The Spatial Ecology and Biological Responses of Wild Fishes Relative to Hydropower Development on the Winnipeg River

by

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Dedication

First, I dedicate this thesis to my wife, Nicole, for her enduring patience, support, and encouragement throughout my graduate studies. To my parents, for providing numerous opportunities for helping me discover and develop my passion for fish and conservation biology, as well as for their support and encouragement during my time in academia. To my FECPL colleagues, for all of the valuable and constructive ideas and feedback related to my research, data analyses, and the many memorable times I shared with many of you during my time at Carleton University.

Abstract

Wild fish population are often impounded by hydropower dams, which can restrict migration and habitat requirements, while making fishes susceptible to deleterious harm from entrainment through spillways and turbines, stranding from dewatering, as well as hydrokinetic developments that are being proposed for installment within tailraces. An acoustic biotelemetry study and model selection analysis was used to investigate the spatial ecology and biological responses from Lake Sturgeon and Walleye relative to hydropower developments on a large boreal shield river system. The results in chapter 2 document the seasonal trends in habitat use, activity responses, and depth use for Lake Sturgeon and Walleye within a run-of-river impoundment. In chapter 3, the telemetry data was used to investigate the risk from hydrokinetic turbines placed within the tailrace of a hydropower generating station on wild fishes. This information will help to inform managers and regulators where Lake Sturgeon and Walleye populations occur, and help guide best practices for commercial operations for hydrokinetic turbines that are placed within tailraces of hydropower stations.

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Co-Authorships

Factors influencing the spatial ecology, activity patterns, and depth use of Lake Sturgeon and Walleye within an impounded reach of the Winnipeg River

Struthers, D.P., L.F.G. Gutowsky, E. Enders, K. Smokorowski, D. Watkinson, A. Silva, M. Cvetkovic, E. Bibeau, and S.J. Cooke

While this study is my own, the research was undertaken as part of a collaborative effort and each co-author played a significant role for its completion. The project was conceived by Struthers, Smokorowski, Enders and Cooke. Fieldwork was completed by Struthers, Silva, Cvetkovic, and Watkinson. All data manipulation and analyses was conducted by Struthers. Data were interpreted by Struthers, Gutowksy, Watkinson, Smokorowski, Enders, and Cooke. All writing was conducted by Struthers. All co-authors provided comments and feedback on the manuscript. This manuscript is being prepared for submission to *Ecology of Freshwater Fish.*

Investigating residency, movement, and depth use of wild fishes to assess exposure risk to hydrokinetic turbine infrastructure and operations in a large river

Struthers, D.P., L.F.G. Gutowsky, E. Enders, K. Smokorowski, D. Watkinson, E. Bibeau, and S.J. Cooke

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Glossary

AIC: Akaike Information Criteria

ANOVA: Analysis of Variance

BIC: Bayesian Information Criteria

CHTTC: Canadian Hydrokinetic Turbine Testing Centre

cms: cubic meters per second (discharge rate)

DE: Detection Efficiency

DU: Designatable Unit

DU5: Designatable Unit 5 (English River - Winnipeg River)

GHG: Greenhouse gas

GLMM: Generalized Linear Mixed-Model

GS: Generating Station

HT: hydrokinetic turbine

LMM: Linear Mixed-Model

MFGS: McArthur Falls Generating Station

PES: Portable Electro-Sedation

rkm: River Kilometer

SSGS: Seven Sisters Generating Station

SR_I: Seasonal Residency Index

VIF: Variance Inflation Factor

VR2W: Vemco Acoustic Monitoring Receiver

General Introduction

Hydropower Development

Canada's commitment under the Copenhagen Accord is to reduce greenhouse gas emissions as a means to combat climate change. Environment Canada (2013) has a goal of reducing GHG emissions by 17%, equivalent to 607 megatonnes, from the 2005 emissions output level by the year 2020. In Canada, hydropower is considered an appropriate solution for reducing emissions because of abundant water resources, competitive energy costs, and a reliable source of clean renewable energy in North America (Cada 2007; Canadian Hydropower Association 2008; Hammar et al. 2013). In 2008, Canada ranked second behind China for world leaders for the generation of conventional hydroelectric energy, producing approximately 70,858 MW/year from approximately 475 generating stations (Canadian Hydropower Association 2008). Canadian rivers also have an untapped technical production potential of 163,173 MW/year (Canadian Hydropower Association 2008). Indeed, hydropower is an optimistic sustainable energy source in Canada for meeting future demands while also having the potential for achieving the 2020 carbon reduction goal.

Conventional hydroelectric generating stations can negatively affect fish and aquatic ecosystems (Cada 1998; Cada et al. 2007). Dam operations can significantly disrupt the natural water dynamics upstream and downstream from generating stations that cause alterations in natural life histories and ecology of fish species and communities (Hayes et al. 2008; EPRI 2011a; Manitoba Fisheries 2012). Hydroelectric dams maintain a water supply by creating reservoirs for ramping up production during peak demand periods or during seasonal water scarcity (Canadian Hydropower Association, 2008). Hydroelectric stations can also create barriers and restrict the long distance migration of adult fish searching for optimal spawning habitat upstream, as well as juvenile fish migrating downstream in search of critical rearing habitat (COSEWIC 2006; Hayes et al. 2008; Lapointe et al. 2013). Hydropower dams can lead to stratification depending on holding duration (Young et al. 2010) which can alter the natural water temperature downstream of hydropower generating station (Baxter 1977). Water temperature is considered the key abiotic factor affecting almost every aspect of life history in fish including spawn timing, egg incubation and survival, growth rate, and metabolism (Brett 1971; Quinn 1996). Thus, the alteration of natural water temperature affects various aspects of natural behaviour and physiology in fish (Quinn 1996). Among other impacts, hydro generating stations can also alter flow velocity, decrease ecological productivity, and change sediment deposition patterns (McKinley et al. 1998; DiStefano & Hiebert 2000).

Particularly concerning for fish is the susceptibility of entrainment through hydropower turbines and spillway that can cause injuries or mortality (Cada et al. 2007; EPRI 2011b). Research found a mortality rate of 30% for juvenile Coho Salmon passing through conventional hydroelectric turbines (Cada et al. 2006). Another study found a large number of Lake Sturgeon were entrained through the spillway of the Little Long GS on the Mattagami River because of foraging habitat that was located immediately upstream of the spillway (Seyler et al. 1996; McKinley et al. 1998). There are a variety of ways for fish to be injured or killed by turbines. Fish mortality by the strike from the leading edges of fast moving turbines is a primary concern (Cada et al. 2007). Abrasion and squeezing can also occur between the stationary structures and mobile parts of the turbines (Cada et al. 2007). Fish passing through conventional turbines can be exposed to severe pressure differentials ranging from 2 kPa up to 460 kPa (EPRI 2011a; Brown et al. 2014). Exposure to sudden decompression increases the likelihood of experiencing injury and mortality from barotrauma (Deng et al. 2007; EPRI 2011a). Barotrauma can include swim bladder rupture, exophthalmia, as well as eversion, embolism and hemorrhaging of internal organs in fishes (Brown et al. 2014). While physostomous fish (e.g., sturgeons, lungfish) can rapidly exchange air in the swim bladder through the pneumatic duct, physoclistous fish (e.g. gadoids, sparids) cannot. Physoclistous fish slowly regulate air exchange via blood diffusion through a network of small vessels located on the swim bladder membrane, making them more susceptible to barotrauma when passing through hydroelectric turbines (EPRI 2011a; Brown et al. 2013; Brown et al. 2014).

Hydrokinetic Turbines

Lately there has been a surge in developing hydrokinetic energy conversion devices in North America for producing clean renewable energy and as a solution for reducing the impact of hydropower on fish and aquatic ecosystem integrity (Cada 2007; SchIizer et al. 2011; Liu and Packey 2014). Hydrokinetic energy conversion devices, synonymously known as hydrokinetic turbines (HTs), generate electricity by garnering the kinetic motion of natural stream flows found in riverine, marine and man-made environments (Cada et al. 2007; Seitz et al. 2011). There have been research interests in hydrokinetic technology since 1979 (Seitz et al. 2011), with tidal and river HT devices emerging in the 1990s (Khan et al. 2008). However, advancing this technology to commercial applications in river systems has been slow due to a variety of technical, economical, and environmental feasibility issues. At the moment, only a limited number of test projects have been completed with very few being in Canadian freshwater or marine environments. However, with increasing demand on hydropower generation there is now greater focus on hydroelectric energy alternatives, which has gathered funding for research and development, and *in situ* testing opportunities with HT technologies (Yuce and Muratoglu 2015).

HTs have been designed to utilize the kinetic energy within river flows, marine tidal areas, marine currents, and constructed waterways (Liu and Packey 2014). The rotational energy of the HTs is converted into mechanical power and then transformed into electrical energy to be supplied to the consumer grid (Cada 2007; SchIizer et al. 2011; Liu and Packey 2014). HTs may be used to augment conventional hydropower generation since demand for hydro-electricity is expected to increase by 1.2% each year for the next two decades in Canada (Canadian Hydropower Association, 2008; Liu and Packey 2014). It is estimated that the generation potential for hydrokinetic technology in Canada to be within the range of 15,000 to 25,000 MW per year (AECOM 2012). Similarly, the United States has estimated the hydrokinetic production potential for riverine systems within the range between 3,400 MW (Hall et al. 2004) and 12,800 MW per year (AECOM 2012). Additionally, there are remote communities that are not linked to the power grid that could utilize HTs if situated near swift rivers (Seitz et al. 2011; Liu and Packey 2014). Indeed, hydrokinetic generation has the potential to offset demands of conventional hydropower generation, provide remote communities with sustainable energy sources, while also reducing the demands on conventional GHG-emitting resources.

