Interdisciplinary Approaches to Enhance Biological Data Collection and Understanding of Arctic Grayling (*Thymallus arcticus*) Spawning Behaviour

by

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Quotes

You will need to know the difference between Friday and a fried egg. It's quite a simple difference, but an important one. Friday comes at the end of the week, whereas a fried egg comes out of a chicken. Like most things, of course, it isn't quite that simple. The fried egg isn't properly a fried egg until it's been put in a frying pan and fried. This is something you wouldn't do to a Friday, of course, though you might do it on a Friday. You can also fry eggs on a Thursday, if you like, or on a cooker. It's all rather complicated, but it makes a kind of sense if you think about it for a while.

— Douglas Adams, The Salmon of Doubt

Insanity (i.e., stupidity) is repeating the same mistakes and expecting different results.

— attributed to Narcotics Anonymous, *pamphlet*

Thesis Supervisor: Associate Professor Brian Heise (PhD)

Abstract

Increased pressure of industrial development in the Arctic drives the need for a better understanding of Arctic fish and their interaction with their habitat. Environmental disturbances resulting from these developments often require off-setting facilities, particularly with respect to Arctic grayling (*Thymallus arcticus*) spawning activity. Furthermore, the Arctic is also expected to experience increased climate change effects resulting in adaptations to Arctic grayling behaviour in response to their changing environment.

Due to the remoteness of sites, climate extremes and variability, fisheries field work in the Arctic typically requires extensive support, such as camp infrastructure, helicopters, and durable equipment. Support costs to undertake these field programs often limit data collection efforts, potentially leading to questionable habitat assumptions being made that will adversely affect fish behaviour.

Using a multi-disciplinary approach, this thesis validated three approaches for improving Arctic grayling enumeration and for establishing a better basis for habitat design criteria: (1) A wildlife camera enumeration technique for Arctic streams was found to be comparable for population estimates when compared to trap boxes and visual stream surveys and able to provide longer data sets with less field time. The use of wildlife cameras is a suitable technique for remote locations but selection will depend on the specific requirements of an enumeration program; (2) Using paired values of depth and velocity, Arctic grayling spawning site selection can be described by the dimensionless Froude number. The preferred Arctic grayling mean Froude number value was found to be 0.27 (SE=0.0045) and was not significantly different between two populations of Arctic grayling in different size streams. This value is also lower than that identified for Sockeye and Atlantic salmon (Froude number = 0.34) which can likely be attributed to their larger size and different spawning behaviour and substrate selections when compared to Arctic grayling; (3) Commonly measured cross-sectional variables of stream discharge and water temperature were linked in a longitudinal manner through Maximum Likelihood Estimation analysis. Such an approach illustrates the importance of standardizing data for meaningful comparison by consideration of the relationship between variables leading up to a life history event, not just the event itself. A relationship was shown between unit discharge and water temperature leading up to the Arctic grayling spawning event.

The enumeration technique was a field project using wildlife cameras images that compared to physical fish counting data being undertaken concurrently by Arctic Canadian Diamond Company Ltd. at Ekati Diamond Mine in the Northwest Territories, Canada. The consideration of spawning activities in relation to habitat and hydraulic characteristics were developed using existing data sets collected as part of regulatory compliance monitoring programs as well as from the available literature.

Keywords: Arctic grayling, spawning, hydrograph, Froude number, habitat, camera, enumeration, Arctic, data standardization

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Thank you to additional collectors of data sets who either provided the information directly to me or, thankfully, made the information available through their publications.

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List of Symbols, Abbreviations and Nomenclature

Abbreviation/Symbol	**Definition**
Arctic Diamond	Arctic Canadian Diamond Company Ltd.
°C	degree Celsius
cm	centimeter
cm^3/s	cubic centimeter per second
Ekati	Ekati Diamond Mine
FL	fork length
HSI	Habitat Suitability Indices
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
km	kilometer
m	meter
m/s	meter per second
m^3/s	cubic meter per second
mm	millimeter

Glossary of Terms

nival	Relating to or a characteristic of a region of perpetual snow (i.e., Arctic)
redd	A hollow dug area in a riverbed made by a trout or salmon to spawn in
Floy® tag	The Floy® T-Bar anchor is used on medium sized fish and is applied with a tagging gun. The tag is inserted below the dorsal fin
Froude number	A dimensionless number used in hydrodynamics describing the gravitational or inertial force relationship between velocity and depth.
Reynolds number	The ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities

CHAPTER 1. THESIS INTRODUCTION

The Arctic is experiencing increased pressures from many sources including industrial development and climate variability (Arctic Climate Impact Assessment, 2015; Government of Northwest Territories, 1998; UK Parliament, 2015). These pressures create the need for improved understanding of Arctic fish and their interaction with their habitats for sound decision making by industry, regulators, and other stakeholders. Due to remoteness and climate, the Arctic presents many challenges for assessing and designing fish populations and fish habitat when compared with less extreme environments and species such as anadromous salmonids of the Pacific Northwest, where extensive information, research, and experience is available.

Because of the remoteness and climate extremes, fisheries work in the Arctic typically requires extensive support, such as camp infrastructure, flight time (plane and/or helicopter) and durable equipment. Capital and operation costs and time factors to undertake field programs often limit the effectiveness and extent of information collection. Consequently, there is a high potential that inappropriate assumptions based on the paucity of relevant information may be made. The resulting decisions may adversely affect the design and implementation of fish habitat projects in the Arctic.

One of the key Arctic sport and food fish species for which information is limited is the Arctic grayling (*Thymallus arcticus*). Industrial development impacts and climate changes on Arctic grayling can result in habitat loss through loss of connectivity or destruction, pollution, hydrologic changes, as well as population impacts through over-fishing. Because Arctic grayling spawning activity is influenced by many factors, techniques and concepts associated with not only biology but also engineering, hydrology, statistics and sociology can be adapted where considered appropriate, to improve our understanding of their behaviour.

This chapter provides background on the Arctic grayling life history and importance; describes the primary geographical location where of the majority of the project data has been sourced; and discusses implications of climate variability on Arctic grayling, as well as an outline of this thesis.

ARCTIC GRAYLING

Arctic grayling are an attractive colourful fish. Males tend to be larger and more territorial (Kratt & Smith, 1980; Tack, 1981), and are often characterized by a large flowing dorsal fin (Figure 1-1) that is used for threat display and to restrain the female during spawning (Beauchamp, 1990).

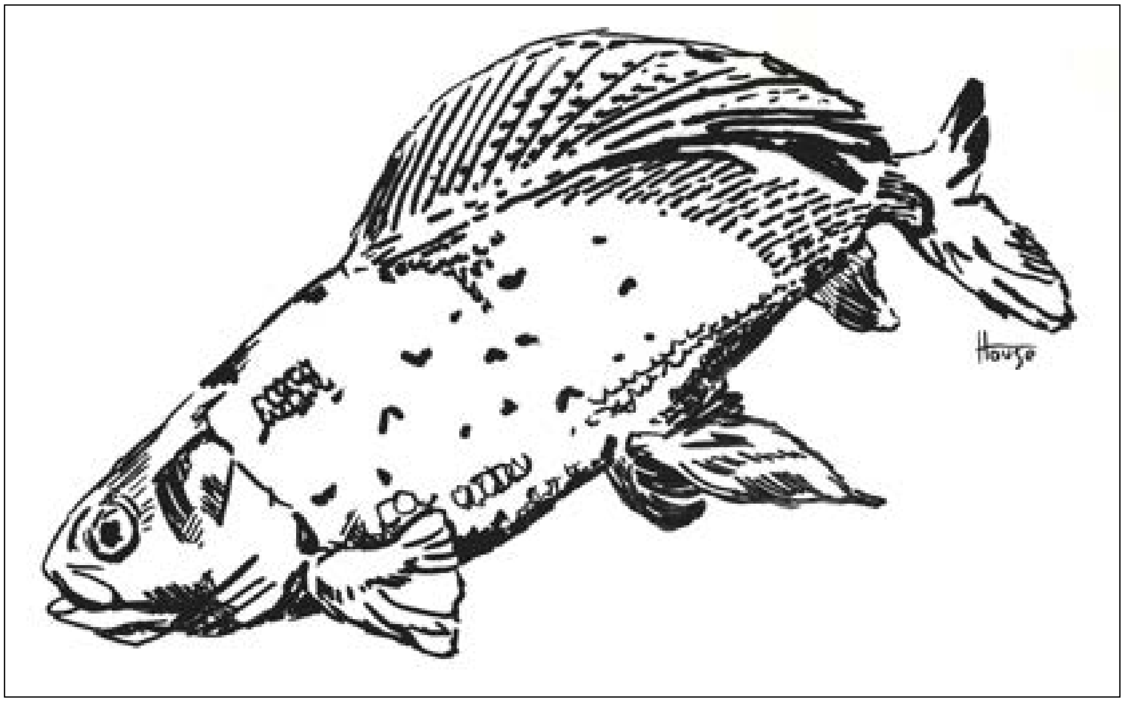

Figure 1-1 Adult Arctic grayling (sketch by author).

Arctic grayling are an important resource for life in the North as a country food supply and for indigenous culture, as a primary element for sport and recreational fishing, and as a potential commercial fishery. It is important that this unique fish be understood to conserve the species for the future, which requires that significantly more information be accumulated as a basis for managing the resource.

Range

In the Northwest Territories (NWT) and Nunavut, they are well distributed on the mainland (Figure 1-2). Historical populations have been extirpated around the Great Lakes. Oregon, Washington, Idaho, Wyoming, and Montana have all introduced Arctic grayling with varying degrees of success.

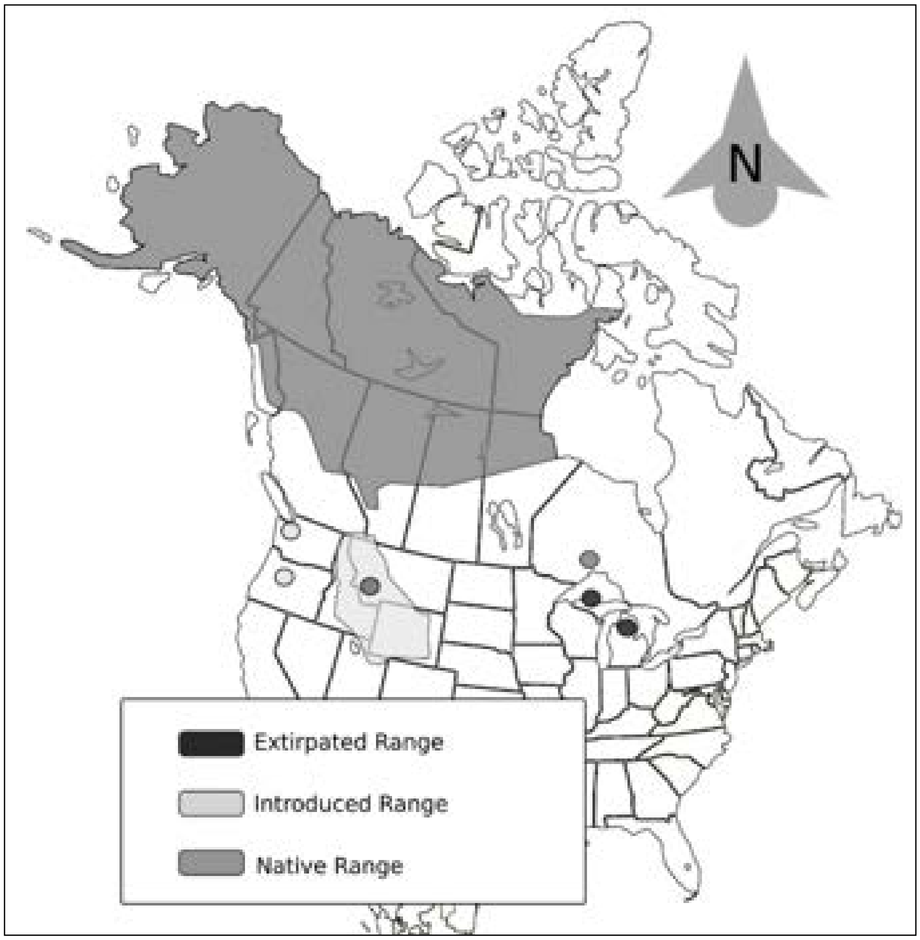

Figure 1-2 North American distribution of Arctic grayling including areas where they have been introduced and extirpated (i.e., historic range) (adapted from (Montana State Government, 2015)).

Life History

The general life history of Arctic grayling is summarized in Figure 1-3. The following definitions (ERM, 2015; Stewart, Mochnacz *et al.*, 2007) are used for Arctic grayling life history stages throughout:

1. **Egg.** Laid in the gravel of streambeds in late May to early June of each year by spawners. Eggs incubate in the substrate before hatching;

2. **Larval.** Has hatched from egg but is not yet free swimming nor has fully absorbed the yolk sac and has not emerged from the gravel

3. **Fry**. The free-swimming stage that emerges from the gravel in mid-June to early-July and rears in streams before migrating out of the stream and into an overwintering lake between July and September. A fry is referred to as such until after its first winter, at which time it becomes a juvenile;

4. **Outmigrant**. A fish that migrates out of stream habitat during the summer. It can be a fry, juvenile or adult, although most outmigrants of a stream are Arctic grayling fry;

5. **Inmigrant**. A fish that migrates into stream habitat during the summer;

6. **Juvenile**. A sexually immature Arctic grayling between two and nine years of age. All juveniles spend winters in lake habitat or in rivers that do not freeze, with some making excursions into streams during the spring and summer of their second to fifth years of life. This life stage ends when fish reach sexual maturity, which for Arctic grayling, occurs between the ages of two and six years;

7. **Adult**. The sexually mature life stage. Adfluvial/lacustrine adults[1] spend most of their time in lake habitat except for a period in spring when they enter streams to spawn or rear;

8. **Spawner**. Adults that have accumulated sufficient energy reserves to undergo sexual ripening in the late winter and early spring and that migrate into streams to spawn during freshet. Only a subset of the adults in the population may have sufficient energy reserves to ripen in any year, hence all spawners are adults, but not all adults are spawners.

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[1] Arctic grayling ≥ 170 mm in fork length are considered adults for this thesis.

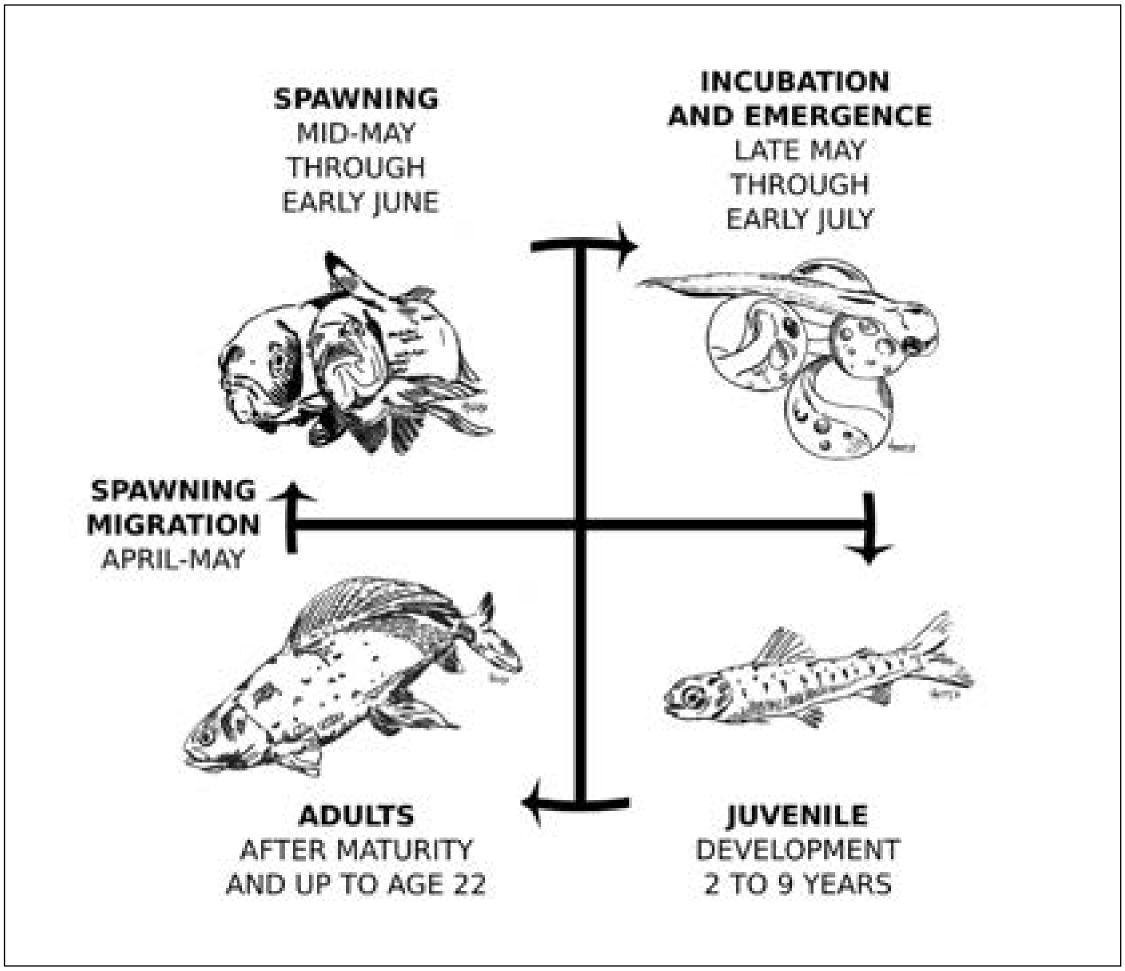

Figure 1-3 General life history of the Arctic Grayling (sketches by author; adapted from (Stewart, Mochnacz *et al.*, 2007))

Arctic grayling are a long lived species with individuals reaching sexual maturity between 2 and 9 years of age (Stewart, Mochnacz *et al.*, 2007). Size generally reflects age, with larger fish being older. This slow growth rate suggests that recovery from a life history or habitat disruption to an age class may be difficult. They are able to spawn multiple times in their lives and can have a lifespan of up to 22 years Stewart, Mochnacz *et al.*, 2007). Arctic grayling spawn in the spring, broadcasting eggs over or shallowly (i.e., 2 to 3 cm) into the gravel (Armstrong, 1986; Bishop, 1971) where they adhere and incubate for approximately two weeks. Incubation duration is temperature dependent. Fry emerge from the gravel a few days after hatching and become free swimming juveniles. The juveniles often overwinter in the deeper water of lakes and rivers.

There are three specific habitat-based life history types of Arctic grayling: adfluvial/lacustrine, fluvial, and stream. Adfluvial/lacustrine spend most of their life in lake environments, and will spawn at inlets or outlets of lakes and smaller tributaries. Fluvial fish live in larger rivers that do not freeze to the bottom in winter and spawn in the same river or its tributaries. Stream resident Arctic grayling spend their entire lives in small streams which are less than 10 m wide (Stewart, Mochnacz *et al.*, 2007) that do not freeze to the bottom in winter. Stream resident populations generally do not occur in the Arctic. Although there is significant overlap between the life histories, there are differences in habitat use.

For the management of Arctic grayling, understanding the different populations and their geographical range is important. Genetic variation between streams within a watershed can be high (Reilly, Paszkowski *et al.*, 2014). Arctic grayling are not a plastic species and may be unable to adapt effectively to environments different from their 'home' conditions (Armstrong, 1986). It is important that conservation starts at the stream level to accommodate subtle differences, such as when studying adfluvial and lacustrine populations that may occur in the same or neighbouring watersheds.

This thesis has examined adfluvial/lacustrine type population spawning behaviour which is the predominant behaviour in the Ekati area as the smaller streams freeze solid in the winter and there are no large rivers in which to overwinter. Adfluvial/lacustrine Arctic grayling typically start movement from their overwintering areas from late April through early July to spawn. Their timing is dependent on their location, with some fish moving in streams under ice while others wait for streams to be free of ice (Stewart, Mochnacz *et al.*, 2007). Generally, fish start spawning as the hydrograph recedes and water temperatures warm (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007). Most adfluvial/lacustrine Arctic grayling migrate to lake outlet/inlets or tributaries where there is flowing water at or near spring break-up (as cited in (Hubert, Helzner *et al.*, 1985)). Once spawning is completed, fish generally move back to their home lake that they overwintered in to feed for the summer (Stewart, Mochnacz *et al.*, 2007).

Spawning Habitat

The territory that male Arctic grayling will protect ranges from approximately 1.0 to 2.4 m radius depending on the stream size (Krueger, 1981). Actual spawning and egg deposition may occur anywhere in the male's protected territory.

Arctic grayling predominately reside in snowmelt driven systems. They generally are observed to spawn on the falling hydrograph. High water events during the egg and larval stage are thought to be extremely detrimental due to displacement and physical injury to egg, larvae, and emerging fry. A representative range of velocity and depth for Arctic grayling spawning habitat preferences from the literature are summarized in Table 1.1.

Spawning substrate ranges from fine silts and sediments to coarse cobble, but the general preference is for pea gravel material (Stewart, Mochnacz *et al.*, 2007). This may be due to the Arctic grayling's lack of deep redd[2] building behaviour when compared with other salmonids such as the Pacific anadromous species. If a redd is built by Arctic grayling, only the top few centimeters of the substrate may be disturbed. Arctic grayling tend to broadcast spawn (Stewart, Mochnacz *et al.*, 2007) more like a broad whitefish (*Coregonus nasus*), though other literature suggests that the male forces the female into the gravel in order to deposit eggs just below the surface (2 to 3 cm) (Armstrong, 1986). Eggs are very sticky prior to water hardening (Bishop, 1971; Tack, 1981) and attach to the substrate. Regardless of digging depth, broadcast or deposition spawning behaviour, many eggs are washed downstream (Armstrong, 1986).

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[2] The fish use their body to dig a small depression, called a 'redd', and is sometimes referred to as a nest in the stream bed to lay eggs generally in riffles and inlets and outlets of pools

Table 1.1 Summary of Arctic grayling Spawning Habitat Characteristics

Location	Depth (m)	Velocity (m/s)
Multiple Locations [a]	Shallow (< 1.0 m)	< 1.5
Providence Creek, NWT [b]	Shallow (< 1.0 m)	-
Upper Granite Lake, Washington [c]	0.25 - 0.35	0.16 - 0.40
Adsett Creek, British Columbia [d]	0.10 - 0.40	0.5 - 1.0
Tyee Lake, Alaska [e]	0.15 - 0.91	-
Mineral Lake, Alaska [e]	0.18 - 0.73	0.34 - 1.4
Fielding Lake, Alaska [e]	0.16	1.2
Habitat Suitability Indices – Canada [f]	0.15 - 0.91	0.34 - 1.19
Upper Big Hole, Montana [g]	0.284 - 0.773	0.21 - 0.47
Multiple Locations [h]	0.31 - 0.91	0.31-0.61

Source:

a. *(Stewart, Mochnacz et al., 2007)*
b. *(Bishop, 1971)*
c. *(Beauchamp, 1990)*
d. *(Northcote, 1993)*
e. *reported in (Krueger, 1981)*
f. *(Larocque, Hatry et al., 2014)*
g. *(Liknes, 1981)*
h. *(Vincent, 1962)*
i. *(Hubert, Helzner et al., 1985; Larocque, Hatry et al., 2014)*

Water Temperature

Water temperature is consistently noted to be a key factor for influencing spawning and migration timing (Stewart, Mochnacz *et al.*, 2007). The literature suggests that for many populations, spawning migration starts when water temperatures are approximately 4°C (Armstrong, 1986). Arctic grayling incubation typically ranges from 12 to 18 days requiring approximately 120 to 180 degree days[3]. Emergence generally occurs when water temperatures are between 10 and 15°C (Armstrong, 1986). Spawning has been observed to be abandoned or postponed if water temperatures are too low (Clark, 1993). Delays in migration can negatively impact the success of Arctic grayling spawning (Fleming & Reynolds, 1991).

CLIMATE VARIABILITY

Climate variability is a growing concern for the Arctic. The Intergovernmental Panel on Climate Change (2015) predictions for the Arctic tends towards increased temperature and rainfall versus snowfall precipitation. Arctic life, including Arctic grayling, will need to adapt to events such as permafrost thawing and drainage pattern changes, hydrologic regime shift from snowmelt to rainfall, warmer water temperatures, and increased anthropogenic pressures.

Warming temperatures in the Arctic has been identified as a cause for changes in the permafrost characteristics (Intergovernmental Panel on Climate Change, 2015). With the projected heaving/settling due to thawing there will be alterations to stream flow paths (Intergovernmental Panel on Climate Change, 2015). These physical alterations may prevent Arctic grayling from reaching historical spawning or rearing habitat. Channel shape may also change, likely becoming wider and shallower. Increased stream sedimentation may also occur due to mobilization of previously frozen banks and stream beds.

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[3] Degree days for incubation are calculated by summing of the average daily water temperature from the day of spawn to the day of emergence.

Snowmelt hydrographs (Figure 1-4) can generally be described as having a steep rising curve starting in the spring as temperatures warm above freezing. Peak discharge is reached once the snow pack has melted. The hydrograph then falls off almost as steeply as it rose, with the occasional smaller sub-peaks due to rainfall.

Future predictions to changes in the hydrograph, as long-term warming trends occur in the Arctic, is a shift to a rainfall driven mixed regime shape (Figure 1-5). This would produce a reduction in the amount of snow contribution to the hydrograph and an increase in spikes throughout the year due to rainfall.

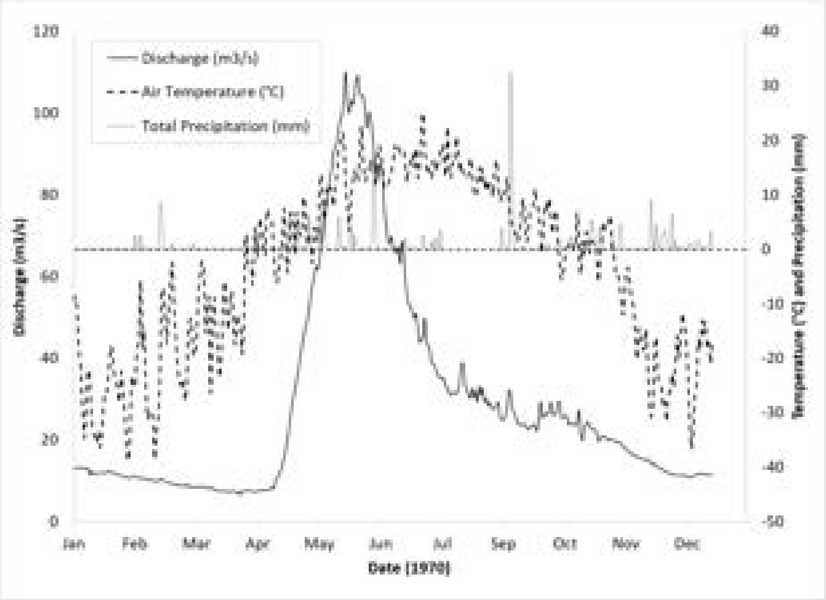

Figure 1-4 Typical Snowmelt Driven Arctic Hydrograph (from Kakisa River Hydrometric Station 07UC001; Hay River A, NWT Weather Information, 1970) Note: Fall precipitation spikes are generally snow not rain and do not affect fall discharge.

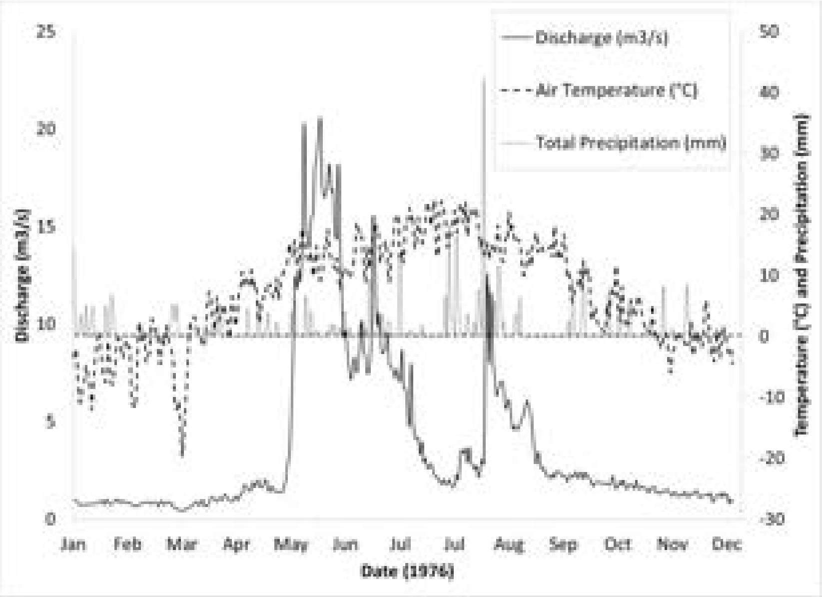

Figure 1-5 Typical Mixed Regime Hydrograph (from Louis Creek at the Mouth (08LB072) with Rainfall Driven spikes during freshet and the fall ; Barriere, BC, Weather Information, 1976). Note: Fall precipitation spikes are generally rain and affect fall discharge.

