, and W. M. Tonn. 2012. The Hydrological Characteristics of a Stream within an Integrated Framework of Lake-Stream

Connectivity in the Lac De Gras Watershed, Northwest Territories, Canada. Canadian Journal of Civil Engineering 39(3):279-292.

Bass, A. L., T. O. Haugen, and L. A. Vollestad. 2014. Distribution and Movement of European Grayling in a Subarctic Lake Revealed by Acoustic Telemetry. Ecology of Freshwater Fish 23(2):149-160.

Beauchamp, D. A. 1990. Movements, Habitat Use, and Spawning Strategies of Arctic Grayling in a Subalpine Lake Tributary. Northwest Science 64(4): 195-207.

Bishop, F. G. 1971. Observations on Spawning Habits and Fecundity of the Arctic Grayling. The Progressive Fish-Culturist 33(1):12-19.

Bond, N., and P. Lake. 2003. Local Habitat Restoration in Streams: Constraints on the Effectiveness of Restoration for Stream Biota. Ecological Management & Restoration 4(3):193-198.

Boyce, M. S., and L. L. McDonald. 1999. Relating Populations to Habitats Using Resource Selection Functions. Trends in Ecology & Evolution 14(7):268-272.

Boyce, M. S., P. R. Vernier, S. E. Nielsen, and F. K. Schmiegelow. 2002. Evaluating Resource Selection Functions. Ecological Modelling 157(2):281-300.

Bradshaw, A. D. 1996. Underlying Principles of Restoration. Canadian Journal of Fisheries and Aquatic Sciences 53:3-9.

Breton, F., A. B. M. Baki, O. Link, D. Z. Zhu, and N. Rajaratnam. 2013. Flow in Nature-Like Fishway and Its Relation to Fish Behaviour. Canadian Journal of Civil Engineering 40(6):567-573.

CBFWA (Columbia Basin Fish and Wildlife Authority). 1999. PIT Tag Marking Procedures Manual. Portland, OR.

Clark, R. A. 1992. Influence of Stream Flows and Stock Size on Recruitment of Arctic Grayling (Thymallus Arcticus) in the Chena River, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 49(5):1027-1034.

Courtice, G., A. B. Baki, D. Zhu, C. L. Cahill, and W. M. Tonn. 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.

DDMI. 1998. No Net Loss Plan. Internal Technical Report Summary. Diavik Diamond Mines, Inc.

Department of Fisheries and Oceans (DFO). 1986. The Department of Fisheries and Oceans Policy for the Management of Fish Habitat. Communications Directorate, Fisheries and Oceans, Ottawa, Ontario, Canada.

DVWK. 2002. Fish Passes: Design, Dimensions, and Monitoring. Rome: FAO, 118 pp.

Environment Canada. 1991. Canadian Climate Normals 1961-1990. Environment Canada, Ottawa, Ont. http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html (June 2014).

Ernst, M. D. 2004. Permutation Methods: A Basis for Exact Inference. Statistical Science 19(4):676-685.

Golder Associates. 2001. West Island Stream Fish Habitat Compensation Works Proposed Design. Diavik Diamond Mines Inc., NWT. Technical Memorandum.

Helfman, G. S. 1993. Fish Behaviour by Day, Night, and Twilight. Pages 479-512 *in* T. J. Pitcher, editor. Behaviour of Teleost Fishes. Chapman and Hall, London.

Hutchings, J. A., and J. R. Post. 2013. Gutting Canada's Fisheries Act: No Fishery, No Fish Habitat Protection. Fisheries 38(11):497-501.

Jepsen, N., A. Koed, E. B. Thorstad, and E. Baras. 2002. Surgical Implantation of Telemetry Transmitters in Fish: How Much Have We Learned? Hydrobiologia 483(1-3):239-248.

Jones, N. E., W. M. Tonn, and G. J. Scrimgeour. 2003a. Selective Feeding of Age-0 Arctic Grayling in Lake-Outlet Streams of the Northwest Territories, Canada. Environmental Biology of Fishes 67(2):169-178.

Jones, N. E., W. M. Tonn, G. J. Scrimgeour, and C. Katopodis. 2003b. Productive Capacity of an Artificial Stream in the Canadian Arctic: Assessing the Effectiveness of Fish Habitat Compensation. Canadian Journal of Fisheries and Aquatic Sciences 60(7):849-863.

Jones, N. E., W. M. Tonn, G. J. Scrimgeour, and C. Katopodis. 2003c. Ecological Characteristics of Streams in the Barrenlands near Lac De Gras, Nwt, Canada. Arctic 56(3):249-261.

Jones, N. E., and W. M. Tonn. 2004a. Enhancing Productive Capacity in the Canadian Arctic: Assessing the Effectiveness of Instream Habitat Structures in Habitat Compensation. Transactions of the American Fisheries Society 133(6):1356-1365.

Jones, N. E., and W. M. Tonn. 2004b. Resource Selection Functions for Age-0 Arctic Grayling (Thymallus Arcticus) and Their Application to Stream Habitat Compensation. Canadian Journal of Fisheries and Aquatic Sciences 61(9):1736-1746.

Jungwirth, M. 1996. Bypass Channels at Weirs as Appropriate Aids for Fish Migration in Rhithral Rivers. Regulated Rivers-Research & Management 12(4-5):483-492.

Jungwirth, M., S. Schmutz, and S. Weiss. 1998. Fish Migration and Fish Bypasses, volume 4. Fishing News Books, Oxford.

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

Katopodis, C., J. Kells, and M. Acharya. 2001. Nature-Like and Conventional Fishways: Alternative Concepts? Canadian Water Resources Journal 26(2):211-232.

Larinier, M. 1998. Upstream and Downstream Fish Passage Experience in France. In: Jungwirth, M., Schumtz, S. and Weiss, S., eds. Fish Migration and Fish Bypasses. Oxford: Fishing News Books, Blackwell Science Ltd, pp. 127-145.

Larinier, M. 2002. Biological Factors to Be Taken into Account in the Design of Fishways, the Concept of Obstructions to Upstream Migration. Bulletin Français de la Pêche et de la Pisciculture 364:28-38.

Lawrence, M., and S. Davies. 1979. Aquatic Resources Survey - Keewatin and Franklin Districts. Canada Department of Indian and Northern Affairs, ESCOM Report No. AI-31:108 pp.

Linsley, R. K., M. A. Kohler, and J. Paulhus. 1982. Hydrology for Engineers. Mcgraw Hill, New York.

Lucas, M. C., E. Baras, T. J. Thom, A. Duncan, and O. Slavík. 2001. Migration of Freshwater Fishes. Blackwell Scientific Press, Oxford.

McPhail, J. D., and C. C. Lindsey. 1970. Freshwater Fishes of Northwestern Canada and Alaska. Fisheries Research Board of Canada Bulletin 173.

Miller, R. B. 1946. Notes on the Arctic Grayling, Thymallus Signifer Richardson, from Great Bear Lake. Copeia 1946:227-236.

Nelson, J. S., and M. J. Paetz. 1992. The Fishes of Alberta. University of Alberta Press, Edmonton.

Noonan, M. J., J. W. A. Grant, and C. D. Jackson. 2012. A Quantitative Assessment of Fish Passage Efficiency. Fish and Fisheries 13(4):450-464.

Northcote, T. G. 1995. Comparative Biology and Management of Arctic and European Grayling (Salmonidae, Thymallus). Reviews in Fish Biology and Fisheries 5(2):141-194.

Power, G. 1997. A Review of Fish Ecology in Arctic North America. In: Reynolds, J. (Ed.), Fish Ecology in Arctic North America, American Fisheries Society, Symposium vol. 19. American Fisheries Society, Bethesda, Maryland, pp. 13 – 39.

Power, M. E. 1987. Predator Avoidance by Grazing Fishes in Temperate and Tropical Streams: Importance of Stream Depth and Prey Size. Pages 333-351 *in* W. C. Kerfoot, and A. Sih, editors. Predation: Direct and Indirect Impacts on Aquatic Communities. University Press of new England, Hanover and London.

Quigley, J. T., and D. J. Harper. 2006. Effectiveness of Fish Habitat Compensation in Canada in Achieving No Net Loss. Environmental Management 37(3):351-366.

R Core Team (2012). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Rawson, D. S. 1950. The Grayling (Thymallus Signifer) in Northern Saskatchewan. Canadian Journal of Fish Culture (8):207-240.

Reed, R. J. 1964. Life History and Migration Patterns of Arctic Grayling, Thymallus Arcticus,(Pallas), in the Tanana River Drainage of Alaska. Alaska. Department of Fish and Game. Rep. No. 2. 30 pp.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A Review of Stream Restoration Techniques and a Hierarchical Strategy for Prioritizing

Restoration in Pacific Northwest Watersheds. North American Journal of Fisheries Management 22(1):1-20.

Schindler, D. W. 2001. The Cumulative Effects of Climate Warming and Other Human Stresses on Canadian Freshwaters in the New Millennium. Canadian Journal of Fisheries and Aquatic Sciences 58(1):18-29.