HTs and Fisheries Assessment

There are a variety of characteristics of HTs that rationalize their efficacy in the future development of hydroelectric generation. Unlike conventional generating stations, hydrokinetic turbines are installed quickly, maintain a small structural footprint, can be easily removed, and minimally alter natural flows (Cada 2007; Seitz et al. 2011; EPRI 2011). Hydrokinetic turbines may also aid in supplying energy to remote locations for reducing energy costs to these communities that are reliant on costly and carbon-emitting diesel generation to meet their energy needs (USDOE 2009; Seitz et al. 2011). The primary mode of injury to fishes from HTs would be from striking the turbine blades or anchoring structure. Field research found promising survival results of fish passage through a patented HT, with a 99% survival rate documented for both small (115-235 mm TL) and large (388-710 mm TL) fish size categories (NAI 2009). Similarly, modelling and flume studies found that hydrokinetic turbines are “fish friendly” with a survival rate of 90-95% for both small and larger fish sizes with passage through three types of hydrokinetic turbine designs: (1) Wekka UPG, (2) Lucid Spherical Turbine, (3) Darrieus-type cross flow turbine (EPRI 2011a; 2011b). Fish are also not exposed to the abrupt pressure changes or cavitation that normally occurs with conventional hydroelectric turbines (NAI 2009; EPRI 2011a). Hydrokinetic turbines do not function with a high pressure penstock elevated above the turbine like that of conventional hydropower stations (Amaral et al. 2012), therefore fish would likely not experience the instantaneous pressure drop when entrained. Thus, there is lower risk of injury or mortality due to barotrauma (EPRI 2011a). Indeed, initial findings for fish survival with regards to HT operations are optimistic for the future development of this technology in flume and aquatic environments.

While there is rationale for developing hydrokinetic systems, there are still a large degree of uncertainty regarding the effects that HT technology may have on wild fish populations and aquatic habitat. Because HT technology is still a relatively novel technology, few studies have been implemented to assess the ecological, physiological, and behavioural aspects of fish in relation to hydrokinetic technologies (EPRI 2011a). While recent studies are optimistic for fish survival when passing through a hydrokinetic turbine (USDOE 2009; EPRI 2011b; Seitz, 2011), these studies were developed in closed laboratory settings consisting of singular turbines and manual manipulating the study parameters over a limited temporal scale. At this time, it is still unclear how fish will behave and physically respond to an array of multiple hydrokinetic turbines on larger spatial and temporal scales within river and marine systems (Cada et al. 2007; Amaral et al. 2012; Hammar et al. 2013). While EPRI (2011b) found favourable results with fish passage survival, they also noted that the probability of fish survival decreases with: (1) larger fish size, (2) increased frequency of passages in the vicinity of an HT per fish, and (3) exceeding a flow velocity of 1.7 m/s.

While these studies are important for fisheries conservation and the promotion of HTs, these studies were limited to a small number of species, which were commonly hatchery reared fish, and tested under controlled conditions that lack realism. In reality, the interactions of fish with hydrokinetic turbines may show different results due to a variety of biotic and abiotic factors that may include, but not limited to, the behavioural ecology of fish species, ontogeny, diel period, seasonality, and hydrodynamics of river systems. Reviewing the literature shows that a variety of questions remain unaddressed for assessing how HT technology may affect how wild fish behave, interact with turbines, and physiologically react in their natural environment.

The impact to aquatic habitat is a concern for developing HT arrays in riverine and marine environments. Hydrokinetic turbines may disrupt the natural sedimentation load and cause erosion on the river substrate (Cada et al. 2007; USDOE 2009; Seitz et al. 2011). Furthermore, hydrokinetic turbines have not been assessed with relation to the cumulative anthropogenic threats already impacting ecosystem integrity. There is also concern regarding the effects of constructing large networks of hydrokinetic turbines implanted in aquatic ecosystems with diverse fish communities (Cada et al. 2007). Additionally, hydrokinetic technology may generate magnetic fields, noise, vibration and chemical pollution that may affect fish behaviour and physiology within proximity to HTs (Cada et al. 2007; Seitz et al. 2011). Many species of fish, for example sturgeon and paddlefish that reside in large turbid systems, are known to utilize chemical, hydrodynamic, and magnetic fields as cues for swimming direction, localized movements, long distance migration, and foraging for prey (Cada and Bevelhimer 2011). It is possible that hydrokinetic turbines may disrupt these environmental cues that these species rely upon for movement and foraging (Cada & Bevelhimer 2011).

While entrainment survival and habitat degradation have been described in the literature, there is limited research that addresses free-ranging fish behaviour and movement relative to hydrokinetic turbine operations. However, recently published research conducted by Hammar et al. (2013) highlighted a number of interesting findings regarding the swimming behaviour of wild fish in proximity to an operational marine hydrokinetic turbine. Larger fish were more cautious and maintained a greater distance from the HT compared to smaller sized fish. The level of avoidance behaviour also differs between feeding guilds (Hammar et al. 2013). Browsers maintained a greater avoidance distance to hydrokinetic turbines than carnivorous fish species. The body morphology of fish associated with different feeding guilds (i.e., ecomorphology) is the likely driver, with compressiform body shapes having less maneuverability compared to fish species with a streamlined fusiform body shape, which are generally stronger swimmers and have greater stability in swift environments (Hammar et al. 2013). Boldness was also a key component for how fish interact with the HT (Hammar et al. 2013). Fishes such as Stumpnose (*Rhabdosargus* spp.) and Wrasse (*Thalassoma* spp.), which are known for their curiosity, were found closer to the hydrokinetic turbine than other species. These initial findings on fish behavioural characteristics are important for bridging fisheries conservation goals regarding HTs (Hammar et al. 2013). However, to my knowledge, the spatial ecology of wild freshwater fish populations is understudied with regard to assessing biological risk for riverine HTs.

Biological and environmental parameters could likely be used to address how fish may interact with HTs placed in their natural aquatic environment. Fish interactions with HTs may occur differentially throughout diel period and seasons. In a recent study focusing on a marine HT, fish avoidance distance was considerably less and fish entrainment occurred at a higher rate during the nocturnal period (Viehman & Zydlewski 2014). The reduction in visual detection during the nocturnal period is the likely cause of this interaction (Viehman & Zydlewski 2014). Additionally, anchoring structure for HTs may provide novel habitat that may attract fish to aggregate for the purposes of spawning, refuge, and/or opportunistic foraging (Cada et al. 2011; Reubens et al. 2013; Veihman and Zydlewski 2014). Anchoring platforms that secure riverine hydrokinetic turbines in place may provide overhead cover for protecting fish from predators, as well as a refuge from swift flows (Cada et al. 2011). The hydrokinetic turbines and the anchoring structure may reduce flow velocity immediately downstream by creating a flow barrier in the mid-channel of the river environment (Cada et al. 2011). Because of this, hydrokinetic turbines may attract fish to HTs for reducing energetic costs associated with swimming and foraging in swift environments. Smaller fish may use HT structure seeking cover to avoid predators, while conserving energy reserves. Opportunistic predacious fish that tend to utilize flow gradients (i.e., eddy lines) may also show an inclination towards HTs with providing an optimal location to feed on small fish being swept through or passing by the turbine structure, while conserving energy (Cada et al. 2011).

Presently, no full-scale operational HT arrays have been developed within Canada due to insufficient environmental assessments and uncertainty in how wild fish will be impacted by this novel technology. Few operational studies have been completed in Canadian rivers (e.g., Groupe RSW in Saint-Laurant, QC). This is due to a variety of reasons, but particularly because of the difficulty of obtaining construction permits and fisheries approval at all levels of government for placing this HT technology into Canadian Rivers and tidal zones (EPRI 2011a).Within Canada, federal legislature restricts any form of development that poses a risk to the wellbeing of fish and fish habitat that support commercial, recreation, or aboriginal fisheries that do not mitigate the deleterious effects towards wild fish populations (Government of Canada 2012). While there is a need for clean renewable energy to reduce our carbon footprint, additional quantitative research is warranted to fully understand the potential impacts from HTs on wild fish populations and their aquatic habitat (Seitz et al. 2011; EPRI 2011b).

Overview of Lake Sturgeon

Lake Sturgeon are the largest endemic freshwater fish residing throughout the Hudson's Bay, Mississippi, and Great Lake drainage systems within Canada and the United States (Peterson et al. 2007; Auer et al. 2013). Historically, Lake Sturgeon were an abundant species in many aquatic systems prior to overexploitation (Harkness and Dymond 1961). Many populations were severely reduced in size within a brief period of time in late-1800s to early- 1900s due to commercial overexploitation (Harkness and Dymond 1961; Auer 2013). For example, commercial catch exceeded 2.1 million kg in 1885 and less than 2300 kg in the early-1920s (Auer 1996). Adult Lake Sturgeon are sensitive to habitat degradation, increasing recreational fishing pressure in certain systems, and migration barriers (e.g., dams) that are impeding their recovery and may alter their natural movement and behaviour (Auer et al. 2013). Lake Sturgeon populations may never fully recover from the historical overexploitation (Haxton et al. 2014). It was predicted to take 60 years for stocks to recover from the period of overexploitation that occurred in the late-1800s and early 1900s (Haxton et al. 2014). This recovery period has already elapsed since all commercial and many recreational fisheries have been eliminated indicating that Lake Sturgeon are still hindered and may not fully recover (Haxton et al. 2014). Many populations remain listed as threatened, endangered, or a species of special concern throughout their range in Canada and the United States (Peterson et al. 2007; Auer et al. 2013). Their slow maturation and high juvenile mortality have delayed their recovery for stocks that have been heavily exploited (Houston 1987; McKinley et al. 1998).