INNOVATIVE TECHNOLOGY AND PERSPECTIVE

Technology is constantly evolving and is often applied and integrated in ways it was not originally intended. Only recently has an integrated approach started to be applied in the natural resource sciences. This may be due, in part, to the evolving regulatory environmental assessment process that has developed in many countries. Such an interdisciplinary approach provides different perspectives reviewing the same information, thus allowing strengths and weaknesses of an approach to be identified more quickly. The same data parameters may be used by multiple disciplines in different ways to describe habitat or other processes. Hydrologic data is routinely needed for water quality analysis and biological assessments. For example, depth and velocity are common parameters used by biologists to describe preferred fish habitat. Engineers and hydrologists also use these parameters to describe hydraulic conditions. By using applied science to identify problems in our current understanding of biological systems, scientific questions can then be identified for re-evaluation and description of experimental data. This approach to existing data sets may yield insights for further examination that otherwise may not be identified by a traditional science approach.

The traditional approach in science is that each discipline researches within their own specialized “box”. Resulting information is shared amongst peers but not readily divulged to other disciplines unless specifically sought after. Data is therefore repeatedly handled in a similar manner each time, with results presented as means, maximums, minimums and the corresponding range. It makes sense then that the results of physical parameters between similar studies would often be consistent with this approach, but our overall understanding of fish life history behaviours are unable to be meaningfully described. Such a gap in understanding can result in a high degree of variation in how the information is then applied in the real world due to such generalities and lack of interactive characteristics.

By examining relationships between parameters using non-traditional biological science approaches, such as those used in the social science or medical realm, insights to behavioural responses may be identified and described. Yet, linking parameters to each other to determine relationships has also only been done to date in a limited manner. This may be due in part to the complexity of analysis that previously had to be undertaken without the benefit of computers, though with the development of more user friendly analysis software, these linkages may now be examined more easily (Roff, 2006)

THESIS OBJECTIVES AND FORMAT

Arctic grayling have been able to adapt to many types of habitat (Armstrong, 1986); however, population differences between streams within a watershed can be high (Reilly, Paszkowski *et al.*, 2014) and suggests that Arctic grayling are not a plastic species and are unable to adapt effectively to environments different from their 'home' conditions. As a result, they can be highly sensitive to changes within a watershed. The primary objective of this work is to examine Arctic grayling interactions with their habitat around spawning, in an effort to enhance our understanding of their behaviour to aid in their protection and conservation as development pressures increase in the North.

The thesis has three subsequent chapters with each addressing Arctic grayling habitat and life history interactions. CHAPTER 2 describes the use of wildlife cameras as a complementary and, potentially, replacement technique in some applications, to traditional trap box enumeration and visual stream counts. CHAPTER 3 discusses a Froude number range that seems to be preferred by Arctic grayling for spawning and incubation. CHAPTER 4 establishes a deeper understanding of spawning migration timing for Arctic grayling using the commonly measured predictor variables of discharge and water temperature, and then applying a multi-disciplinary approach of analysis. CHAPTER 5 is a concluding chapter which integrates and summarizes the previous three chapters.

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CHAPTER 2. EVALUATION OF WILDLIFE CAMERA EFFECTIVENESS TO ENUMERATE AN ARCTIC GRAYLING (*THYMALLUS ARCTICUS*) POPULATION IN A SMALL ARCTIC STREAM

ABSTRACT

Arctic grayling (*Thymallus arcticus*) are an important fish in the Arctic and are often a species of interest for environmental monitoring programs which necessitates collection of reliable data. Arctic data collection is often time consuming due to remoteness, distances to and between sites, weather hindrances, and field support requirements. Assessment methods that reduce field requirements and are more adaptable to changing conditions need to be examined to improve our understanding of this species.

Although cameras have been used for enumeration of fish for many years, expensive hardware and complex installations are generally required. This study examined the suitability of wildlife cameras on a small stream as an alternate technique of Arctic grayling enumeration versus traditional trap box and visual stream survey enumeration techniques.

Two camera locations with two cameras at each location were established on an Arctic stream diversion channel constructed to offset habitat destruction at an open pit mine in the Northwest Territories (UTM 12W 516250E 7181750N). Regulatory requirements for fish monitoring by means of trap boxes and visual stream surveys was executed by the Mine Operations, thereby facilitating an excellent opportunity to compare the use of wildlife cameras.

The results of this study indicate that there is no overall significant difference between the wildlife cameras with either trap box or visual stream count methods for fish presence/absence determination and population estimation studies. Results for all enumeration techniques were comparable considering locations of installations relative to habitat features (e.g., deep pools) that may influence migration, spooking due to perceived threat, or physical conditions such as stream turbidity or high flows. The cameras were able to record both tagged and untagged fish, approximate size for identifying maturity (i.e., large versus small), and the direction of travel.

The wildlife cameras may be installed prior to spring break up, photographing migrating fish prior to the ability to install trap boxes due to ice cover, as well as can be operated through higher flows or debris issues when traps may be circumvented or blown out. The cameras also do not appear to deter fish from migrating as trap boxes and visual stream counts may. The cameras are not, based on the methodology used for this study, a replacement enumeration technique that can be used for detailed population monitoring programs where fish health (i.e., weight, length) is also being collected. Cameras also have the advantage of being able to be deployed in remote conditions with minimal on-going support requirements. This resulting reduction in time is in the order of 12 to15 times that required for trap boxes and visual stream surveys. The savings in time also can results in significant cost savings.

Ultimately, monitoring program objectives will determine the most appropriate enumeration technique for a particular application; however, wildlife cameras are a valid tool that can be particularly useful in remote Arctic environments for fish enumeration., Their usage offer benefits compared with other field data collection techniques including personnel safety, quicker and earlier mobilization, less disruption to normal fish behaviour, reduced interference to natural stream flow, reduced labour to obtain equivalent data, and greater degree and range of portability.

INTRODUCTION

The increased pressure of industrial development in the Arctic creates the need for a better understanding of Arctic grayling (*Thymallus arcticus*) and their interaction with Arctic habitat. Where impacts may occur, environmental assessment and supporting baseline analysis of the fisheries resources is required by regulatory agencies (Government of Canada, 2020). The baseline environmental assessments range from desktop reviews to extensive enumeration studies in the field. Due to the remoteness of sites, climate extremes and variability, field work in the Arctic typically requires extensive support, such as camp infrastructure, helicopters, and durable equipment in addition to initiating data collection programs with correct timing. Depending on the type of program to be delivered, these factors can result in costs being up to 8 to 19 times higher than work in the south (Mallory, Gilchrist *et al.*, 2018). Budget limitations on these support requirements and environmental constraints such as weather, often limit field data collection. Consequently, incorrect assumptions could be made that may influence significant resource management decisions by regulators, industry, and other stakeholders.

These larger fish enumeration programs require significant field work, often over a large area with many streams, to establish where fish may be present and what habitat they are using. Presence/absence programs can be equally as challenging to deliver as absence can never be proven (Portt, Coker *et al.*, 2006). As a result, these types of programs in the Arctic require extensive labour and equipment for verification purposes.

Enumeration Techniques

There are numerous methods for counting fish (Table 2.1). Enumeration methods should be selected for the data requirement needs and suitability for the site conditions. Some methods are more suited for Arctic stream conditions than others.

Table 2.1 Comparative Summary of Fish Enumeration Methods (adapted from (William, William *et al.*, 2016))

Method	Typical Sites (Stream Size; Water Clarity)	Advantages	Disadvantages
Trapping (e.g., weir, net, fence)[1]	Best for medium and small	Easy sampling of age, sex, length, genetics, tagging	Expensive (equipment/personnel); May hinder natural fish movements; Counts can be in error due to circumvention of fence in high water; Turbulence due to poor fence maintenance (debris) resulting in fish stress or avoidance
Visual Stream Walks[2]	Medium to Small; Clear	Does not hinder fish passage	Expensive (personnel); Turbulence or bad light can make counts difficult; spooks fish; Can be difficult to count large numbers of fish
Electroshocking[3]	Medium to Small; Clear	Easy sampling of age, sex, length, genetics, tagging	Expensive (equipment/personnel); May hinder natural fish movements; More appropriate for small rather than large fish
Observation Tower[4]	Large; Clear	Does not hinder fish passage	Expensive (personnel); Turbulence or bad light can make counts difficult
Sonar/ Resistivity[5]	Medium to Large; Turbid	Not affected by turbulence; Records of run can be saved and reviewed; Playback can be slowed and counts repeated for QA/QC; Does not obstruct fish passage	Expensive (equipment/personnel); Lengthy footage review; Accuracy suffers at highest densities
Video[6]	Small to Medium; Clear	Records of run can be saved and reviewed; Playback can be slowed and counts repeated for QA/QC; Does not obstruct fish passage	Expensive (equipment/personnel); Lengthy footage review; May hinder natural movements of fish; Diversion panels/nets can catch debris
Time lapse photography[7]	Medium to Small; Clear	Inexpensive; Can be left unattended for several days depending on record collection interval; Records of run can be saved and reviewed as well as slowed and counts repeated for QA/QC; Does not obstruct fish passage; decreased impacts on wildlife	Narrow stream width (<15m) and shallower depth (<1m)

Notes:

1. *(BC Ministry of Environment Lands and Parks, 1997; Fleming & Reynolds, 1991; Murauskas, Fryer et al., 2014; Portt, Coker et al., 2006; William, William et al., 2016)*
2. *(Taccogna & Munro, 1995).*
3. *(BC Ministry of Environment Lands and Parks, 1997; Jones & Tonn, 2004; Scottish Fisheries Co-ordination Centre, 2007; Witkowska-Walczak, Slawinski et al., 2014)*
4. *(Edwards, 2005; William, William et al., 2016)*
5. *(Alaska Department of Fish and Game, 2020; Beaumont, 2016)*
6. *(William, William et al., 2016)*
7. *(Misna, 2014; William, William et al., 2016)*

Trapping

Trapping programs have variable equipment needs depending on if adults or juveniles are being captured. The success of a trap program relies on the probability that a fish will encounter the trap, enter the trap and remain within it for assessment (Portt, Coker *et al.*, 2006). Regardless, trapping still requires multiple persons and many person field days to be effective. Trapping often delays fish by holding them for a period of time as well as requires direct handling which causes increased stress levels (BC Ministry of Environment Lands and Parks, 1997; Fleming & Reynolds, 1991; Murauskas, Fryer *et al.*, 2014). High water levels may circumvent traps resulting in fish going around them. Debris (i.e., sticks, leaves) can also be troublesome as they impinge on the upstream side, artificially increasing water levels that may result in circumvention or causing a complete washout of the fence itself. Conversely fish may not approach a structure due to predation concerns or other instinctive reasons (Portt, Coker *et al.*, 2006).

Visual Stream Survey

Visual stream surveys or walks can be used to collect adult spawning or juvenile rearing information. They are used for population estimates in a stream reach and to identify spawning or rearing locations, timing and any other behaviours (Taccogna & Munro, 1995). A minumum of two people are required to conduct a stream walk for safety reasons. In the Arctic a third person may be needed as a wildlife spotter. Often environmental conditions do not permit a visual survey to occur due to high flows or floods, turbidity, or unsafe bank conditions (Taccogna & Munro, 1995). Visual survey do have limitations, such as duplicate counts of fish and observer influence (i.e., spooking or attracting fish) (Hayes, Bence *et al.*, 2007) but results can be compared between years (Taccogna & Munro, 1995).

Electroshocking

Electroshocking in the Arctic is a multi-person field program often used for small bodied fish sampling. Special training is required for equipment operators (Portt, Coker *et al.*, 2006; WorkSafeBC, 2020). Equipment must be certified and can be heavy. Special clothing is required for its safe operation (i.e., non-leaky waders, proper footwear, polarized glasses, and linesman gloves) (Scottish Fisheries Co-ordination Centre, 2007). Safety concerns are numerous from the use of the gear itself and field conditions (e.g., flowing water, slippery rocks), to potential wildlife interaction (e.g., bears). Electroshocking effectiveness relies, in part, on the conductivity of the water, which in the Arctic is often low (Witkowska-Walczak, Slawinski *et al.*, 2014) resulting in difficulties catching fish. This means that additional effort is required to ensure that assessment requirements are met as many fish may not be captured due to electrical field avoidance or too narrow of a field. The required settings to capture fish in low water conductivity conditions also increase the risk of physical injury (Scottish Fisheries Co-ordination Centre, 2007). Due to the need for a multiple person field crew to conduct an assessment, fish may also spook from the crew's physical presence prior to being near the field (Portt, Coker *et al.*, 2006). The habitat in many Arctic streams also makes netting fish difficult due to the large interstitial voids between boulders (Jones & Tonn, 2004). These factors combine to increase handling of the fish resulting in increased stress levels (BC Ministry of Environment Lands and Parks, 1997).

Observation Towers

Observation towers are often used where there are large numbers of fish to be counted on a large stream and are often used for anadromous salmon runs such as Sockeye (*Oncorhynchus nerka*) and Coho (*Oncorhynchus kisutch*) (Edwards, 2005). Lighting and turbidity can affect the ability to count fish and can vary throughout the day depending on site conditions (William, William *et al.*, 2016). When applied to some areas in the Arctic, towers may not be a practical option due to the infrastructure needs for relatively small populations of Arctic grayling when compared to anadromous salmon species and the typical stream size being enumerated.

Sonar and Resistivity Counters

Where conditions are turbid, or the stream is large, and there are a large number of fish, sonar and resistivity counting are often viable options. Sonar uses high frequency sound waves to detect a fish and, depending on the type of sonar, fish can be counted up to 45 m away (Alaska Department of Fish and Game, 2020). Sonar can be used for fish length estimation. Resistivity counters rely on the change in resistance in the water as fish swim across an array of electrodes (Beaumont, 2016). Fish size can be estimated based on the level of change in the resistivity measured. These techniques generally require infrastructure such as a weir (Figure 2-1) or some form of stream bed modification to improve counts by encouraging fish to swim a certain path in relation to the counter and/or to reduce background noise. Such infrastructure is generally expensive to construct and not mobile if other sites are to re-use counting equipment. The counters themselves are also expensive and require calibration to ensure the counts are accurate.

Figure 2-1 Deadman River resistivity counter at low flow (photo by author)

Video

Video enumeration is one option with examples found throughout the world in both marine and fresh water environments. Uses include monitoring of fishways and underwater observations (Tompkins, Benner *et al.*, 2014; Yukon Energy, 2020); however, cost of the technology and the supporting infrastructure requirements (i.e., tunnels, diversion panels) are often the limiting factors for implementation (William, William *et al.*, 2016). Where there are large numbers of fish there may be justification for such investment, but as much of the Arctic is not assessed, time is initially spent conducting presence/absence work to identify the extent to what further assessment is required.

Video cameras have been used at fish passage structures (e.g., fish ladders) at locations such as the Somass River on the west coast of Vancouver Island (Tompkins, Benner *et al.*, 2014) and the Yukon River at the Whitehorse Rapids Dam Whitehorse Fishway (Yukon Energy, 2020). At these locations, cameras are placed at the side through a viewing tunnel section of the passage structure and/or above the flow for recording images. As more detailed information is the objective of these installations, the video imagery allows for counting by species, determination of size, detection of external marks such as adipose fin clips, and assessment of external fish condition. These types of camera installations generally require significant infrastructure to build and operate and are generally not readily transportable.

Photography

Still photography is able to take photos at specific intervals and has been used at several sites and conditions. Generally, a light coloured stream bed is installed in a structure to concentrate fish under a camera set a specific interval to take a photo. For example, outmigration of emergent Sockeye salmon fry is done from Chilko Lake with a large weir to direct the fish swim path using a high resolution still camera (Tompkins, Benner *et al.*, 2014).

In Alaska, wildlife cameras have been trialed successfully for anadromous salmon enumeration (Misna, 2014; William, William *et al.*, 2016). The trial observed adult Sockeye salmon (*Oncorhynchus nerka*) migrating upstream in streams up to ~15 m wide and 1 m deep (William, William *et al.*, 2016). Light coloured panels were installed over the stream bed to provide contrast in images for counting (Figure 2-2) due to the size of the stream and distance from the camera. This work was compared to conventional video analysis methods and was found to be nearly as accurate but required less labour, money and effort (William, William *et al.*, 2016).

Wildlife cameras are relatively inexpensive and durable. Depending on the monitoring program objectives, they can be a cost-effective supplementary or alternative data collection method to provide longer data sets with less direct field time than other traditional techniques, such as trapping; however, alternate enumeration methods need to be proven effective for a particular application before their use will be generally accepted. When there is a very short enumeration window, the cameras can be installed early and removed late to ensure the event period is captured.

Figure 2-2 Image from Alaska fish camera enumerating adult salmon (Misna, 2014)

Thesis Chapter Objectives

This thesis chapter examines the use of wildlife cameras for Arctic grayling spawner enumeration in a small arctic stream. The objective is to establish the effectiveness and reliability of the wildlife cameras, when compared to concurrently running upstream/downstream trapping and visual stream survey programs. It is expected that the wildlife cameras in this application should result in comparable fish overall counts but with reduced field time, no fish handling, and less interruption of migration than trap box and visual stream count monitoring programs.

METHODS

Study Area

The study area is located approximately 300 km northeast of Yellowknife, NWT, at the Ekati Diamond Mine (Ekati) (UTM 12W 518161E 7176636 N) (Figure 2-3) operated by Arctic Diamond. The Pigeon Stream Diversion (PSD) (UTM 12W 516152E 7181720 N) was designed and constructed as replacement stream habitat (i.e., offsetting) to allow for the development of Pigeon Pit at the Ekati Diamond Mine (Rescan Environmental Services Ltd., 2010). The PSD replaces the stream section that is now occupied by an open mine pit. Construction of the PSD was undertaken between the winters of 2011 and 2014 (ERM, 2015).

Pigeon Stream and the PSD flow in a south westerly direction from Upper Pigeon Pond to Fay Bay. Pigeon Stream and the PSD provide spawning and rearing habitat as well as habitat connectivity for Arctic grayling. Lake trout (*Salvelinus namaycush*) and sculpins (Cottidae) are also known to use the Pigeon Stream and the PSD habitat (Rescan Environmental Services Ltd., 2010).

Permits

All work was performed under Thompson Rivers University animal care protocol #100811. This study was conducted in partnership with Arctic Canadian Diamond Company Ltd. (Arctic Diamond) under the Ekati Engineering and Environmental Monitoring Programs in 2014 and 2015 as permitted through the Aurora Research Institute.

Figure 2-3 Location of the Ekati Diamond Mine in the Northwest Territories, Canada. Base image (Natural Resources Canada, 2020)

Trap Box Monitoring Data

The first year of post-construction monitoring of the PSD began in 2014 by Arctic Diamond (ERM, 2015). Methods for trap box enumeration were previously established and conducted independently of this study. Data from this independent monitoring was used to compare the camera counts. The trap box methods have been summarized for informational purposes and to support understanding of camera installation and location selection. Based on the methodology, it is assumed that the trap box counts are representative of a population estimate because it counts all fish in the PSD.

Arctic grayling spawners were enumerated using the four adult upstream/downstream traps (Figure 2-4; (ERM, 2015, 2016)). There are two adult upstream/downstream traps on Pigeon Stream and two on the PSD (Figure 2-5, Figure 2-6, Figure 2-7, and Figure 2-8). All traps were installed and operated during the period when fish were observed to start migrating, typically shortly after spring break-up through to the end of spawning. The PSD freezes solid in the winter so there are no fish within the channel until break-up. Traps were generally inspected twice a day during spawning. Captured fish without tags were tagged using Floy® tags (Figure 2-9, Figure 2-10). As per the monitoring program criteria, fish greater than 170 mm were measured for length and mass (ERM, 2015, 2016; Rescan Environmental Services Ltd., 2010) and were considered spawners. Fish observed moving upstream at trap box #2 (Figure 2-4) or downstream at trap box #3 would have been previously tagged at traps boxes #1 and #4 respectively. Fish that were untagged at trap boxes #2 and #3 would have been in the PSD between traps prior to the trap boxes being installed. Results for trap boxes #2 and #3 in 2014 and 2015 were used for this study. These trap boxes were located downstream (#2) and upstream (#3) of the reach where the cameras were located.

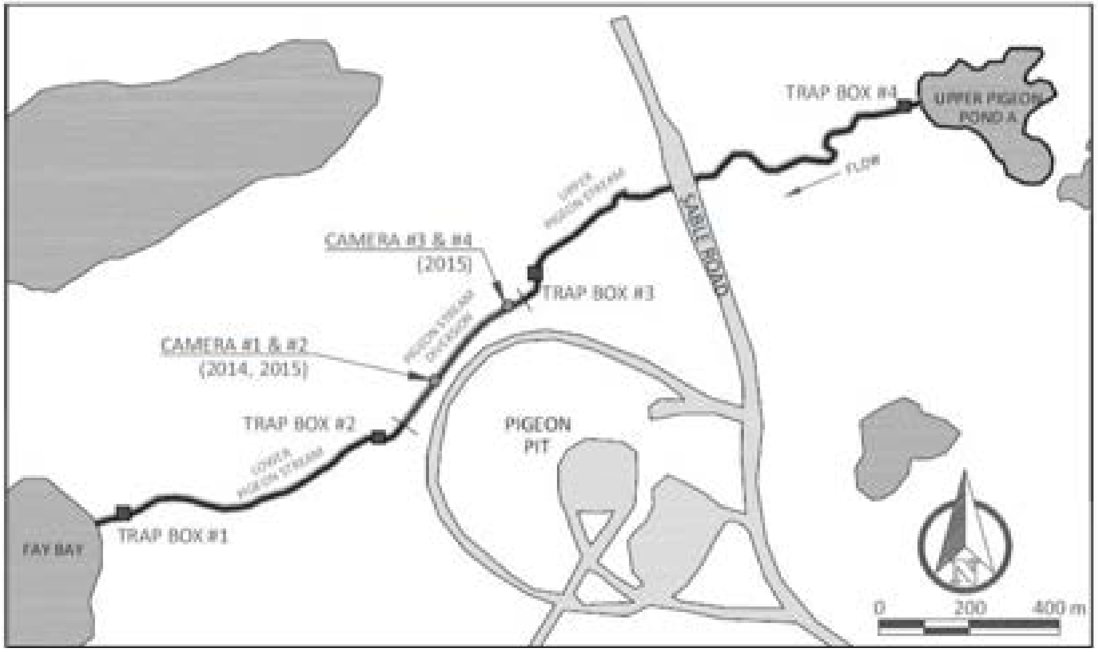

Figure 2-4 Location of cameras and trap boxes on the PSD (adapted from (ERM, 2015); base image (Google Earth, 2014))

Figure 2-5 Upstream/downstream fish trap box 2 installed early June, 2014 on the Pigeon Stream, Ekati (ERM, 2015). Data obtained from this trap were used for comparison to the cameras.

Figure 2-6 Upstream/downstream fish trap box 2 installed June 9, 2015 on the Pigeon Stream, Ekati. (ERM, 2016) Data obtained from this trap were used for comparison to the cameras.

Figure 2-7 Upstream/downstream fish trap box 3 installed early June, 2014 on the Pigeon Stream, Ekati. (ERM, 2015) Data obtained from this trap were used for comparison to the cameras.

Figure 2-8 Upstream/downstream fish trap box 3 installed June 9, 2015 on the Pigeon Stream, Ekati (ERM, 2016). Data obtained from this trap were used for comparison to the cameras.

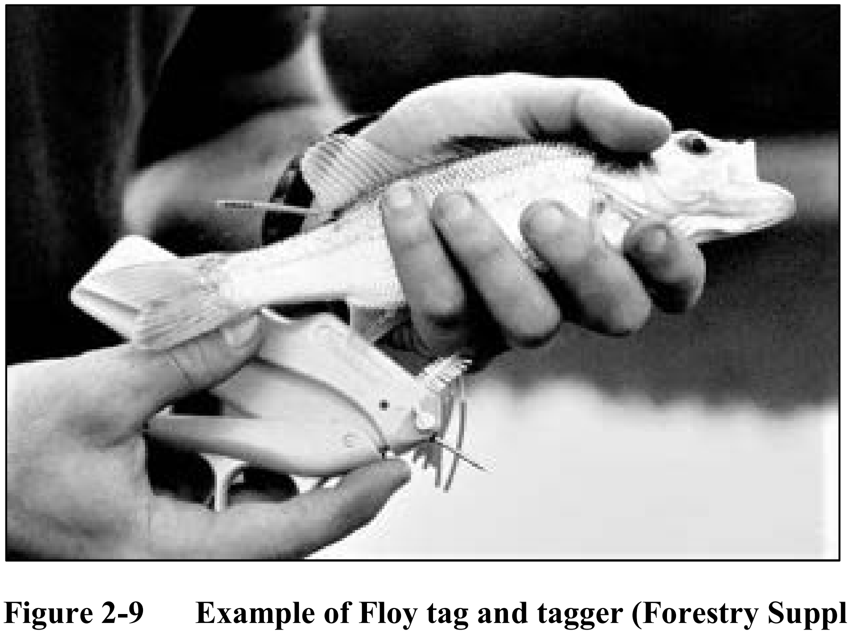

Figure 2-9 Example of Floy tag and tagger (Forestry Suppliers, 2014).

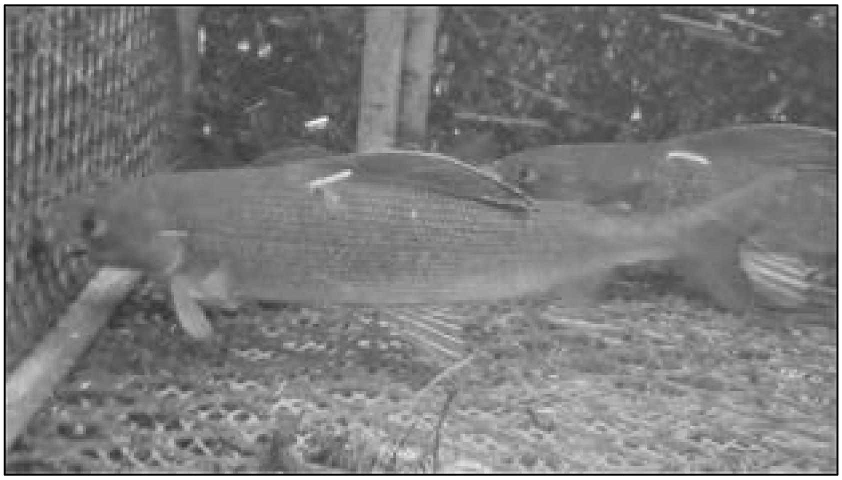

Figure 2-10 Adult Arctic grayling in trap box at Ekati (ERM, 2015). Note: Floy tag presence by dorsal fin.

Visual Spawning Survey

Visual spawning surveys (Figure 2-11) were conducted as part of the Ekati PSD monitoring program throughout the spawning period (Rescan Environmental Services Ltd., 2010). Surveys were conducted walking the stream banks in an upstream direction to record the age class (i.e., adult), location, direction, and inferred behaviour (e.g., migrating, spawning) of the observed fish. Visual stream surveys may not have been conducted every day during the monitoring period due to the number of fish being processed in the trap box and other physical monitoring tasks. For this thesis, fish observation between trap boxes #2 and #3 were included.

Figure 2-11 Tagged, adult Arctic grayling observed during a visual spawner survey in Upper Pigeon Stream, June 9, 2014 (ERM, 2015).

Visual spawning surveys were used for population estimates in a stream reach and to identify spawning locations, timing and any other behaviours. These surveys were generally in a upstream direction and were undertaken several times during the spawning periods in 2014 (ERM, 2015) and 2015 (ERM, 2016). The results of the visual spawner surveys from 2014 and 2015 were used for this study.

The visual spawning surveys of the PSD were not used for population estimates as part of the monitoring program of the channel; however, it is possible to estimate the population based on the counts (Taccogna & Munro, 1995). For this thesis, fish were distinguished as tagged and untagged then summed for the total count of the visual survey. The area-under-the-curve method (Parsons & Skalski, 2010) was then used to estimate the population from the visual stream survey counts.

Camera Installation

This study used Reconyx® wildlife cameras (HC500 HyperFire Semi-Covert IR) (Figure 2-12). The cameras were installed on the PSD (Figure 2-14, Figure 2-15) at existing footbridge crossings between trap boxes #2 and #3. These locations were selected for access, for battery and memory card changes and for ease of mounting, channel shape, and lighting. Substrate in the channel at these locations was relatively uniform in colour and texture to provide improved contrast against the fish when reviewing the images

The cameras were mounted directly over the channel to view as much of the channel as possible. The two PSD bridge locations enabled the camera mounting over the stream channel at approximately 1.5 to 2.0 m height allowing the majority of the full PSD channel width to be viewed. In 2015, two cameras were mounted side by side and timed to attempt stereo image capture with the intent to better estimate fish size.

Figure 2-12 Reconyx HC500 HyperFire Semi-Covert Camera (Reconyx, 2013).

Cameras were installed in May of both 2014 and 2015; however, they were decommissioned for the winter in late September in both years. The cameras were operated over the 2014 and 2015 open water seasons (Figure 2-13), which coincided with the PSD monitoring by Arctic Diamond. Based on the PSD plans (Rescan Environmental Services Ltd., 2010) and field assessment, the PSD channel was of suitable width such that fish concentrator panels were not needed to direct fish past the camera image area.