Scott, W. B., and E. J. Crossman. 1973. Freshwater Fishes of Canada. Fisheries Research Board of Canada Bulletin 184.

Scrimgeour, G. J., W. M. Tonn, and N. E. Jones. 2014. Quantifying Effective Restoration: Reassessing the Productive Capacity of a Constructed Stream 14 Years after Construction. Canadian Journal of Fisheries and Aquatic Sciences 71:589-601.

Southwood, T. 1977. Habitat, the Templet for Ecological Strategies? The Journal of Animal Ecology:337-365.

Stewart, D. B., N. J. Mochnacz, J. D. Reist, T. J. Carmichael, and C. D. Sawatzky. 2007. Fish Life History and Habitat Use in the Northwest Territories: Arctic Grayling (*Thymallus arcticus*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2797: vi + 55 pp.

Van Wyhe, G. 1961. Inventory and Cataloguing of Sportfish and Sportfish Waters of the Cappoe River and Prince William Sound Drainages. Alaska Dept. Fish and Game. Ann. Rep. Of Prog 1962:227-243.

Vincent, R. E. 1962. Biogeographical and Ecological Factors Contributing to the Decline of Arctic Grayling, *Thymallus arcticus* Pallus, in Michigan and Montana. Ph.D. Thesis, University of Michigan, Ann Arbor:169 pp.

Wickham, H. 2009. ggplot2: Elegant Graphics for Data Analysis. Springer New York.

Winter, J.D. 1996. Advances in Underwater Biotelemetry. *In* Murphy, B.R. and Willis, D.W. eds. *Fisheries Techniques.* 2nd edition. 555-590 pp. Bethesda, Maryland. American Fisheries Society.

Wojcik, F. J. 1955. Life History and Management of the Grayling in Interior Alaska. M.Sc. Thesis. University of Alaska, Fairbanks: 54 pp.

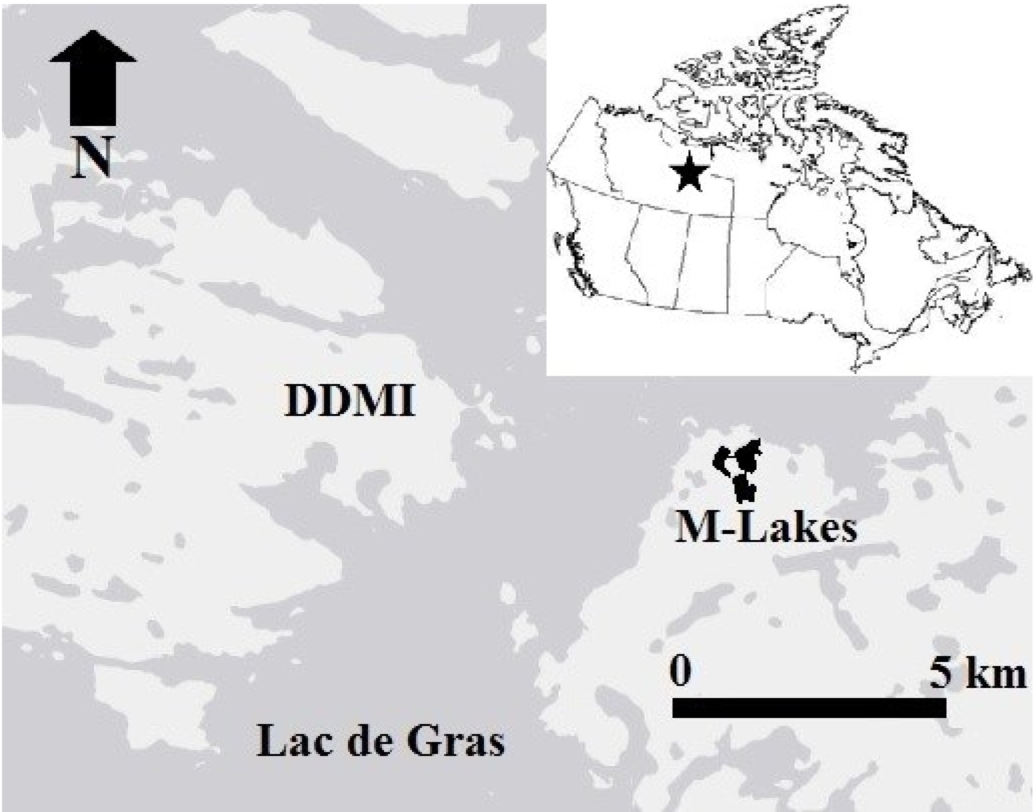

FIGURE 3.1.—Map showing the location of the M-Lakes fish habitat compensation site (three lakes and associated streams) in relation to Diavik Diamond Mine (DDMI) and Lac de Gras. Insert: location of study area in the Northwest Territories, Canada.

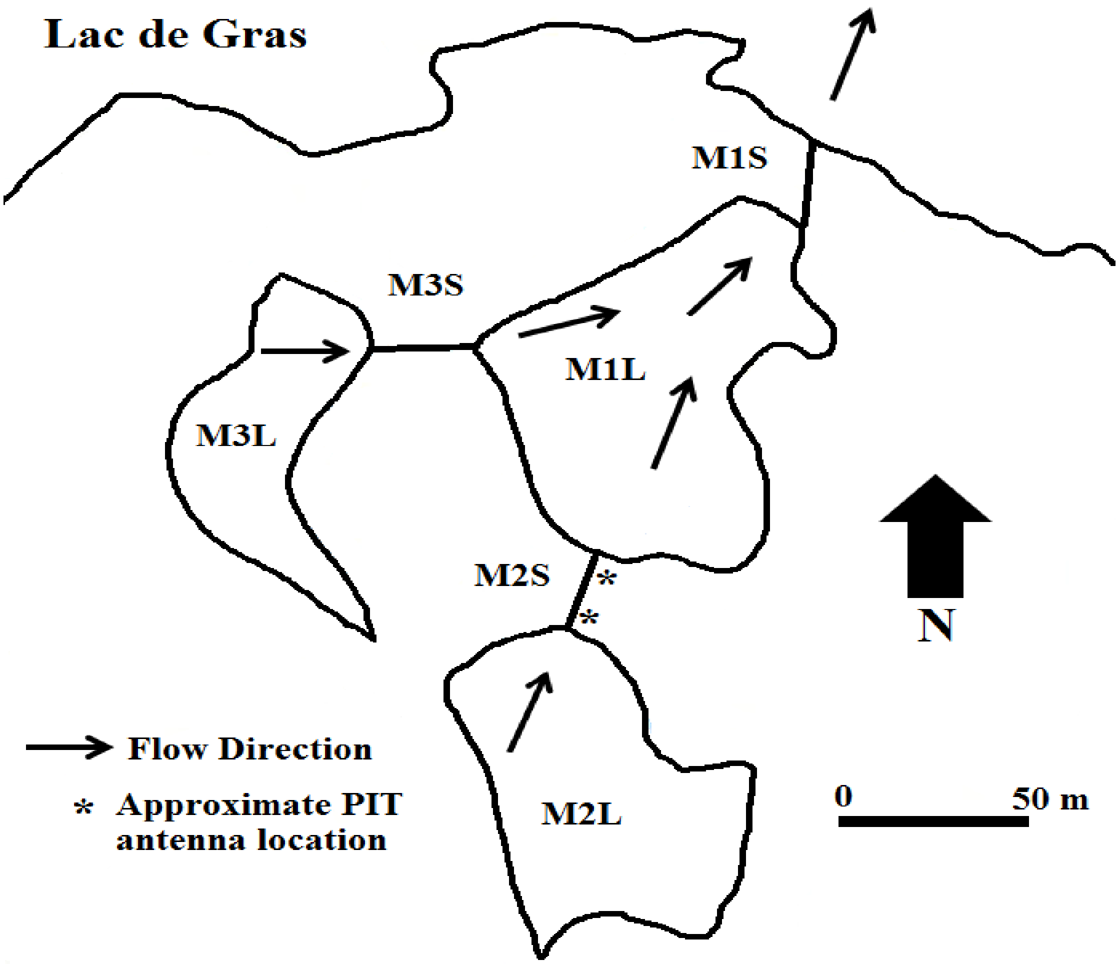

FIGURE 3.2.—Map showing the M-Lakes fish habitat compensation site. M-Lakes were originally connected by channels impassable to fish (Golder Associates 2001); in 2011 two gabion-style pool-weir fishpasses (M1S and M3S) and one nature-like choke-pool fishpass (M2S) were constructed to enhance stream connectivity in this pristine system.

FIGURE 2.3.—Nature-like choke-pool fishpass (M2S), facing downstream, 4 June 2013. The black hoop is the upstream PIT antenna, the constricting "choke" is immediately behind this antennae, and the relatively wide "pool" is immediately downstream of the choke. This fishpass was not retrofitted for 2013. Photo by Fred Noddin.