Lake Sturgeon utilize a variety of habitats depending on season and life history stage (Kerr et al. 2010). Lake Sturgeon are a demersal fish that generally cruise over the substrate in deeper waters to forage for benthic invertebrates by sifting through sediments (Peterson et al. 2007), while avoiding ambient light and fluctuations in water temperature (Auer et al. 2013). Their body shape makes them highly efficient at moving across the bottom substrate within swift flow (Auer et al. 2013). Lake Sturgeon are often found in large turbid rivers or lakes (Auer et al. 2013), where home ranges expand as fish reach maturity (Auer 1996). In the spring, they are known to migrate upstream to spawning habitats, where they can negotiate flows greater than 1.5 m/s by utilizing habitat near the shoreline or moving into deeper water where flow velocity is lower (Kerr et al. 2011).

Lake Sturgeon either exhibit “one-step” or “two-step” spawning migrations. In one-step, adults spawn soon after upstream migration to their spawning location (Gerbilskiy 1957; Peterson et al. 2007). With the “two-step” strategy, individuals migrate in the fall, overwinter near the spawning location, and subsequently spawn in the spring season of the following year (Bemis and Kynard 1997; Peterson et al. 2007). These strategies are likely dependent on the length of the migration and favourable conditions for overwintering near the spawning grounds. Lake Sturgeon migrations can be affected by electric-magnetic fields (EMF). Electrical powerlines, which are often associated with hydropower generating stations (GS) that run along or above the water can affect their upstream migration route selection (Auer et al. 2013). Water temperature and discharge are thought to be important cues for initiating upstream spawning migration for Lake Sturgeon (Bruch and Binkowski 2002; Lallaman et al. 2008), with spawning occurring when temperature range between 8.8 -19.1^{o} C (Bruch and Binkowski 2002). Many studies have focused on the spawning movements of Lake Sturgeon, while less is known with regards to their seasonal movements and space-use (Houston 1987; McKinley 1998; Borkholder et al. 2002). Many populations are now restricted to impounded aquatic systems, both in smaller run-of-river and larger reservoirs (Barth et al. 2011; McDougall et al. 2013a, 2014) potentially restricting habitat available for foraging, spawning, overwintering, as well as gene flow between adjacent populations (Barth et al. 2011).

Overview of Walleye

Walleye are one of most economically important inland fisheries in Canada (Scott and Crossman 1973; Post 2002). Furthermore, many populations are heavily targeted recreational fisheries across their range in Canada and the United States (Sullivan 2003; Bozek et al. 2011). Walleye are a coldwater species with their northern and southern latitudinal range restricted by water temperature (Bozek et al. 2011). Walleye tend to mature slowly in high latitudes, such as in the Winnipeg River and other systems within the region reducing recruitment rates. Low recruitment rates and fishing exploitation can lead to population declines in systems located at high latitudes in the 1990s (Sullivan 2003). Walleye are adapted to flowing water with abundant populations occurring in large rivers systems, while are less successful in smaller tributaries and streams (Kitchell et al. 1977). Walleye generally have an affinity to shorelines when moving (Kelso 1978), and are more active when foraging during the crepuscular and nocturnal periods (Reed

1962; Kelso and Ward 1977). Walleye are known to become more active as water temperature increases in the spring (Paragamian 1989).

Walleye tend to home towards their natal spawning location during the spring and early-summer, which can consist of lengthy migrations of 50 to 300km, with timing of migration and peak-of-spawn thought to be dependent on water temperature (Bozek et al. 2011). Walleye are a schooling species, and homing to natal spawning areas is thought to be an adult-learned behaviour that older individuals teach to younger conspecifics as a strategy to increase reproductive success at optimal spawning habitats (Olson et al. 1978). Depending on latitude, Walleye will initiate upstream migration to spawning areas when temperatures are between 1-7^{o} Celsius. Generally, when temperatures range between 4 and 14^{o} Celsius (Bozek et al. 2011), Walleye will broadcast spawn in riffle habitat characterized by cobble-gravel substrate and moderate flow velocities (Priegel 1970; Paragamian 1989; Stevens 1990). Post-spawn, they then move downstream and utilize a variety of depths during the summer season to forage, which are located at flow boundaries and upper edges of pools (Paragamian 1989). Walleye are known to roam far from the spawning grounds during the open-water foraging period in summer and autumn (Bozek et al. 2011; Hayden et al. 2014), however site fidelity to smaller areas of riverine habitat have also been documented (Crowe 1962; Colby et al. 1979). Optimal temperatures for growth, metabolism, and foraging is within the range of 18-24^{o} Celsius (Wismer and Christie 1987; Christie and Regier 1988; Bozek et al. 2011).

Research Significance

Evaluating fish interactions with riverine hydrokinetic turbines in their natural environment requires *in-situ* data collected from free-ranging individuals. Preliminary results from laboratory and modelling studies have found that hydrokinetic technology minimally impact fish survival (NAI 2009; EPRI 2011ab). While these initial, controlled laboratory studies are optimistic for operational "fish friendly" turbines, the implications regarding fish behaviour and spatial ecology remain largely unaddressed due to insufficient research in the field. Consequently, this data deficiency has restricted project managers from attaining installation permits and fisheries approval for developing pilot projects and full scale operations in North America (EPRI 2011a). It is important that field research is implemented to understand the complex responses of fishes and aquatic ecosystems towards hydrokinetic technology in a natural setting.

Through a multi-stakeholder partnership, the *Canadian Hydrokinetic Turbines Testing Centre* (CHTTC*;* Figure 1.1) has been developed for testing three common hydrokinetic turbine designs. The CHTTC research programme is supported through a 3 year grant from Natural Resources Canada through the *eco-Energy Innovation Initiative* (ecoEII) to promote the research and development of sustainable green energy technology in Canada. Several private HT developers (*New Energy Corporation; Mavi Innovations; Clean Current Power Systems*) have planned to install and perform operational tests at the CHTTC. In September 2013, the installation of a ducted axial-flow turbine (Clean Current Power Systems, Vancouver, B.C; Figure 1.2) was the first to be installed and intermittently tested across 2013-2014. The HTs from the other companies have been installed and intermittently tested on top-water barges from 2013 to 2015. This research project provides an opportunity to address the broad contexts of the movement ecology and physical responses for important fish species residing at the CHTTC.

Since Lake Sturgeon and Walleye are important and highly managed fishes in Canada, these species are the focus of my research (Figure 1.3). Due to their relatively large size and rheotaxic behaviour, populations of these species may be at risk of blade strike, entrainment, or other associated impacts with future HT projects being planned in swiftwater environments. In addition, Fisheries and Oceans Canada (DFO) and the Manitoba Water Stewardship-Fisheries Branch has expressed interest in gathering information on the spatial ecology of these species within impounded reaches. This information would be useful for directing management plans for Lake Sturgeon and Walleye within run-of-river impoundments. Therefore, there are two objectives that are addressed in my thesis. First, chapter 2 will characterize the spatial ecology of Lake Sturgeon and Walleye throughout an impounded reach located on a large temperate river system. Equally important, the objective for chapter 3 will be to perform a biological risk assessment (Figure 1.4) for hydrokinetic turbines operations occurring at the CHTTC that are undergoing pre-commercial operations by monitoring the residency, movement, and depth-use of Lake Sturgeon and Walleye. Overall, this thesis provides pertinent biological results to inform management actions for the conservation of these fishes in impounded river systems, and to guide best practices for HT operations in river systems where Lake Sturgeon and Walleye reside.

Figures

Figure1.1. The Canadian Hydrokinetic Turbine Testing Centre (CHTTC) located at the Seven Sisters GS tailrace on the Winnipeg River. The top image provides an overview of SSGS tailrace, while the bottom shows the SSGS powerhouse (left) and a downstream view of the SSGS tailrace (right).

Figure 1.2. The substrate-anchored hydrokinetic turbine that was installed and periodically tested throughout 2013 - 2014 at the Canadian Hydrokinetic Turbine Testing Centre (CHTTC) by Clean Current Power Systems (Vancouver, BC, Canada).

Figure 1.3. Examples of the tagged Lake Sturgeon (top) and Walleye (bottom) that were passively-monitored with acoustic telemetry across a multi-seasonal period within an impounded reach located between the Seven Sister GS and McArthur Falls GS on the Winnipeg River, MB.

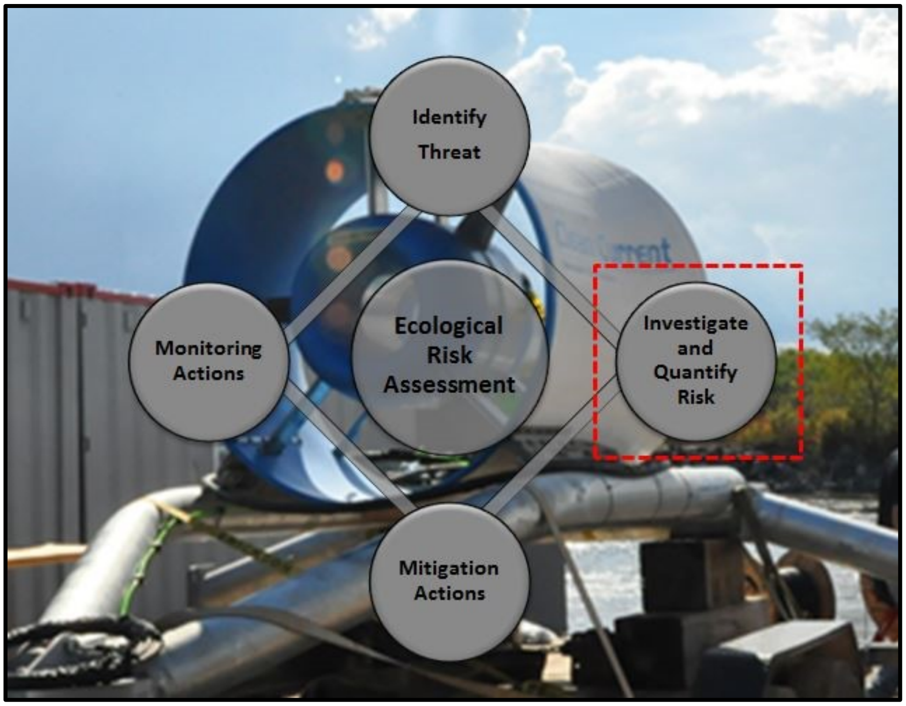

Figure 1.4. *Ecological Risk Assessment* framework that is commonly used for evaluating threats to wildlife and ecosystem structure. This was the overarching framework for chapter 3, which investigated the risk of hydrokinetic turbine operations for wild fish residing at the *Canadian Hydrokinetic Turbine Testing Centre* on the Winnipeg River, MB.