Cameras were set to take an image at one minute intervals 24 hours per day with the built-in infra-red flash for night images. Battery and memory cards were changed approximately every 21 days to minimize the potential for missed image collection. Based on field experience when using these cameras for wildlife observations, lithium batteries were used, not rechargeable or alkaline types (Freeman, 2014). As per the Reconyx® camera manufacturer website, the lithium batteries provide brighter, more consistent night time illumination with the infrared flash and are able to withstand cold temperatures as low as -40°C, making them suitable for Arctic applications.

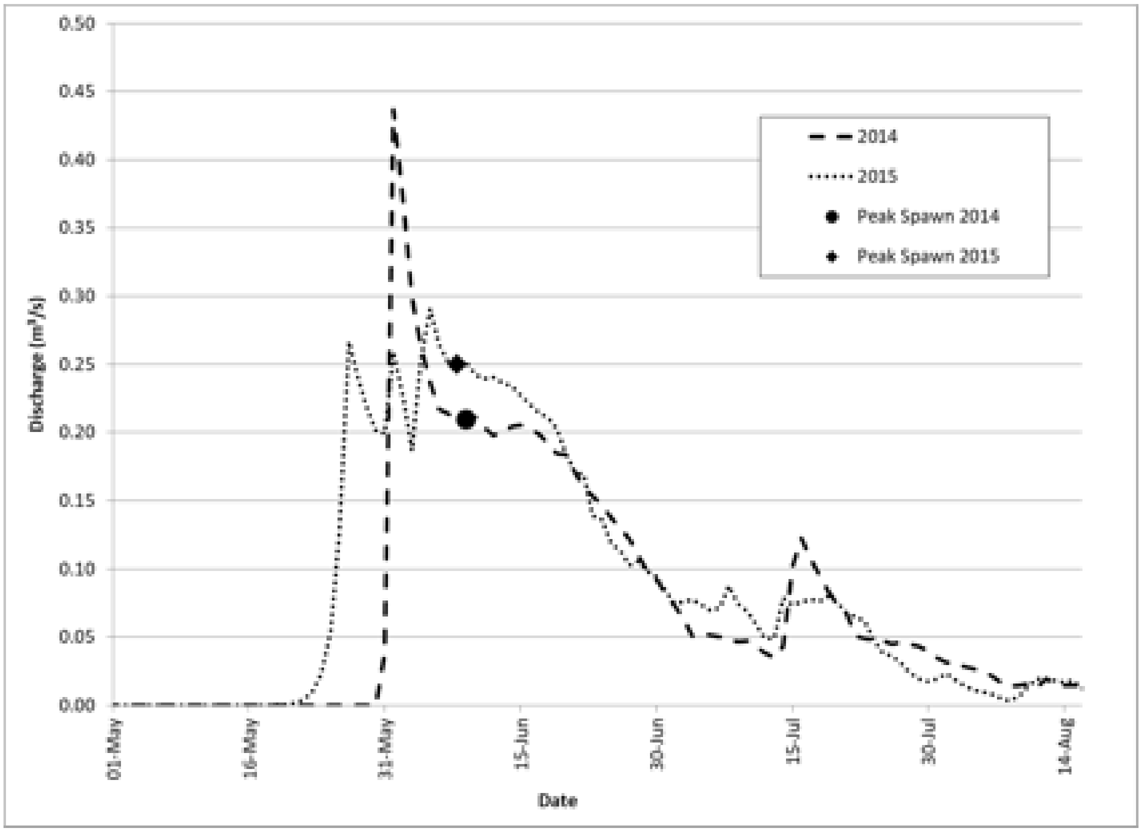

Figure 2-13 Hydrograph for the PSD in 2014 and 2015 and each year's date of peak spawn. The peak discharge in 2014 was higher than 2015; however the 2015 discharge (0.25 m3/s (ERM, 2016)) at the time of peaks spawning greater than in 2014 (0.21 m3/s (ERM, 2015))

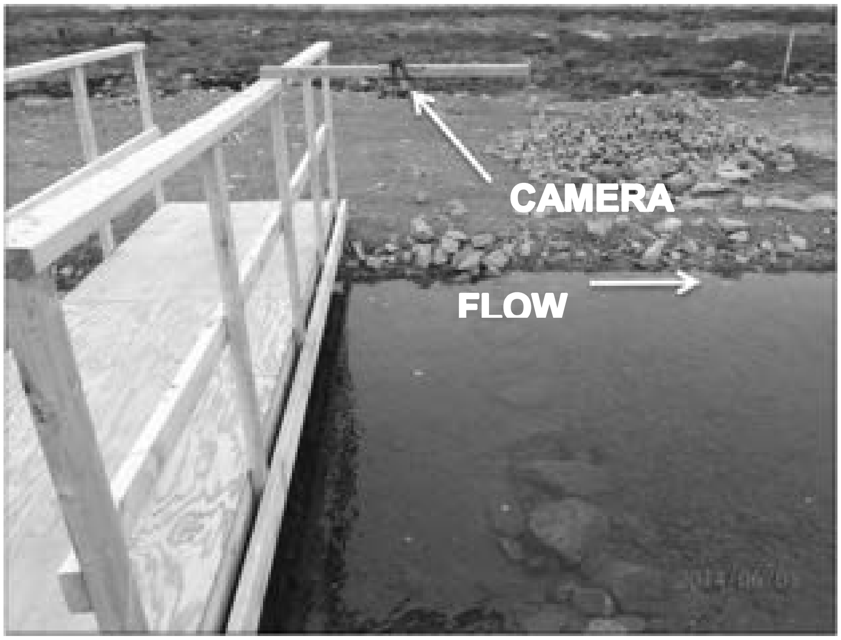

Figure 2-14 Side view of Camera #1 mounted on the South side of the downstream bridge over the PSD in 2014. Only downstream side was used in 2015 (photo by author).

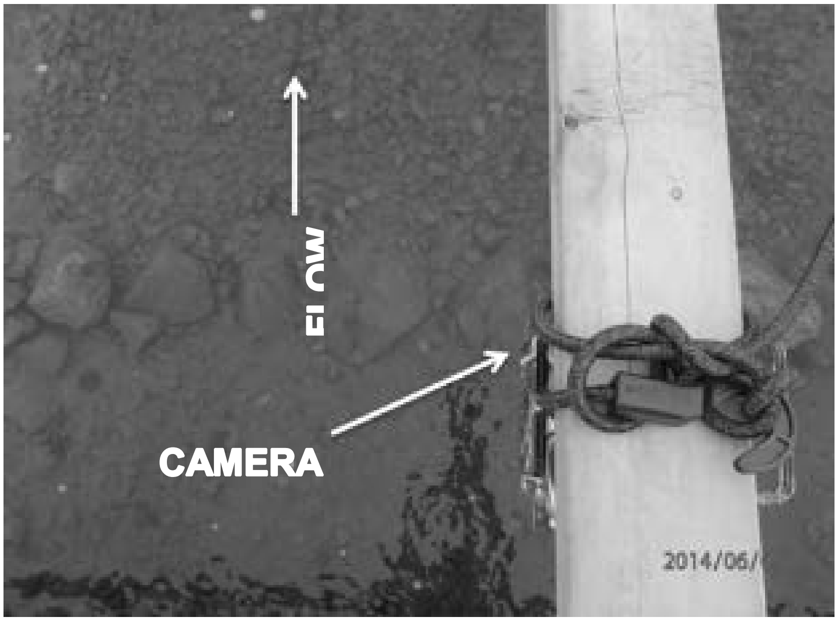

Figure 2-15 Top of Camera #1 mounted on the South side of the downstream bridge over the PSD in 2014 (photo by author).

Image Review and Data Analysis

The individual images were reviewed manually. Camera images are able to be evaluated by individuals familiar with visual spawning surveys counting techniques as the images are similar to that which would be seen in the field under similar conditions. For quality control purposes, four random days for each year of image files and all images identified with fish were reviewed a second time. Fish were counted and identified by species, approximate size for estimating maturity, and direction of travel (based on fish direction). The coloured Floy® tags, part of the Ekati PSD monitoring program, were attached to fish greater than 170 mm and were visible in the images, were also noted. Based on the methodology, it is assumed that the camera counts are representative of a population estimate, as it is assumed all fish are counted.

All fish moving upstream into the PSD through box trap #2 and downstream through trap box #3 were considered to be tagged fish. The trap box counts were assumed to be absolute and total counts, as fish greater than 170 mm were tagged and all fish moving should be captured by the traps regardless of direction travelled. Where untagged fish were present in the PSD, it was likely due to migration prior to trap box installation or trap circumvention, such as during high water, or due to tagging gun malfunctions (i.e., no tag could be implanted) (ERM, 2015).

The spawning period was considered to be from the initiation of the trap boxes and cameras with open water (i.e., late May / early June) through to June 30th each year. The daily and cumulative counts from the camera images were compared to the daily and cumulative counts from the trap boxes. The 2014 cameras 1 and 2 were not combined as, although in close proximity, they were considered to be at different stations (i.e., not side by side) on the PSD. The 2015 cameras 1 and 2 were totaled as they were considered to be at the same station (i.e., side by side). In 2015, Cameras 3 and 4 counts were combined for the same reason (i.e., side by side). Potential duplicate image counts were reviewed and adjusted as necessary.

As it is expected that the final counts of the cameras should be equivalent to the trap boxes and the visual stream survey population numbers, Chi-squared test[4] was used to test the objective that there is no significant difference among the three enumeration methods.

RESULTS

Images

Examples of images with tagged and untagged adult Arctic grayling are shown in Figure 2-16 and Figure 2-17. Tagged fish were able to be identified with ease unless the camera only captured a partial view of a tagged individual which excluded the tag location near the base of the dorsal fin. This happened in only a few instances.

Occasionally, some images were difficult to view due to surface conditions created by precipitation, icing, or high winds. Turbidity also limited effective viewing of some night images. Other images were of poor quality due to the camera focusing on something very close to the lens such as rain or snow (Figure 2-18) or mosquitos, blackflies or spiders (Figure 2-19) or lighting conditions such as extreme shadow (Figure 2-20) or excessive/reflecting flash (Figure 2-21).

Arctic grayling were the dominant fish species present in the PDC during the camera deployment spawning time period. Adult Arctic grayling are easily viewed in the image during the day and night. Tagged and untagged fish were generally readily identifiable where the dorsal area of the fish was captured in the image.

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[4] Chi-squared table used from (Jones, 1996)

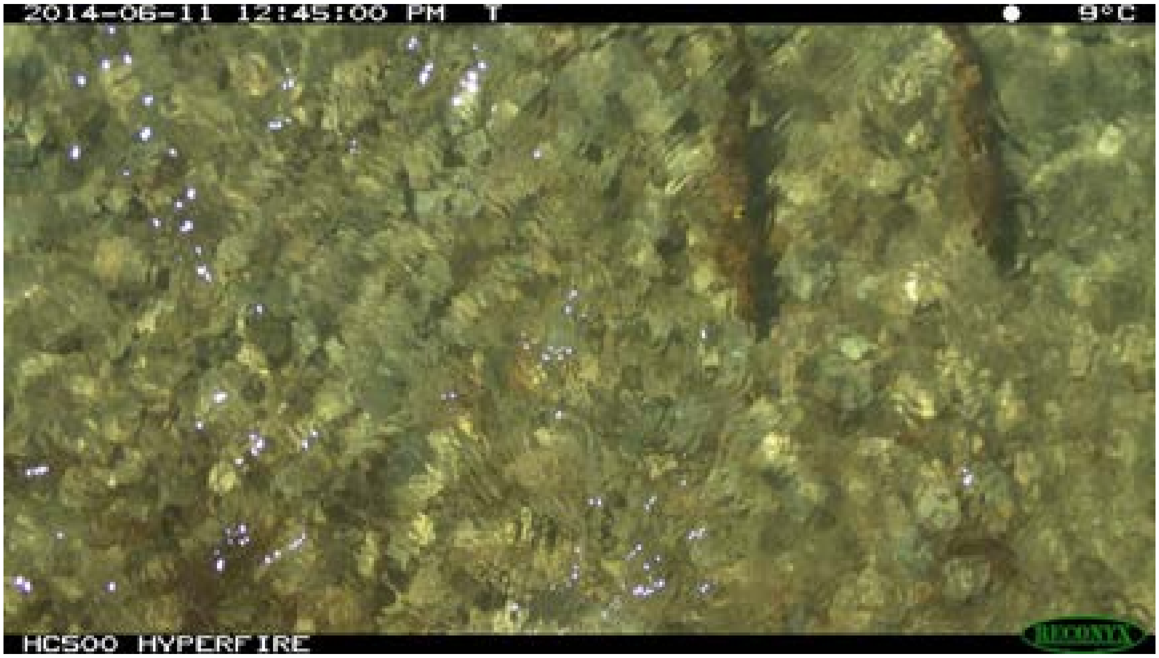

Figure 2-16 Camera 1 image (2014-06-11 12:45) shows 2 adult tagged Arctic grayling moving upstream.

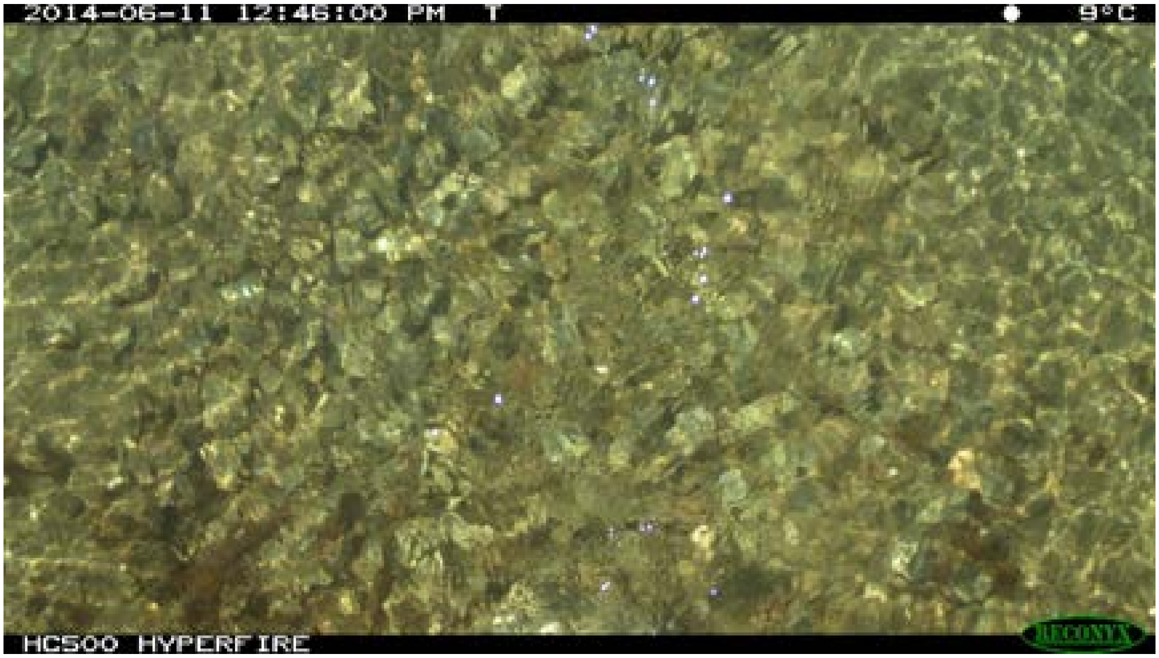

Figure 2-17 Camera 1 image (2014-06-11 12:46) shows no fish in the stream channel during the day.

Figure 2-18 **Camera 3 image from 2015 (2015-06-01 09:25) showing precipitation and subsurface ice affecting the image. Note: Icing conditions on stream bottom and edges.**

Figure 2-19 **Camera 2 image from 2014 (2014-06-06 21:09) showing what appears to be a spider leg blocking a portion of the image.**

Figure 2-20 **Camera 2 image from 2014 (2014-06-25 14:45) showing how the sun that creates shadows affecting the image.**

Figure 2-21 **Camera 2 image from 2015 (2015-05-31 02:07) showing flash 'spot lighting' the image.**

Duplicate Counts

There were four occurrences in 2015 where there may have been duplicate observations of fish with Cameras 1 and 2 (Table 2.2). This results in the potential of four additional observations between Camera 1 and 2. There were likely no duplicate counts of fish with Camera 3 and 4 based on the fish observation and image time. Although the timing on the images is very close, it is difficult to confirm if these were definitively the same fish in the images. As a result, the Camera 1 and 2 duplicates were not excluded for the analysis.

Duplicates were not considered for 2014 counts as cameras were at different stations and the counts were not combined.

As the duplicate counts were not at the same image time stamp, the images could not be used to estimate the size of fish.

Table 2.2 Potential duplicate counts in 2015 noted between Camera 1 and 2.

Date	Camera 1 Time of Observation	Camera 1 Number of fish	Camera 2 Time of Observation	Camera 2 Number of Fish	Potential Duplicate Count
2015-05-29	06:33	1	06:47	1	1
2015-06-06	15:18	1	15:17	1	1
2015-06-07	11:58	3	12:05	3	3
2015-06-11	05:12	1	05:13	1	1

Camera Function

Batteries and card replacement or check was done approximately every 21 days and provided consistent data recording. Images were continuously recorded during the spawning period at the 1 minute interval.

Image Review Time

The cameras were deployed for a total of 59 days. There were 26 days in 2014 with 74,789 images reviewed and 33 days in 2015 with 147,962 images reviewed. Total number of hours to review the all images was 40 hours (5 person days) (Table 2.3) with 18.8 hours (2.3 person days) for 2014 and 21.2 hours (2.7 person days) for 2015. The average number of images that were reviewed per minute was 142. Images were found to be reviewed quickly due to consistent background reference for the majority of images. Fish were readily distinguishable by their size and shape over the stream bed (Figure 2-16, Figure 2-17). Shadows, vegetation and current patterns occasionally required additional time review to confirm fish presence or not, and once a visual pattern was established in the image review time continued to be rapid. Camera images were reviewed prior to tabulating trap box and visual stream survey counts to avoid potential bias.

Table 2.3 Summary of Image Review Time

Camera	Year	Total Count Time (minutes)	Number of Images	Rate of Count (images/minute)	Number of Days Camera Deployed	Time to Review (hr)
1	2014	691	37754	120	26	11.5
2	2014	438	37035	95	26	7.3
1	2015	375	48019	130	33	6.2
2	2015	329	47969	157	33	5.5
3	2015	268	47945	181	33	4.5
4	2015	298	47229	167	33	5.0
Total		2399	265951	(Average) 142	185	40.0

Notes:

1. *Ice cover prevented observation for approximately 36 hours of images in 2015 for Cameras #3 and #4.*
2. *Number of images varies due to initial deployment, battery/card and final retrieval times.*

2014 Camera Comparison to Trap Box Counts

The 2014 camera counts (combined tagged and untagged) were compared with the trap boxes within the PSD by both the trap boxes and cameras. Based on the counts of the trap boxes, there were up to 35 fish in the PSD between May 31 and June 30, 2014 (Table 2.4, Figure 2-22, and Figure 2-23). Camera 1 observed 24 tagged and 8 untagged fish (total 32) while Camera 2 counted 38 tagged and 10 untagged fish (total 49). The cameras also recorded more untagged fish than the trap boxes caught[5], particularly camera 2 in 2014 (Table 2.4). When the untagged fish (i.e., 11 fish) are removed from the camera 2 count, there were 49 fish viewed by camera 2 and 32 fish trapped resulting in no significant difference in the two methods (χ^2=0.26). Due to the camera arrangement in 2014, fish may have been observed by both Camera 1 and 2. Only three spawners (i.e., > 170 mm) were counted moving downstream at trap box 2 and none upstream at trap box #3 (i.e., out of the area with cameras) in 2014. Where untagged fish were observed by the cameras, these fish were either in the reach prior to trap box installation or avoided the trap boxes during high water (ERM, 2015).

Table 2.4 Summary of Total Adult Counts in 2014

Year	Location	Number of Adult Fish		
		Tagged	Untagged	Total
2014	Trap Box 2 Upstream	25	5	30
	Trap Box 2 Downstream	3	0	3
	Trap Box 3 Downstream	5	0	5
	Trap Box 3 Upstream	0	0	0
	Camera 1[1]	24	8	32
	Camera 2[1]	38	11	49

Note:

Direction of fish travel was not distinguished for camera counts

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[5] Combined count of upstream trap box 2 and downstream trap box 3 for total fish in the reach

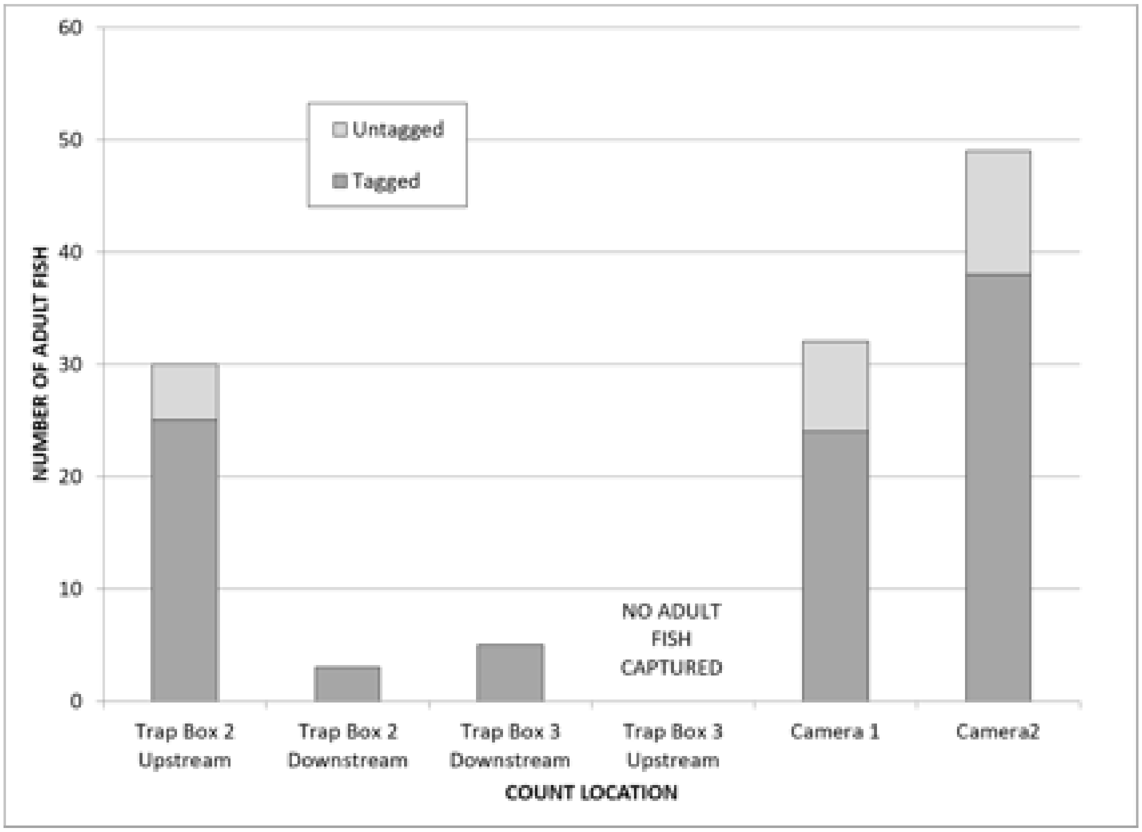

Figure 2-22 Total number of tagged and untagged adults counted at each location between May 31 and June 30, 2014. Total fish in the reach of interest were considered to be the sum of the cumulative counts of "trap box 2 upstream" and" trap box 3 downstream". This sum was compared to the individual counts for camera 1 and camera 2.

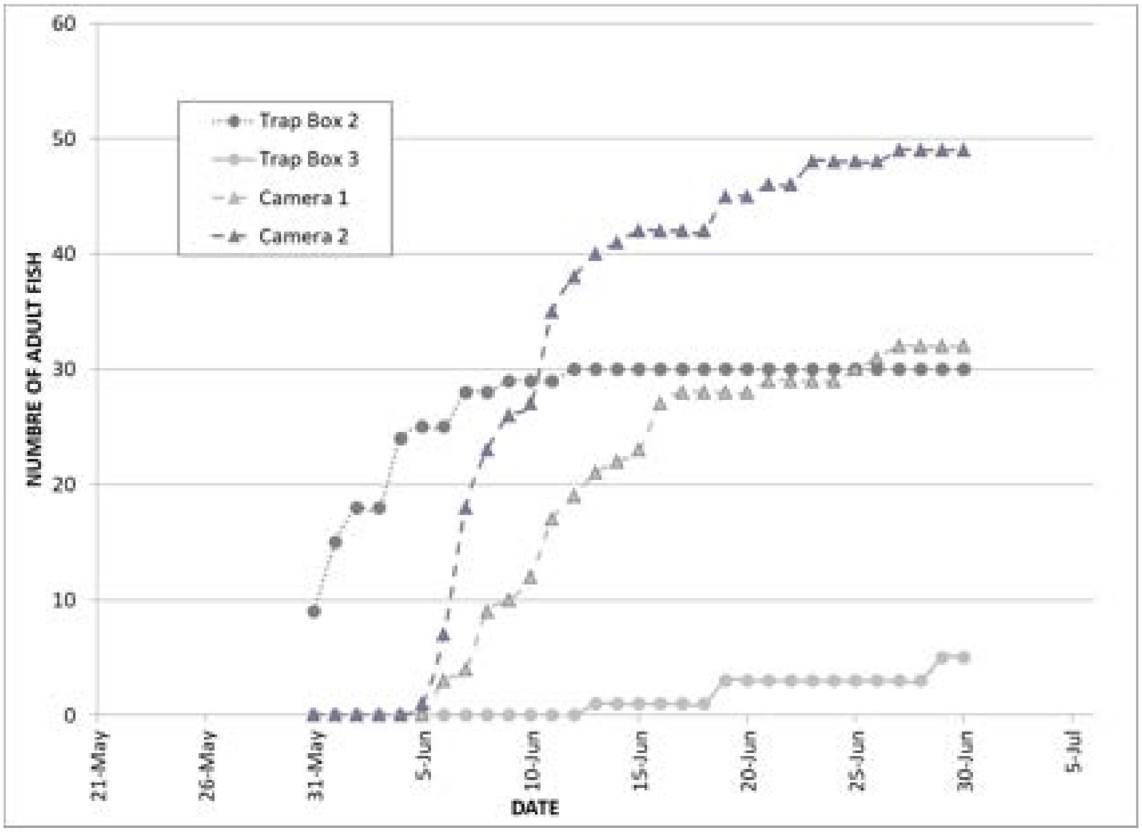

Figure 2-23 Cumulative counts for trap box #2 upstream, #3 downstream, and cameras between May 31 and June 30, 2014. The rate at which fish were observed by the traps and the cameras suggests the movement of Arctic grayling in the PSD.

2015 Camera Comparison to Trap Box Counts

Based on the counts of the trap boxes, there were up to 85 fish in the PSD between May 25 and June 30, 2015 (Table 2.5, Figure 2-24, and Figure 2-25). Cameras 1 and 2 observed 78 tagged and 37 untagged fish while Cameras 3 and 4 counted 19 tagged and 10 untagged fish. The cameras also recorded more untagged fish than the trap boxes caught[6] with the combined cameras 1 and 2 in 2015 (Table 2.5) than were captured in the trap boxes. With the untagged fish (i.e., 37 fish) removed from the combined camera 1 and 2 count, there were 78 fish viewed by cameras and 85 fish trapped, resulting in no significant difference in the two methods (χ^2=0.58)

Table 2.5 Summary of Total Adult Counts in 2015

Year	Location	Number of Adult Fish		
		Tagged	Untagged	Total
2015	Trap Box 2 Upstream	44	0	44
	Trap Box 2 Downstream	6	1	7
	Trap Box 3 Downstream	41	0	41
	Trap Box 3 Upstream	5	0	5
	Camera 1	52	22	74
	Camera 2	26	15	41
	Camera 3	7	2	9
	Camera 4	12	8	20

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[6] Combined count of upstream trap box 2 and downstream trap box 3 for total fish in the reach

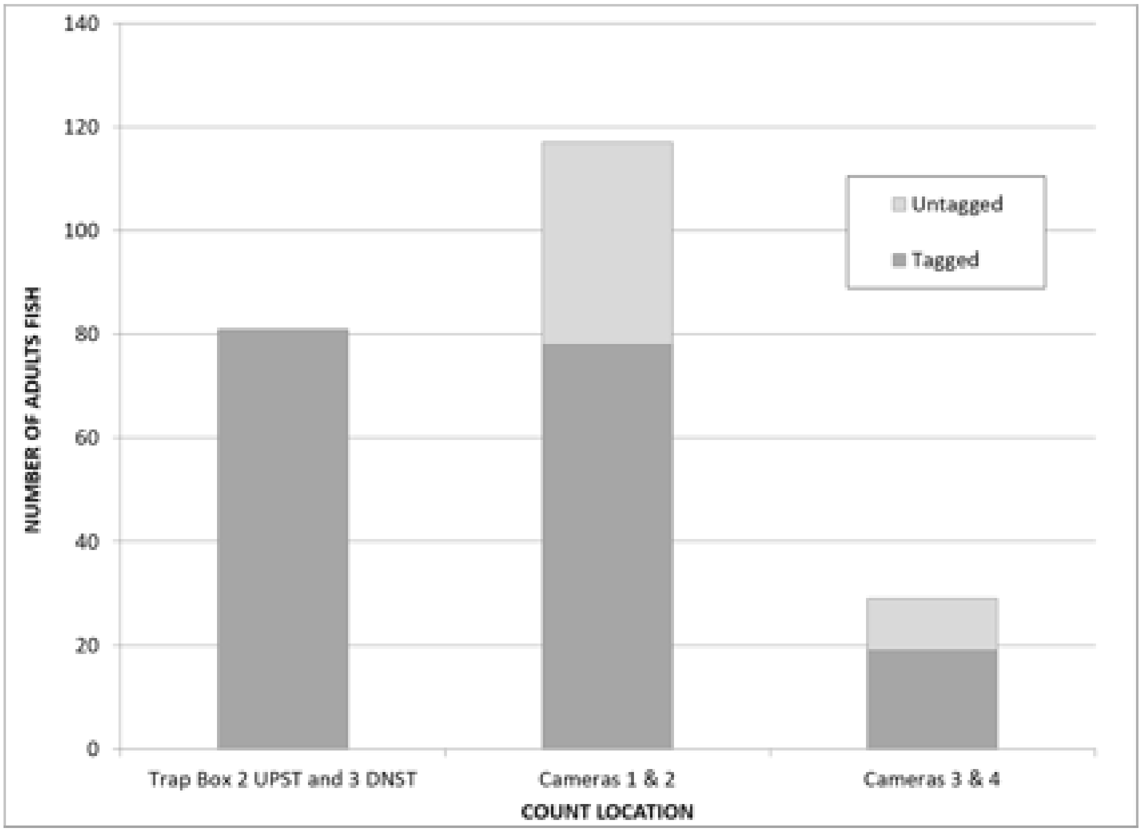

Figure 2-24 Combined total number of tagged and untagged adults counted at both trap boxes and at each camera station between May 25 and June 30, 2015. Total fish in the reach of interest were considered to be the sum of the cumulative counts of "trap box 2 upstream" and" trap box 3 downstream". This sum was compared to the combined counts for camera 1 and 2 as well as camera 3 and 4 due to the side-by-side camera set up in 2015.