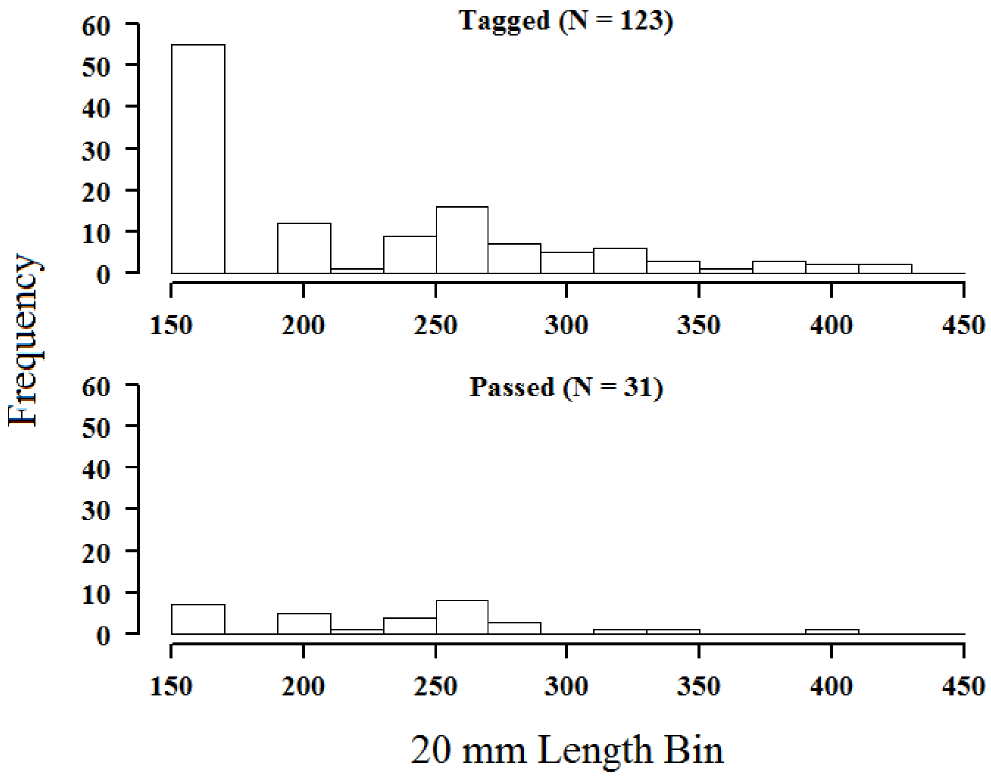

FIGURE 3.4.—Length frequency distribution of Arctic Grayling tagged (upper panel) and detected passing through the fishpass by PIT antennae (lower panel) in the M2S nature-like fishpass during 2012-2013.

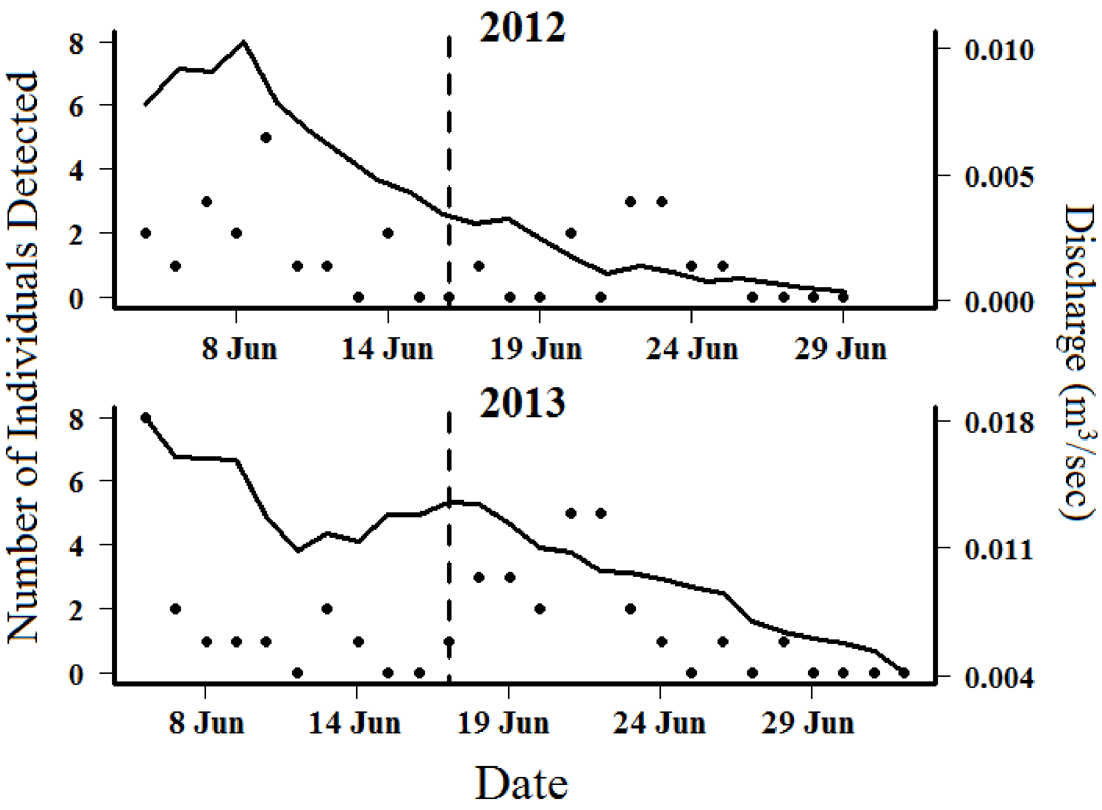

FIGURE 3.5.—Total number of individual fish detected per day (circles) and mean discharge (solid line) vs. date in the M2S nature-like fishpass during 2012-2013. Dashed line represents cutoff for the 10-d spawning period. Note: discharge scales differ for 2012 and 2013.

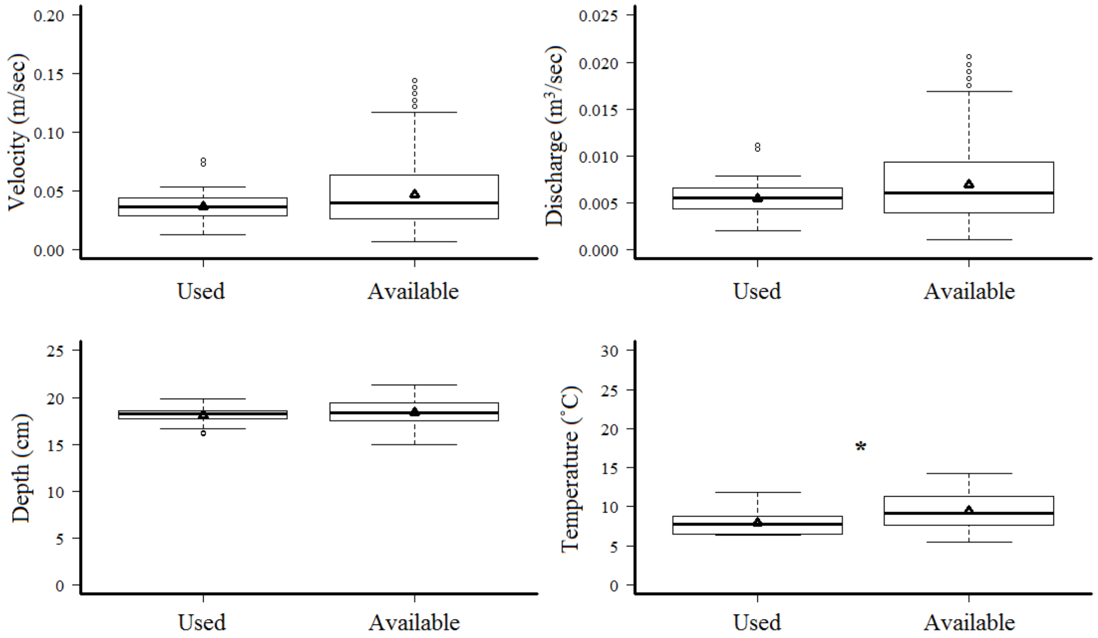

FIGURE 3.6.—Boxplots showing passages (“Used”) compared to the environmental conditions available (“Available”) in the M2S nature-like fishpass during the spawning period (5-15 June) 2012. The thick line indicates the median value, while the triangle demarcates the mean value. Asterisks indicate significant differences in medians at $P \leq 0.05$.