Factors influencing the spatial ecology, activity patterns, and depth use of Lake Sturgeon and Walleye within an impounded reach of the Winnipeg River

Abstract

Impoundments of free-flowing rivers for hydropower generation often confine fish to relatively small reaches that can restrict movement, limit habitat availability, and alter life history strategies. Lake Sturgeon and Walleye are two species that are often confined to impoundments placed in sequence due to hydropower infrastructure. Gathering information about habitat use and biological responses to environmental cues is important for understanding how these species use habitats that result from impoundments. Here, acoustic telemetry was used to describe the seasonal habitat use, swimming activity rates, and depth use for Lake Sturgeon and Walleye within an impounded reach on the Winnipeg River, Manitoba. Lake Sturgeon were distributed in different habitat types likely for spawning, foraging, and overwintering. The tagged Walleye demonstrated high site fidelity to the upstream habitat situated near the tailrace of a hydropower facility. This area is likely used by Walleye for spawning, foraging, and overwintering given the high residency here throughout all months compared to all other habitat types. Both species were more active with increasing water temperatures, and when residing in habitat types located farther upstream, but were minimally active during the winter season throughout the impounded reach. Lake Sturgeon utilized deeper waters as depth availability increased with habitat located further downstream, which is a backwater area associated with the downstream dam. However, Walleye generally remained in depths between 4-7 meters across habitats and seasons, which are likely favoured for foraging success. Overall, these results provide information on the seasonal

habitat use and biological responses to environmental cues for Lake Sturgeon and Walleye that will enhance management and ecological understanding for populations that are confined to impounded reaches.

Introduction

Large rivers are often impounded for hydropower (Cada 1998; Bednarek et al. 2001). There is considerable diversity in hydropower infrastructure and operations, but in general a dam is built to store water and/or create hydraulic head and then water is released through turbines to generate electricity (Baxter 1977; Bednarek et al. 2001). Storage reservoirs and run-of-the-river systems are both common and lead to the creation of impoundments (Geen 1974; Baxter 1977) that can affect the natural flow regime of river systems (Poff et al. 1997). In north temperate regions, Lake Sturgeon and Walleye are two fish species that are often found in larger storage reservoirs and smaller sized run-of-river reservoirs (McDougall et al. 2014; Haxton 2011, 2015). These species are migratory, often moving large distances between foraging/overwintering and spawning locations across the seasons (Caswell et al. 2004; Haxton et al. 2015). Fragmented river systems may hinder the wellbeing of Lake Sturgeon and Walleye populations by reducing habitat availability and cause genetic structuring (i.e., patterns in the genetic makeup; Gyllensten 1985) that may make them less capable of coping with environmental (e.g., drought, extreme flooding events) or anthropogenic stressors such as abrupt discharge reductions, habitat alterations, or recreational fishing and harvesting (Saunders et al. 1991; Haxton et al. 2015). In Canada, populations of Lake Sturgeon have been listed as a species of special concern, threatened or endangered across their range (COSEWIC 2006) and is being considered by Fisheries and Oceans Canada for federal protection under the *Species at Risk Act* (SARA; DFO 2007). Every decade, Lake Sturgeon populations in Canada are reassessed *by Committee on the*

Status of Endangered Wildlife in Canada (COSEWIC) using science-based information to develop recovery strategies and focus management priorities. Additionally, Walleye are an important commercial, subsistence, and recreational fishery in Canada, which includes populations in the Hudson Bay drainage basin (Bozek et al. 2011).

Building an understanding of the behaviour and spatial ecology of free-ranging fish populations is important for improving conservation and restoration management plans (Caro et al. 1998; Cott et al. 2015). The spatial ecology, movement, and behaviour of fish are generally related to biological and environmental cues such as water temperature, ambient light, water flow, and ontogeny (Lucas et al. 2001). For example, environmental parameters such as water temperature and flow rate are thought to initiate spawning behaviour in the early spring for Lake Sturgeon (Forsythe et al. 2012; Auer et al. 2013). Additionally, Walleye are a photophobic species that are generally more active during the crepuscular and nocturnal periods (Swenson and Smith 1973; Kelso 1978; Einfalt et al. 2012), while spawning activity and foraging is closely related to photoperiod and water temperature (Ellis and Giles 1965; Ryder 1977). Seasonal movements and habitat selection of Lake Sturgeon and Walleye have been related to ontogeny, water temperature, and flow rates in past research (Auer 1996; Knights et al. 2002; Peterson et al. 2007). The seasonal migratory behaviour of Lake Sturgeon and Walleye, to make use of various habitats for different life history purposes, can make them susceptible to various threats. However, habitat use, movements and biological responses to environmental cues are not well documented for Lake Sturgeon or Walleye on large rivers that are impounded. Being able to predict and comprehend habitat and biological responses within a fragmented system can help to conserve and restore Lake Sturgeon and Walleye populations more effectively.

Using biotelemetry, researchers can investigate animal space-use and movement patterns over large distances with minimal human inference when collecting data (Cooke et al. 2004; Hussey et al. 2015). Additionally, biological sensor transmitters (i.e., those that transmit depth and activity) are a novel tool for generating detailed animal-borne information to make inferences about behaviour, physiology, and spatial ecology that can help inform management strategies for the species of interest (Cooke et al. 2004; Wilson et al. 2015). For this research, an acoustic telemetry array and model selection was used to investigate the habitat use, swimming activity, and depth use for Lake Sturgeon and Walleye in a run-of-river impoundment situated on a large boreal shield river system. This research will build upon the fundamental ecological knowledge of how these fishes move throughout run-of-river impoundments. Specifically, I explore two questions: 1) how do Lake Sturgeon and Walleye utilize different habitat types within an impounded reach on a seasonal basis? 2) can swimming activity rates and depth use be inferred by abiotic parameters such as water temperature, diel periods, seasonality, and among habitat characteristics? This information will build upon the fundamental understanding of these two fishes, and enhance management of Lake Sturgeon and Walleye populations in an impounded river system.

Methods

Study Location

This study was completed in an impounded reach located on the Winnipeg River, which extends 260 km from Lake of the Woods, ON to Lake Winnipeg, MB and has 8 run-of-river hydropower facilities located along the river system. The study reach is bound on the upstream end by the Seven Sisters Generating Station (SSGS; 50° 7’ 14”N, 96° 1’ 04”W) and the downstream end by

McArthur Falls Generating Station (MFGS; 50° 23' 52"N, 95° 59' 50"W). The telemetry array extends across 50km of riverine and lacustrine habitat that covered the total potential distance between the hydropower dams and a large extent of the backwater area of the MFGS (Figure 2.1). The upper 12 km of the impounded reach is characterized by mostly riverine habitat, while the remaining 30 km is mainly lacustrine which is associated with the backwater area of the MFGS. Depth availability within each habitat type (outlined below) was inferred based on maximum depth provided by the tagged fish. Rather than measuring depth availability based on bathymetry data, this method provides an accurate measure of useable depths within each habitat type based on biological data that was collected across 331 monitoring days. Depth availability varied throughout the impoundment. Maximum depth availability was 9.3 meters in the riverine habitat, 13.6 meters in the SSGS habitat, and 14.7 meters in the riverine-lacustrine habitat. While the maximum depth in this impounded reach has been measured at 24 meters (Manitoba Fisheries Branch 2012), the maximum depth in the acoustic monitoring array was found to be 20 meters, which was located in the lacustrine habitat associated with the backwater area of the MFGS.

Fish Capture and Transmitters

Based on recent assessments completed within this impounded reach, Lake Sturgeon of all age classes currently reside within this reach, and recruitment is occurring (Hrenchuk et al. 2009; Manitoba Fisheries Branch 2012). Past research at this study location found that Lake Sturgeon utilize the Seven Sisters GS tailrace and spillway in late spring to spawn, and also documented relatively high numbers of Walleye residing downstream of the Seven Sisters GS (Hrenchuk 2009).

Fish capture and surgical implantation procedures were conducted during the period of May 20 – June 2, 2014. Multi-panel multifilament gill nets with large mesh size (200 mm to 300 mm) and boat electrofishing were used to capture Lake Sturgeon. Gill net panels were placed in deep pools situated downstream of the Seven Sisters GS tailrace. The gill nets were set at dusk (~1700 - 2100 CDT) and pulled at dawn (soak time of ~12 hours). Lake Sturgeon are resilient to gill net capture, with minimal physiological stress or bodily harm occurring (Baker et al. 2008; Thiem et al. 2011). No immediate mortality or severe injury was observed for the tagged Lake Sturgeon from the capture efforts. Walleye were captured with a combination of fine- (10-20 mm) and large- (200-300 mm) meshed multi-paneled gillnets, as well as with boat electrofishing during the crepuscular and nocturnal periods. Upon capture, the Lake Sturgeon and Walleye were placed in holding tanks filled with ambient river water prior to surgical procedures. The total length (TL, measured to the nearest mm) and weight (kg, measure to the nearest g) was recorded for each individual during the tagging procedure. During the capture period, no individual Lake Sturgeon or Walleye were recaptured while netting or electrofishing.