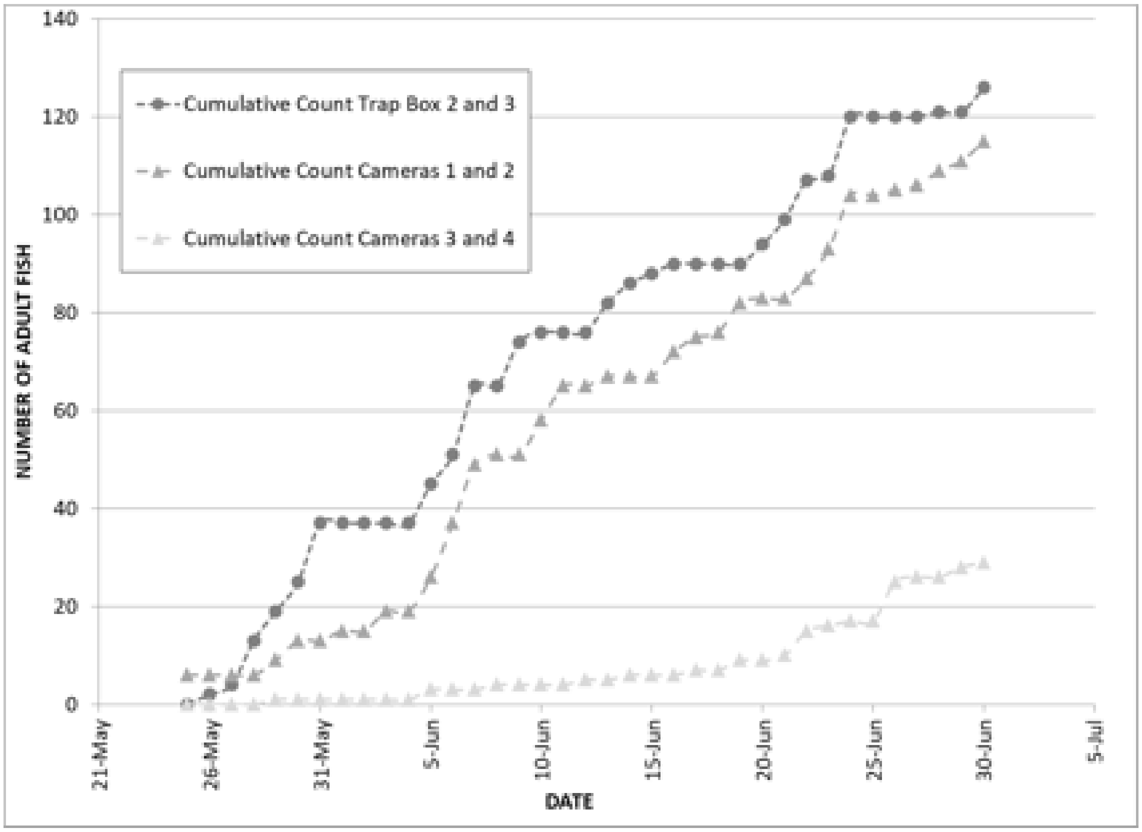

Figure 2-25 Cumulative combined trap box 2 and 3 and camera 1-2 and 3-4 counts between May 25 and June 30, 2015. The rate at which fish were observed by the traps and the cameras suggests the movement of Arctic grayling in the PSD.

2014 Camera Comparison to Visual Spawning Survey

The 2014 camera counts observed fewer fish than the visual spawning survey. The visual surveys enumerated a total of 54 fish versus the camera #1 of 32 and camera #2 of 39 fish between May 31 and June 27, 2014 (Table 2.6).

Table 2.6 Summary of Total Adult Counts for Visual Spawning Survey and Cameras in 2014

Year	**Location**	**Number of Adult Fish**		
		Tagged[1]	Untagged[1]	Total
2014	Visual Spawning Survey[1]	41	16	57[2]
	Camera 1	24	8	32
	Camera 2	28	11	39

[1] *Actual fish count*

[2] *Population estimate using "Area Under the Curve" method*

2015 Camera Comparison to Visual Spawning Survey

The 2015 camera counts observed more fish than the visual spawning survey. The visual spawning survey observed 37 fish and cameras #1 and #2 counted 115 fish between May 25 and June 20, 2015 and 29 fish for cameras #3 and #4 (Table 2.7).

Table 2.7 Summary of Total Adult Counts for Visual Spawning Survey and Cameras in 2015

Year	**Location**	**Number of Adult Fish**		
		Tagged[1]	Untagged[1]	Total
2015	Visual Spawning Survey	23	14	37[2]
	Camera 1	52	22	74
	Camera 2	26	15	41
	Camera 3	7	2	9
	Camera 4	12	8	20

[1] *Actual fish count*

[2] *Population estimate using "Area Under the Curve" method*

Statistical Comparison 2014

Using the Chi-squared test (n=3, p=0.05, χ^2=5.99), the 2014 counts of the combined counts by trap boxes #2 and #3 and the total counts of camera #1 (χ^2 = 0.26), camera #2 (χ^2 = 5.60) showed no significant difference between the enumeration methods.

The 2014 visual stream survey population estimate (n=3, p=0.05, χ^2=5.99) showed a significant difference compared to camera #1 (χ^2 = 10.96) and showed no significant difference compared to camera #2 (χ^2 = 1.12).

Statistical Comparison 2015

When comparing the 2015 counts using the Chi-squared test (n=3, p=0.05, χ^2=5.99), the combined counts by the trap boxes #2 and #3 and the combined counts of camera #1 and #2 (χ^2 = 10.59) as well as the combined counts of camera # 3 and #4 (χ^2 = 36.89) were shown to have a significant difference from the combined trap box count.

The 2015 visual stream survey (n=3, p=0.05, χ^2=5.99) population estimate was shown to have significant difference from both combined counts of camera #1 and #2 (χ^2 = 164.43); however, no significant difference for camera #3 and #4 (χ^2 = 1.73).

DISCUSSION

Camera to Trap Box Comparison

The wildlife cameras produced results comparable to trap boxes though where discrepancy occurred it was easily addressed by the nature of the methods used for counting. Variations in counts between the trap boxes and cameras, over the monitoring period may be the result of trap aversion, individual fish migration/holding behaviour, proximity of the traps and cameras relative to certain habitat types, surface icing, image recording interval, and trap circumvention (e.g., high water by-pass channel) or installation timing (ERM, 2015).

The cameras also recorded more untagged fish than the trap boxes caught[7], particularly camera 2 in 2014 (Table 2.4) and the combined cameras 1 and 2 in 2015 (Table 2.5) than were captured in the trap boxes. When the untagged fish (i.e., 11 fish) are removed from the camera 2 count, there were 49 fish viewed by camera 2 and 32 fish trapped resulting in no significant difference in the two methods (χ^2=0.26). Similarly in 2015, with the untagged fish (i.e., 37 fish) removed from the combined camera 1 and 2 count, there were 78 fish viewed by cameras and 85 fish trapped, resulting in no significant difference in the two methods (χ^2=0.58). This suggests that the cameras were successful in counting fish in the channel as fish that were not previously captured by the traps were observed.

The cameras also had benefits over the trap boxes. It was inferred from the images that the cameras did not seem to influence fish migratory behaviour with the use of infrared flash as was the case noted by William, William et al. (2016) with their use of wildlife cameras. This is unlike trap boxes where fish are often noted to not move into them until the evening hours (Beauchamp, 1990; Cahill, Howland *et al.*, 2016), and some fish may avoid them completely. Fish were observed to hold and move at all times of the day, able to move freely upstream or downstream of the cameras (William, William *et al.*, 2016). This is advantageous when comparing the cameras to other methods such as trap boxes and visual surveys which can influence fish behaviour (BC Ministry of Environment Lands and Parks, 1997; Taccogna & Munro, 1995).

The cameras also were able to identify untagged fish in the PSD reach that either migrated in early or avoided the trap boxes during high water. This is likely due to the installation of the cameras prior to complete loss of ice cover. Ice cover prevents trap boxes from being installed, resulting in uncounted fish that have moved in early under the ice. The cameras are able to observe these fish as they move through a reach once the ice cover starts to disappear. This likely explains the number of untagged fish in the PSD reach between trap box 2 and 3 that were observed by the cameras. Trap boxes enable biologists to distinguish

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[7] Combined count of upstream trap box 2 and downstream trap box 3 for total fish in the reach

individual fish based on tag number; however, the cameras could only identify tagged and untagged fish for counting purposes.

Unlike trap boxes though the cameras were not able to provide detailed information, such as lengths and weights; however, counts for population estimates and presence/absence were achievable. Modifications may be possible with a two camera installation to measure fish length through triangulation (i.e., stereo imagery) of the images.

Camera to Visual Spawning Survey Comparison

The wildlife cameras also produced results comparable to visual surveys though where discrepancy occurred it was easily addressed by the nature of the methods used for counting. The counts from visual spawning survey can vary depending on lighting (i.e., reflection of the sun on the water surface), avoidance of or attraction to the stream observer, weather (e.g., rain distorting the water surface), habitat features, water colour and turbidity, type of fish being counted and fish behaviour (Taccogna & Munro, 1995). Visual counts in some areas of the PSD were likely underestimated due to willow stands or overhanging stream banks obstructing access and view of the stream in some areas as well as pool habitats where fish may have been holding and not visible due to pool depth (ERM, 2015). These habitat features may also influence fish movement and potentially camera counts. Visual surveys can also influence fish behaviour due to the perceived predatory threat of the surveyor (BC Ministry of Environment Lands and Parks, 1997; Taccogna & Munro, 1995); however, the cameras did not seem to influence fish migratory behaviour with the use of infrared flash in the PSD as was the case noted by William, William et al. (2016).

Visual surveys are often limited by turbidity though may be intermittent in such condition depending on precipitation and stream bank stability. Small snowmelt driven, arctic streams are generally clear flowing during most of the Arctic grayling migration period, enabling the cameras to take images effectively for a high percentage of the deployment time. However, even in somewhat turbid conditions of 2015, fish could still be observed in the PSD due to tag presence or shallow water and their swim path. Where turbidity may be a concern, noting swim path behaviour can be used for camera site selection. This is the same technique that has been used for other visual surveys such as on the Fraser River manually near Hell’s Gate where fish use the hydraulics to swim near shore around and over certain rocks. As the fish swim past the rock, the hydraulics force them to swim close enough to the surface, allowing them to be observed, thus enabling improved counting. Likewise for the Deadman River resistivity counter with a Crump weir (Figure 2-1), the weir shape encourages the fish to swim closer to the electrodes for a more accurate measurement. Such a structure may also encourage fish to swim closer to the surface thus improving camera counts in turbid conditions and able the cameras to be used on streams other than in the Arctic.

The visual surveys counted fewer tagged fish than either the trap boxes or the cameras (Table 2.4, Table 2.5, Table 2.6, and Table 2.7). There are two possibilities for this to have occurred. Counts by the cameras may have been higher as the tags may have been retained by fish tagged during previous years’ monitoring activities[8] and these fish had missed the trap boxes (i.e., high water circumvention or early migration before traps installed) or the same tagged fish were counted by stream surveyors multiple times. The visual surveys may also have missed fish that were well hidden by habitat features or surveyor avoidance.

Unlike visual surveys, the camera installations are also able to record at night. Due to the extended daylight hours in the Arctic during Arctic grayling spawning migration, images can still be collected. There is also less infra-red flash reliance with the extended daylight improving the overall average image quality and extending battery life. The infra-red flash did not appear to bother the fish with several being observed at the same location for extended periods (i.e., >15 minutes) both during the day and night.

Image Review

Images were easily reviewed manually. Experienced stream walkers were able to look at images and identify fish much as they do in the field. Although not part of this study, lay

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[8] Arctic grayling may spawn several times over their lifespan and it is possible that Floy tags are retained by an individual for multiple years.

people (i.e., non-fisheries specialists) were asked to look at the images and were able to recognize fish with minimal training. As the Arctic grayling population in the PSD is relatively small, many images reviewed did not have fish present and could be evaluated very quickly. For example, images were quickly reviewed and discounted due to ice cover such as in 2015, where a period of complete surface icing was experienced at all four camera locations on June 1st and 2nd. Image review time though was slower for some images that were difficult to view due to focus issues associated with insects as well as surface conditions created by precipitation or high winds. Turbidity also limited some images as the focus of the camera changed from the substrate to the water surface resulting in a low contrast image; though in this study fish could still be observed. In the Arctic, turbid events are generally short (i.e., <24 hours) (William, William et al., 2016) as was the case in this study. These images required some additional review time to confirm fish presence/absence. Review time is also slowed when including juvenile fish[9], variable image quality due to reflection, weather, insects, or a school of fish holding for an extended period[10]. Even under these conditions, deployment and data collection were still possible with useful data collected in a time and labour efficient manner.

Camera Cost Benefits

Fish enumeration techniques such as trap boxes and visual stream counts are generally labour intensive. Arctic field support costs, including transportation and camp costs, can be 8 to 19 times that of working in southern, temperate regions (Mallory, Gilchrist *et al.*, 2018; Task Force on Northern Research, 2000). The time to review 59 days of images from 2014 and 2015 was approximately 40 hours (i.e., 5 person days). Even allowing for additional time for installation, decommissioning, and travel[11] for a camera program, the total time is only about a quarter to a third needed for a similar field trap box program. The cost

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[9] Due to number present in image and recording of image information

[10] The same fish or group of fish appears in several sequential images

[11] Travel time varies depending on base location and final destination but is generally 1 to 2 days per direction

savings from using cameras may then be directed to other aspects of field programs, such as more detailed habitat surveys.

Camera Maintenance

In the application and setup used for this study, the camera card and battery changes were appropriate and had no breaks in recording during the spawning period. To reduce the potential for breaks in image collections and minimize the servicing interval, cameras could be installed with a solar panel and battery system or, alternatively, redundant multiple cameras could be installed with a time delay start. Camera stability is also important. For this study having the footbridges provided an excellent stable mounting platform. When installing them in more remote areas they should be secured to ensure stability from both weather and wildlife influences.

Camera Installation Considerations

As with any method there is room for improvements in future applications, and cameras are no exception. Location selection is important whether for box traps or cameras. Fish movement is a variable that must be considered along with proximity to habitat features such as holding pools and channel cross sectional shape. Hydraulic deterrence from holding at the camera location should also be considered in location selection (William, William *et al.*, 2016). Site selection is an important criterion when deploying the cameras to ensure satisfactory image quality including aspect, objects that can cause shadows (e.g., structures, vegetation), shelter to prevent incorrect object focusing (e.g., bugs, heavy rain/snow), and substrate contrast (uniformity of gravels, weed growth). Images that were half in sun and half in shade took longer to review as quick assessment was not possible due to variation in shadows or glare (William, William *et al.*, 2016).

Adjacent habitat features, near the camera location, may also influence movement behaviour within the channel. For example, fish may hold at a feature in preference to moving. In the PSD, approximately 60 m upstream of trap box #2 and 50 m downstream from the foot bridge where cameras #1 and #2 are located, there is a large, deep pool (surface area approximately 225 m^2, estimated depth >4 m) (Figure 2-26) (ERM, 2015, 2016). Fish likely hold in this pool for extended periods and may not venture far from it due to the cover that the depth provides until they are ready to spawn. Due to its depth, this pool was also difficult to count fish in by visual stream surveyors. Conversely, at the upstream footbridge, where cameras #3 and #4 were installed there were no such features, rather the adjacent habitat was riffle/run with no deep pools. The adjacent habitat differences may influence migratory behaviour past a particular point. Camera installation locations should consider such habitat features when being selected.

Figure 2-26 Looking upstream to large pond and bridge location of Camera #1 and #2 installation (photo credit: ERM)

Channel shape and flow patterns may also influence camera results based on the path that fish are more likely to use in the channel. Centering the camera over the path most likely to be traveled should capture the greatest number of fish images. This type of consideration is also done for visual stream counts where counters watch a particular spot on the river based on the hydraulic conditions that fish prefer. Counts are improved where the stream is shallow (<1 m) and a smooth water surface exists for improved visibility (William, William *et al.*, 2016). On wider streams cameras may be installed either high over the stream channel or concentrating panels may be used to direct fish movement.

Unlike the Alaska wildlife camera trials (Misna, 2014; William, William *et al.*, 2016) where a larger (i.e., >10 m width) stream was enumerated, the PSD is a small stream (i.e., <3 m width). The proximity of the camera relative to the PSD is closer, allowing for greater detail in the images to observe for presence of tags and species. Floy tags can also be colour coded to year, species or sex as appropriate to improve count detail with the cameras. The natural stream bed was a suitable background for this study due to the size of the stream and proximity of the camera over the stream; however, using a high contrast background may permit more efficient analysis and counting of the images by using software[12]. An example setup would use an opaque white board or sheeting held in place with anchor pins, sandbags, and/or rocks at the edges to ensure a ‘seal’ and prevent fish from finding alternative routes past the camera image (William, William *et al.*, 2016). Material selection for a background should be considered to ensure that there is minimal or no adverse interaction in the environment as well as be transportable with simple installation and minimal maintenance.

CONCLUSIONS

The results of this study indicate that the wildlife camera, trap box, and visual survey methods for fish presence/absence determination and preliminary population estimation studies are comparable. Though some differences did arise between the methods, the differences can be explained due to camera locations, relative to habitat features and the

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[12] Common free software that could be used is ImageJ

nature of the enumeration methods themselves (i.e., spooking fish, trap circumvention). Similar to the other methods, cameras are able to record both tagged and untagged fish, estimate approximate size for identifying maturity, and the direction of travel. Additionally, the cameras may be installed prior to spring break up, photographing migrating fish prior to installation of traps, as well as can be operated through higher flows or debris issues when traps may be circumvented or blown out.

Equipment, such as the trap boxes and electroshockers, may also hinder assessment efforts in remote areas considering transport and equipment back-up requirements should there be parts failures or shipping issues which can result in additional field time or incomplete data collection due to delay. These techniques, while effective, may be more suitable for detailed assessment work where fish health (i.e., precise weight, length) are needed once basic presence/absence and preliminary population numbers have been determined by other means such as wildlife cameras.

Cameras have the advantage of being able to be deployed in remote conditions with minimal on-going support requirements. For this thesis, time required to analyze the images (i.e., 40 hours for 59 days of camera deployment) is much less than the field time (i.e., 8 days for camera versus 59 days for trap boxes) required collecting similar data for the same time period. This can reduce field costs for Arctic programs.

Ultimately, monitoring program objectives will determine the most appropriate enumeration technique for a particular application. Wildlife cameras though are a valid tool that can be particularly useful in remote Arctic environments as well as systems with similar conditions, for fish enumeration particularly where presence/absence and preliminary population estimates are needed.

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CHAPTER 3. ARCTIC GRAYLING (*THYMALLUS ARCTICUS*) PREFERRED SPAWNING SITES AS DESCRIBED BY THE FROUDE NUMBER

ABSTRACT

Many factors impact fish spawning patterns including the hydraulic characteristics of streams. The habitat parameters velocity and depth are generally reported as independent ranges and not paired values. The Froude number (*Fr*) is a dimensionless hydraulic relationship commonly used by engineers and hydrologists to describe the interaction between velocity and depth. The 2014 and 2015 data sets for the Ekati Diamond Mine operated by Arctic Canadian Diamond Company Ltd., approximately 300 km northeast of Yellowknife, Northwest Territories, Canada for the habitat and spawner assessment of the Pigeon Stream Diversion were used to establish a Froude number mean for spawning Arctic grayling. A second data set of paired velocity and depth for a population in the Fond du Lac River, Saskatchewan, was found through data mining. Arctic grayling at the Ekati site selected a mean of Froude numbers (0.27, SE=0.0045), which was significantly different from the measured available habitat (p=0.00043) in the Pigeon Stream Diversion. The Froude number at spawning sites at Ekati was not significantly different (p=0.724) from those of the Fond du Lac River population. The estimated Froude number range for Arctic grayling appears to be lower than for both Atlantic (*Salmo salar*) and Sockeye (*Oncorhynchus nerka*) salmon, (*Fr* 0.2 to 0.4), possibly due to the different nature of egg deposition behaviour and physical size among the species. These results suggest that fisheries managers need to consider fish behavioural responses in relation to the linkages between habitat parameters such as velocity and depth, not just independently.

INTRODUCTION

Successful fish spawning and egg incubation require stream flow to remove wastes, provide oxygen, prevent sedimentation, and minimize dislodgement of eggs (Long, 2007). To identify and evaluate spawning habitat, many physical parameters are routinely measured to determine the conditions to meet these requirements. Typical parameters measured include stream velocity, water depth, temperature, pH, stream width, discharge, substrate and bed stability, channel gradient, instream cover, vegetation cover, groundwater influences, and oxygen transfer capacity (Johnston & Slaney, 1996; Slaney & Zaldokas, 1997). Means and ranges of these parameters are generally used to describe spawning site preference for a particular fish species. A qualitative comparison of these individual parameters is frequently used to describe the habitat conditions. Unfortunately, identifying independent ranges for each parameter does not describe the interaction between two or more and the possible linkages between these parameters and spawning site selection. Quantitative means, on the other hand, can describe the interaction between some parameters to describe fish spawning sites, particularly depth and velocity, using common engineering hydraulic relationships. These relationships between velocity and depth can be used to describe hydraulic conditions and are becoming more commonly used to describe aquatic habitat (Danehy & Hassett, 2016; Gegužis, Baublys *et al.*, 2014). The Froude number (*Fr*) is one such dimensionless relationship that is becoming more common to describe fish habitat, particularly spawning habitat.

Arctic grayling Spawning and Incubation

Arctic grayling typically start moving from their overwintering areas to spawn from late April through early July. Generally, fish start spawning as the hydrograph recedes and water temperatures warm (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007). Male Arctic grayling will protect a territory approximately 1.0 to 2.5 m radius depending on the stream size (Bishop, 1971; Krueger, 1981). Actual spawning and egg deposition may occur anywhere in the male’s protected territory. Hydraulic conditions are likely key to Arctic grayling spawning success. High water events, for example, during egg incubation and larval development can be extremely detrimental due to sedimentation, displacement, and physical injury.

Arctic grayling spawning substrate ranges from fine silts and sands to coarse cobbles, but they generally prefer pea gravel size (i.e., 6 to 40 mm though up to 64 mm diameter) material (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007). Interestingly, the preferred substrate size does not appear to be dependent on the size of the watercourse or discharge (Stewart, Mochnacz *et al.*, 2007), though this aspect has not been examined in detail. Most Arctic grayling tend towards broadcast spawning somewhat like a broad whitefish (*Coregonus nasus*), although there are instances where eggs can be more concentrated in their deposition due to the male forcing the female into the gravel to deposit eggs just below the surface (i.e., 2 to 3 cm) (Armstrong, 1986; Bishop, 1971). Regardless of spawning behaviour, many eggs can be dispersed downstream from the spawning activity (Armstrong, 1986). Eggs are very sticky before water hardening (Tack, 1981) allowing them to attach to the substrate. Incubation is water temperature dependent, typically requiring between 13 and 15 days. Arctic grayling larvae remain in/on the stream bed substrate until their yolk sack is fully absorbed (Armstrong, 1986), and they become free swimming fry 3 to 5 days later.

Dimensionless Hydraulic Numbers

Dimensionless numbers are used by many disciplines to describe a system's behaviour. Often they describe the relationship between two physical parameters. Two common dimensionless numbers that relate velocity and depth are the Reynolds number and Froude number. These numbers are commonly used by hydrologists and engineers to describe hydraulic conditions in open channels.

Reynolds Number

The Reynolds number is used to describe laminar or turbulent flow conditions. Laminar open channel flow is generally described at Reynolds values of less than 500 to 2500 depending on the boundary conditions with flow becoming turbulent around a value of 1400 (Knighton, 1998). The Reynolds number (Re) relationship[13] relates the mean velocity, the depth of flow, and the kinematic viscosity of water. Flow is generally turbulent in

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[13] $Re = VD/v$ Where the mean velocity = V in m/s, the depth of flow = D in m , and the kinematic viscosity of water = v in kg/m^2

naturally flowing systems as the viscous forces are overcome by the inertial forces. At the very thin boundary layer (i.e., right at the stream bed) the flow is close to laminar where velocity approaches zero because the friction force is predominant. This boundary layer is extremely thin and although egg deposition mostly occurs on top of, or very near, the surface of the substrate, the flow would still be considered turbulent around and over the deposited eggs. Therefore, the frictional forces are not particularly meaningful in describing appropriate streamflow characteristics for spawning habitat.

Froude Number

The Froude number can be used to describe stream habitat types and hydraulic complexity (Boavida, Santos *et al.*, 2011; Boavida, Santos *et al.*, 2013; Gegužis, Baublys *et al.*, 2014). The mean Froude number is representative of habitat types whereas the Froude number range provides a measure of habitat complexity (Danehy & Hassett, 2016). Complex channels generally have more types of habitat available and therefore the Froude number will have a greater variance (Danehy & Hassett, 2016). For example, the Froude number had a greater range and more uniform distribution in a natural stream than in a regulated stream (Danehy & Hassett, 2016; Gegužis, Baublys *et al.*, 2014). The use of a Froude number permits a quantitative description of habitat where qualitative comparisons with velocity and depth have previously been made (Hilldale & Mooney, 2007).

The Froude number describes the gravitational or inertial force relationship between velocity and depth. The Froude number is calculated using mean velocity (V in m/s), the depth of flow (D in m), and force of gravity ($g = 9.81\ m/s^2$) as follows:

$$\mathrm{Fr} = \mathrm{V}/\sqrt{\mathrm{gD}}$$

Froude number values greater than 1 describe supercritical flows like those observed in rapids and waterfalls; Froude numbers less than 1 describe subcritical flows like those observed in lower gradient watercourses (Fox & McDonald, 1985), and conditions associated with Arctic grayling spawning habitat (Stewart, Mochnacz *et al.*, 2007).

The Froude number is not scale dependent and thus allows rivers and small streams to be compared and permits data from one population to be used for another with only a minor degree of validation needed. A Froude number range that describes the preference for Arctic grayling spawning could support improved habitat predictions where fish are not necessarily observed but are understood to be present, as well as improve the design of modifications to existing or new habitat to increase the potential productivity.

For many species, including Arctic grayling, limited work has been done linking velocity and depth parameters together, though it has been identified that trout prefer spawning areas with specific combinations of depth and velocity more than either parameter alone (Shirvell & Dungey, 1983) and Froude number ranges have been identified for Okanagan Sockeye salmon (Long, 2007) and Scottish Atlantic salmon (Moir, Gibbins *et al.*, 2004; Moir, Soulsby *et al.*, 1998). Estimated representative ranges of velocity and depth applicable to adfluvial Arctic grayling spawning habitat preferences from the literature are summarized in Table 3-1. Such a broad Froude number range suggests that Arctic grayling will spawn in almost any non-whitewater or waterfall condition. This does not make sense as adfluvial Arctic grayling spawning habitat is described by the literature as areas with surface current velocities less than 1.4 m/s, varying water depths and relatively small, unembedded gravels about 2.5 cm in diameter, which, from a Froude number description perspective, would only describe a portion of the reported ranges as in Table 3-1. Similarly, Habitat Suitability Indices (HSI) are commonly used for habitat description and preference. Generally, HSIs are developed for individual parameters of habitat preference and are not integrated with other parameters. Using the Canadian HSI preferred values for Arctic grayling, the preferred depth range is from 0.15 to 0.91 m and the preferred velocity range is 0.34 to 1.19 m/s (Larocque et al., 2014) (Table 3-1). When calculating the Froude values for the potential pairs from these values, the resulting range is 0.06 to 0.82 with an average of 0.44 (Table 3-1). A similar Froude number range (0.09 – 0.60) with an average of 0.35, can be established from the American HSI literature (Hubert, Helzner *et al.*, 1985). Estimation of the Froude number from both collected data and HSIs thus show the importance of linking the two parameters effectively to describe the hydraulic conditions for Arctic grayling spawning.