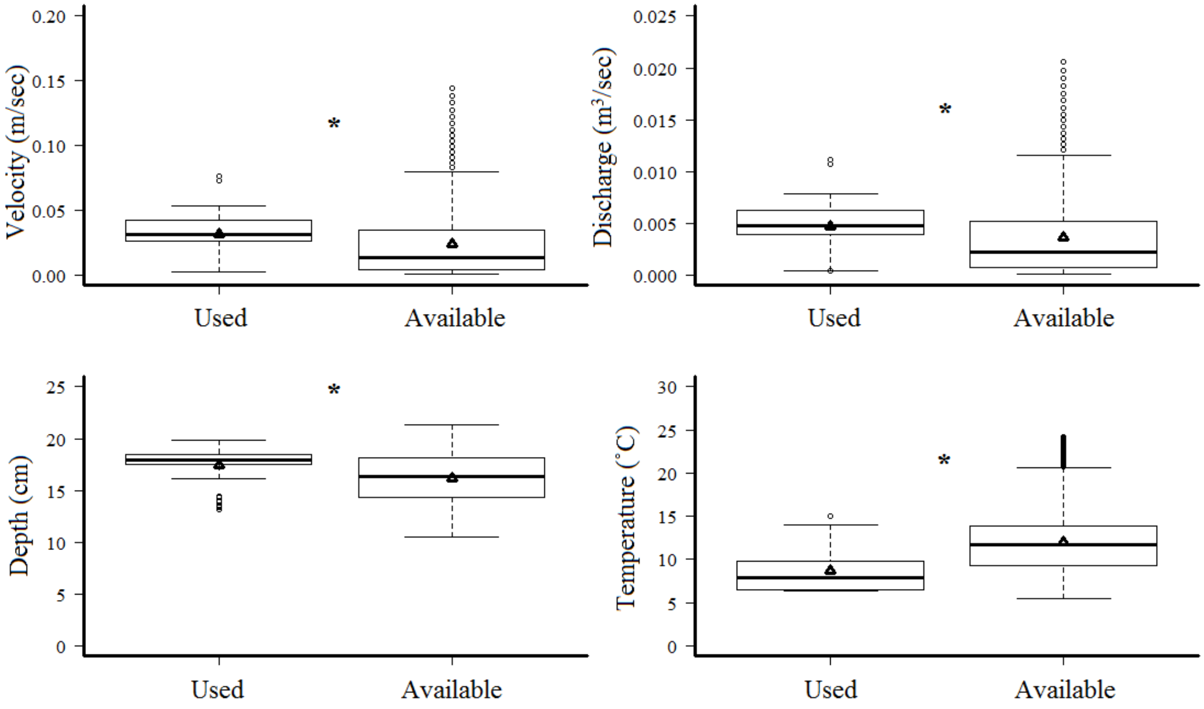

FIGURE 3.7.— Boxplots showing passages (“Used”) compared to the environmental conditions available (“Available”) in the M2S nature-like fishpass during the entire monitoring period (5 to 28 June) 2012. The thick line indicates the median value, while the triangle demarcates the mean value. Asterisks indicate significant differences in medians at $P \leq 0.05$.

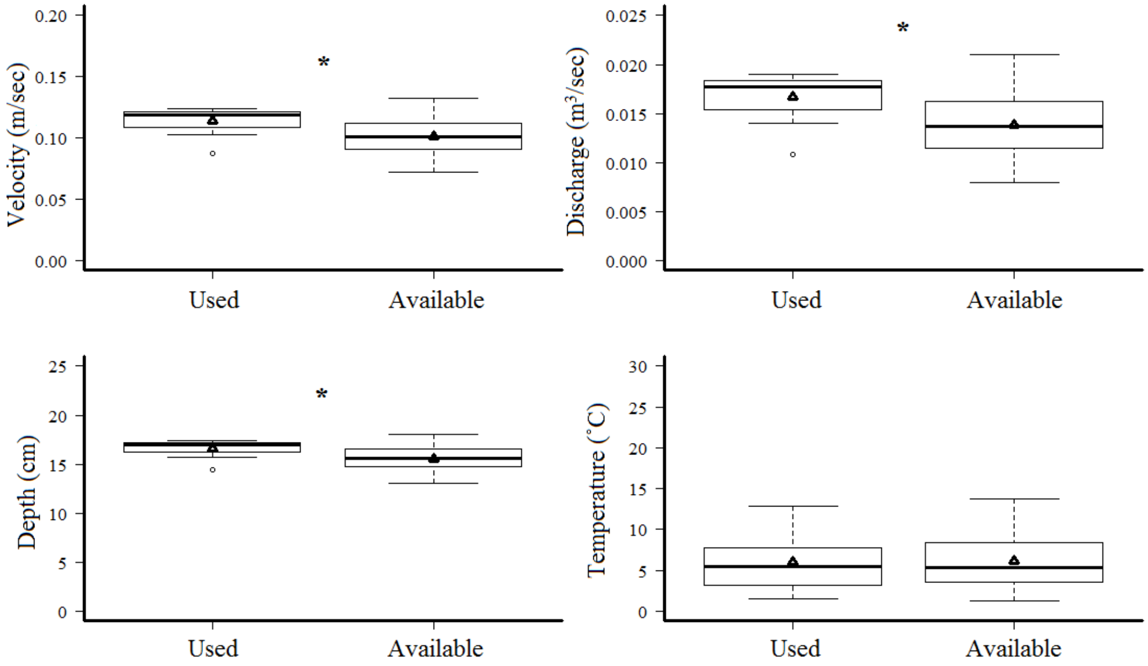

FIGURE 3.8.—Boxplots showing passages (“Used”) compared to the environmental conditions available (“Available”) in the M2S nature-like fishpass during the spawning period (6-16 June) 2013. The thick line indicates the median value, while the triangle demarcates the mean value. Asterisks indicate significant differences in medians at $P \leq 0.05$.

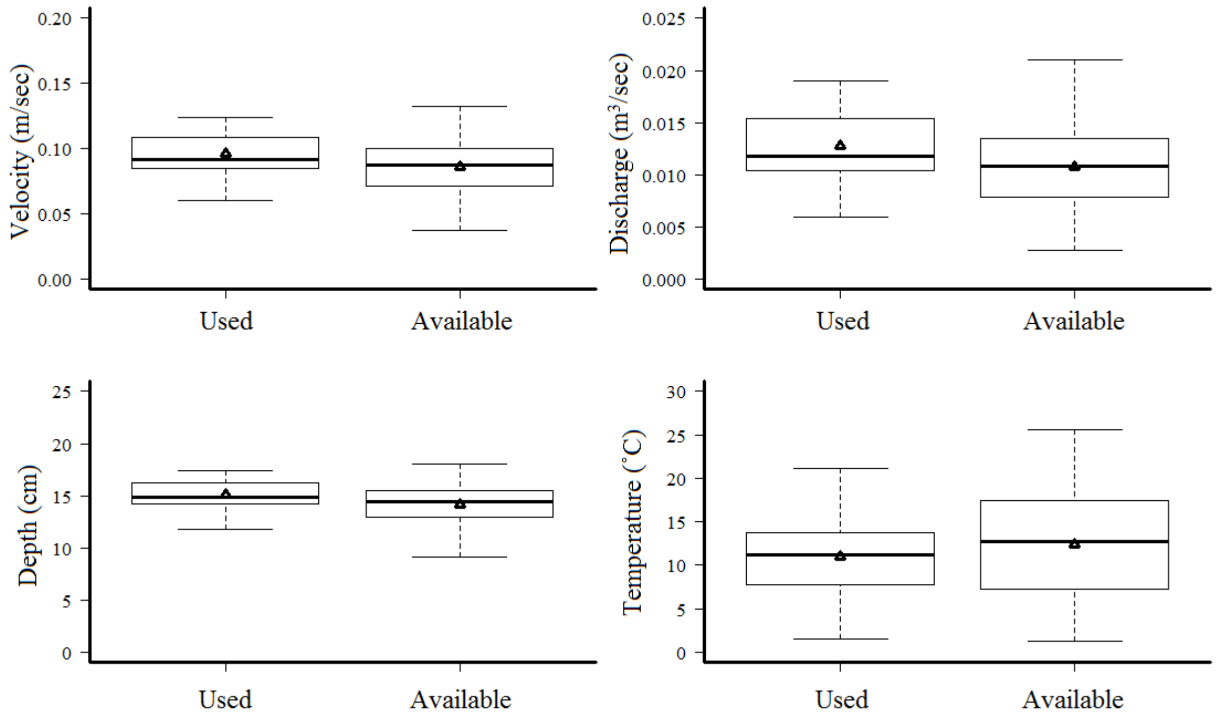

FIGURE 3.9.— Boxplots showing passages ("Used") compared to the environmental conditions available ("Available") in the M2S nature-like fishpass during the entire monitoring period (6 June to1 July) 2013. The thick line indicates the median value, while the triangle demarcates the mean value. Asterisks indicate significant differences in medians at $P \leq 0.05$.