Acoustic biotelemetry was used to passively-monitor Lake Sturgeon and Walleye throughout the impounded reach during the monitoring period. This study implanted positional transmitters (n = 40; V13-1L; lifespan: 818 days; Vemco, Halifax, NS), as well as sensor transmitters (n = 40; V13AP-1L; lifespan: 649 days; Vemco, Halifax, NS) that provided a 1:1 ratio of depth (i.e., hydrostatic pressure; maximum depth of 68 meters) and swimming activity (i.e., tri-axial accelerometers; maximum range of 3.43 m/s^2). The transmitters were divided equally between Lake Sturgeon (n = 40) and Walleye (n = 40) for both transmitter models (i.e., 20 V13-1L and 20 V13AP-1L per species). All transmitters have a unique coded ID and a transmission frequency of 69 kHz. The acoustic transmitters were manufacturer with a random delay range of 50-130 seconds, with a nominal average delay of 90 seconds, to reduce transmitter collisions from multiple tagged fish.

Lake Sturgeon Tagging Procedures

Individuals were immobilized in a fine-mesh cradle submerged in ambient river water, and were ventrally-orientated to catatonically immobilize and access the incision location. The head and gills remained submerged in a trough filled with river water, which was refreshed between capture events, to maintain normal respiration during the surgeries. All surgical tools and acoustic transmitters were disinfected using a 10% povidone-iodine solution (Betadine®, USA), and nitrile gloves were worn while performing surgical procedures. A small incision (~2 cm) was made with a scalpel on the midline positioned slightly posterior to the pectoral girdle. Either a V13-1L or V13AP-1L acoustic transmitter was inserted posteriorly into the coelom cavity, followed by 3 interrupted sutures (3-0 polydioxanone-II violet monofilament; Ethicon USA) to close the wound. No anesthetic was used on Lake Sturgeon, and all surgeries took less than 5 minutes to complete. Each Lake Sturgeon was returned to a holding tank and released 10-15 minutes post-surgery below the netting site (~0.5 km).

Walleye Tagging Procedures

Similarly, individual Walleye (n = 40) were intra-coelomically implanted with either a V13-1L or V13AP-1L acoustic transmitter. Certain aspects of the surgical procedure (i.e., tool disinfection, gloves worn, and incision closure procedure) were identical to the methods used on Lake Sturgeon. However, there were some modifications for immobilizing Walleye during surgical procedures. Stage-4 electroanesthesia (Summerfelt and Smith 1990) was administered using a Portable Electrosedation Unit (PES; Smith-Root, USA; Vandergroot et al. 2011) prior to surgical implantation to immobilize fish during surgery. The PES was set to 100 hz, 25% duty cycle, and 40 volts. Pulsed detect current is an appropriate anesthetic for adult Walleye because it provides a surgery window of 250-350 seconds, fish recover quickly with minimally impact to vertebral integrity (Vandergroot et al. 2011). Upon stage-4 anesthesia, Walleye were placed supine in a padded v-shaped trough. Ambient river water was continuously pumped over the gills (using a recirculating flow-through pump system) to maintain normal respiration during the surgical period (< 5 minutes). A small incision was made slightly posterior to the pectoral girdle on the ventral mid-line, with a transmitter then inserted posteriorly into the coelomic cavity, followed by 3 interrupted sutures to close the wound. Each fish was given 5-10 minutes to recover from surgery by being placed in a container filled with ambient river water, then subsequently released downstream of the Seven Sisters GS.

No Lake Sturgeon or Walleye died during surgical procedures. All tagged fish were below the 2% tag to fish weight ratio as a means to minimize the chance of altering their natural movement behaviour due to transmitter presence (Gallepp and Magnuson 1972; Ross and McCormick 1981; Rogers and White 2007). Fish handling and surgical procedures were approved and followed the Canadian Council on Animal Care protocol (AUP #101065). This research project was approved by Manitoba Water Stewardship, Fisheries Branch under Scientific Collection Permit No 14-14.

VR2W Telemetry Array

A network of 32 acoustic monitoring receivers (VR2W; Vemco, NS) was set up through the impounded reach to passively monitor the tagged fish (figure 1.1). The receivers were set as singular or paired (i.e., one set on each side of the river) depending on river width and flow characteristics. Prior to receiver placement, stationary range testing (V13-1L: same model as fish transmitters) was completed to determine the maximum detection range of VR2Ws across flow characteristics (i.e. high, moderate, minimal velocity) to determine appropriate positioning of the individual receivers to maximize detection coverage within different habitat types. The stationary range tests found the detection range to be considerable less (~50-75 meters) within the SSGS tailrace due to ambient noise and turbulence, compared to riverine (200 meters) and lacustrine (~400-500 meters) habitat. Due to the limited detection range in the tailrace, the acoustic receivers were closely spaced together to maximize detection coverage in the tailrace area. The SSGS tailrace extends ~1.2 km downstream from the powerhouse, with a width of 50-70 meters. The upper region of the tailrace (0 – 400 meters) was unsuitable for placing VR2Ws due to swift currents and the lack of suitable anchoring locations. There was no receivers were placed in the spillway region because this area was dangerous to navigate by boat and logistically challenging to place receivers here for the entire monitoring period. Receivers were spaced farther apart throughout the riverine and lacustrine habitat because of the greater detection radius and likelihood of detecting tagged fish. The VR2Ws were affixed to 3/8" braided line, and situated between the granite block (27 – 36 kg) anchor and a sub-surface buoy. The receivers that were placed in riverine habitat were shore-tethered using 1/4" galvanized steel cable, and positioned 50-200 meters from the shoreline within 2-6 meters of water. Receivers located in the lacustrine habitat were bottom-set within 5-11 meters of water. An additional trailing anchor was attached to 30 meters of line, and a grapple hook was used to retrieve these receivers when offloading data. Receiver deployment commenced from June 2 to August 9, 2014. As such, the passive monitoring period commenced from August 10, 2014 to July 6, 2015 inclusively once all receivers were in position. Data that was collected prior to installing the full array was not used in the analyses to balance sampling effort through the study reach.

Database Management

False-positive transmissions needed to be identified and filtered from the database prior to performing analyses. False-positive detections can occur when multiple tag transmissions collide when detected by a receiver, resulting as an erroneous tag ID being recorded (Skalski et al. 2002; Pincock 2011). False-positives were first assessed in the Vemco User Environment (VUE; Vemco, NS) as single detections from unidentified coded transmitters. The database was further filtered by assessing spatiotemporal order of detections to remove any additional false-positive detections. Distance and time between consecutive detections was calculated. If a fish was detected at an unrealistic speed between two consecutive detections (i.e., movement velocity of >5 m/s), they were assessed and removed if deemed erroneous (Skalski et al. 2002; Pincock 2011).

Due to the placement of the receivers, a transmission from a fish could be detected multiple times if fish is within the listening range of multiple receivers. As such, duplicate transmissions were filtered from the database by identifying consecutive detections that were recorded less than the minimal tag delay (i.e., <50 seconds). If a fish suddenly stopped moving (i.e., no change horizontally, vertically, or in swimming speed), then the data were inspected and removed if the transmitter was considered to have either been expelled from the fish, or the fish had died. Data filtration was completed using the R Statistical Environment (R Core Development Team, 2014), MS Access (2010), and VUE software (Vemco, NS). The internal clocks of the VR2Ws drift over time, therefore time of arrival for detections were corrected using VUE prior to implementing the data filter queries.

After filtration, the telemetry data were summarized by seasons, habitat types (defined below), and diel periods (i.e., day and night). Daily discharge data (cms [$m^3 \cdot s^{-1}$]) for the SSGS tailrace and spillway were provided by Manitoba Hydro (see Figure 2.2). Daily water temperature readings were provided by the town of Powerview-Pine Falls, which were taken in an adjacent impoundment farther downstream (Figure 2.2). Daily solar information was retrieved online (acquired from www.ptaff.ca) and used to summarize the detection data into diel periods (i.e., day: > local sunrise and < local sunset; night: > sunset and < sunrise). For each receiver, a river distance in kilometers (rkm) was measured using the path tool in Google Earth. The measurements were determined by the sum of linear distances within water from the SSGS to each receiver, which accounted for the tortuosity of the impounded reach.

Habitat Use

For the purposes of investigating habitat use across the impounded reach, the VR2W receivers were aggregated into four general habitat types based on general flow characteristics and rkm position measured from the Seven Sisters GS, which included: (1*) SSGS*, 12 VR2Ws, rkm 0-2 (2) *Riverine*, 7 VR2Ws, rkm 3-11 (3) *Riverine-Lacustrine*, 5 VR2Ws, rkm 12-22 (4) *Lacustrine*, 11 VR2Ws, rkm 24-49 (Figure 1.1). The VR2Ws were grouped by habitat type to reduce autocorrelation between detection events and making inferences across the broader habitat use within the impoundment given the layout of the receiver array in the study system. No receivers were placed immediately below the SSGS spillway and powerhouse to due logistical and safety reasons.