Table 3-1 Summary of Arctic grayling spawning habitat characteristics as reported in the literature and range for the corresponding Froude numbers.

Location	Depth (m)	Velocity (m/s)	Calculated Froude Number Estimate From Value Range[2]
Multiple Locations [a]	Shallow (< 1.0 m)	< 1.5	N/A [1]
Providence Creek, NWT [b]	Shallow (< 1.0 m)	-	N/A
Upper Granite Lake, Washington [c]	0.25 - 0.35	0.16 - 0.40	0.08 - 0.24
Adsett Creek, British Columbia [d]	0.10 - 0.40	0.5 - 1.0	0.18 - 0.62
Tyee Lake, Alaska [e]	0.15 - 0.91	-	N/A
Mineral Lake, Alaska [e]	0.18 - 0.73	0.34 - 1.4	0.08 - 0.90
Fielding Lake, Alaska [e]	0.16	1.2	0.96
Habitat Suitability Indices – Canada [f]	0.15 - 0.91	0.34 - 1.19	0.06 - 0.82
Upper Big Hole, Montana [g]	0.284 - 0.773	0.21 - 0.47	0.11 - 0.15
Multiple Locations [h]	0.31 - 0.91	0.31-0.61	0.11 - 0.31
Habitat Suitability Indices - US[i]	0.3 – 0.6	0.3-1.0	0.09 – 0.60

Notes:

1. *N/A - Unable to determine Froude number estimate from data presented*
2. *The range of values is established by calculating the Froude number for the maximum depth with maximum velocity, maximum depth with minimum velocity, minimum depth with maximum velocity, and minimum depth with minimum velocity. The lowest and highest values were then selected for reporting the calculated Froude number estimates*

Source:

a. *(Stewart, Mochnacz et al., 2007)*
b. *(Bishop, 1971)*
c. *(Beauchamp, 1990)*
d. *(Northcote, 1993)*
e. *reported in (Krueger, 1981)*
f. *(Larocque, Hatry et al., 2014)*
g. *(Liknes, 1981)*
h. *(Vincent, 1962)*
i. *(Hubert, Helzner et al., 1985; Larocque, Hatry et al., 2014)*

Thesis Chapter Objectives

This thesis chapter examines the Froude number relationship between available paired data for Arctic grayling to the measured available habitat and Froude numbers developed for other species. High water events during the Arctic grayling egg and larval stage can be extremely detrimental due to displacement and physical injury. The Froude number is a hydraulic dimensionless number that relates velocity and depth. It can be used to describe and compare hydraulic conditions. The literature describes velocity and depth for Arctic grayling as independent ranges not related habitat parameters. As a result, a wide range of hydraulic conditions could be interpreted as being suitable habitat, many of which would contradict observed field conditions.   It is hypothesized that a Froude number can be identified to describe Arctic grayling spawning sites. It is expected that Arctic grayling spawning will occur at Froude numbers much less than 1 as the stream hydraulics with greater values would have the potential to disturb incubating eggs and larvae. The Froude number value for Arctic grayling also is expected to be lower than the values identified for other species, such as Atlantic and Sockeye salmon (i.e., mean $Fr < 0.34$) (Long, 2007; Moir, Soulsby *et al.*, 1998), due to spawning behaviour and fish size differences.

METHODS

Study Area

The study area is located approximately 300 km northeast of Yellowknife, Northwest Territories (NWT), Canada, at the Ekati Diamond Mine (Ekati) (UTM 12W 518161E 7176636 N) (Figure 3-1) operated by Arctic Canadian Diamond Company Ltd. (Arctic Diamond).). The development of the mine disturbed fish habitat. To offset some of the loss of fish habitat due to mine development, the Pigeon Stream Diversion (PSD) (UTM 12W 516152E 7181720 N) was designed and constructed as stream habitat offsetting to allow for the development of the Pigeon Pit at the mine (Rescan Environmental Services Ltd., 2010). The PSD is approximately 4 km from Ekati Camp by mine road. Construction of the PSD was undertaken between the winters of 2011 (Rescan Environmental Services Ltd., 2010) and 2014 (ERM, 2015).

Figure 3-1 Location of the Ekati Diamond Mine in the Northwest Territories, Canada. Base image (Natural Resources Canada, 2020)

Pigeon Stream and the PSD flow in a south-westerly direction from Upper Pigeon Pond to Fay Bay. Pigeon Stream and the PSD provide spawning and rearing habitat as well as habitat connectivity for Arctic grayling, Lake trout (*Salvelinus namaycush*), and sculpins (Cottidae) (Rescan Environmental Services Ltd., 2010).

Data Mining

The data used in this thesis was mined from the 2014 and 2015 monitoring reports for the PSD. Data collected for the monitoring program included paired velocity and depth values throughout the channel (Figure 3-2), identification of spawning locations, and daily discharge. Topographic survey[14] information (i.e., elevation and horizontal coordinates) of the PSD were collected in and around habitat structures (i.e., boulder clusters, rocky ramps) as part of the required assessment monitoring of the PSD by Arctic Diamond (ERM, 2015, 2016) to described the representative flow patterns in the channel, but not randomly selected. The sites were not selected based on spawning observations.

Figure 3-2 Author measuring the velocity and depth as part of the PSD monitoring program, June 4, 2014

Estimation of Habitat Types

The PSD averages 3.0 m in width and is relatively uniform in cross-sectional shape. It was assumed that an Arctic grayling male would be protecting the entire channel width for spawning (Figure 3-3) as Arctic grayling tend to be more broadcast spawners than redd or deep nest builders (Armstrong, 1986). Visual spawning survey results were used to identify

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[14] Topographic survey used a total station to collect vertical and horizontal point information to ±5 mm or better resolution. Further details regarding the survey methods may be found in ERM, 2015, 2016.

spawning locations. The observed positions from the visual spawning surveys of the spawning Arctic grayling were used to identify the points for hydraulic measurements[15].

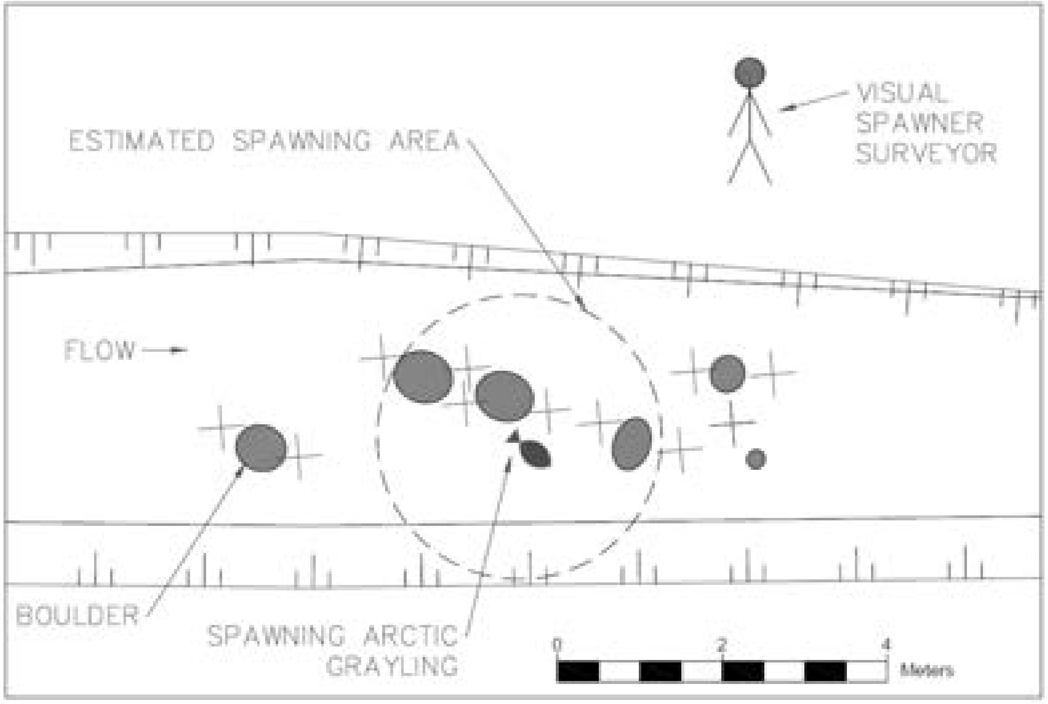

Figure 3-3 Schematic example of topographic survey, velocity/depth measurements, and visual spawner surveyor locations plotted relative to spawning fish. Velocity/depth measurements are identified by (+).

Visual stream surveys were conducted by Arctic Diamond contractors during the spawning period, with fish observed in the PSD from May 28 to June 29 in 2014 and May 31

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[15] Stream walkers typically walked the top of the PSD bank rather than in the stream. Observed spawning Arctic grayling coordinates from the visual spawner survey were then overlaid on the velocity/depth map (Figure 3-3). Often the spawner's coordinates were to the side and not within the channel alignment, likely due to the visual spawner surveyor's observation location during the survey being on the top of the bank not in the stream (Figure 3-3). The spawner location was corrected by moving the fish coordinates perpendicularly onto the center line of the channel from the measured location.

to July 1 in 2015. Velocity and depth measurements were completed just before and at peak spawn during a few days after June 5, 2014 and June 7, 2015. The distance from an observed spawning location to the measured velocity/depth paired point locations were 3.0 m or less. Using the data collected in 2014 and 2015, a plan was created in AutoCAD Civil 3D to layout the habitat feature and velocity/depth map as well as spawner locations. Using the plan, the nearest three velocity/depth measurements (Figure 3-3) to the observed spawning location were then averaged to estimate a Froude number value for that spawning location. Paired values that were not near an observed spawning location describe the measured available habitat[16] characteristics. The total number of velocity/depth measurements made for all measured available habitat types in the PSD for 2014 was 330 and for 2015 was 560.

Other Data Sets

A data mining exercise was performed to gather additional data for analysis to support and compare Arctic grayling spawning Froude number estimates. These data must have paired velocity and depth information relative to the spawning location to be used to calculate the Froude number. This allowed the identification of potential population consistencies or variations and avoided the wide discrepancies in Froude numbers that arise as previously described (Table 3-1). Also, the depth and velocity must have been collected relatively close to values at peak spawn (i.e., within 3 to 5 days) to minimize the variation of the stream discharge. These paired data Froude number estimates were compared to those found in the PSD.A data mining exercise was performed to gather additional data for analysis to support and compare Arctic grayling spawning Froude number estimates. These data must have paired velocity and depth information relative to the spawning location to be used to calculate the Froude number.

Statistical Analysis

As stream discharges in 2014 and 2015 were different, the Froude numbers were calculated separately to identify the possible impact of site selection characteristics based on

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[16] Measured available habitat is all habitat regardless of type (i.e., spawning, rearing, migration, holding).

different discharges. Site selection by spawning Arctic grayling was compared using the variable calculated (i.e., Froude number) and the habitat type (i.e., measured available and spawning) and years (i.e., 2014 and 2015). Depending on data set size (i.e., N<50 or N>50), data were checked for normality using Ryan-Joiner (similar to Shapiro-Wilk) and Kolmogorov-Smirnov; however, not all of the data sets (i.e., measured available habitat 2014, measured available habitat 2015) were determined to be normal. Due to data set size and not needing to transform the data to normal, non-parametric Mann-Whitney tests were performed for each case[17]. Statistical analysis was conducted using Minitab 19. Tests were considered statistically significant at $\alpha=0.05$.

RESULTS

PSD Results

During 2014 there were 12 observations of Arctic grayling spawners in the PSD and in 2015 there were 56 observations. The PSD discharge was similar between 2014 and 2015 monitoring programs. The PSD flow at peak spawn on June 9, 2014 (Figure 3-4) was estimated to be 0.21 m^3/s and then receded to 0.10 m^3/s by emergence (ERM, 2015). In 2015 peak spawn occurred on June 8, 2015, when peak flow was 0.25 m^3/s (Figure 3-4). PSD spawning flows in 2015 were higher than in 2014, though the maximum peak flow for the freshet was higher in 2014 (Figure 3-4). Flows receded to 0.12 m^3/s (2014) and 0.1 m^3/s (2015) by the time of emergence (Figure 3-4). Based on the velocity/depth mapping (ERM, 2016), Arctic grayling were generally observed spawning in areas with mean velocities of approximately 0.32 m/s in both years. The average depth was 0.36 m. for the measured available habitat[18] which was lower than in the 2015 measurement of 0.48 m. The available habitat mean velocity in 2014 was 0.32 m/s and in 2015 was 0.39 m/s (Table 3-2).

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[17] The data were also analyzed assuming that the non-normal data sets were of a large enough size that normality could be overlooked. Variance was checked between the years and habitat types prior to performing two-sample t-tests. The end results were similar to the Mann-Whitney analysis.

[18] Measured available habitat is all habitat regardless of type (i.e., spawning, rearing, migration)

The 2014 available habitat mean Froude value in the PSD was 0.19 (max = 0.73; min = -0.03; SE=0.0064) and the mean spawning Froude value was determined to be 0.23 (max = 0.31; min = 0.14; SE=0.018) in 2014. In 2015, the available habitat mean Froude value was 0.19 (max = 0.93; min = 0.00; SE=0.0063) and mean spawning Froude value was 0.28 (max = 0.48; min = 0.09; SE=0.015). The Mann-Whitney analysis showed there was no significant difference between the 2014 and 2015 measured available habitat Froude number values (P=0.212).

The 2014 and 2015 spawning Froude numbers (Table 3-2, Figure 3-5) were checked for variance and were determined to have equal variance (P=0.141). The measured available habitat was shown to not have equal variance (P=0.008). Mann-Whitney showed no significant difference between the measured available 2014 and 2015 (P=0.688) or the spawning 2015 and 2015 (P=0.212). As there was no difference between 2014 and 2015 Froude numbers for either the measured available or spawning habitat, the values were combined.

The combined years mean Froude number value for the PSD measured available habitat was 0.19 (max = 0.93; min = 0.03; SE=0.013) and Arctic grayling spawning is 0.27 (max = 0.48; min = 0.09; SE=0.0045). The combined 2014 and 2015 Froude number value range for the measured available habitat (-.03 to 0.93) is greater than the selected spawning habitat (0.09 to 0.48) (Figure 3-6). Spawning occurred on the falling hydrograph after peak discharge in both years. Although the discharge was slightly higher in 2015 that 2014, Arctic grayling still spawned at a similar mean Froude number though the range was slightly expanded in 2015 (Figure 3-6).

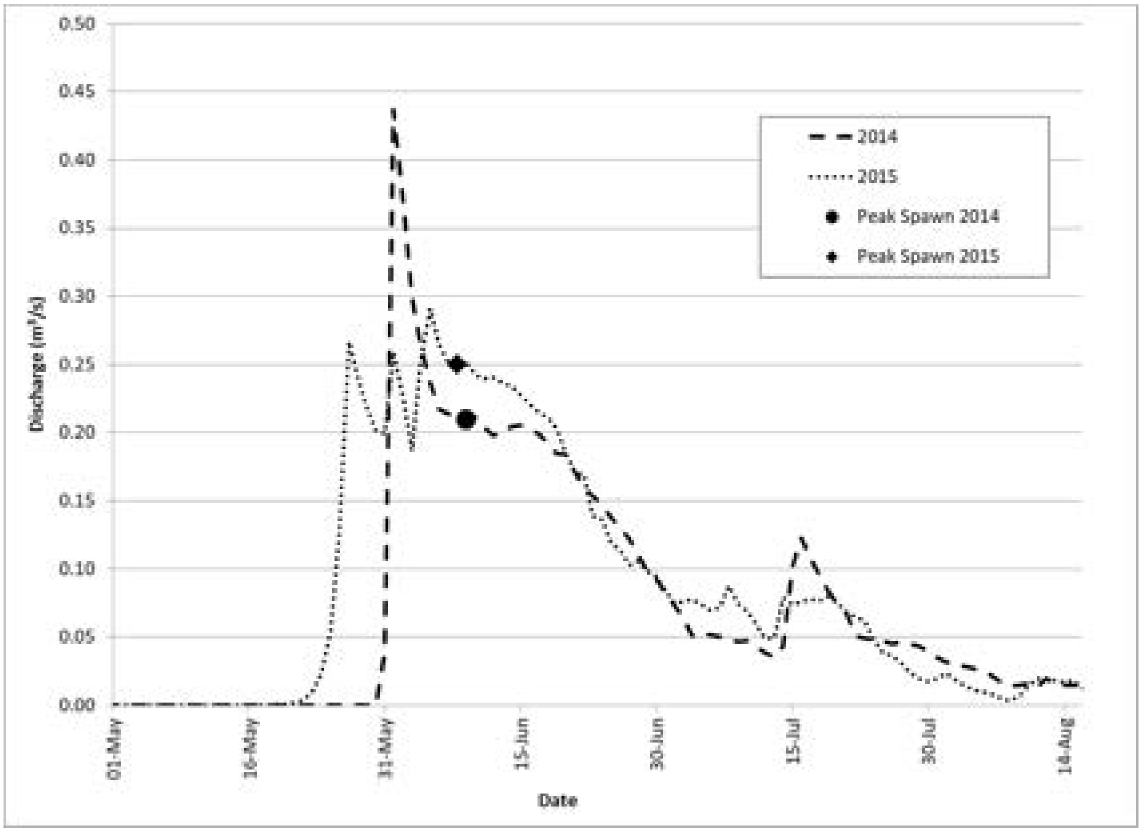

Figure 3-4 Hydrograph for the PSD in 2014 and 2015 and each year's date of peak spawn. The peak discharge in 2014 was higher than 2015; however the 2015 discharge (0.25 m^3/s (ERM, 2016)) at the time of peaks spawning greater than in 2014 (0.21 m^3/s (ERM, 2015)).

Table 3-2 Summary of the measured and calculated value ranges for both the measured available habitat and the observed spawning locations in the PSD

Location	Habitat Type	Sample Size	Depth (m) [2]	Velocity (m/s) [2]	Froude[3]
PSD 2014	Spawning[1]	12	0.26 - 0.36	0.19 - 0.45	0.14 - 0.31
PSD 2014	Available[4]	330	0.23 - 0.33	0.12 - 0.52	0.00 - 0.73
PSD 2015	Spawning[1]	43	0.36 - 0.60	0.15 - 0.49	0.09 - 0.48
PSD 2015	Available[4]	560	0.26 - 0.52	0.13 - 0.59	0.00 - 0.93
PSD Combined	Spawning[1]	55	0.30 - 0.62	0.19 - 0.45	0.09 - 0.48
PSD Combined	Available[4]	890	0.33 - 0.61	0.19 - 0.45	0.00 - 0.93

1. *Spawner observation for spawning site selection and spot measurements for available habitats*
2. *Range of measured values*
3. *Range of Froude number calculated using measured paired values of velocity and depth*
4. *Measured available habitat is all habitat regardless of type (i.e., spawning, rearing, migration, holding)*

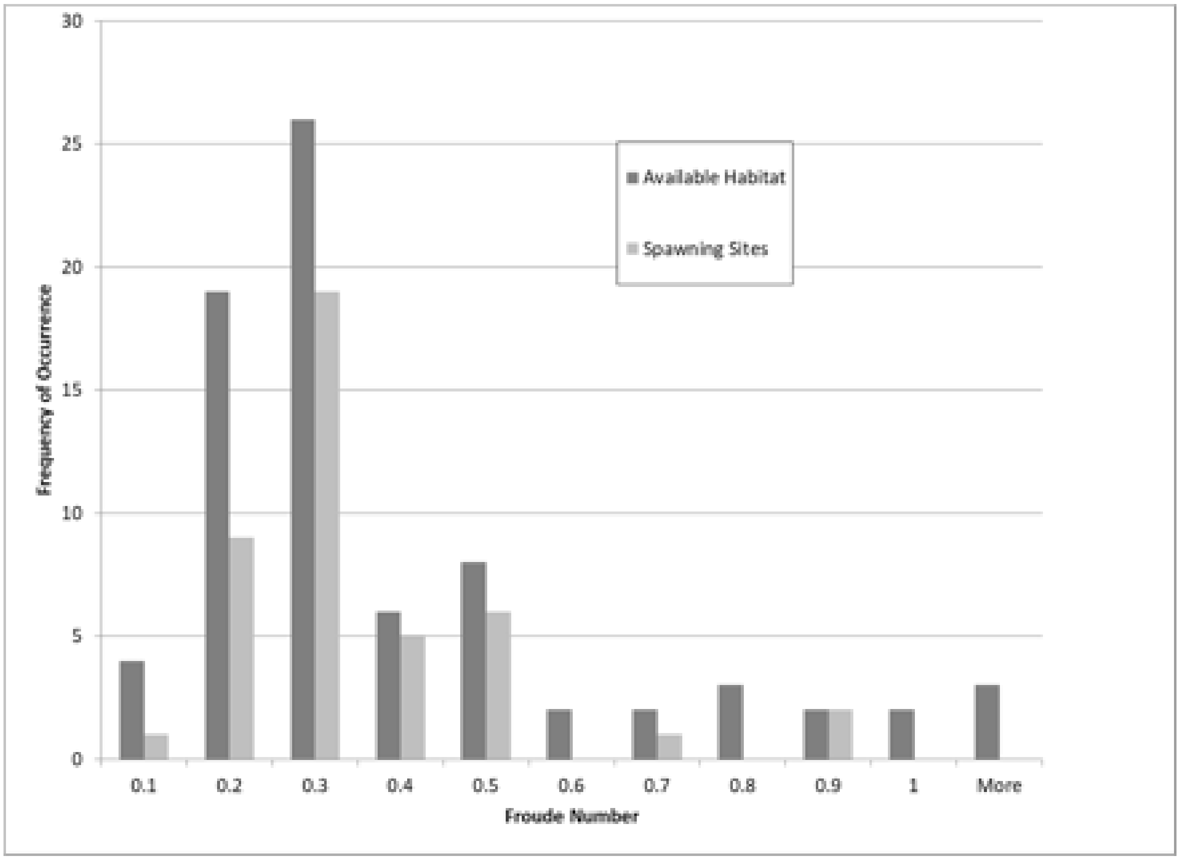

Figure 3-5 Histogram showing combined 2014 and 2015 frequency of occurrences of Froude values for Arctic grayling spawning and measured available habitat in the PSD.

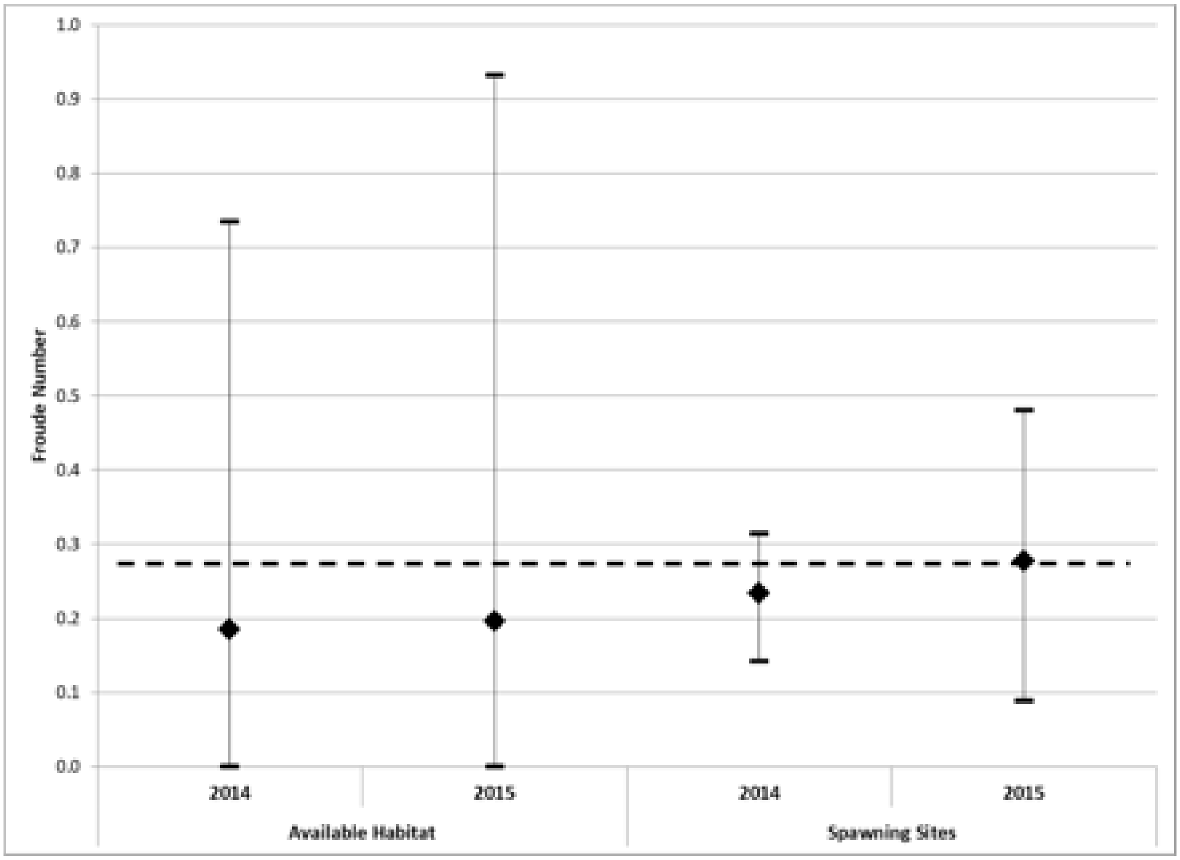

Figure 3-6 Ranges and means of Froude numbers in the PSD measured available and Arctic grayling spawning habitat for 2014 and 2015. The dashed line is the combined 2014 and 2015 mean spawning Froude number value (Froude number = 0.27) for the PSD.

Data Mining

Paired data sets were difficult to find as velocity and depth are generally reported as ranges. Only one suitable data set was identified. The Fond du Lac River (FDL) is significantly larger with spawning discharge in the order of 400 m^3/s (Golder Associates, 2013) compared to the PSD (discharge < 1 m^3/s). The FDL data points were selected based on expectation to find a spawning location. Spawning location was confirmed using a kick test[19] rather than a spawning survey approach; therefore, data points were not random but skewed to spawning preference. The individual Froude numbers were calculated using the paired velocity and depth data for the incubating egg sites. The Froude number mean value for the measured available habitat is 0.36 (max = 1.76; min = 0.00; SE=0.025) and spawning habitat is 0.30 (max = 0.87; min = 0.08; SE=0.022); Table 3-3, Figure 3-7, Figure 3-8). A Mann-Whitney test showed no significant difference between the FDL measured available habitat and spawning habitat (p = 0.571). A Mann-Whitney test showed no significant difference for the spawning Froude number between the PSD and FDL (P=0.724).

Table 3-3 Summary of measured and calculated value ranges for the observed spawning and incubating egg locations for Fond du Lac River 2010/1012

Data Set	Habitat Type	Sample Size [1]	Depth (m) [2]	Velocity (m/s) [2]	Froude [3]
Fond du Lac River, Saskatchewan (2010/2012)	Incubating Eggs	56	0.15 - 0.86	0.0 - 1.26	0.08 - 0.87
Fond du Lac River, Saskatchewan (2010/2012)	Available[4] Habitat	124	0.15 - 0.91	0 - 1.33	0.00 - 1.76

1. *Measured sites*
2. *Range of measured values*
3. *Froude number calculated using measured paired values of velocity and depth*
4. *Measured available habitat is all habitat regardless of type (i.e., spawning, rearing)*

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[19] A kick test is where one foot is used to kick the streambed to dislodge the substrate in the direction of the net. Animals or eggs dislodged from the substrate will be washed into a net downstream from the kicked streambed.