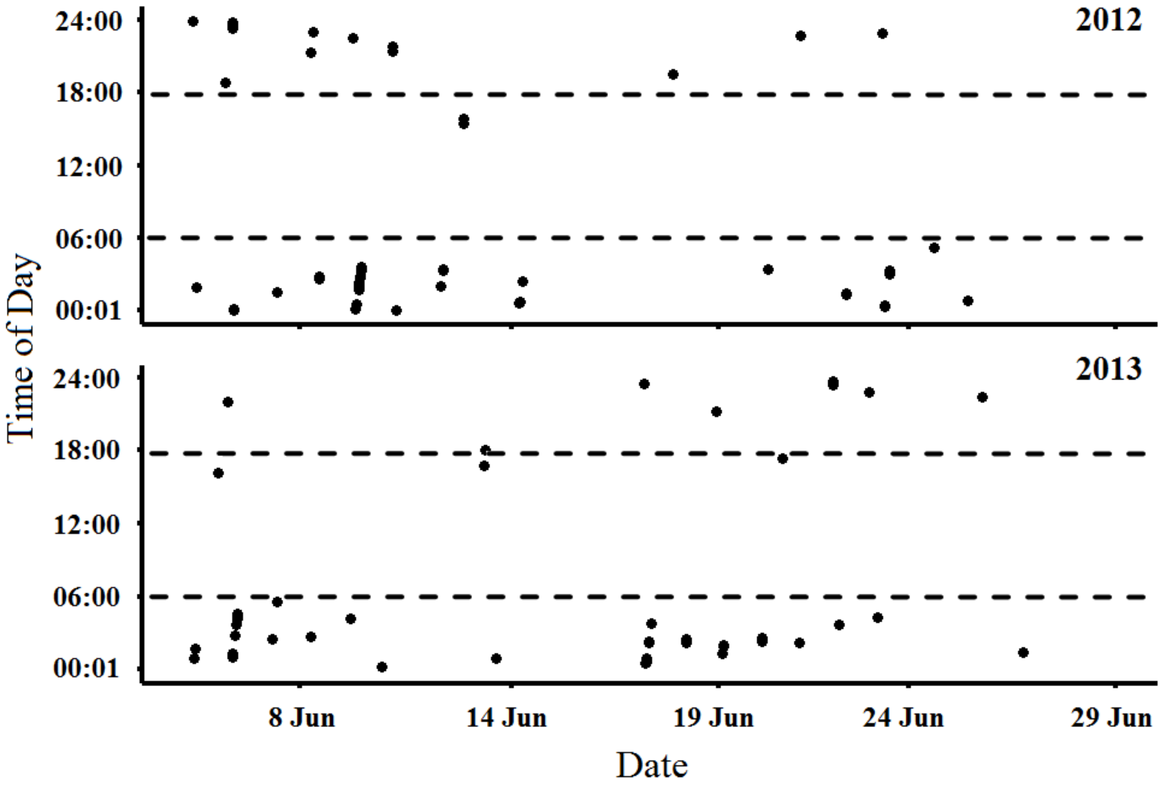

FIGURE 3.10.—Timing of passage events in the M2S nature-like fishpass during 2012 (upper panel) and 2013 (lower panel). Dashed horizontal lines demarcate 06:00-17:59 vs. 18:00-05:59.

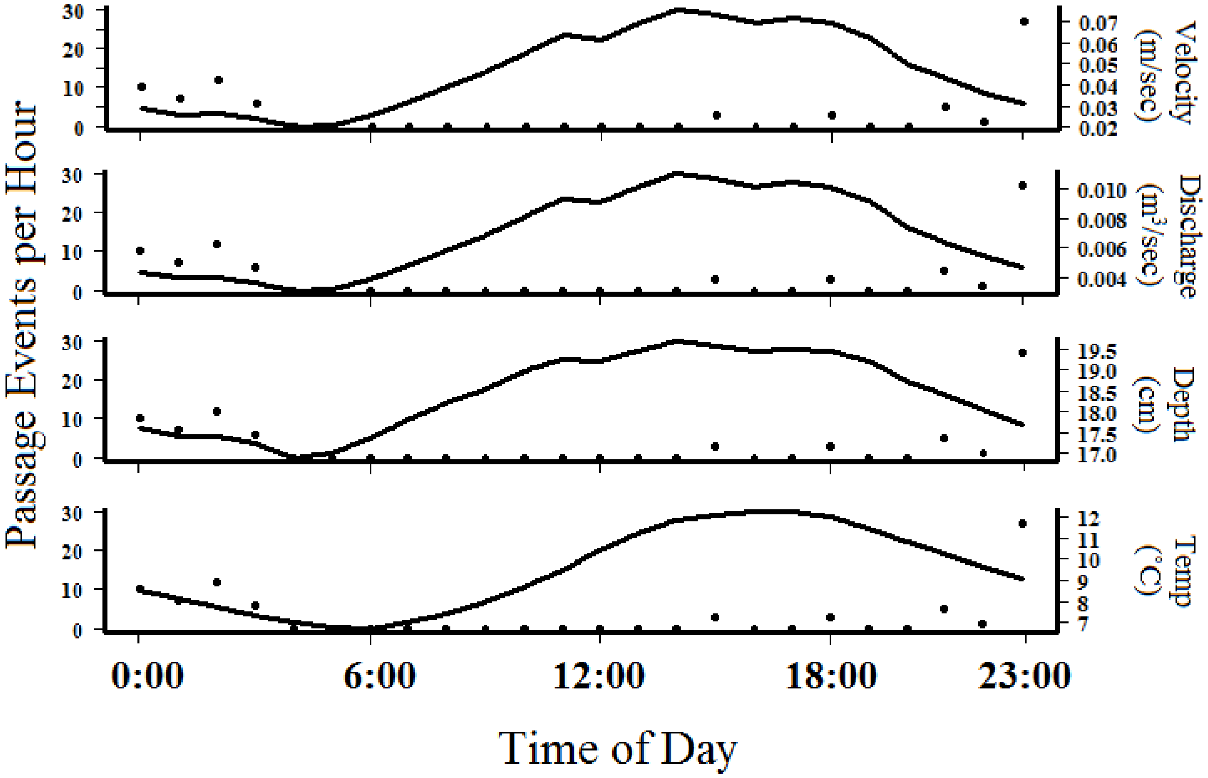

FIGURE 3.12.—Total number of passage events per hour (circles) plotted against mean hourly velocity, discharge, depth, and temperature (solid lines) during the spawning period (6-16 June) 2013

Chapter IV: Thesis Synthesis and Conclusion

In Canada, the Fisheries Act provides the seminal legislation outlining the conservation and management of fish habitat. Under the former (pre-2013) Fisheries Act and Policy for the Management of Fish Habitat, the primary goal of habitat management in Canada was to prevent the loss or damage of aquatic habitat and ensure the ongoing sustainability of fish productivity (Minns 1997). In situations where unavoidable habitat losses occurred, habitat compensation projects were used to recompense the losses through the restoration of damaged, enhancement of existing, or creation of entirely new aquatic habitats (DFO 1986). However, fish habitat compensation has proven largely ineffective at achieving the primary goal of preventing the loss of productive fish habitat in Canada (Quigley and Harper 2005).

The general failure of fish habitat compensation suggests a collective inability to develop management strategies or design compensation projects capable of achieving no net loss. For example, Quigley and Harper (2005) showed that fewer than 5% (103/2500) of fish habitat compensation projects on which they had information were ever evaluated, and suggested this lack of case study evaluations was a major obstruction limiting the efficacy of habitat management and science in Canada. Others have suggested that a general paucity of information available on fish-habitat relationships has reduced the probability that a particular habitat manipulation will achieve desirable ecological outcomes (Bradshaw 1996; Drodge et al. 1999). Further still, in the event that a compensation project was actually evaluated in a scientifically defensible manner, subsequent cases of adaptive management of any form are exceedingly rare or altogether nonexistent (Quigley and Harper 2006). Thus, a clear dearth of information on the science and management of habitat compensation currently exists in Canada.

The development of the Diavik diamond mine in the Barrenlands region of northern Canada resulted in the elimination of pristine headwater lakes and streams (DDMI 1998), and Fisheries Act authorization required Diavik Diamond Mines Inc. (DDMI) offset these losses through several fish habitat compensation projects. One project, the M-Lakes fish habitat compensation project, was intended to enhance the productive capacity of a pristine headwater lake-stream complex through enhanced stream channel connectivity among isolated, yet habitable lakes (Golder 2001). In autumn 2011, three fishpasses (two gabion-style pool-weir, one nature-like choke-pool fishpass) were constructed to enhance connectivity in the M-Lakes system.

Chapter 2 presented a case study evaluation of the M-Lakes project from a fish-oriented perspective. I used three lines of evidence, passive integrated transponder (PIT) telemetry, and visual and electrofishing surveys that showed the gabion-style fishpasses at the M-Lakes compensation site did not increase upstream connectivity for fishes. However, the M-lakes nature-like fishpass was judged as successful using the same criteria. Interestingly, the gabion-style fishpasses remained ineffective at increasing upstream connectivity even after substantial efforts were made to retrofit the fishpasses. This was likely due to the relatively small catchment sizes of the headwater M-Lakes and streams; despite some short-term improvements in flow characteristics following the retrofits, these streams ultimately yielded inadequate water flows for pool-weir style fishpasses with >2% slope (Courtice et al. 2014).