For exploring habitat use, I calculated residency for Lake Sturgeon and Walleye within each habitat type. Residency was calculated as the proportion of tagged individuals that were detected for each given monitoring day within each habitat type. For a fish to be present, it was required to be detected 2 or more times on a given day within each specific habitat type. To investigate temporal trends in habitat use, the daily residency were averaged based on the month of the monitoring period for each habitat type. This also reduced temporal autocorrelation between observations while providing an appropriate timescale to infer seasonal habitat use. With the proportional data structure, I used a generalized linear model (GLM) with a binomial error distribution (Zuur et al. 2009) to interpret residency across monitoring months and habitat types. To account for overdispersion in the data (i.e., variance > mean), a quasi-GLM model was used to correct the standard errors (Zuur et al. 2009). A separate model was generated for each species to discriminate species-specific trends in residency across the impounded reach. The statistical analysis was completed in the R statistical environment (R Core Team 2014).

Swimming Activity and Depth Use

The swimming activity rates (tri-axial accelerometer sensors; m/s^2) and vertical space-use (hydrostatic pressure sensors; m) were investigated to understand how Lake Sturgeon and Walleye respond to environmental parameters when fish are residing in different habitats within run-of-river impoundments. Daily averages for individual fish were calculated when an individual was detected a minimum of 10 times in each habitat type. From the daily count of sensor detections, an average depth and swimming activity value was produced for individual fish. The daily average sensor values were then aggregated by monitoring month, diel period, species, and habitat type. For the analysis, I used linear mixed-models (LMM) to make inferences for swimming activity rates and depth use. Furthermore, Lake Sturgeon and Walleye were modelled separately to make species-specific inferences. When modelling activity rates and depth use, the full candidate models included diel periods, habitat type, and water temperature. Discharge was not included in the model as it was found to be collinear with water temperature when assessing the variance inflation factor (VIF > 2). To maintain temporal dependency and minimize collinearity with the water temperature variable, the data was grouped into four seasons: (A) *Summer*: June – August (B) *Autumn*: September – November (C) *Winter*: December – February (D) *Spring*: March – May. Fish ID was included as a random intercept for each model due to the nested data structure and assessed whether it improved model fit using the information-theoretic approach (AIC; Zuur et al. 2009). Habitat type was included as a variance covariate to maintain homogeneity of variance across the levels of this model term (Zuur et al. 2009). Two-way interactions between "water temperature – habitat type" and "diel period – habitat type" were included when modelling swimming activity and depth use for each species. Data analyses were implemented using the *lmer* function as implemented by the "nlme" package (Pinheiro et al. 2015) in the R Statistical Environment (R Core Team 2014).

To find the most parsimonious models, I began with full fitted models that included all main terms and any relevant two-way interaction and used backwards model selection with applying the information-theoretic approach (AIC, BIC, log-likelihood) to assess model fit and the relative importance for model parameters. For the modelling procedures, the parameter significance was assessed at 0.05 critical threshold using type III sum of squares. For all results, the mean and standard error are provided. Tukey post-hoc tests using the "multcomp" package (Hothorn et al. 2008) was used to make pairwise comparisons when the final models indicated a significant result for habitat type or season. Parametric assumptions were investigated with plotting normalized residuals against fitted values for each explanatory term, pair-plots, and

Cleveland dot-plots. Collinearity in model terms was assessed using VIF in the “car” package (Fox and Weisberg 2011). Independence was investigated by generating correlation lag-plots using the *acf* function in the “car” package (Fox and Weisberg 2011), which provides an indication of auto-correlation in the observations. The assumption of residual homogeneity was checked by plotting normalized residuals against fitted values, and against each fixed model term that was either included or dropped during the model selection process.

Results

During the monitoring period, the acoustic array retrieved 2,930,684 valid detections. Two Walleye (Walleye 05; Walleye 18;) were reported as retained by anglers (last detected at Station 30, July 2014; last detected at Station 15, May 2015). Seven additional Walleye (Walleye 26, 08, 10, 11, 15, 34, and 40) were determined to have either died or expelled their tags during the monitoring period**.**

Lake Sturgeon

Habitat Use

Lake Sturgeon and Walleye exhibited different patterns in habitat use across the impoundment (Figure 2.3). Lake Sturgeon were not evenly distributed across the impounded reach because there were differences found with residency across the habitat types (χ^2 = 639, d.f. = 3, P < 0.0001). When addressing seasonal patterns in residency, a larger proportion of the Lake Sturgeon utilized the SSGS habitat type in the months of May ($\bar{x}$ = 0.31 ± 0.02) and August ($\bar{x}$ = 0.21 ± 0.01) (Figure 2.4). On average, residency were low at the SSGS habitat type through all other months (range: 0.10 – 0.16; Figure 2.4). Lake Sturgeon demonstrated a considerable amount of variation in habitat use across the months of the acoustic monitoring period (χ^2 =

309.9, d.f. = 11, $P < 0.0001$; Figure 2.4). The lacustrine-riverine habitat type generated the highest rate of residency ($\bar{x} = 0.19 \pm 0.004$) throughout the monitoring period, this was used by a larger proportion of the tagged fish in October ($\bar{x} = 0.32 \pm 0.04$) and November ($\bar{x} = 0.25 \pm 0.02$). Lake Sturgeon heavily utilized the lacustrine habitat in the months of July ($\bar{x} = 0.19 \pm 0.03$) and August ($\bar{x} = 0.19 \pm 0.02$), then decreased here as autumn approached. Lake Sturgeon appeared to move out of the lacustrine habitat, and upstream into the lacustrine-riverine habitat type as autumn progressed (Figure 2.4). During the winter months (December to February), residency was relatively uniform across habitat types, except that the riverine habitat was marginally utilized by the tagged Lake Sturgeon (Figure 2.4).

Swimming Activity

The fitted model to explain Lake Sturgeon swimming activity rates included habitat type, diel period, season, water temperature, and the 'water temperature∗habitat type' interaction (table 2.1). The inclusion of Fish ID as a random effect improved model suitability when investigating swimming activity (ΔAIC = -193.6). In addition, including a variance covariate for monitoring month improved the residual homogeneity of variance in the candidate models. The two-way interaction for 'habitat type∗diel period' was dropped during the backwards model selection. Although diel period was retained in the final model for explaining variation in sturgeon swimming activity, it was not significant at the 5% threshold ($\chi^2 = 3$, d.f. = 1, $P < 0.083$; Table 2.2). Lake Sturgeon demonstrated higher swimming activity rates as water temperatures increased ($t = 14.7$, $P < 0.0001$; Figure 2.5; Table 2.2), but this trend was dependent on the habitat type where the tagged fish were residing ($\chi^2 = 53.6$, d.f. = 3, $P < 0.0001$; Table 2.2). Lake Sturgeon were generally more active as water temperatures increased, except in the habitat near the SSGS where activity rates were somewhat similar across the water temperature range (figure

2.5). Lake Sturgeon exhibited considerable variation in swimming activity rates across different habitats (χ^2 = 126.3, d.f. = 3, P < 0.0001; Figure 2.6), with all pairwise comparisons between habitat types demonstrating different activity rates (Table 2.3). In general, Lake Sturgeon were more active near the SSGS ($\bar{x}$ = 0.60 m/s^2 ± 0.045, range = 1.48) and in the riverine habitat ($\bar{x}$ = 0.67 m/s^2 ± 0.057, range = 1.16), while relatively less active in the riverine-lacustrine ($\bar{x}$ = 0.37 m/s^2 ± 0.023, range = 1.09) and lacustrine ($\bar{x}$ = 0.42 m/s^2 ± 0.024, range = 0.85) habitat types. Swimming activity was also varied substantially on a seasonal basis (χ^2 = 60.1, d.f. = 3, P < 0.0001; Figure 2.6; Table 2.2). Activity rates for Lake Sturgeon ranged between 0 – 1.48 m/s^2 across the seasons. Peak activity rates for Lake Sturgeon occurred during the summer season ($\bar{x}$ = 0.60 m/s^2 ± 0.03), while swimming activity rates were somewhat lower during the spring ($\bar{x}$ = 0.50 m/s^2 ± 0.032) and autumn ($\bar{x}$ = 0.50 m/s^2 ± 0.033), and were much less active in the winter season ($\bar{x}$ = 0.20 m/s^2 ± 0.033).

Depth Use

Lake Sturgeon were frequently found deeper in the water column (mean = 7.12 m ± 2.91) compared to Walleye (mean = 4.73 m ± 1.77) throughout the monitoring period (Figure 2.7). The final fitted model for explaining depth use included habitat type, water temperature, season and the habitat type - temperature interaction (Table 2.4). The random effect of Fish ID was found to improve the candidate full model for Lake Sturgeon (ΔAIC = -86.5) and including habitat type as a variance covariate improved residual homogeneity for modelling depth use (ΔAIC = -21.7). Depth use for Lake Sturgeon varied across the seasons (χ^2 = 17.2, d.f. = 3, P < 0.001; Figure 2.8; Table 2.5) with fish using shallower depths in autumn ($\bar{x}$ = 7.07 m ± 0.29) than the summer ($\bar{x}$ = 7.61 m ± 0.36; z = 3.34, P = 0.004; Table 2.6). Lake Sturgeon also exhibited variation in depth use across habitat types (χ^2 = 130.3, d.f. = 3 , P < 0.0001; Figure 2.9), with differences found between all habitats except when comparing the riverine-lacustrine and lacustrine habitat types ($z = 2.3$, $P = 0.084$; Table 2.6). Water temperature was retained in the model due to the interaction with habitat type (Table 2.4), but was not a significant main term by itself (Table 2.5). The interaction between water temperature and habitat types was an important predictor for explaining trends in depth use for Lake Sturgeon ($\chi^2 = 10.4$, d.f. = 3, $P = 0.015$; Table 2.5). As water temperature increased, Lake Sturgeon moved into deeper water in the riverine habitat and shallower in the riverine-lacustrine habitat, while there was marginal change in depth use at the SSGS and lacustrine habitat types (Figure 2.10). Lake Sturgeon moved into deeper waters when in the SSGS habitat type between 8 – 12^{o} Celsius (Figure 2.10).