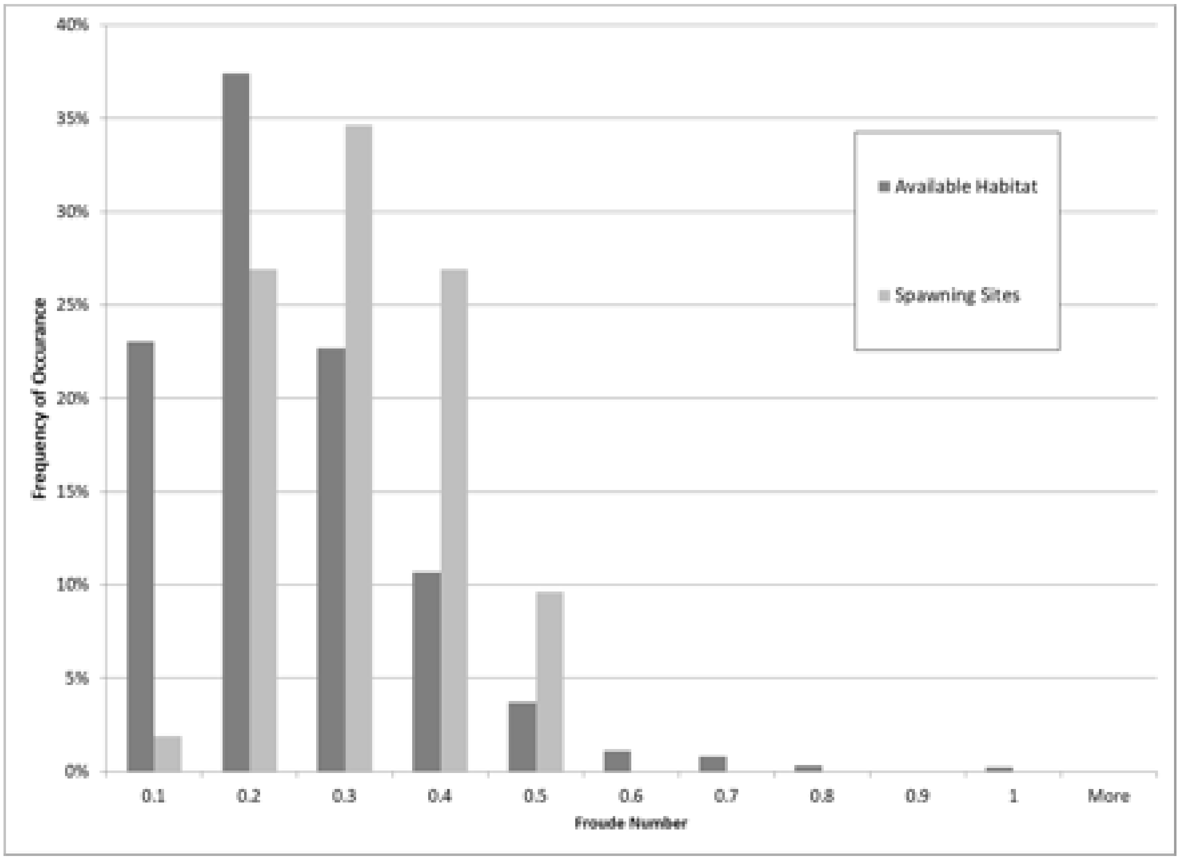

Figure 3-7 **Histogram showing the frequency of occurrences of Froude values for measured available habitat and spawning sites in the FDL.**

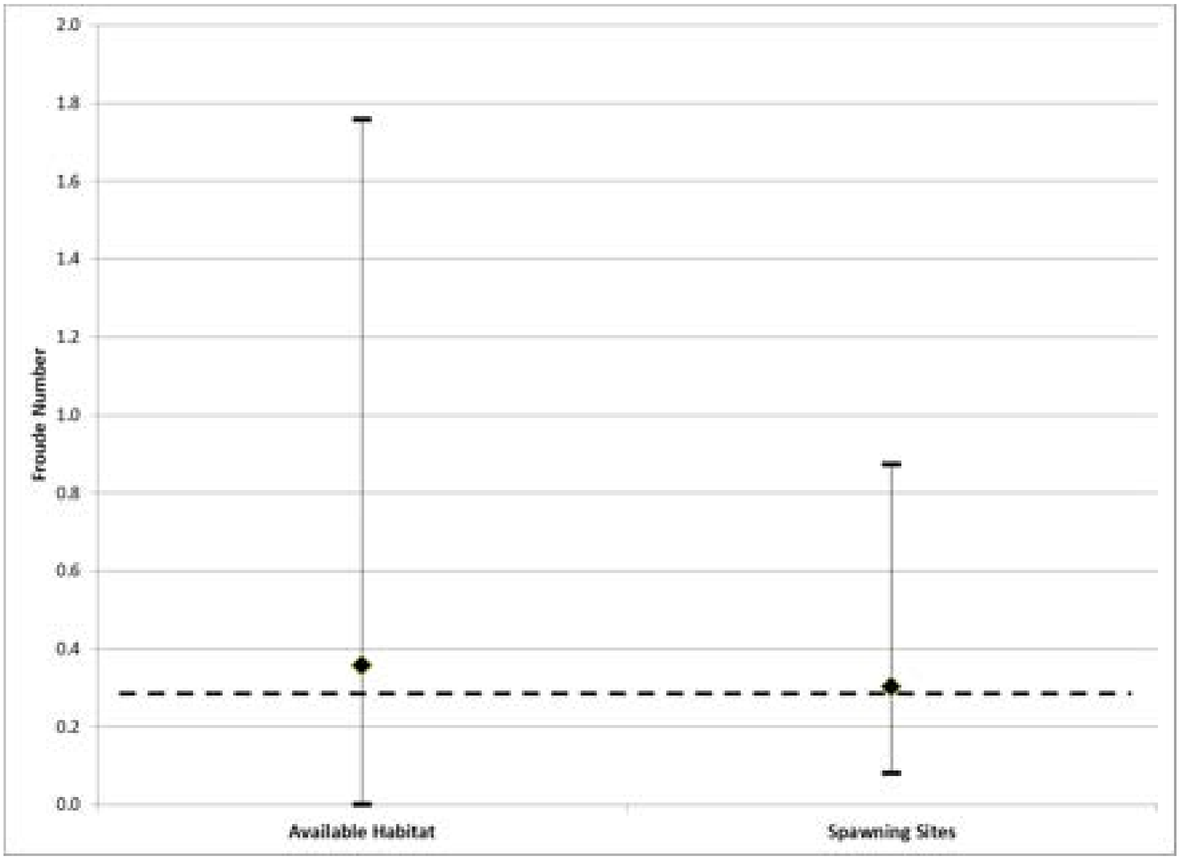

Figure 3-8 Ranges and means of Froude numbers in the measured available (Froude number = 0.36) and spawning habitat (Froude number = 0.30) for FDL. The dashed line is the mean combined year spawning Froude number value for the PSD (Froude number = 0.27).

DISCUSSION

PSD Froude Number

Arctic grayling in the PSD spawned in a narrower range of Froude numbers (*Fr* = 0.09 to 0.48; mean = 0.27, SE=0.00) relative to the measured available habitat (*Fr* = 0.00 to 0.9; mean = 0.19, SE=0.01). This indicates that there is a hydraulic preference for spawning which can be described as a relationship between velocity and depth. The wider range of the measured available habitat Froude numbers suggests that a variety of habitat types exist in the PSD. The measured available habitat area, based on the Froude number values will likely change each year depending on the discharge (Moir, Gibbins *et al.*, 2004) and the specific channel shape. It should be reasonable to expect fish to spawn in similar Froude values each year even though the location of spawning may vary based on depth and velocity with the differing flows.

In 2015, there were more fish present than in 2014, suggesting that the fish may be competing for the preferred spawning areas (i.e., same Froude number locations) but were limited in the territory available specific to a mean value. With increased territorial competition sites may be selected as a result of availability and not on preference alone as has been identified in other species such as Atlantic salmon (Moir, Soulsby *et al.*, 1998). This may explain the slightly expanded Froude number range in 2015 ($Fr = 0.09$ to 0.48) versus 2014 ($Fr = 0.14$ to 0.31).

Data Mining Comparisons

The FDL Froude number mean ($Fr = 0.30$) was comparable and not significantly different to the PSD ($Fr = 0.27$; 2014 and 2015 combined). As the Froude number is scalable, the equivalency in values between the PSD and FDL suggests that these values can be applied to other populations in a variety of watercourse sizes. In addition, the data collected for the PSD and FDL was done using different methods (i.e., spawner location versus kick-tests) to identify spawning sites for velocity/depth measurements with no significant difference in the Froude number results. The range of Froude numbers appears to be consistently preferred between populations and streams; however, the most available Froude number in a system also appears to describe the preferred spawning habitat value systems (Figure 3-5, Figure 3-7). Arctic grayling appear to have adapted to the dominant hydraulic behaviour in their available environment during spawning. Such an adaptation emphasizes the importance of understanding a system's hydrograph in relation to spawning behaviour.

In the FDL there were more Froude number values greater than 0.3, but these were generally noted to be associated with a larger substrate size where there were several eggs observed, or sand, where there were few eggs. The generally larger substrate compared to the

PSD[20], would be more stable at higher values of the Froude number. This may be why the fish have selected such sites. It is suspected that in the areas with high Froude numbers and fine substrate, eggs may have been displaced from sites upstream or been washed downstream during spawning (Armstrong, 1986). Only the presence of eggs, not their viability, was noted for the FDL study (Golder Associates, 2013). Site selection influence by the Froude number value with substrate size was not examined (Golder Associates, 2013). Arctic grayling may select higher Froude values where there is a large substrate size present for spawning. Substrate adaptations may also occur based on the preferred Froude number. During years of high discharge, fish may spawn in similar Froude number areas but may select a larger substrate than in lower discharge years. Interestingly, for both the PSD and FDL, the range of Froude numbers is distributed in a similar manner relative to the habitat available. It would be expected that fish would adapt to be able to make use of the maximum optimum condition by the area available during spawning.

Other Species Comparisons

There appears to be consistency between these two populations of Arctic grayling for a spawning Froude number value, and a difference from other species. Although there is some overlap in the range of Froude numbers measured for Arctic grayling and Sockeye and Atlantic salmon, the Froude values for Arctic grayling were generally less than those measured for the other two species which have a mean Froude number of 0.34 (Long, 2007; Moir, Gibbins *et al.*, 2004; Moir, Soulsby *et al.*, 1998). The lower Froude value may be a result of their biology and life history. Arctic grayling are more broadcast spawners versus deep redd building of Sockeye and Atlantic salmon. Somewhat higher Froude numbers would be expected to support conditions for adequate interstitial flow in redds for incubating eggs of the two salmon species. Whereas Arctic grayling tend to deposit their eggs at or near the streambed surface, a lower Froude number at the spawning site would be expected to be more favourable as there would be reduced bedload transport and potential egg displacement, though a high enough value would be required for oxygenation and waste removal. Physical

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[20] PSD substrate size is described as some fines but predominately gravel (i.e., 4 to 64 mm diameter) with cobbles and small boulders (i.e., >64 mm diameter) (ERM, 2015).

size differences between the three species[21] may also influence the capability of a species to use a set of conditions (i.e., larger substrate, greater water velocity) in the stream environment. The substrate used by Sockeye and Atlantic salmon is generally larger than that used by Arctic grayling[22] which tend to prefer pea gravel size (i.e., up to 64 mm diameter) material (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007).

Hydraulic Considerations

Arctic grayling generally spawn at the surface of or a few centimeters below the substrate (Armstrong, 1986; Bishop, 1971), and therefore experience less dispersion and remobilization of eggs on a falling hydrograph. Arctic grayling often use smaller gravel substrates (i.e., 6 to 40 mm though up to 64 mm diameter) for spawning (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007). By spawning when discharge is decreasing, bed mobilization sediment transport is reduced. Any shifts in the hydrograph from rainfall rather than snowmelt driven may adversely affect spawning. Maintenance of the historical hydrograph shape and the resulting Froude number range in a stream is critical for the success of spawning for Arctic grayling.

Arctic grayling have struggled for success or have been extirpated in areas where there have been hydraulic changes such as reservoirs (Northcote, 1995). These hydraulic alterations may have resulted in changes to key habitats that now are not as favourable to their success. Arctic grayling generally spawn on the receding hydrograph with emergence occurring approximately three to four weeks later, depending on temperature, during low water (Armstrong, 1986). The Froude number would generally be decreasing during the incubation period as velocity and depth would decrease in a non-linear manner. For example,

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[21] Sockeye salmon are generally 50 to 71 cm in length and 5.4 kg at maturity (Pacific Salmon Commission, 2020); Atlantic Salmon are generally 70 to 75 cm in length and 4.5 kg at maturity (US Fish and Wildlife Service, 2020b); Arctic grayling are generally 38 to 50 cm in length (Stewart, Mochnacz *et al.*, 2007) and maximum 3.8 kg (US Fish and Wildlife Service, 2020a)

[22] Substrate is accepted to be a suitable mix of material sized from 16 to 64 mm in size for Atlantic salmon (Louhi, Mäki-Petäys *et al.*, 2008) and 4 to 63 mm for Sockeye salmon (Lorenz & Filer, 1989; Young, 2005).

in areas upstream of impoundments there may be increases in depth and reduction in velocity, resulting in significantly lower Froude numbers during spawning. Conversely, increased discharges or hydrograph shifts may increase velocities and depths resulting in higher Froude numbers, adversely affecting the spawn timing and subsequent incubation due to potential bed movement. Lower Froude values would also suggest less bed load and sediment transport and therefore reduced disturbance to the incubating eggs and emerging larvae as a result of bed mobility. These conditions should contribute to improved spawning success.

Other hydraulic considerations for Arctic grayling included potential shifts in the hydrograph due to climate variability. The peak and subsequent falling hydrograph for migration and spawning activity movement (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007) is a theme that is often described but not correlated in the literature on multiple systems (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007). Predictions for the Arctic are generally warming trends and increased rainfall (Intergovernmental Panel on Climate Change, 2015). A shift from a snowfall to a rainfall-driven hydrograph may result in multiple peaks in the hydrograph during the spring spawning period during incubation. Rainfall hydrographs typically have extended duration and multiple peaks compared to snowmelt hydrographs. This potentially will result in higher instream velocities for longer periods with the likely consequence of increased stream bed movement, putting eggs and larvae at higher risk of displacement and physical damage, consequently reducing their survival potential. Such a shift may reduce the available habitat for spawning as well. Often, fisheries managers assume that fish, such as Arctic grayling and anadromous salmonids, will return to the same spot year after year. This assumption is usually based on the physical habitat (i.e., substrate) being consistent between years. While this is generally true when discharge conditions are similar, a high or low flow year may see the corresponding hydrologic conditions (i.e., Froude number values) change. Fish may then be seen spawning in alternate locations with a more optimal spawning Froude number, but fisheries managers do not recognize the possible reasons for the change. A multi-disciplinary set of lenses is needed to ensure that the interaction of a species with its environment is holistically viewed. If fisheries managers can recognize how Arctic grayling respond to changing hydrologic conditions, decision making can be made to improve successful spawning and potentially other life history events.

To support changing habitat conditions, habitat restoration is often used to improve habitat values for fish. Arctic grayling habitat restoration design understanding is in its infancy relative to Pacific salmon habitat. Techniques that have been developed for Pacific anadromous salmon have, in many cases, been applied directly to Arctic grayling without consideration of scale or the fish's life history. Habitat features, such as V-weirs and pool creation (Canadian Natural Resources Limited, 2015) are commonly used either in existing rivers or constructed habitats. Many of these techniques need further refinement to ensure Arctic grayling spawning habitat design criteria are appropriately defined in conjunction with physical structures that are appropriate to their environment (e.g., permafrost considerations in the Arctic). Understanding of Arctic grayling hydraulic preferences for spawning through the Froude number will enhance the design of habitat restoration and offsetting complexes. This will allow for improved Arctic grayling productivity potential in these channels.

Future work

While a Froude number range and mean preferred value have been identified for Arctic grayling, additional work is required to ensure that the significance of the Froude number is put in context to the bigger picture for the understanding of Arctic grayling eco-hydraulics. Four examples of additional work from this study include: (1) The Froude number should not be used solely as a singular set of values at a specific life history event, rather it should be further examined relative to the changing environment that the fish experience. Additional study is needed to understand the extent of habitat use in years where there are more fish as the range of Froude numbers for spawning use appears to increase, possibly due to territorial behaviour; (2) The change in a particular site should also be examined over multiple discharges and hydrograph shapes to identify how fish may change site selection. Discharge is also likely a key factor where substrate size influences the selection of a site with the Froude number. During years of high discharge, fish may spawn in similar Froude number areas but may select a larger substrate than in lower discharge years. Further work is required to identify any linkages in this respect; (3) Although the Froude number is scalable between large and small watercourses, different substrate sizes may also influence spawning locations selected depending on the stream size as the available habitat types may vary; and (4) Other Arctic grayling life history events may also be better described by using the Froude number to describe habitat, such as juvenile feeding and holding areas. Regardless, it is important to look at Arctic grayling spawning success relative to habitat differences (i.e., discharge, Froude number, and substrate).

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CHAPTER 4. LIKELIHOOD OF SPAWNING EVENT OCCURRENCE FOR ARCTIC GRAYLING (*THYMALLUS ARCTICUS*) BASED ON THE RELATIONSHIP BETWEEN TWO COMMONLY MEASURED HABITAT PARAMETERS OVER TIME

ABSTRACT

Fish movement and timing behaviours have been noted by humans for sustenance or cultural reasons for millennia. Though these are still important, the overall understanding of a fish's life history interaction within an ecosystem is critical to protect them from increasing development pressures and to assess their ability to adapt to climate variability. Environmental conditions can limit success of fish life history events, such as spawning. In addition to physical habitat features, such as substrate size and cover, environmental conditions such as temperature and discharge influence spawning movement and subsequent spawning success. These parameters are generally described as independent values or ranges of values with limited description and understanding of their interactions that contribute to a spawning event. For Arctic grayling spawning, there has long been an accepted connection between water temperature and discharge. When described, typically only averages and ranges have been used. Linkages are loosely defined as they relate to overall behaviour in life history. Using an event analysis approach, the likelihood of these parameters occurring together on a given day leading up to and after spawning, can more effectively describe fish response and support the occurrence of an event such as peak spawn. Improved description of spawning timing can result in improved predictions of behavioural reaction to changing environmental conditions. Event analysis permits a response description that is not tied to a precise date. To better address conditions for spring spawners, such as Arctic grayling, there will be implications resulting from the improved understanding of relationships between discharge and temperature, specifically rule curve development for flow releases from impoundments. Hydrograph development will have additional complexity to reflect both discharge and temperature relationships with appropriate timing. The resulting potential improvement in habitat protection and restoration investment could be significant making the effort worthwhile.

INTRODUCTION

It is important to understand the life history of Arctic grayling (*Thymallus arcticus*) as a basis for evaluating increased development pressures and climate variability impacts. In general, they are a fish that is observed to be sensitive to their environment and changes within it (Reilly, Paszkowski *et al.*, 2014), though a thorough understanding of their behaviour and interaction with the environment as related to their life history is limited. A more detailed life history of Arctic grayling has been presented in CHAPTER 1.

Arctic Grayling Life History

Spawning is a key life history stage that often can be a limiting factor for Arctic grayling populations through lack of habitat or less than ideal conditions (Cahill, Howland *et al.*, 2016; Stamford, John Hagen *et al.*, 2017). Arctic grayling are a fish that predominately resides in nival (i.e., snowmelt driven) systems with peak spawning identified during the falling hydrograph in many watersheds (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007). They spawn early in the year and have a short incubation period, Arctic grayling are sensitive to hydrologic and temperature changes within a watershed during migration prior to spawning and egg incubation. Their populations do not appear to have the same plasticity[23] for adaptation as other popular sport fish further south, such as rainbow trout (*Oncorhynchus mykiss*) , which are also spring spawners (Stamford, John Hagen *et al.*, 2017).

Although Arctic grayling have adapted to many types of habitat, they lack plasticity to adapt to habitat changes (Armstrong, 1986).This limiting characteristic is not well understood or described in the literature, but may be a contributing factor to the poor success where Arctic grayling have been transplanted into watersheds or in watersheds with hydrographic changes (e.g., impoundments for hydroelectricity or agriculture).

The two environmental parameters of temperature and discharge are usually recognized as being key factors for spawning timing (King, Gwinn *et al.*, 2015). Both

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[23] The ability to adapt to changes in environment or differences between its various habitats by an organism

parameters are generally accepted as influencing spawning migration, peak spawning, and subsequent success for incubation and emergence. These environmental covariates need to be considered when designing flow regimes (King, Gwinn *et al.*, 2015) for Arctic grayling and potentially other spring spawners.

Temperature at Spawning

In the literature, water temperature is consistently identified as a parameter for spawning and migration timing (Stewart, Mochnacz *et al.*, 2007). The literature suggests that for many Arctic grayling populations, spawning migration starts when water temperatures are approximately 4°C (Armstrong, 1986). Spawning has been observed to be abandoned or postponed if water temperatures are too low for migration (Clark, 1993). Delays in migration can negatively impact the success of Arctic grayling spawning (Fleming & Reynolds, 1991). Arctic grayling spawning also has been observed to occur as much as four weeks later in headwaters than near the mouth in the same stream (Tack, 1981); this may possibly be due to distance travelled. Arctic grayling egg incubation typically ranges from 12 to 18 days requiring approximately 120 to 180 degree days. Emergence generally occurs when water temperatures are between 10 and 15°C (Armstrong, 1986).

Discharge at Spawning

Snowmelt occurs in spring shortly after air temperature rises above freezing, quickly releasing water that is stored in the winter snowpack. The high flows are typically the source of the annual peak discharge which often occurs immediately after ice break-up in lakes and channel reaches particularly in smaller drainage basins. High flows can last as little as a few days in smaller drainages. Additional details regarding nival hydrographs are described in CHAPTER 1.

Permafrost can limit the groundwater contributions to small streams; consequently, flows may stop after freshet until rains begin in the late summer and early fall. For rivers draining larger watersheds, the freshet peak may be delayed relative to smaller drainages as snowmelt from upper portions of the watershed is routed through the drainage network (Pike, Redding *et al.*, 2010; Rescan Environmental Services Ltd., 2013).

Impoundments and diversions often create significant pressures linked to fish populations decline, including Arctic grayling (Alberta Sustainable Resource Development, 2005; Stamford, John Hagen *et al.*, 2017). Regulated system hydrograph behaviour for hydroelectric or water withdrawal may be different than that experienced by a natural nival/Arctic system.

Discharge is a commonly used parameter when describing a stream and fish habitat; however, meaningful comparisons between various sized watercourses are difficult to ascertain. Unit discharge is a hydrologic manipulation to standardize. Such a standardization to describe fish and fish habitat generally relates smaller scale habitat dimensions (e.g., stream width) (Dunbar, Pedersen *et al.*, 2010). Hydrologists commonly describe and compare watercourses by stream discharge to watershed area (i.e., $m^3/s/km^2$).

The factors that cause different spawning periods between adjacent watersheds remain unexplained. Arctic grayling spawning generally occurs on the falling hydrograph (Stewart, Mochnacz *et al.*, 2007; Warren & Jaeger, 2017), although specifics describing where on the hydrograph has not been identified further in the literature. This is likely due to comparisons based on discharge (i.e., volume/time) rather than standardized unit discharge (e.g., percent of mean annual discharge (Tennant, 1976) or volume/time/watershed area). By using unit discharge, streams may be compared to each other, thus facilitating the evaluation of fish responses between watersheds, regardless of stream size.

Climate Responses

Climate change predictions for the Arctic tend toward increased temperature and rainfall versus snowfall precipitation trends (Intergovernmental Panel on Climate Change, 2015). Such conditions will require Arctic Grayling to adapt to conditions such as permafrost thawing and drainage pattern changes, hydrologic regime shift from snowmelt to rainfall, warmer water temperatures, and an increase in anthropogenic pressures (i.e., easier access to Arctic).

The snowmelt hydrograph generally can be described as having a steep peak as temperatures warm above freezing. The hydrograph then falls off, generally without significant sub-peaks due to little precipitation in the form of rain. In those systems where sub-peaks are frequent or large on the falling hydrograph, Arctic grayling do not appear to be as prevalent or successful (Warren & Jaeger, 2017) and climatic shifts towards greater influence of rain may result in extirpation under such conditions.

Climate variability in the Arctic has been identified as a cause for changes in the permafrost characteristics. With the projected heaving/settling due to thawing (Intergovernmental Panel on Climate Change, 2015) there will be stream alterations that may prevent Arctic grayling from reaching traditional spawning habitat. Hydrograph alteration and change in temperature buffering from groundwater may also occur.

Event Analysis Approach

Environmental biological data is generally treated as within population independent absolutes or ranges of values, rather than evaluated based on the trends to describe triggers leading up to an event occurrence (Singer & Willett, 2003). Cross sectional (i.e., weighted average) data is what traditionally describes habitat and response conditions in biological science. A cross-sectional data approach permits examination of different populations or individuals that are observed at a single point in time only. Unfortunately, by doing so, the full range of observations that is typically what aquatic species need to thrive is oversimplified by relying on only mean and extreme temperatures without regard for how temperatures change throughout a day, season, or year (Hinrichsen, Steele *et al.*, 2016; Steel, Tillotson *et al.*, 2012)

An example of cross-sectional data sets in the case of Arctic grayling would be describing water temperature, either as an average or range of values, only on the day that peak spawning event occurs. The literature then reports Arctic grayling peak spawning occurring at a temperature between 4 and 6 °C (summarized from multiple references in (Stewart, Mochnacz *et al.*, 2007)). Any linkages to this spawning day value range or average to the preceding days' temperatures are not considered. A summary approach does not provide any indication as to why fish may spawn within that temperature range or what other influences may be at work (e.g., fish ripeness, stream discharge). As a result, this cross-sectional data analysis approach appears to have created a degree of stagnation in the development of further understanding through examination of parameter and trends linkages.

Event history analysis examines time intervals between consecutive changes of state defined by some qualitative variable and within some observable variable (Jones & Wood, 2012; Singer & Willett, 2003). The analyses of events are evaluated as a result of a series of changing conditions that have occurred prior to the event itself to compare individuals or populations. These data sets are referred to as longitudinal. Longitudinal data allows for tracking changes of an individual or population over a period of time (e.g., days, months, years) for the event analysis or timing prediction. The gradient of the selected parameters is used to explain the causal relationship between an individual or population and the environmental conditions (Singer & Willett, 2003).

Longitudinal data is commonly used by other disciplines, such as the social sciences and medicine, for analysis. An analysis question in these fields of research would follow a parameters over time that may contribute to a life event (e.g., marriage, staying out of jail, heart disease, obesity) and then determine the likelihood of the event occurring and when it may occur. In medicine, for example, the following of dietary intake and link to heart disease or obesity could be examined. In the social sciences, the influence on a life event such as staying out of jail based on the consumption of alcohol or having a significant other could be addressed by longitudinal data collection and event analysis. By applying this approach of environmental and biological analysis to Arctic grayling, a similar question would be “Does Arctic grayling spawning occur later under warmer water temperature and lower discharge conditions”.

Longitudinal data can be compiled from a series of cross-sectional data even when it has not been intentionally collected (Singer & Willett, 2003). This is advantageous for environmental data as preceding event information is often collected until the event is deemed to have occurred, but is then unused in traditional cross-sectional approach to subsequent analyses.

In the literature, water temperature and discharge are consistently identified factors for spawning and migration timing (Armstrong, 1986; Stewart, Mochnacz *et al.*, 2007). To date, the approach for describing a spawning event has been to use averages and ranges for each parameter but not the interaction and how these parameters change over time prior to the event of spawning and corresponding fish response to these changes.

There are also many benefits to prediction that an event analysis approach using likelihood would have over a typical probability approach. Unlike probability analysis which relies on the end event to be the sole predictor of its occurrence, maximum likelihood estimation (MLE) considers the conditions that may influence the event's occurrence. An event analysis MLE approach would permit the likelihood of an event from occurring under a set of prior, though variable, conditions.

Probability predictions are limited by the possibility of outcomes, for example, a coin toss. A coin toss, regardless of the individual making the toss will have a 50 % chance of heads and 50% chance of tails. Under normal conditions (i.e., no cheating) the expected results of 50/50 will not change, regardless of who is tossing the coin.

Likelihood predictions consider influences on the individual or population. One could consider the event of a successful basketball free throw for example (Wheelan, 2013). Although the probability of the outcome is still the same, 50% chance of going in the hoop and 50% chance of missing, the likelihood that a shot would be made or missed will be influenced by a variety of factors applicable to the individual taking the shot. In this case, the likelihood of a shot being made by an individual could be examined based on height and years of training. It would be expected that an NBA player who is tall with years of practice will have a higher likelihood of making the shot than a kindergartener who can't see the top of the kitchen counter and has never played with a basketball from making the same shot.

The same approach can be used when evaluating environmental events. When applying an event analysis MLE approach to Arctic grayling spawning, the influences of unit discharge and water temperature experienced by fish leading up to the spawning event should influence the likelihood of a spawning event occurring under a given pairing of values.

Thesis Chapter Objectives

This chapter examines spawning migration for Arctic Grayling using the commonly measured predictor variables of discharge and water temperature, and then applying an inter-disciplinary MLE analysis to develop a deeper understanding of these parameters influence on peak spawn timing. The resulting understanding can be used from a management perspective to improve hydrograph development, field program timing, regulator/stakeholder decision making, and habitat restoration outcomes.

METHODS

Spawning migration and spawning event timing are influenced by several environmental variables. Only water temperature and discharge were analyzed as other data sets were limited in number, incomplete, and/or are influenced by other parameters (e.g., air temperature) (King, Gwinn *et al.*, 2015).

Data Sets

Data sets were obtained from the appendices and tables of publicly available reports and peer reviewed papers. Where available, the raw data sets were obtained and reviewed for supporting information. A total of 34 data sets were used in this thesis.

The majority of suitable data sets for the analysis (Figure 4-1) were from reports for the Polar-Vulture stream, Lower Panda Diversion Channel (PDC), and the Pigeon Stream Diversion (PSD) at Ekati Diamond Mine (Ekati) owned by Arctic Canadian Diamond Company Ltd. (Arctic Diamond). The Ekati data from 1999 to 2011 provided 28 data sets[24].