Chapter 3 examined fish-habitat relationships, and documented the habitat selection patterns of Arctic Grayling *Thymallus arcticus* as they passed through the nature-like fishpass at the M-Lakes site. I used a combination of PIT tagging, telemetry, and hydraulic measurements to explore fish length in relation to passage, compare the environmental conditions during passage events to available environmental conditions, and quantify the timing of grayling passage through this fishpass. While grayling showed little selectivity for the factors analyzed, I documented the first clear evidence of diel periodicity in passage activity for this species, and suggested this pattern represented a response to avian predation given the shallow depth of the nature-like fishpass.

West Island Compensation Project—The information contained in Chapter 2 of this thesis was used in an adaptive manner to guide the design and construction of a similar but separate fish habitat compensation project at DDMI. This project, the West Island fish habitat compensation project, was intended to increase stream channel connectivity between an isolated headwater lake and Lac de Gras (LDG), and to provide spawning habitat for Arctic Grayling and Longnose Sucker *Catostomus catostomus* (DDMI 1998). The West Island stream was approximately 420 m in length, and originally featured a diffuse, braided channel. Stream slope averaged 2.5%, but the slope of the lower 25 m of stream was 12.5% and featured numerous cascades impassable to fish (Golder 2001). The West Island fishpass was to be constructed in autumn 2012 with 20-27 gabion-style pool-weirs (Golder 2001). However, hydraulic (Courtice et al. 2014) and fish passage (Chapter 2) findings from M-Lakes during spring 2012 showed that gabion-style pool-weir fishpasses were ineffective in small headwater lake-stream systems on the Barrenlands. Our M-Lakes observations helped persuade DDMI and Fisheries and Oceans Canada to adaptively change the West Island project from a gabion-style pool-weir to a nature-like fishpass design.

During autumn 2012, G. Courtice and I guided the construction of the West Island fishpass for five weeks; we employed boulder-weirs, boulder-chokes and pools, and rocky ramps using boulders found on site during stream channel excavation (Figure 4.1). We also extended the mouth of the West Island fishpass by approximately 10 m into Lac de Gras to overcome issues observed at the M1S-LDG connection at M-Lakes. Additionally, we used a water pump to simulate low flows through the West Island fishpass during construction (G. Courtice, pers. comm.), and then modified any problematic hydraulic structures while the construction crew and equipment were on site and available for use. I placed willows *Salix spp.* removed during construction between boulders and into the banks of the fishpass to facilitate riparian vegetation growth and to provide cover for fish. Willow cuttings were placed mainly in the upper two-thirds of the fishpass as allowed by time and construction operation constraints. The West Island fishpass is currently being evaluated by three graduate students at the University of Alberta.

Future Studies— I offer several recommendations for future studies on Barrenlands streams and lakes. The spatial distribution of small (≤150 mm) fish in fishpasses and streams was an important line of evidence for evaluating the M-lakes fishpasses. Thus, I recommend future studies evaluating Barrenlands streams use minnow traps in addition to visual and electrofishing surveys. Minnow traps are effective for documenting the spatial distribution of small fishes (e.g. Tonn and Paszkowski 1987), are easy to transport and use, and can be left in streams overnight. GoPro® video cameras were also useful tools for documenting fish location and spawning in streams, but the short (< 5 hours) battery life of these units was problematic (C.L. Cahill, G. Courtice unpublished data).

A final recommendation regarding Barrenlands fishpass construction is based on my observations of the original construction and involvement with retrofitting the ineffective M-Lakes fishpasses and my role in guiding construction of the West Island fishpass. The importance of having a freshwater biologist onsite throughout the entire retrofitting or construction process cannot be overemphasized. The construction crews contracted to build fishpasses at DDMI were highly skilled, but had little-to-no biological training. Crews occasionally struggled with interpretation of the construction plans provided to them, and having a biologist show up for a day or two did not provide sufficient guidance for compensation projects that took weeks to complete. When unplanned situations arise during construction, crews with excavators and a dearth of biological training should not be left to make decisions on their own.

Conclusion

Fish habitat compensation projects are rarely evaluated in a scientifically defensible manner (Quigley and Harper 2006), and should be treated as experiments to systematically reduce uncertainty and guide future management decisions (Walters and Hilborn 1978; Walters and Holling 1990). This thesis advances the current state of habitat compensation science in northern Canada by providing a defensible case study upon which fish habitat managers can base future stream enhancement objectives; it also contributes new information on Arctic Grayling passage through a successful nature-like fishpass. Moreover, the lessons learned in Chapter 2 of this thesis were applied to another whole-ecosystem manipulation in an adaptive management framework, and this manipulation is currently being evaluated in a scientifically defensible manner. Collectively, these contributions increase the likelihood that future fish habitat management projects in the Barrenlands region will achieve conservation goals. I recommend against using gabion-style pool-weir fishpasses in headwater lake-stream systems when stream flow is limited, and suggest that resource managers desiring to enhance connectivity in future projects adaptively experiment with (and formally evaluate) nature-like fishpasses. Any such projects should pay careful attention to hydraulic considerations such as catchment size and stream slope (see also Courtice et al. 2014), and stream length. I further recommend ecologists make an effort to determine if the diel periodicity in Arctic Grayling passage events I observed is a widespread phenomenon (i.e., occurs in other streams or fishpasses). If so, it may be possible to design critical experiments, with appropriate controls, to better understand the causal mechanisms driving this behavior. Ultimately, the M-Lakes fish habitat compensation project provided many important lessons despite the apparent difficulties discussed within this thesis.

References

Bradshaw, A. D. 1996. Underlying Principles of Restoration. Canadian Journal of Fisheries and Aquatic Sciences 53:3-9.

Courtice, G., A. B. Baki, D. Zhu, C. L. Cahill, and W. M. Tonn. 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.

Diavik Diamond Mines, Inc. (DDMI). 1998. No Net Loss Plan. Technical Report Summary. Diavik Diamond Mines, Inc.

Department of Fisheries and Oceans (DFO). 1986. The Department of Fisheries and Oceans Policy for the Management of Fish Habitat. Communications Directorate, Fisheries and Oceans, Ottawa, Ontario, Canada.

Drodge, G., M. H. Beauchesne, and G. Feltham. 1999. National Habitat Referral Study: project report. Prepared for Department of Fisheries and Oceans, Ottawa, by KPMG, pp. 41.

Golder Associates. 2001. West Island Stream Fish Habitat Compensation Works Proposed Design. Diavik Diamond Mines Inc., NWT. Technical Memorandum.

Harper, D. J., and J. T. Quigley. 2005. No Net Loss of Fish Habitat: A Review and Analysis of Habitat Compensation in Canada. Environmental Management 36(3):343-355.

Minns, C. K. 1997. Quantifying "No Net Loss" of Productivity of Fish Habitats. Canadian Journal of Fisheries and Aquatic Sciences 54(10):2463-2473.

Quigley, J. T., and D. J. Harper. 2006. Effectiveness of Fish Habitat Compensation in Canada in Achieving No Net Loss. Environmental Management 37(3):351-366.

Tonn, W. M., and C. A. Paszkowski. 1987. Habitat Use of the Central Mudminnow (*Umbra limi*) and Yellow Perch (*Perca flavescens*) in *Umbra-Perca* Assemblages: The Roles of Competition, Predation, and the Abiotic Environment. Canadian Journal of Zoology 65(4):862-870.

Walters, C. J., and R. Hilborn. 1978. Ecological Optimization and Adaptive Management. Annual Review of Ecology and Systematics 9:157-188.

Walters, C. J., and C. S. Holling. 1990. Large-Scale Management Experiments and Learning by Doing. Ecology 71(6):2060-2068.

FIGURE 4.1.—The West Island nature-like fishpass during summer 2014. The lake in the upper-right portion of the photograph is West Island Lake, while the lake at the bottom of the image is Lac de Gras. This fishpass is approximately 300 m in length, and took five weeks to construct during autumn 2012. Photo by Fred Noddin.

References

Aarestrup, K., M. C. Lucas, and J. A. Hansen. 2003. Efficiency of a Nature-Like Bypass Channel for Sea Trout (Salmo Trutta) Ascending a Small Danish Stream Studied by Pit Telemetry. Ecology of Freshwater Fish 12(3):160-168.

Alberta Environment and Sustainable Resource Development and Alberta Conservation Association. 2005. Status of Arctic Grayling (*Thymallus arcticus*) in Alberta. Edmonton, AB.

Angell, A. C., and J. R. Parkins. 2011. Resource Development and Aboriginal Culture in the Canadian North. Polar Record 47(01):67-79.

Armstrong, R. H. 1986. A Review of Arctic Grayling Studies in Alaska, 1952-1982. University of Alaska. Institute of Arctic Biology, 0568-8604.

Baki, A. B. M., D. Z. Zhu, M. F. Hulsman, B. D. Lunn, and W. M. Tonn. 2012. The Hydrological Characteristics of a Stream within an Integrated Framework of Lake-Stream Connectivity in the Lac De Gras Watershed, Northwest Territories, Canada. Canadian Journal of Civil Engineering 39(3):279-292.