Walleye

Habitat Use

The residency for Walleye were different among the habitat types ($\chi^2 = 11{,}976$, d.f. = 3, $P < 0.0001$). The habitat near the SSGS was found to have highest rates of residency ($\bar{x} = 0.37 \pm 0.004$), while the tagged Walleye minimally resided in the riverine ($\bar{x} = 0.06 \pm 0.002$), riverine-lacustrine ($\bar{x} = 0.06 \pm 0.002$), and lacustrine ($\bar{x} = 0.04 \pm 0.001$) habitat types (Figure 2.11). Residency was also found to change according the month of the monitoring period ($\chi^2 = 148.3$, d.f. = 11, $P < 0.0001$). Interestingly, Walleye were less present near the SSGS in the months of June ($\bar{x} = 0.28 \pm 0.007$) and July ($\bar{x} = 0.22 \pm 0.007$), which was subsequently followed by highest residency at the habitat at this habitat type in August ($\bar{x} = 0.44 \pm 0.007$) and September ($\bar{x} = 0.47 \pm 0.006$). Residency remained elevated throughout the fall and into the winter months within the habitat situated near the SSGS powerhouse and spillway (Figure 2.11). Walleye were found to mainly utilize the riverine habitat type in May ($\bar{x} = 0.13 \pm 0.004$) and June ($\bar{x} = 0.09 \pm 0.005$).

Walleye appear to utilize the riverine-lacustrine habitat type as an overwintering site, although to a lesser extent compared to habitat near the SSGS (Figure 2.11). Residency were highest in the riverine-lacustrine habitat type in December ($\bar{x} = 0.08 \pm 0.002$), January ($\bar{x} = 0.09 \pm 0.002$), and February ($\bar{x} = 0.09 \pm 0.001$). Walleye minimally resided within the riverine-lacustrine habitat between May to October (range: 0 – 0.03; Figure 2.11), while the tagged Walleye were minimally present in the lacustrine habitat type across the entire monitoring period (range: 0.03 – 0.06; Figure 2.11).

Swimming Activity

The fitted model for explaining patterns in swimming activity for Walleye included habitat type, water temperature, season, and the 'habitat type∗water temperature' interaction (Table 2.1). The inclusion of Fish ID as a random effect was found to improve model suitability when modelling swimming activity for Walleye (ΔAIC = -87.7) and the inclusion of month as variance covariate improved the residual homogeneity in the candidate models. The two-way interaction for habitat∗diel was dropped, while retaining the habitat∗temperature interaction ($\chi^2 = 13.9$, d.f. = 3, $P < 0.003$). Because diel period was dropped in the final fitted model for explaining swimming activity for Walleye, there was no significant difference documented with swimming activity rates between the day and night periods. When investigating the relationship between water temperature and habitat type, swimming activity increased with rising water temperature, but at different rates depending on habitat type ($t = 4.5$, $P < 0.0001$; Figure 2.12). The activity rates for Walleye varied considerably across the habitat types ($\chi^2 = 18.9$, d.f. = 3, $P < 0.0001$; Table 2.2, Figure 2.13) with different activity rates between all habitat types except for the riverine and riverine-lacustrine habitat types (Table 2.3). Walleye were more active in the riverine ($\bar{x} = 0.56$ m/s^2 $\pm$ 0.03) and SSGS ($\bar{x} = 0.55$ m/s^2 $\pm$ 0.03), while were less active in the riverine-lacustrine ($\bar{x}$

= 0.33 m/s^2 ± 0.02) and lacustrine ($\bar{x}$ = 0.35 m/s^2 ± 0.07) habitat types throughout the monitoring period. Swimming activity was also explained by seasonality (figure 2.13). Walleye were most active during the summer ($\bar{x}$ = 0.72 m/s^2 ± 0.043) and autumn ($\bar{x}$ = 0.62 m/s^2 ± 0.041), moderately active in the spring ($\bar{x}$ = 0.40 m/s^2 ± 0.027), and were relatively inactive during the winter period ($\bar{x}$ = 0.19 m/s^2 ± 0.016).

Depth Use

On average, Walleye frequented shallower depths than Lake Sturgeon (Figure 2.7), residing at an average depth of 4.82 m (± 1.77) throughout the monitoring period. The random effect of Fish ID was found to improve the candidate models for Walleye (ΔAIC = -81.2) and inclusion of habitat type as a variance covariate improved residual homogeneity when modelling depth use for Walleye (ΔAIC = -2.8). When investigating the predicted model terms for explaining depth use for Walleye, the best fitting model only included habitat type (χ^2 = 71.8, d.f. = 3, P < 0.0001; Table 2.5). During the model selection process, the terms for diel period, season, water temperature, and the two-way interactions were sequentially dropped from the final model (Table 2.4), indicating that these model terms were not important for explaining the depth use for Walleye in the impounded reach. Although depth use varied across the habitat types, the tagged Walleye generally utilized similar depths when residing in the lacustrine habitat ($\bar{x}$ = 4.32 m ± 0.44), the SSGS habitat ($\bar{x}$ = 4.89 m ± 0.14), and in the riverine habitat ($\bar{x}$ = 4.36 m ± 0.16; Table 2.6). In contrast, Walleye generally reside at greater depths when residing within the riverine-lacustrine habitat ($\bar{x}$ = 7.1 m ± 0.34; Figure 2.14).

Discussion

Relatively few studies have focused on addressing the habitat use and movement responses of Lake Sturgeon and Walleye within run-of-river impoundments on large river systems. The purpose of this research was to gain insights into the spatial ecology of two migratory species, Lake Sturgeon and Walleye, which often populate impounded reaches. To my knowledge, this is the first telemetry study to link habitat use, activity rates, and depth use to investigate the spatial ecology of Lake Sturgeon and Walleye within an impounded reach on a large boreal shield river. The study reach was situated between two hydroelectric generating stations, restricting the upstream and downstream movement of these populations and limiting habitat availability that could place these fish at greater risk of anthropogenic stressors. For example, fish stranding (see Nagrodski et al. 2012) at the base of the SSGS spillway has been a concern due to discharge reductions at the SSGS spillway (K. Kansas, Fisheries Biologist, Manitoba Water Stewardship, Fisheries Branch, Pers. Comm.), which may occur when discharge rates are lowest during autumn and winter (Figure 2.2). Entrainment through sluice gates and turbines at the McArthur Falls GS also poses a risk to these populations within this impounded system. Entrainment events have been documented for Lake Sturgeon at adjacent hydropower facilities on the Winnipeg River (McDougall et al. 2011, 2014) and elsewhere (McKinley 1998). This could either lead to injury, mortality, but may also supplement populations that are located downstream side of the hydropower facilities, but has not been documented in this reach. Walleye have also been studied closely at hydropower stations, with entrainment being documented through turbines and spillway gates (Spinelli 2010). Furthermore, there is concern with regards to the potential for deleterious harm from hydrokinetic turbines that have recently begun pre-commercial testing at the Seven Sisters GS tailrace.

Lake Sturgeon

The tagged Lake Sturgeon moved throughout the impoundment during the monitoring period for spawning and foraging purposes. Other research has shown that Lake Sturgeon tend to migrate out of lake environments after the winter, and move upstream to spawn, which often occurs at migration barriers if passage is not possible (e.g., dams, hydropower facilities; Rusak and Mosindy 1991; Peterson et al. 2007). Similar results were found here with a moderate proportion of the tagged individuals congregating near the Seven Sisters GS in May 2015 (Figure 2.4), this corresponded with the spawning season. The tagged Lake Sturgeon were captured in the previous spring/summer near the SSGS tailrace that is a known spawning location (Hrenchuk et al. 2009). Lake Sturgeon are considered to spawn intermittently, taking 2-7 years between subsequent spawning events (Roussow 1957; Auer et al. 1999). In some instances, non-spawning conspecifics may migrate with spawning conspecifics (Peterson et al. 2007). The tagged Lake Sturgeon may have returned to the SSGS area to spawn, or be non-spawning individuals that have co-migrated with the spawning cohort. In June, residency returned to similar levels that were documented prior to the spawning season at the SSGS habitat type. Some individuals remained in the SSGS habitat, while a number of the tagged individuals moved downstream to foraging habitat located in the riverine-lacustrine and lacustrine habitat immediately after the spawning season. Previous research in other river systems found similar upstream and downstream movements in the periods before and after the spawning season (McKinley et al. 1998; Borkholder et al. 2002; Lallaman 2008). Some individuals remained in the area immediately downstream of the SSGS during the summer and fall, which indicates that this habitat is likely a suitable for foraging area for Lake Sturgeon during the open-water period. Also, the late summer and autumn periods were characterized by elevated discharge rates (Figure 2.2). Given that Lake Sturgeon are known to response to flow (McDougall et al. 2013b), the tagged individuals may have been attracted to the swift hydraulic conditions near the SSGS during this period of elevated discharge. Lake Sturgeon were most active when residing near the SSGS likely because the tagged individuals were residing in swifter conditions than would be experienced downstream. Lake Sturgeon likely have to negotiate swift conditions while foraging and spawning in the SSGS habitat, which could be energetically taxing and influence behaviour and survival (Thiem et al. 2015).