Data mining was done to obtain additional data from Arctic grayling populations outside those in the Ekati area (Figure 4-1), where suitable (i.e., similar level of detail/information collected and reported). These additional six data sets include populations from Montana, Alaska, and Alberta. Using data from outside the NWT will permit comparisons among populations in the analysis, supporting a species driven likelihood of environmental behaviour response(s). The following spawning data sources were also used in this thesis: (1) Kakisa River, NWT (R. W. Moshenko & Low, 1983); (2) Gibbon River,

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[24] PDC Annual reports (Dillon Consulting Ltd., 2000, 2001, 2003; Rescan Environmental Services Ltd., 2003a, 2003b, 2005a, 2005b, 2005c, 2006a, 2006b, 2006c, 2007a, 2007b, 2007c, 2008a, 2008b, 2008c, 2008d, 2008e, 2008f, 2010b, 2011a, 2011b, 2012); PSD Annual reports (ERM, 2015, 2016; Rescan Environmental Services Ltd., 2010a, 2015, 2016);

Montana (Steed, 2007); (3) Big Hole, Montana (Bradley B. Shepard & Oswald, 1990); (4) Alberta (Bond & Machniak, 1977); (5) Piledriver Slough, Alaska (Fleming, 1995).

Where all data was not available (e.g., discharge was not included) in the above sources, the information was obtained for the watercourse from either Water Survey Canada (Environment Canada, 2015) or USGS Water Data Discovery (USGS, 2015).

Spawning fish were considered to be those greater than 170 mm fork length unless the documents indicated smaller fish were in spawning condition for the particular population (i.e., maturity measure record). Missing data can be dealt with in the analysis for MLE by the software (MINITAB).

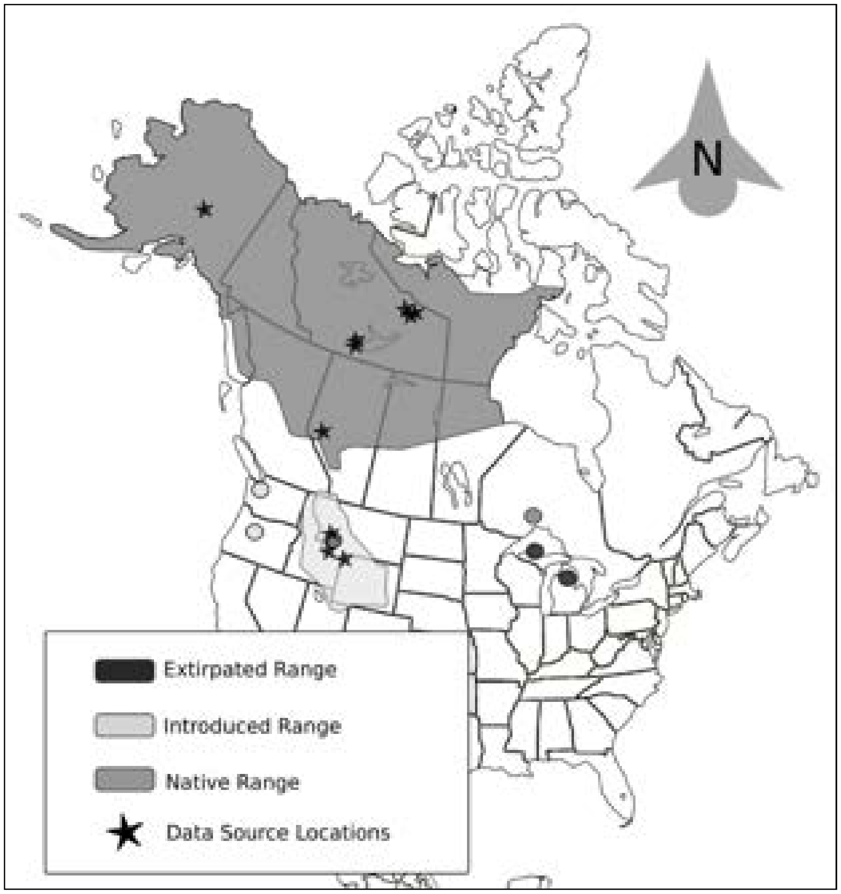

Figure 4-1 Locations of data sets used for analysis relative to Arctic grayling range are indicated by black stars (adapted from (Montana State Government, 2015))

Data Standardization

Longitudinal data analysis requires data to be standardized. This is generally done for time, although it can also be done for other parameters. In this thesis, both time and discharge were standardized.

Standardization was done to allow for comparison of the peak spawn date ('Day of Spawning') rather than annual date as spawning occurs at different times in different watersheds. The date for peak spawn was converted to 'Day of Spawning' as Day 0 for the analysis. The 'Day of Spawning' is described as 50% of the fish have moved in to spawn unless the data source described either temperature units or otolith measurements to back calculate the date of peak spawn (i.e., "Day of Spawning"). Generally, the day of peak spawn estimation methods were within a day or two regardless of method used. Where a larger variation was noted, counting issues were identified (i.e., fish were able to circumvent the trap box during a high-water event) and are able to account for the discrepancy. Where spawning was identified to occur before peak discharge, two conditions were noted: either a significant rain event occurred or the system was regulated (i.e., impoundment release).

Discharge is often problematic to compare between watersheds in relation to biological responses; therefore, to evaluate the discharge, rates were standardized to watershed area (km^2) to provide 'unit discharge'. The day of peak mean discharge was considered to be Day '0' for Day of Discharge.

The obtained data for water temperature and discharge have been treated as longitudinal data and analyzed to describe event occurrences due to gradient changes over time. As such, each location and year combination has been treated as an 'individual' to allow for the changes that occur each year to be analyzed and then compared to the other 'individuals' to establish a relationship for the entire population. For example, the PDC 1999, PDC 2000, and PDC 2003 are all 'individuals' in this thesis analysis.

Data has been centered on the event occurrence(s) (i.e., spawning date, peak unit discharge) to permit analysis of multiple location (loc/yr) conditions before the spawning event to be compared and show the rates of change around an event more clearly. This centering does not affect the daily rate of change that occurs for a given loc/yr prior to an event.

Using the traditional cross sectional statistical approach to estimate spawning date by days after peak discharge, it is evident that the 4 day with a SD of ± 3 days may result in significant over or under estimation for Arctic grayling, though does provide a window to focus this study's further analysis for active influence between water temperature and unit discharge. The linkage of discharge and other parameters permits narrowing the spawning timing and corresponding conditions.

Analysis was conducted over the time period of 8 days prior to what was identified to be the spawning day for an individual loc/yr to 2 days after this event. The resulting period analyzed therefore is 11 days in length. This was done based on the stabilization of the hydrograph and the mean number of days post peak discharge.

Event Analysis and Maximum Likelihood Estimation

MLE is a common approach for parameter estimation (Myung, 2002), MLE is asymptotically unbiased (i.e., consistent). As such the method converges on the true values of the populations parameters, asymptotically normally distributed such that sampling distributions are approximately normal with known variance, and asymptotically efficient with standard errors that are smaller than are derived from other methods (Singer & Willett, 2003). Most models require a large sample; this number can vary but is generally considered to be 30 or more. Maximum likelihood models can also be developed with missing data.

The likelihood function to be derived is from the product of probabilities or probability densities for each parameter. This parameter is *theta* (θ). Once θ is defined for each parameter a composite maximum likelihood model may be created. Residuals are assumed to be normally distributed and that residuals are independent of the model's predictors.

MLE describe the values of the unknown parameters to maximize the expectation of the event occurring based on the observed data. These parameters determine the maximum likelihood that the models developed, will produce data that is actually observed. It is assumed that each data point is generated independently of the others and identically distributed, the sample is then considered to be random.

The composite likelihood relationship is described for a particular Day of Spawning (D) as a function of water temperature ($\mathrm{T_w}$) and unit discharge ($\frac{\mathrm{Q}}{\mathrm{A}}$) and the likelihood parameter(s) (*θ*) where:

$$\mathrm{D} = \mathrm{f}(\mathrm{T_w}, \frac{\mathrm{Q}}{\mathrm{A}})$$

Therefore, the composite likelihood function to be determined can be described as:

$$\mathrm{L(D)} = \mathrm{f}\left(\theta_{\mathrm{T_w}} \middle| \mathrm{T_w}\right) + \mathrm{f}\left(\theta_{\frac{\mathrm{Q}}{\mathrm{A}}} \middle| \frac{\mathrm{Q}}{\mathrm{A}}\right)$$

The above function assumes that the relationship between *D* and each parameter is linear, although it is understood that pairwise interaction terms may improve model fit (Yuan, 2007).

RESULTS

Plots of Q (Figure 4-2) and $\frac{\mathrm{Q}}{\mathrm{A}}$ (Figure 4-3) versus Day of Spawn illustrate data standardization. Arctic grayling may spawn under a very wide range of flows (0.096 to 33.90 $\mathrm{m^3/s}$), with no observable pattern other than the generalization that spawning occurs on the receding hydrograph. When the discharge is standardized by area ($\frac{\mathrm{Q}}{\mathrm{A}}$), it is possible to visually identify a convergence of $\frac{\mathrm{Q}}{\mathrm{A}}$ values between 0.001 and 0.04 $\mathrm{m^3/s/km^2}$ (range 0.00069 to 0.079 $\mathrm{m^3/s/km^2}$) near the Day of Peak Spawn (Figure 4-3) for the majority of watersheds. It should also be noted that the higher $\frac{\mathrm{Q}}{\mathrm{A}}$ values do not necessarily pair with the higher Q values due to watershed area.

For reference purposes, a traditional statistical analysis for cross-sectional data was completed for the peak spawn day (i.e., *D* = 0) summarizing all sites and years together, results are presented in Table 4-1.

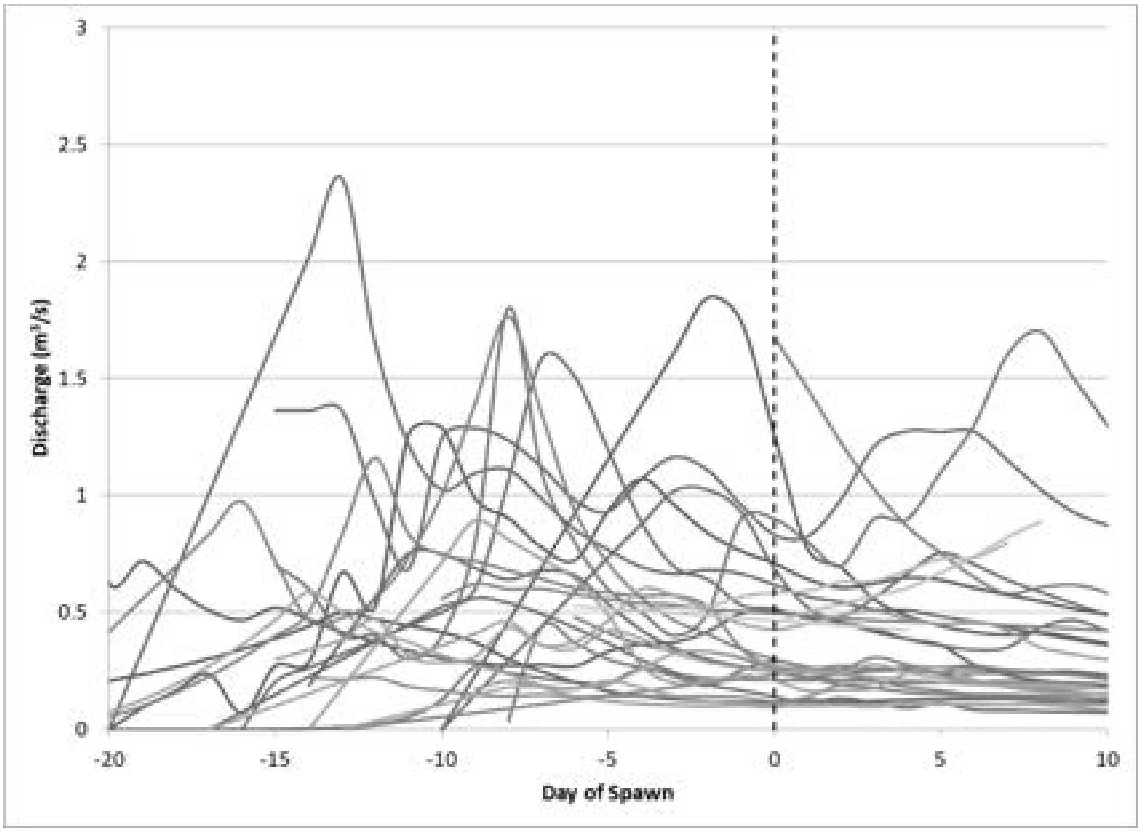

Figure 4-2 Discharge versus Day of Spawn Day (peak spawn is dashed line) for all Locations/ Years. Note that data sets with peak discharge greater than 3 m^3/s were not included for clarity but are similar in their apparent variability. In general, the peak spawn (i.e., Day of Spawn = 0) is observed to occur on the receding hydrograph.

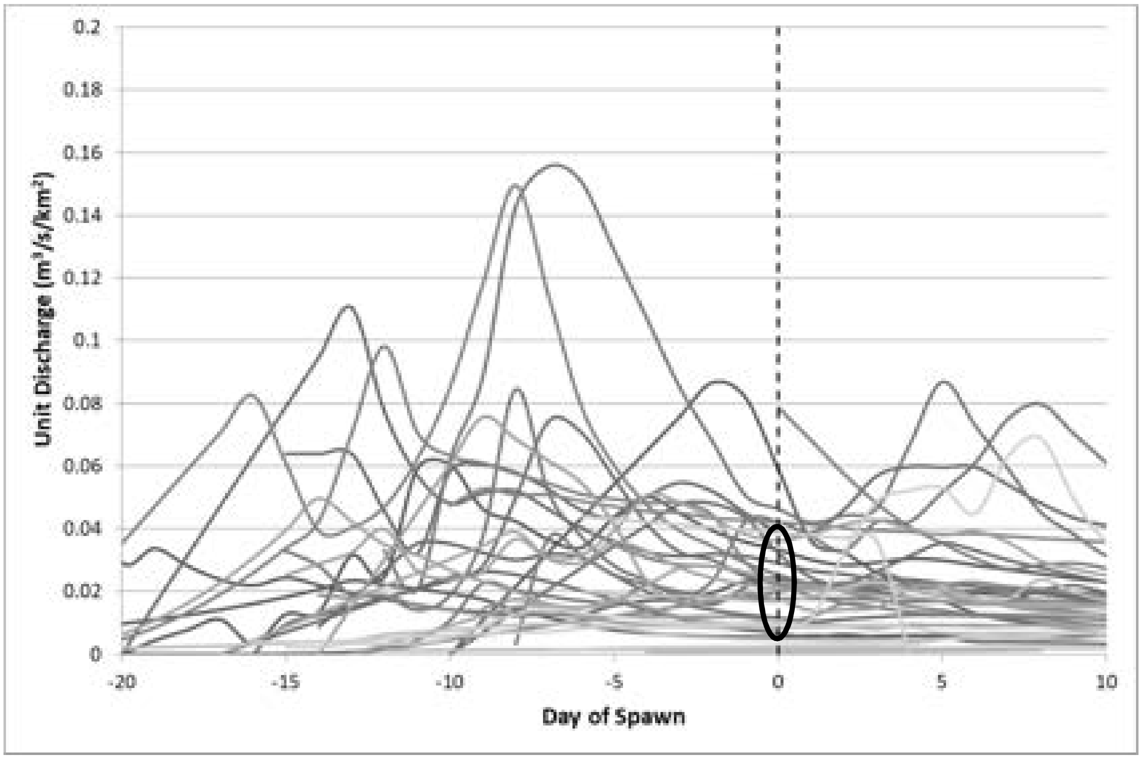

Figure 4-3 **Unit Daily Discharge verses Day of Peak Spawn Years (peak spawn is dashed line) for all Locations/Years. Unit Discharges are included for all discharges. Note the relatively high degree of variability in Unit Discharge prior to the day of peak spawn (i.e., Day of Spawn = 0). The black oval outline identifies the general area of convergence of Unit Discharge values at peak spawn as the rate of change in Unit Discharge flattens.**

Table 4-1 **Traditional cross sectional reporting of summary statistics for peak spawning day (Day = 0)**

Variable	N	Mean	SE Mean	SD
Unit Discharge ($m^3/s/km^2$)	30	0.024	0.0024	0.015
Daily Water Temperature (°C)	26	5.0	0.60	0.30
Number of Days from Peak Unit Discharge to Peak Day of Spawn		4.4	0.25	3.9
Number Days from Peak Day of Spawn to Peak Unit Discharge		-4.5	0.24	3.8

To determine the window for maximum likelihood analysis, the traditional cross sectional analysis approach was used. This identifies that spawning can generally be expected to occur about 4 days (± 4 days SD) after peak discharge. Using this information, the duration of influence for analyzing the longitudinal data was determined to be about 8 days (i.e., Mean + SD) prior to peak spawning to 2 days after peak spawning. This window also captures the variation of peak spawn event timing determination between otolith analysis and temperature units from emergence. Using this time window, the resulting plots (Figure 4-4) suggest that the slope (i.e., rate of change) of the $\frac{\text{Q}}{\text{A}}$ is relatively consistent among individual location/years. A similar plot review was conducted for T_w (Figure 4-5) with a similar visual pattern. T_w was observed to be increasing as the hydrograph recedes. For both the $\frac{\text{Q}}{\text{A}}$ and T_w , it is this relationship of their slopes that describes the response (i.e., spawning).

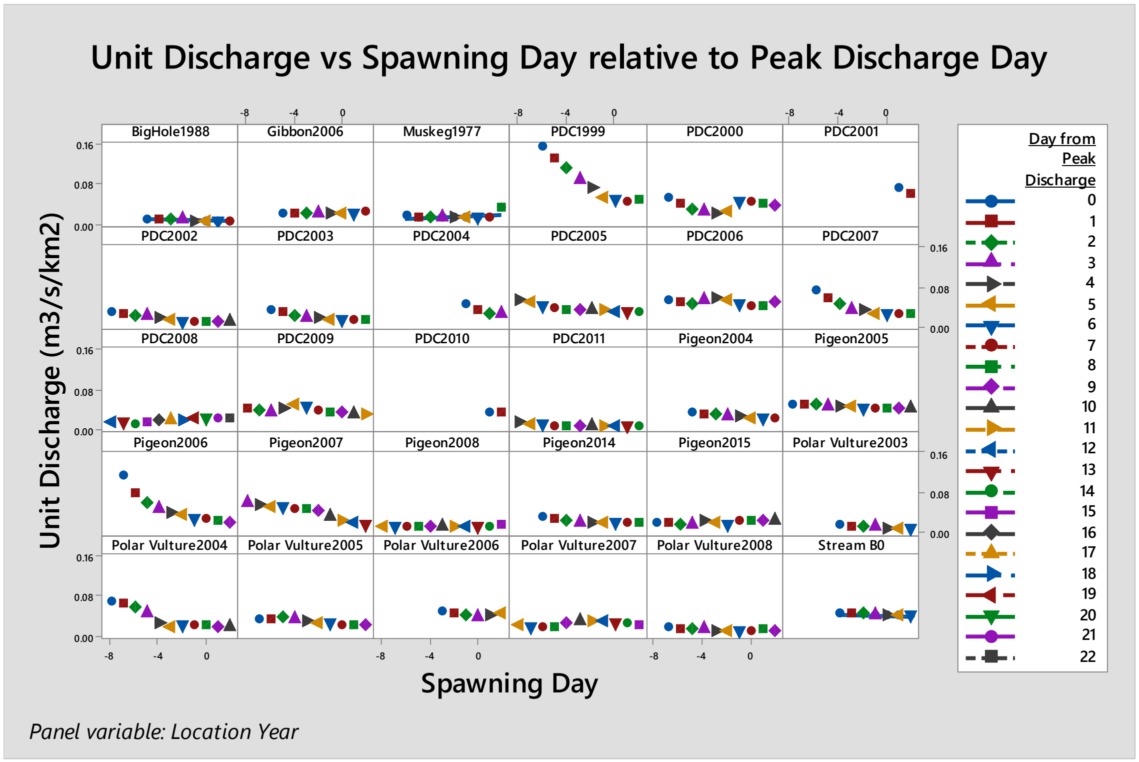

Figure 4-4 Unit Daily Discharge from Day of Peak Unit Daily Discharge plotted versus Spawning Day for each Location/Year. Note the generally consistent slopes. Where the slope is steeper, such as for PDC 1999, ice jams or rain events were noted in the records.

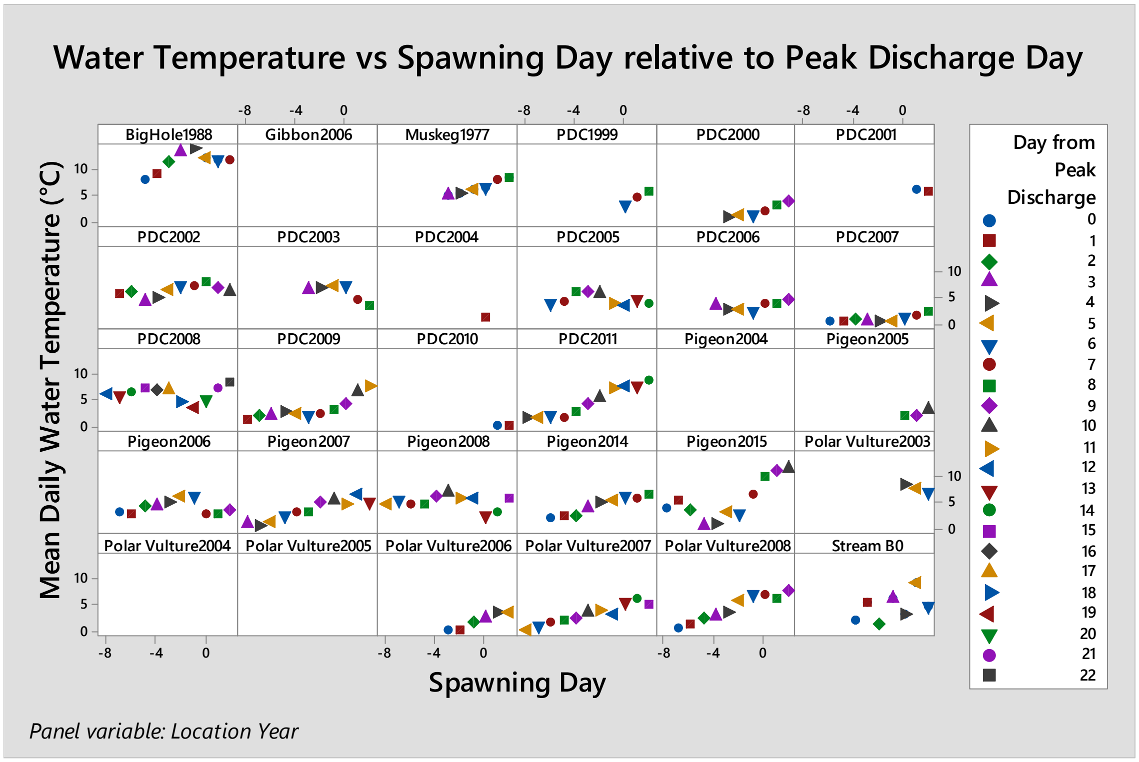

Figure 4-5 **Water Temperature from Day of Peak Unit Daily Discharge plotted versus Spawning Day for each Location/Year. Note the generally consistent slopes.**

Unit discharge ($\frac{Q}{A}$) was plotted (Figure 4-6) for each *D* versus T_w suggesting that when $\frac{Q}{A}$ is high the T_w is cooler and conversely smaller when warmer. The relationship (i.e., slope) between T_w and $\frac{Q}{A}$ is visually consistent for the days leading up to and after spawning (Figure 4-6) and particularly strong at *D* -1 and 0. It would be expected to converge at this time around the spawning event, which is expected to have a specific set or range of conditions. The variation may be accounted for by how the original peak spawning event was identified (i.e., otolith analysis and temperature units from emergence).

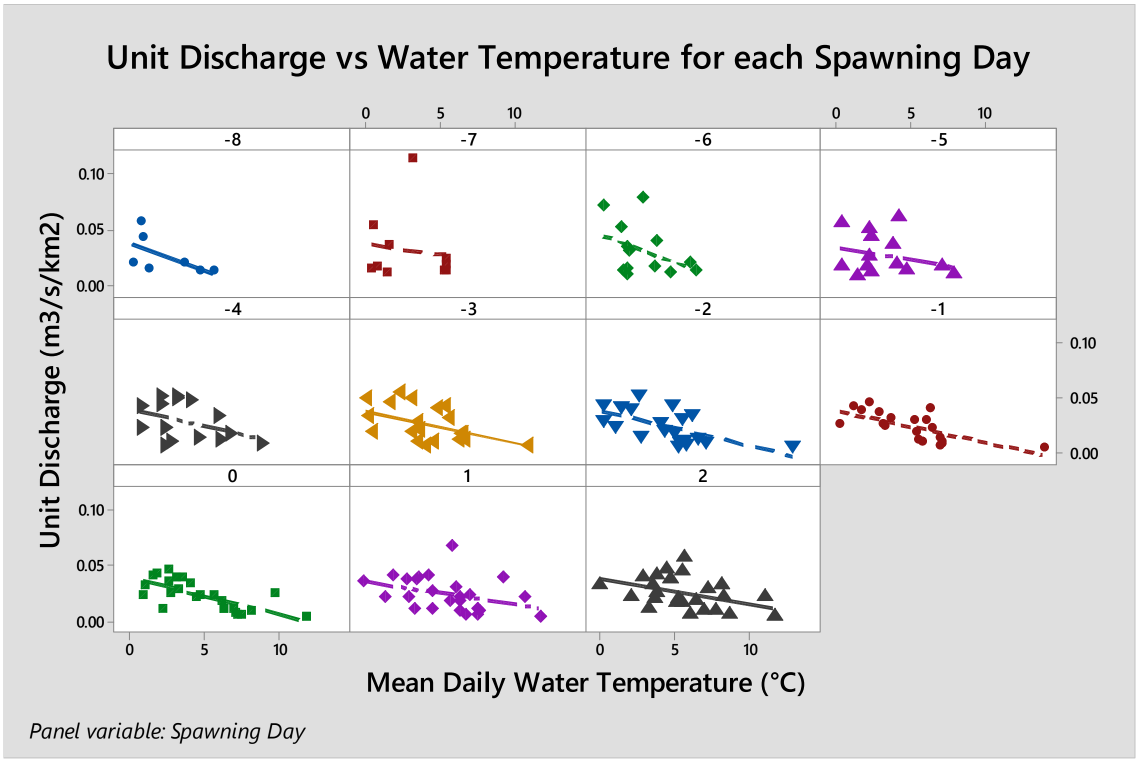

Figure 4-6 Unit Discharge vs Water Temperature relative to Spawning Day. Note the relationship becoming more confined closer to Spawning Day = 0.

The likelihood estimates for each *D* were plotted to develop a relationship between T_w and $\frac{Q}{A}$ (Figure 4-7). The resulting regression relationships between *D* are for $\frac{Q}{A}$:

$$\frac{Q}{A} = 7E-05\ D3 + 0.0007\ D2 - 0.0006\ D + 0.0256 \qquad R^2 = 0.95$$

And for T_w:

$$T_w = 0.4073\ D + 6.356 \qquad R^2 = 0.97$$

The relationship for *D* with T_w and $\frac{Q}{A}$ is plotted in Figure 4-8.