Bass, A. L., T. O. Haugen, and L. A. Vollestad. 2014. Distribution and Movement of European Grayling in a Subarctic Lake Revealed by Acoustic Telemetry. Ecology of Freshwater Fish 23(2):149-160.

Beauchamp, D. A. 1990. Movements, Habitat Use, and Spawning Strategies of Arctic Grayling in a Subalpine Lake Tributary. Northwest Science 64(4): 195-207.

Bishop, F. G. 1971. Observations on Spawning Habits and Fecundity of the Arctic Grayling. The Progressive Fish-Culturist 33(1):12-19.

Bond, N., and P. Lake. 2003. Local Habitat Restoration in Streams: Constraints on the Effectiveness of Restoration for Stream Biota. Ecological Management & Restoration 4(3):193-198.

Boyce, M. S., and L. L. McDonald. 1999. Relating Populations to Habitats Using Resource Selection Functions. Trends in Ecology & Evolution 14(7):268-272.

Boyce, M. S., P. R. Vernier, S. E. Nielsen, and F. K. Schmiegelow. 2002. Evaluating Resource Selection Functions. Ecological Modelling 157(2):281-300.

Bradshaw, A. D. 1996. Underlying Principles of Restoration. Canadian Journal of Fisheries and Aquatic Sciences 53:3-9.

Breton, F., A. B. M. Baki, O. Link, D. Z. Zhu, and N. Rajaratnam. 2013. Flow in Nature-Like Fishway and Its Relation to Fish Behaviour. Canadian Journal of Civil Engineering 40(6):567-573.

Brouha, P. 1993. Emulating Canada: Recognizing Existing Aquatic and Fish Habitat Area as Invaluable. 18(10):4.

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

Bunt, C. M., S. J. Cooke, and R. S. McKinley. 2000. Assessment of the Dunnville Fishway for Passage of Walleyes from Lake Erie to the Grand River, Ontario. Journal of Great Lakes Research 26(4):482-488.

Bunt, C. M., T. Castro-Santos, and A. Haro. 2012. Performance of Fish Passage Structures at Upstream Barriers to Migration. River Research and Applications 28(4):457-478.

Clark, R. A. 1992. Influence of Stream Flows and Stock Size on Recruitment of Arctic Grayling (Thymallus Arcticus) in the Chena River, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 49(5):1027-1034.

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

CBFWA (Columbia Basin Fish and Wildlife Authority). 1999. PIT Tag Marking Procedures Manual. Portland, OR.

Cooke, S. J., and S. G. Hinch. 2013. Improving the Reliability of Fishway Attraction and Passage Efficiency Estimates to Inform Fishway Engineering, Science, and Practice. Ecological Engineering 58:123-132.

Courtice, G., A. B. Baki, D. Zhu, C. L. Cahill, and W. M. Tonn. 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.

Department of Fisheries and Oceans (DFO). 1986. The Department of Fisheries and Oceans Policy for the Management of Fish Habitat. Communications Directorate, Fisheries and Oceans, Ottawa, Ontario, Canada.

Department of Fisheries and Oceans (DFO). 2013. The Deparment of Fisheries and Oceans Fisheries Productivity Investment Policy. 2013. Available: http://www.dfo-mpo.gc.ca/pnw-ppe/offsetting-guide-compensation/index-eng.html (June 2014).

Diavik Diamond Mines, Inc. (DDMI). 1998. No Net Loss Plan. Technical Report Summary. Diavik Diamond Mines, Inc.

DVWK. 2002. Fish Passes: Design, Dimensions, and Monitoring. Rome: FAO, 118 pp.

Drodge, G., M. H. Beauchesne, and G. Feltham. 1999. National Habitat Referral Study: project report. Prepared for Department of Fisheries and Oceans, Ottawa, by KPMG, pp. 41.

Environment Canada. 1991. Canadian Climate Normals 1961-1990. Environment Canada, Ottawa, Ont. http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html (June 2014).

Ernst, M. D. 2004. Permutation Methods: A Basis for Exact Inference. Statistical Science 19(4):676-685.

Fisheries Act. R.S.C. 1985. c. F-14. 2013. Available: http://www.dfo-mpo.gc.ca/habitat/changes-changements/index-eng.htm (June 2014).

Foulds, W. L., and M. C. Lucas. 2013. Extreme Inefficiency of Two Conventional, Technical Fishways Used by European River Lamprey (Lampetra Fluviatilis). Ecological Engineering 58:423-433.

Gavrilchuk, K., and V. Lesage. 2014. Large-scale marine development projects (mineral, oil and gas, infrastructure) proposed for Canada's North. Can. Tech. Rep. Fish. Aquat. Sci. 3069:viii + 84 pp.

Golder Associates. 2001. West Island Stream Fish Habitat Compensation Works Proposed Design. Diavik Diamond Mines Inc., NWT. Technical Memorandum.

Harper, D. J., and J. T. Quigley. 2005. No Net Loss of Fish Habitat: A Review and Analysis of Habitat Compensation in Canada. Environmental Management 36(3):343-355.

Helfman, G. S. 1993. Fish Behaviour by Day, Night, and Twilight. Pages 479-512 *in* T. J. Pitcher, editor. Behaviour of Teleost Fishes. Chapman and Hall, London.

Hulsman, M.F. 2012. Influence of Fish Competitors on Lake Trout Tropic Ecology in Sub-Arctic Lakes. M.Sc. Thesis. University of Alberta. 108 pp.

Hutchings, J. A., and J. R. Post. 2013. Gutting Canada's Fisheries Act: No Fishery, No Fish Habitat Protection. Fisheries 38(11):497-501.

Jepsen, N., A. Koed, E. B. Thorstad, and E. Baras. 2002. Surgical Implantation of Telemetry Transmitters in Fish: How Much Have We Learned? Hydrobiologia 483(1-3):239-248.

Jones, N. E., W. M. Tonn, and G. J. Scrimgeour. 2003a. Selective Feeding of Age-0 Arctic Grayling in Lake-Outlet Streams of the Northwest Territories, Canada. Environmental Biology of Fishes 67(2):169-178.

Jones, N. E., W. M. Tonn, G. J. Scrimgeour, and C. Katopodis. 2003b. Ecological Characteristics of Streams in the Barrenlands near Lac De Gras, Nwt, Canada. Arctic 56(3):249-261.

Jones, N. E., W. M. Tonn, G. J. Scrimgeour, and C. Katopodis. 2003c. Productive Capacity of an Artificial Stream in the Canadian Arctic: Assessing the Effectiveness of Fish Habitat Compensation. Canadian Journal of Fisheries and Aquatic Sciences 60(7):849-863.

Jones, N. E., and W. M. Tonn. 2004a. Enhancing Productive Capacity in the Canadian Arctic: Assessing the Effectiveness of Instream Habitat Structures in Habitat Compensation. Transactions of the American Fisheries Society 133(6):1356-1365.

Jones, N. E., and W. M. Tonn. 2004b. Resource Selection Functions for Age-0 Arctic Grayling (Thymallus Arcticus) and Their Application to Stream Habitat Compensation. Canadian Journal of Fisheries and Aquatic Sciences 61(9):1736-1746.

Jones, N. E., G. J. Scrimgeour, and W. M. Tonn. 2008. Assessing the Effectiveness of a Constructed Arctic Stream Using Multiple Biological Attributes. Environmental Management 42(6):1064-1076.

Jungwirth, M. 1996. Bypass Channels at Weirs as Appropriate Aids for Fish Migration in Rhithral Rivers. Regulated Rivers-Research & Management 12(4-5):483-492.

Jungwirth, M., S. Schmutz, and S. Weiss. 1998. Fish Migration and Fish Bypasses, volume 4. Fishing News Books, Oxford.

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

Katopodis, C., J. Kells, and M. Acharya. 2001. Nature-Like and Conventional Fishways: Alternative Concepts? Canadian Water Resources Journal 26(2):211-232.

Knaepkens, G., K. Baekelandt, and M. Eens. 2006. Fish Pass Effectiveness for Bullhead (Cottus Gobio), Perch (Perca Fluviatilis) and Roach (Rutilus Rutilus) in a Regulated Lowland River. Ecology of Freshwater Fish 15(1):20-29.

Krajick, K. 2001. Barren Lands: An Epic Search for Diamonds in the North American Arctic.

Laine, A., R. Kamula, and J. Hooli. 1998. Fish and Lamprey Passage in a Combined Denil and Vertical Slot Fishway. Fisheries Management and Ecology 5(1):31-44.

Larinier, M. 1998. Upstream and Downstream Fish Passage Experience in France. In: Jungwirth, M., Schumtz, S. and Weiss, S., eds. Fish Migration and Fish Bypasses. Oxford: Fishing News Books, Blackwell Science Ltd, pp. 127-145.

Larinier, M. 2001. Environmental Issues, Dams and Fish Migration. FAO Fisheries Technical Paper (419):45-89.

Larinier, M. 2002. Biological Factors to Be Taken into Account in the Design of Fishways, the Concept of Obstructions to Upstream Migration. Bulletin Français de la Pêche et de la Pisciculture 364:28-38.

Lawrence, M., and S. Davies. 1979. Aquatic Resources Survey - Keewatin and Franklin Districts. Canada Department of Indian and Northern Affairs, ESCOM Report No. AI-31:108 pp.

Linsley, R. K., M. A. Kohler, and J. Paulhus. 1982. Hydrology for Engineers. Mcgraw Hill, New York.

Lucas, M. C., E. Baras, T. J. Thom, A. Duncan, and O. Slavík. 2001. Migration of Freshwater Fishes. Blackwell Scientific Press, Oxford.

Mallen-Cooper, M., and D. A. Brand. 2007. Non-Salmonids in a Salmonid Fishway: What Do 50 Years of Data Tell Us About Past and Future Fish Passage? Fisheries Management and Ecology 14(5):319-332.

Mallen-Cooper, M., and I. G. Stuart. 2007. Optimising Denil Fishways for Passage of Small and Large Fishes. Fisheries Management and Ecology 14(1):61-71.

McPhail, J. D., and C. C. Lindsey. 1970. Freshwater Fishes of Northwestern Canada and Alaska. Fisheries Research Board of Canada Bulletin 173.

Miller, R. B. 1946. Notes on the Arctic Grayling, Thymallus Signifer Richardson, from Great Bear Lake. Copeia 1946:227-236.

Minns, C. K. 1997. Quantifying “No Net Loss” of Productivity of Fish Habitats. Canadian Journal of Fisheries and Aquatic Sciences 54(10):2463-2473.

Minns, C. K., and J. E. Moore. 2003. Assessment of Net Change of Productive Capacity of Fish Habitats: The Role of Uncertainty and Complexity in Decision Making. Canadian Journal of Fisheries and Aquatic Sciences 60(1):100-116.

Nelson, J. S., and M. J. Paetz. 1992. The Fishes of Alberta. University of Alberta Press, Edmonton.

Noonan, M. J., J. W. A. Grant, and C. D. Jackson. 2012. A Quantitative Assessment of Fish Passage Efficiency. Fish and Fisheries 13(4):450-464.

Northcote, T. G. 1995. Comparative Biology and Management of Arctic and European Grayling (Salmonidae, Thymallus). Reviews in Fish Biology and Fisheries 5(2):141-194.

Olden, J. D., D. A. Jackson, and P. R. Peres-Neto. 2001. Spatial Isolation and Fish Communities in Drainage Lakes. Oecologia 127(4):572-585.

Power, G. 1997. A Review of Fish Ecology in Arctic North America. In: Reynolds, J. (Ed.), Fish Ecology in Arctic North America, American Fisheries Society, Symposium vol. 19. American Fisheries Society, Bethesda, Maryland, pp. 13 – 39.

Power, M. E. 1987. Predator Avoidance by Grazing Fishes in Temperate and Tropical Streams: Importance of Stream Depth and Prey Size. Pages 333-351 *in* W. C. Kerfoot, and A. Sih, editors. Predation: Direct and Indirect Impacts on Aquatic Communities. University Press of new England, Hanover and London.

Quigley, J. T., and D. J. Harper. 2006. Effectiveness of Fish Habitat Compensation in Canada in Achieving No Net Loss. Environmental Management 37(3):351-366.

R Core Team (2012). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Rawson, D. S. 1950. The Grayling (Thymallus Signifer) in Northern Saskatchewan. Canadian Journal of Fish Culture (8):207-240.

Reed, R. J. 1964. Life History and Migration Patterns of Arctic Grayling, Thymallus Arcticus,(Pallas), in the Tanana River Drainage of Alaska. Alaska. Department of Fish and Game. Rep. No. 2. 30 pp.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A Review of Stream Restoration Techniques and a Hierarchical Strategy for Prioritizing

Restoration in Pacific Northwest Watersheds. North American Journal of Fisheries Management 22(1):1-20.

Schindler, D. W. 2001. The Cumulative Effects of Climate Warming and Other Human Stresses on Canadian Freshwaters in the New Millennium. Canadian Journal of Fisheries and Aquatic Sciences 58(1):18-29.

Scott, W. B., and E. J. Crossman. 1973. Freshwater Fishes of Canada. Fisheries Research Board of Canada Bulletin 184.

Scrimgeour, G., N. Jones, and W. M. Tonn. 2013. Benthic Macroinvertebrate Response to Habitat Restoration in a Constructed Arctic Stream. River Research and Applications 29(3):352-365.

Scrimgeour, G. J., W. M. Tonn, and N. E. Jones. 2014. Quantifying Effective Restoration: Reassessing the Productive Capacity of a Constructed Stream 14 Years after Construction. Canadian Journal of Fisheries and Aquatic Sciences 71:589-601.

Southwood, T. 1977. Habitat, the Templet for Ecological Strategies? The Journal of Animal Ecology:337-365.

Stewart, D. B., N. J. Mochnacz, J. D. Reist, T. J. Carmichael, and C. D. Sawatzky. 2007. Fish Life History and Habitat Use in the Northwest Territories: Arctic Grayling (*Thymallus arcticus*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2797: vi + 55 pp.

Stuart, K.M., and G.R. Chislett. 1979. Aspects of the life history of the Arctic grayling in the Sukunka drainage. British Columbia Fish and Wildlife Branch, Prince George. 111 pp.

Thompson, W. L. 2003. Hankin and Reeves' Approach to Estimating Fish Abundance in Small Streams: Limitations and Alternatives. Transactions of the American Fisheries Society 132(1):69-75.

Tonn, W. M., and C. A. Paszkowski. 1987. Habitat Use of the Central Mudminnow (*Umbra limi*) and Yellow Perch (*Perca flavescens*) in *Umbra-Perca* Assemblages: The Roles of Competition, Predation, and the Abiotic Environment. Canadian Journal of Zoology 65(4):862-870.

Underwood, A. 1991. Beyond Baci: Experimental Designs for Detecting Human Environmental Impacts on Temporal Variations in Natural Populations. Marine and Freshwater Research 42(5):569-587.

Underwood, A. 1994. On Beyond BACI: Sampling Designs That Might Reliably Detect Environmental Disturbances. Ecological applications 4(1):3-15.

Van Wyhe, G. 1961. Inventory and Cataloguing of Sportfish and Sportfish Waters of the Cappoe River and Prince William Sound Drainages. Alaska Dept. Fish and Game. Ann. Rep. Of Prog 1962:227-243.

Vincent, R. E. 1962. Biogeographical and Ecological Factors Contributing to the Decline of Arctic Grayling, *Thymallus arcticus* Pallus, in Michigan and Montana. Ph.D. Thesis, University of Michigan, Ann Arbor:169 pp.

Walters, C. J., and R. Hilborn. 1978. Ecological Optimization and Adaptive Management. Annual Review of Ecology and Systematics 9:157-188.

Walters, C. J., and C. S. Holling. 1990. Large-Scale Management Experiments and Learning by Doing. Ecology 71(6):2060-2068.

Wickham, H. 2009. ggplot2: Elegant Graphics for Data Analysis. Springer New York.

Winter, J.D. 1996. Advances in Underwater Biotelemetry. *In* Murphy, B.R. and Willis, D.W. eds. *Fisheries Techniques.* 2nd edition. 555-590 pp. Bethesda, Maryland. American Fisheries Society.

Wojcik, F. J. 1955. Life History and Management of the Grayling in Interior Alaska. M.Sc. Thesis. University of Alaska, Fairbanks: 54 pp.

Zippin, C. 1956. An Evaluation of the Removal Method of Estimating Animal Populations. Biometrics 12(2):163-189.

APPENDIX. — Fish species composition in Lac de Gras (LDG), M-lakes (M1L, M2L, M3L), and Reference Lakes (R6L1, R6L2) as determined by experimental gillnet, electrofishing, and hoop net surveys during 2000-2013 from the Barrenlands, Northwest Territories, Canada. Scientific names: Arctic Grayling *Thymallus arcticus*, Burbot *Lota lota*, Cisco *Coregonus artedi*, Lake Trout *Salvelinus namaycush*, Lake Whitefish *Coregonus clupeaformis*, Longnose Sucker *Catostomus catostomus*, Ninespine Stickleback *Pungitis pungitis*, Northern Pike *Esox Lucius*, Round Whitefish *Prosopium cylindraceum*, Slimy Sculpin *Cottus cognatus*. Data from LDG taken from Golder Associates (2001).

	Species									
	Arctic Grayling	Burbot	Cisco	Lake Trout	Lake Whitefish	Longnose Sucker	Ninespine Stickleback	Northern Pike	Round Whitefish	Slimy Sculpin
Lake										
LDG	+	+	+	+	+	+	+	+	+	+
M1L	+	+	-	+	-	-	+	-	+	+
M2L	+	+	-	+	-	-	+	-	+	+
M3L	-	+	-	+	-	-	-	-	-	+
R6L1	+	+	-	+	-	-	+	-	+	+
R6L2	+	-	-	-	-	-	-	-	-	-