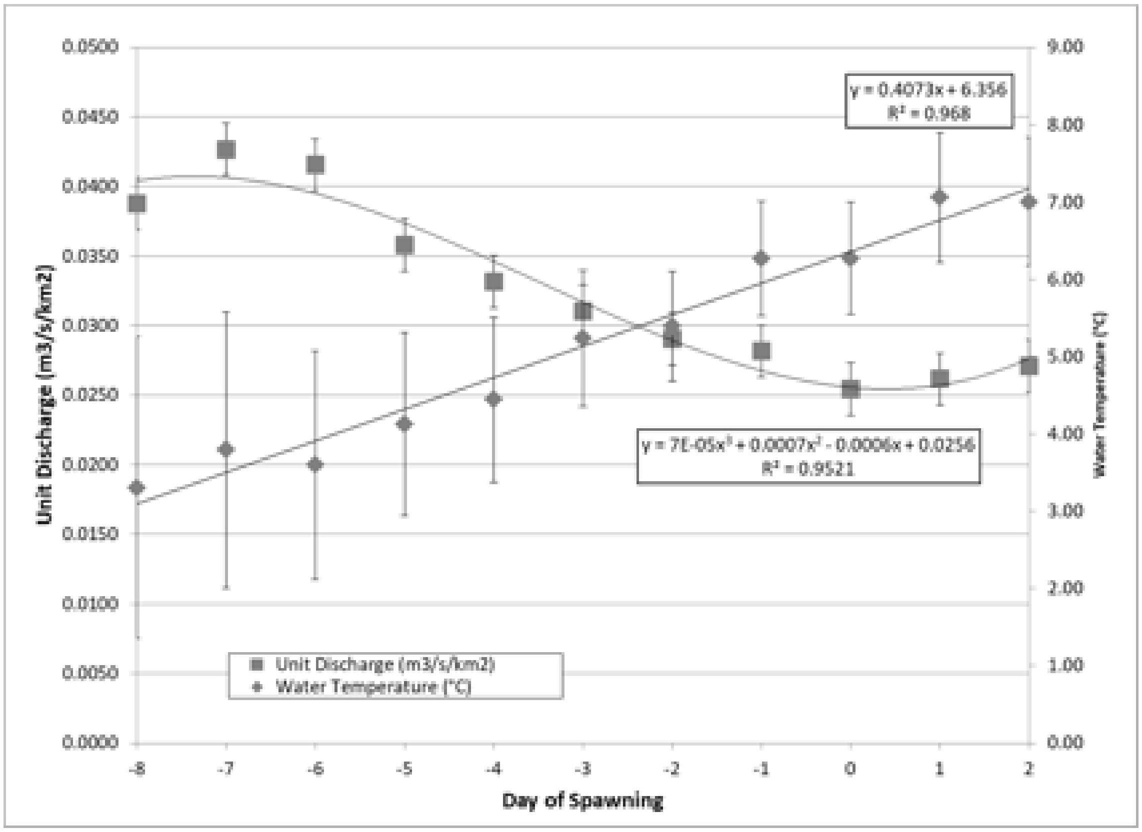

Figure 4-7 **Plotted likelihood relationship for Unit Discharge versus Water Temperature Prior to and After Spawning (Note: Day of Spawn identified for each point)**

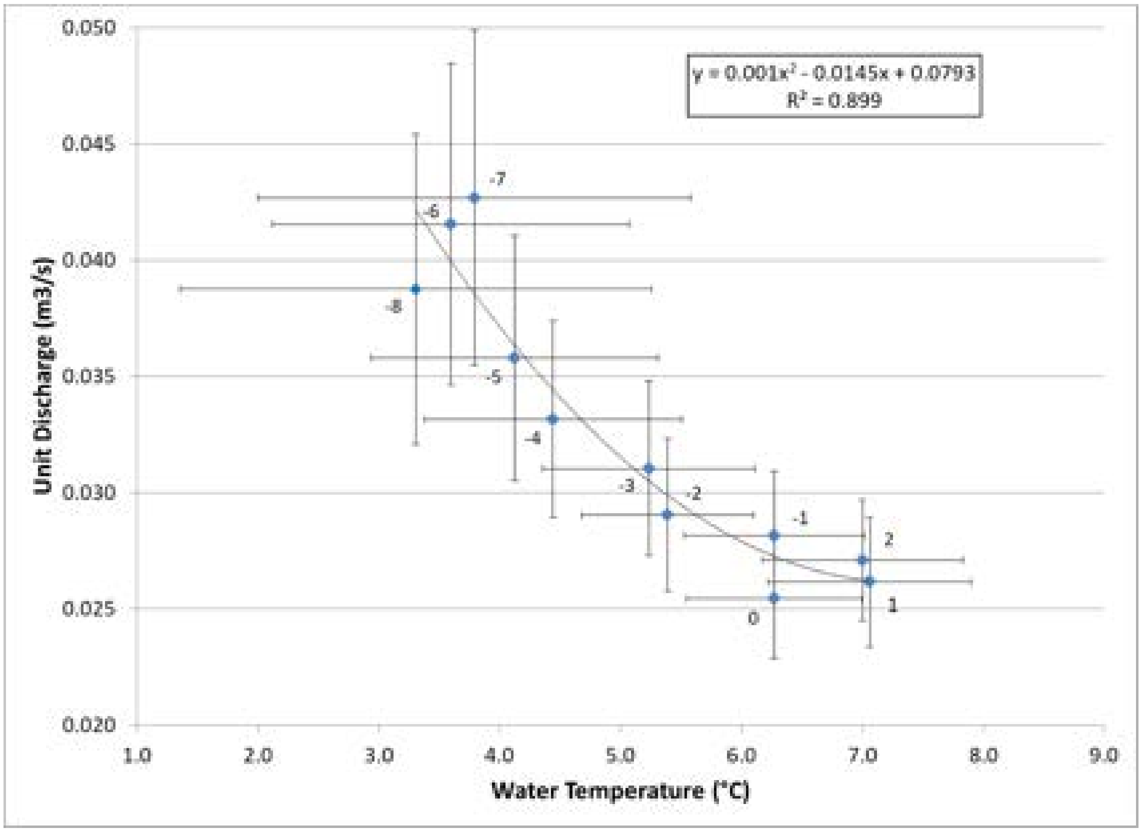

Figure 4-8 Plotted likelihood result Unit Discharge versus Water temperature for each Day of Spawn. Note the flattening of the curve at and after spawning (i.e., Day of Spawn >-1) and increased variability earlier (i.e., Day of Spawn<-5).

DISCUSSION

There has long been an accepted, if not fully understood, connection between water temperature and discharge for Arctic grayling spawning; however, only averages and ranges have been used to describe the relationship with minimal linkage as it relates to overall behaviour in the fish life history. By using an event analysis approach, the likelihood of these parameters occurring together as pairs on a given day leading up to and after spawning, fish response can be more effectively described and support the occurrence of an event such as peak spawn. The results support such a linkage between water temperature and unit discharge in relation to Arctic grayling spawning. This would not have been possible to identify unless an event analysis approach had been undertaken.

Data standardization is key when looking at event analysis. In this case of Arctic grayling spawning, multiple years of data from the same watershed can be compared to each other as well as other watersheds. Location will always influence timing due to latitude and natural weather and hydrologic patterns in the spring; however, these patterns are consistent around the life history events. When time is standardized to the day of the spawning event itself (i.e., $D = 0$), the visual review of the data (Figure 4-3) suggests a relationship between the event of spawning and unit discharge.

If the data had been approached in more cross sectional manner, it may have been presented as a range of unrelated values or averages. Any patterns to the day fish spawn at for either discharge or temperature may not have been noted.

In addition to time, discharge is an important parameter to standardize. Watershed comparisons have been limited to describing spawning occurring on the falling hydrograph only, with no further description (Stewart, Mochnacz *et al.*, 2007). This was consistent with the results in this thesis but the point on the hydrograph at which peak spawning occurs has not previously been defined by the literature. Where definition has been attempted it was based on absolute discharge not discharge per watershed area or time standard (i.e., day to event versus calendar date). There are significant limitations when using discharge as a habitat variable as comparisons between watersheds may not be possible. When examining the discharge data, the focus is on the absolute magnitude of the discharge without a consideration or understanding of how it relates to a watershed's characteristics. Once discharge is standardized as unit discharge, comparisons between watersheds of different size and morphology can be undertaken to understand fish response better beyond a single population. By using unit discharge, which is a common hydrologic measure, in a more biological sense, comparisons can be made among multiple populations in different watersheds.

Water temperature was shown to be continually increasing in relation to the unit discharge around the time of spawning. Traditional cross-sectional data analysis for water temperature indicate at peak spawn for all sites, of 5.1 °C (SE = ±0.5°C) , This value is between previously reported temperature values of between 4 and 6°C for which Arctic grayling spawning will occur (Stewart, Mochnacz *et al.*, 2007) as expected. Temperature on the Day of Spawn = 0 was shown to be 5.9°C (SE ±0.83°C) using a MLE approach.

The relationship between unit discharge and water temperature (Figure 4-6) was consistent for each day of spawn. The strongest relationship between water temperature and unit discharge appears to be on the day before and the day of spawning. This suggests that it is not the actual temperature that is experienced but rather how temperature changes and converges over time in relation to unit discharge that determines when Arctic grayling are likely to spawn.

The relationship between unit discharge and water temperature leads to several potential implications to Arctic grayling life history, not only the event of spawning itself but also spawning ripening, incubation, and emergence success.

Ripening Influences

Female salmonids require a period of time prior to spawning to develop eggs. Ripening is a life cycle process that is most commonly described in the literature for aquaculture as a process leading up to an event (i.e., longitudinally often with reference to temperature units) rather than the end result (i.e., cross sectionally). Wild fish stock references tend to describe only the stages (i.e., physiologic changes) not the influences (i.e., environmental conditions) on the fish.

Arctic grayling begin migration to the spawning grounds as streams open up and are generally ripe by the time they reach the spawning grounds (Bishop, 1971). It has been shown that delays can result in female Arctic grayling not spawning (Fleming & Reynolds, 1991); however, reasons why spawning did not occur have not been assessed or discussed. Eggs have also been stripped from multiple females and fertilized but success has been noted to be variable with no noted reason(s) even though hatchery methodology was consistent (Bishop, 1971). Spawning has been observed to be abandoned or postponed if water temperatures are too low (Clark, 1993)

Other species have similar impacts with respect to temperature and subsequent success for spawning. In Atlantic salmon, over ripening has been shown to have a negative influence on egg viability with egg mortality, infertility and malformation increasing after ovulation (de Gaudemar & Beall, 1998). Water temperature has also been shown to influence gamete production in European grayling (*Thymalus thymallus*), and when gametes were compared in altered temperature regimes to natural fluctuations, quality was reduced (Lahnsteiner & Kletzl, 2012). Perhaps a similar condition develops in Arctic grayling. It has been observed that larger fish may spawn later (Alaska Department of Fish and Game, 2020) perhaps due to ripening effects in relation to temperature and discharge based on the distribution within a watershed as part of spawning cues.

Incubation and Emergence

Spawning is the focus of this thesis but, subsequent life history events are dependent on spawning success. Incubation and emergence may also be influenced by the time of spawn. Incubation and subsequent emergence is described to occur based on longitudinal temperature effects as timing is estimated using degree days[25]. Generally, this occurs 8 to 27 days at water temperature of 2.0 to 16.1 °C (Stewart, Mochnacz *et al.*, 2007), with about 186 degree days being required to hatch at a mean temperature of 5.8°C and 175.76 degree days at a mean of 7.1 °C (Kratt & Smith, 1980).

Emergence from the gravel typically occurs between late June and early July (i.e., the beginning of summer) for most populations. Primary productivity would be starting to increase at this time and having emergence at this time may improve the survival of fry. If emergence is not optimal, stream conditions (e.g., depth, velocity) may not be ideal and food source may be unavailable.

In this study, the data set with the latest spawning date had the latest emergence date and had a warm water temperature and very low unit discharge. If temperature fluctuation response is similar for Arctic grayling the implications for climate variability may be better understood.

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[25] Degree days for incubation are calculated by summing of the average daily water temperature from the day of spawn to the day of emergence.

There may also be a preference for warmer temperatures and lower flows, possibly because of a shorter incubation time based on thermal degree days and less risk of displacement of the incubating eggs. A linkage between water temperature and unit discharge to spawning timing and the subsequent success of incubation and emergence should be considered for future work. Some work undertaken for White Sturgeon (*Acipenser transmontanus*), a species that also spawns on the receding hydrograph, was conducted using a cross sectional and probability data analysis approach and described higher flows being associated with lower temperatures (Paragamian & Wakkinen, 2011). Individually the parameters of water temperature and discharge have been linked to life history events for other species (Paragamian & Wakkinen, 2011; Steel, Tillotson *et al.*, 2012). In the case of Steel, Tillotson *et al.* (2012), the analysis used a longitudinal approach, and showed the influence of water temperature on emergence timing.

Impoundment Effects

The majority of the populations that were used in this analysis were not influenced by unnatural impoundments (e.g., constructed dams) with artificial and controlled releases. The literature (Nuhfer, 1992; Stewart, Mochnacz *et al.*, 2007) suggests that many streams with impoundments have low population numbers of Arctic grayling, though it is often attributed to water withdrawals during rearing, flow releases causing scour during incubation, and any resulting discontinuous habitat connectivity (Kaya, 1992; Nelson, 1954). Perhaps, a contributing reason is also the shift in hydrograph and corresponding water temperature relationship. This could result in several degrees of temperature difference between the natural and altered hydrographs.

Release curves are generally developed to follow a similar shape as the natural hydrograph for release where there are environmental concerns; although, there is generally no consideration or incorporation of water temperature regarding high or low flows and their influence on fish. A typical impoundment hydrograph would result in a lower and later than natural peak discharge because of storage (Godfrey & Carter, 1960). For impoundments it would be expected that fish experience a lower unit discharge at that particular temperature than would otherwise be experienced at the natural curve at the same time. Such hydraulics and temperature variations may cause fish to wait to spawn, consequently reducing the potential for spawning success. When the flow is very low and unit discharge is being kept to a minimum, water temperatures may be higher than would occur under normal conditions, resulting in an earlier spawn which in turn may affect emergence timing. Implications could be significant for Arctic grayling and potentially other spring spawning fish. Some work has been done looking at discharge influence on White Sturgeon spawning although a cross sectional approach was used for the analysis (Paragamian & Wakkinen, 2011).

While physical impacts to habitat such as substrate erosion and fine deposition are factors that limit spawning success, often just improving the physical habitat alone does not meet the restoration or offsetting goals of a site (Harper & Quigley, 2005; Spänhoff & Arle, 2007). By identifying the linkages between habitat parameters (i.e., water temperature and unit discharge) to describe conditions at life history events such as spawning, the understanding of the event can be improved. Linkage between the parameters at a small scale (i.e., within the confidence levels) may not be significant; however, when a discharge's shape is altered enough with respect to the temperature profile (Figure 4-9) there may be significant impact to spawning time and potentially subsequent emergence success. Fish may: (1) delay spawning due to too high of discharge resulting in poor emergence timing; (2) spawn early due to temperatures and have eggs displaced due to the higher discharge; or (3) may not spawn at all. Incubation and emergence success may also be impeded due to altered habitat conditions (e.g., Froude number) and reducing overall spawning success. An altered hydrograph may also result in a peak flow after peak spawn, resulting in egg displacement due to increased flow.

Spawning delays have also been shown to reduce spawning success. It has been identified that spawning delays not exceed three days for Arctic grayling (Fleming & Reynolds, 1991). Later spawn timing would also alter emergence causing it to be later, which may not be optimal.

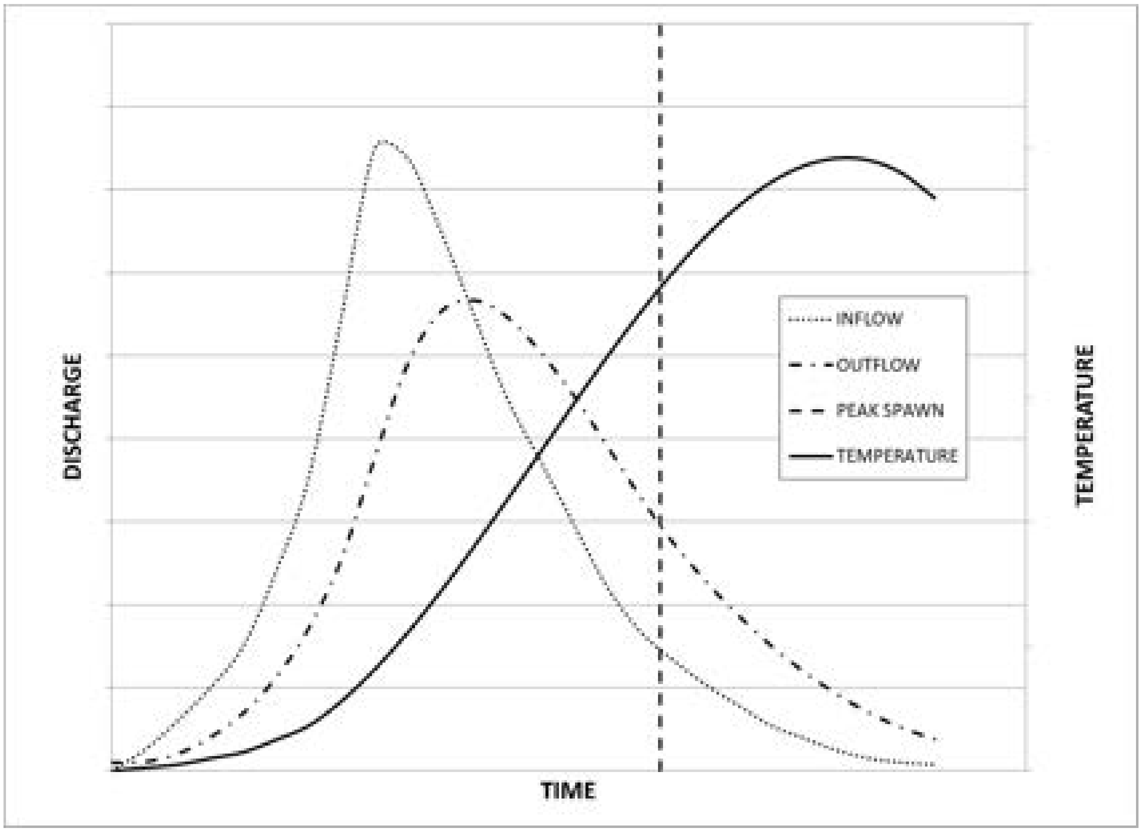

Figure 4-9 An example hydrograph illustrating the differences between inflow natural and impounded outflows with respect to water temperature and uninfluenced spawning timing. The discharge may be very different in a managed system resulting in fish potentially being ready to spawn earlier due to temperature changes but may be delayed by the increased discharge experienced. These altered conditions may result in fish not spawning.

Limiting factors for reduced success on impounded systems have been identified, but even though interventions may have been made to address the perceived impacts, the desired response in a population has not been achieved. For restoration and mitigation, discharge and substrate are often manipulated. Temperature is only considered where there is an obvious and significant deviation from natural conditions (i.e., typical ranges of value) but is not usually directly linked to discharge. When looking at limiting factors for Arctic grayling, or potentially other spring spawning fish understanding the hydrologic and temperature interactions is importance; however, identifying linkages between habitat parameters has only been done in a limited manner.

For example for the PDC 1999, there was a large spike created in the hydrograph due to the removal of an ice jam (Dillon Consulting Ltd., 2000), thus exaggerating the peak flow value and likely altering the peak timing for spawning. From the data, this peak discharge likely occurred before peak spawning but did cause an inflated unit discharge value due to the short term flow increase due to the jam's breach. This scenario shows how impoundments can impact the hydrograph (i.e., the hydrograph downstream of the ice jam had a delayed peak with respect to the natural hydrograph and when the jam was removed the discharge went from low to very high before returning to natural/uninfluenced level). Impacts on spawning may have occurred as a result of this inflated peak unit discharge. This possibility is supported as even though there had been more spawners present in 1999, the overall juvenile count in 1999 was less than in 1998 (Dillon Consulting Ltd., 2000). There may have been a ripening interference due to the ice jam that resulted in fewer viable eggs and/or displacement of eggs due to secondary spikes in the hydrograph. With the ice jam, migrating fish would have experienced lower flows and lower temperature as they moved upstream, thus 'thinking' freshet is later. When the ice jam was removed the fish were possibly not ripened enough to match the flow conditions for optimal spawning and perhaps spawned later as a result. It was noted that fish spawned 'later in the calendar year' than 1998 even though general spring conditions were described as being similar to the previous year (Dillon Consulting Ltd., 2000).

Temporal Referencing

Temporal scale may be an important factor to consider as well from a management perspective with regards to temperature and discharge alteration from nature. In the case of Chinook salmon, the shorter a time scale is (i.e., >8 day) the greater the significance in water temperature variability seems to be (Steel & Lange, 2007). An Arctic nival watershed freshet peak can occur very quickly after spring thaw and Arctic grayling spawning often occurs about 4 days after the peak. The temperature changes are important to fish physiology and behaviour. The natural temperature pattern is likely altered even further with any potential for impoundment.

Additional investigation into the relationship of discharge and temperature to spawning timing and subsequent success of Arctic grayling and other spring spawning species such as Sturgeon (Acipenseridae) and Steelhead trout (*Oncorhynchus mykiss*) populations that are subject to impoundments, from an event analysis approach is warranted to meet conservation goals.

Climate Adaptation Potential

Climate variation may also impact Arctic grayling spawning time; however, the potential for adaptation may be better than under impoundment conditions. This is because discharge and water temperature are still occurring in a natural response, though the timing may be earlier than is currently experienced.

The expected increase in precipitation (Intergovernmental Panel on Climate Change, 2015) will cause higher or multiple peak discharges. This change in discharge may be of greater concern to Arctic grayling due to the physical characteristics (i.e., Froude number) being higher during incubation than currently estimated (CHAPTER 3). Greater unit discharge that is rainfall based may also be warmer than snowmelt influenced run off which may also affect incubation timing.

Temperature needs to be looked at not only from the perspective of a life history event occurring but also the implications on the physiology (i.e., ripening) of the fish (McCullough, Bartholow *et al.*, 2009). Work has been undertaken illustrating the importance of temperature fluctuation and degree day influence on emergence timing for Chinook salmon (*Oncorhynchus tshawytscha*) (Steel & Lange, 2007; Steel, Tillotson *et al.*, 2012). Further work is needed with regards to Arctic grayling incubation and emergence response to hydrograph and temperature variations and the emergent fry’s subsequent success.

Habitat Management and Restoration/Offsetting Implications

Significant funds have been spent on improving fish habitat throughout North America. Many habitat projects address limiting factors for spawning, often noted to be spawning habitat (i.e., gravel, suitable water depth) and instream cover. Success of restoration investments varies, though spring spawners downstream of impoundments typically do not have the desired improvements to these physical restoration works even though gravel placements and channel manipulations match the physical requirements identified for the population.

Consideration should be given to use of standardized parameters for other habitat or life history concerns. Low flows and high temperatures are critical for many salmonids, particularly interior populations of Pacific salmon. Low flows are generally described as a percentage (usually about 10 percent) of mean annual discharge (MAD) (Barton, Sundt *et al.*, 2020). Using MAD as a descriptor may not be the most appropriate when compared to unit discharge. MAD is often related to a single point in a watershed and the watershed hydrograph must be known to provide values for critical flows and is not specifically related to a life history event. Unit discharge is scalable to streams with similar characteristics and a wide range of watershed areas. Unit discharge can also be linked to life history events to describe habitat conditions.

When discussing fish mortality, a temperature threshold is generally described as a single peak value, where it may be exposure to consistent increase of temperature(s) over a period of time. The likelihood of mortality of a fish in relation to temperature may be better described using an event analysis approach rather than a critical absolute value as currently done. Such an approach could consider acclimation, length of exposure as well as the varying temperatures over the course of a day (i.e., cooler at night, warmer during the day). Further work is needed to develop an understanding of high temperature and low flow conditions as they relate to many fish species, including Arctic grayling.

With discharge and temperature not being linked together other than as a general range of suitable values, there appears to be a significant gap that has not been explored. Although the physical habitat (i.e., substrate, depth) may be present, the supporting conditions (i.e., discharge and temperature) for a successful life history event may not be present. A review of these conditions and interactions with each other may result in a potential improvement in restoration success that could be significant.

Consideration should also be given to other spring spawning species, such as sturgeon and Steelhead trout, and available data should be revisited with a longitudinal approach. There are several regulated watersheds[26] where these fish have been to have conservation concerns and have had limited response to habitat restoration works. These species may also display a spawning behavioural response to temperature and unit discharge similar to Arctic grayling.

CONCLUSION

The connection between water temperature and discharge for Arctic grayling spawning has long been accepted, if not fully understood; however, the traditional cross sectional analysis approach uses only averages and ranges to describe the relationship with minimal linkage as it relates to overall behaviour in the fish's life history. By using an event analysis approach, the likelihood of these parameters occurring together as pairs on a given day leading up to and after spawning, fish response can be more effectively described and support the occurrence of an event such as peak spawn.

The approach in using discharge and non-discharge parameters is identified as important in development of flow regimes (King, Gwinn *et al.*, 2015) for Arctic grayling as well as other species. An understanding of such a linkage is potentially critical for conservation. Other spring spawning species, such as sturgeon and Steelhead trout, have been identified in many regulated watersheds to have conservation concerns and may respond to temperature and unit discharge similarly to Arctic grayling.

The connection between discharge and temperature may impact rule curve development for flow releases from impoundments. The development of managed hydrographs that reflect both discharge and temperature relationships with appropriate timing will create additional complexity for rule curves for impoundments; however, the potential improvement in fish and restoration success in impacted streams could be significant.

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[26] Within British Columbia fish populations include Bonaparte and Deadman River Steelhead, Mabel Lake Rainbow trout, and Nechako and Columbia River sturgeon

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CHAPTER 5. CONCLUSION

All three hypotheses tested in this thesis validated novel and interdisciplinary concepts to improve Arctic grayling enumeration, habitat development and overall understanding of fish life history events. A strong theme in each chapter is the establishment of distinctive viewpoints and the incorporation of other discipline methods and techniques in relation to biological data interpretation. Each chapter describes a novel approach in relation to more traditional methods: CHAPTER 2 addresses the use of wildlife cameras for fish enumeration during spawning; CHAPTER 3 relates hydrology to spawning site selection regardless of watershed size; CHAPTER 4 describes stream flow and temperature changes leading up to the Arctic grayling spawning event. By applying methods and techniques used in other disciplines, potential efficiencies can be developed and existing data sets can be reexamined for deeper meaning and greater understanding.

Although past scientific efforts have used similar techniques and consistent results and conclusions, they were not able to advance a deeper understanding of fish and habitat interactions. Environmental science generally relies on traditional analysis (i.e., averages, means, maximum, minimums) approaches and treatment of data parameters individually before comparison. Data in the past has only described the Arctic grayling spawning event itself rather than exploring the conditions that lead up to, or even follow, an event. The traditional approach of data presentation should not be accepted as the final understanding. Rather this approach could be used for the initial description of a lesser understood species to provide a basis for further study. Additionally, statistical review is generally undertaken in a cross sectional manner and does not permit comprehensive insight or discussion for trends and influences to the specific event. In other disciplines, such as social sciences or medicine, data sets are often looked at in a longitudinal interrelated manner or how things respond with respect to external influences. In engineering for example, data is often standardized for comparison or parameters are integrated for analysis. For an expanded understanding of Arctic grayling spawning behaviour, future collected habitat data needs to be presented differently than the traditional averages and ranges, and the parameters examined as a complete integrated event rather than those at a single occurrence. With this methodology, a deeper understanding of the relationships between parameters can be described as can the biological response to them.

Data collection is needed for all scientific endeavors and the way of presenting data in an environmental context needs to incorporate multiple discipline perspectives to improve our understanding of fish behavioural interactions with the environment. In some cases, the data required to revisit parameter interactions likely exists already, but it has just been largely unused due to the limitations of past analytical approaches. All three chapters were supported by data mining, although some limitations are evident. For example, finding the data presented in a usable format is limited as averages and ranges are usually published rather than paired information that can more readily be used for event analysis. Questions may also be asked in regards to the quality of data that is found. Methodology must be reviewed from each set to ensure that data collection methods and representations are consistent and relevant. Regardless, it is worth the effort to find additional existing comprehensive data sets for identifying the data patterns and improving the statistical analysis defensibility.

Information to support management decisions must incorporate more than just mean, minimum and maximum values that are provided in a traditional cross sectional analysis approach. It is apparent that the natural changes in and the relationships between parameters (i.e., water temperature, discharge) must be further developed and understood to effectively predict and plan in response to environmental changes, be they from industrial development or climate variability. Furthermore, collected data from any watershed can be focused using standardization (e.g., unit discharge) thus improving usefulness across geophysical characteristics when habitat design is addressed.

Stream alterations can be better managed such as through hydrograph development. Hydrographs are currently developed for impoundments looking at discharge and may only consider temperature influences if there is a significant deviation from the range of acknowledged values (e.g., discharging from surface rather than from depth). A more relevant approach is required in hydrograph development to consider the relationship between discharge and temperature in providing appropriate cues for spawning maturity and subsequent successful emergence.

FUTURE WORK

Any technique or approach has potential for refinement and expansion, be it for a site-specific condition or as a technique in general. The tools developed in this thesis are no exception.

The use of wildlife cameras in CHAPTER 2 could have improvements undertaken for counting efficiency. Rather than manually counting each image, software, such as ImageJ, could be used to undertake the initial screening. Success with computerized counting would also be improved with the inclusion of a high contrast background in the field thereby further reducing the time required to review the images.

Future work related to spawning selection and the Froude number in CHAPTER 3 includes the evaluation of the Froude number value with respect to the substrate size of the preferred spawning areas, how the Froude number changes during incubation and spawning success, and the examination of juvenile Froude number preference with respect to predation behaviour. Additional sites could also be evaluated to confirm a common Froude number across different populations. While a Froude number range and mean preferred value have been identified for Arctic grayling, additional work is required to ensure that the significance of the Froude number is put in context to the bigger picture for the understanding of Arctic grayling eco-hydraulics.

The CHAPTER 4 approach in using discharge and non-discharge parameters was shown to be important for the development of flow regimes which has been shown for species other than Arctic grayling (King, Gwinn *et al.*, 2015). The connection between discharge and temperature will potentially impact rule curve development for flow releases from impoundments to enhance fish spawning success. An understanding of such a linkage is potentially critical for conservation. Other spring spawning species, such as sturgeon and Steelhead trout, have been identified in many regulated watersheds to have conservation concerns and may be found to respond to temperature and unit discharge similarly to Arctic grayling. Extensive physical habitat restoration work (e.g., gravel placement. spawning channels) to improve spawning success has been undertaken for many of these populations, often with limited success. Perhaps the limiting factor for these populations is not the physical habitat, rather the environmental conditions leading up to spawning. There are many data sets available that can be compiled to further examine life history or behavioural responses not only for Arctic grayling, but for other species as well.

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