Lake Sturgeon are thought to prefer deep, slower moving waters when foraging in the summer (Peterson et al. 2007; Auer et al. 2013), which is consistent with our results. The tagged individuals demonstrated higher activity rates in the summer than other seasons in the riverine-lacustrine and lacustrine habitat type, which may be related to foraging behaviour. The depth use results indicate that Lake Sturgeon utilize the greater depths available in the lacustrine habitat, which coincides with the summer period when water temperature were highest. Lake Sturgeon likely move upstream into the riverine-lacustrine habitat type as water temperature decline as autumn progresses (Figure 2.4). The riverine-lacustrine habitat type is likely an optimal foraging area for Lake Sturgeon prior to the overwintering period, yet is less utilized in the summer months due to elevated water temperatures.

From investigating depth use (Figure 2.7, 2.9), Lake Sturgeon changed their depth frequently across months and habitat types. Lake Sturgeon are demersal, having high fidelity with the substrate to overwinter, spawn, and forage (Scott and Crossman 1973; Auer et al. 2013). Because the tagged individuals moved throughout the impounded reach, it is unlikely that Lake Sturgeon are selecting specific depths, but rather are limited by the depth availability within the habitat types. Instead, depth use is dependent on seasonal habitat preferences that were used for different biological purposes. However, depth use in the SSGS habitat type was greater in the spring season as Lake Sturgeon moved into the SSGS tailrace. Lake Sturgeon are likely utilizing the SSGS tailrace in the late spring and early summer to spawn where greater depths are available (i.e., 7- 14 m), and when discharge rates gradually increase (Figure 2.2). Although measurements were not taken, the bottom of the tailrace is likely an area of lower velocity at greater depth (Allan and Castillo 2007) so the tagged individuals may reside here as a method for minimizing energy expenditure. In other seasons, Lake Sturgeon utilized shallower depths when residing within the SSGS habitat type. Given that depth only exceeds 7 meters in the tailrace within the SSGS habitat type, it is likely that Lake Sturgeon do not utilize the tailrace much throughout summer, autumn, and winter since they are generally found in shallow depths. According to water temperature readings, Lake Sturgeon utilized greater depth associated with the SSGS tailrace when water temperatures ranged between 8-12^{o} Celsius. As these temperatures are within the optimal range for spawning, this is likely when the spawning cohort utilized the SSGS tailrace to spawn. These temperatures occurred between May 5th – May 26th, 2015 (Figure 2.2).

The tagged Lake Sturgeon utilized shallower depths during the summer, autumn, and winter when in the SSGS habitat type (Figure 2.9). Spilling was dramatically reduced throughout the summer and fall at the SSGS, with peak discharge rates occurring in August (>1200 cms) and approached 0 cms in October, 2014. Discharge rates dropped from 68 cms on October 6th to 0 cms on October 7th, 2014. There were a few periods when spilling began, which were followed by spillway closure (e.g., March 9th and June 6th, 2015). Although daily spilling reductions were infrequent, this could cause stranding to some extent. Since Lake Sturgeon and Walleye were residing in the SSGS habitat type when the spillway discharge is reduced, they could be at risk of being stranded at the base of the spillway gates (Nagrodski et al. 2012). However, due to logistical and safety constraints, I was unable to monitor the tagged fish in close proximity to the SSGS spillway (i.e., <1.5 km from spillway) and could not measure the occurrence and frequency of stranding.

Walleye

Walleye appeared to favor swifter habitats (i.e., SSGS and riverine habitat types) than the tagged Lake Sturgeon across the monitoring period. The results indicate that the habitat located close to the SSGS (rkm 0-2) was highly utilized by the tagged Walleye throughout the spring, autumn, and winter months. While past studies have found that Walleye commonly migrate large distances between foraging and spawning habitats (Hayden et al. 2014), other research has documented that Walleye utilize small habitat areas during the foraging season that are located in close proximity to where spawning occurred in early spring (Colby et al. 1981; Crowe 1962; DePhilip et al. 2005). Interestingly, there was a pronounced increase in Walleye residency in the SSGS habitat type in August and September 2014, which coincided with highest discharge rates and water temperatures. With Walleye being less present in the lacustrine and riverine-lacustrine habitats, it appears that SSGS habitat type is likely important for spawning in the spring, foraging during late-summer and autumn, and for overwintering, while the downstream habitat is not preferred. The Seven Sisters generating station may provide a unique forage habitat as it is a barrier to small bodied fish moving upstream, and entrained fish would likely be susceptible to predation. Previous research on this system also noted relatively high numbers of Walleye in proximity to the SSGS and in the riverine habitat when performing gill net transects completed during the open-water seasons in 2008 and 2009 (Hrenchuk 2009). The tagged Walleye appeared to overwinter near the SSGS, but also some individuals moved downstream to the riverine-lacustrine habitat to overwinter.

The two farthest receivers of the telemetry array did not detect any tagged Walleye, which is another indicator that Walleye tagged near the Seven Sisters GS have some degree of fidelity to the upper region of this impoundment, while they do not utilize all areas of the backwatered region associated with the McArthur Falls GS. Walleye generally have three life history strategies, which include 1) river resident – river spawning, 2) lake resident – lake spawning, and 3) lake resident – river spawning (Bozek et al. 2011), with distinct populations being found to utilize riverine and lacustrine habitats depending on the life history strategy that has been selected depending on habitat availability (Palmer et al. 2005). Although there was some variation in the residency, it may be likely that the majority of the tagged Walleye are "river resident - river spawning" individuals, as they were captured and tagged near the SSGS. Only a small proportion of the tagged Walleye were found residing in the lower reaches of the impoundment, these are possibly "lake resident – river spawning" individuals. As such, there are likely different life history strategies being employed by Walleye throughout the impoundment. An important consideration for fisheries managers would be to address recreational catch rates and habitat restoration measures based on habitat characteristics, rather than at the reach-wide scale given that there likely several populations of Walleye within impounded reaches depending on availability and diversity of habitat types.

Swimming activity rates for Walleye were dependent on water temperature. In general, the tagged individuals were more active in the summer and autumn seasons when water temperature was rising (Figure 2.12). Walleye became more active as water temperatures approached ~20^{o} Celsius when residing in the SSGS, lacustrine, and riverine habitat types (Figure 2.12). These temperatures are likely favourable for Walleye when foraging during the summer and fall seasons, while lower temperature appear to reduce activity, particularly in the winter months. Similarly, past research has documented water temperatures between18-24^{o} Celsius are optimal for growth and foraging (Wismer and Christie 1987; Christie and Regier 1988). The peak of spawn for Walleye is thought to occur when temperatures range between 4-14^{o} Celsius, with the optimal spawning temperature being 7.7^{o} Celsius, and utilize coarse substrate to broadcast their eggs (Scott and Crossman 1973; Bozek et al. 2011). Walleye likely utilize the area near the Seven Sisters GS to spawn based on the high residency, the availability of suitable spawning substrate (coarse-grain material; Hrenchuk 2009), and elevated swimming activity rates in the spring season in the SSGS habitat type. Walleye have been found to spawn in and around tailrace waters in other impounded systems (Crowe 1962; Paragamian 1989; DePhilip et al. 2005).

Walleye depth use was different when compared to Lake Sturgeon. In general, Walleye frequented shallower depths than Lake Sturgeon throughout the impoundment (Figure 2.7, 2.8). This result may be related to the availability of deeper water habitats in the riverine-lacustrine and lacustrine habitat types, while Walleye mainly remained upstream in the SSGS and riverine habitat types where water depths are generally shallower (Figure 2.14). However, depth use for Walleye was similar between the lacustrine, riverine, and SSGS habitat types, which indicates that walleye are preferentially selecting depth between 4-7 meters for foraging purposes (Figure 2.8, 2.14). Walleye have a subretinal tapetum (Wunder 1930) that make them adapted for dimly-lit conditions. Previous work by Ryder (1977) found that ambient light level of 1-10% reach depths between 4-7 meters at Shebandowan Lake during the open-water season. Walleye are likely selecting this depth range as a method to balance prey availability (e.g., Yellow Perch [*Perca flavescens*]; Forney 1974) and successfully capturing prey in dim-light conditions. Walleye were found at greater depths in the riverine-lacustrine habitat type, but only reside in this habitat type at a relatively high rate during the winter months. The results indicate that Walleye remain in similar water depths across the full diurnal cycle. However, previous research suggests that Walleye do change depths between diel periods (Ellis and Giles 1965), with transitions into shallower waters as night progresses (Bozek et al. 2011). The conflicting results with the findings for this research is likely because Walleye were residing downstream of the SSGS in swift conditions, which may make diel vertical movements (DVM) unnecessary (Ellis and Giles 1965). Additionally, DVM may not have occurred for Walleye because the depth availability was restricted to 6-7m outside of the SSGS tailrace.

Management Implications

The goal of this study was to provide fisheries management with pertinent information that can be applied to improve conservation measures. This study documented interesting findings regarding the spatial ecology of two heavily managed fish species in North America. To my knowledge, this is the first telemetry study to combine information on habitat use and biological response in a multi-species assessment within an impounded reach of a large river system. The generated information is critical for describing how these fish species utilize different habitats and how they move through fragmented systems on a multi-seasonal basis. This will help to enhance the fundamental understanding and management of these species.

Both Lake Sturgeon and Walleye are targeted by recreational fisheries within this region of Manitoba. Additionally, there are cumulative threats from hydropower operations (i.e., stranding, entrainment, habitat alterations) and the recent formation of a hydrokinetic testing centre at the SSGS tailrace that is currently performing pre-commercial operations. In particular, the upstream habitat should be a priority for habitat and fisheries protection given that both species reside here to some extent throughout the seasons, but predominantly during the spawning and foraging periods. This information will also assist managers with future sampling for population assessments given the seasonal trends in residency across different habitat types. With stranding events of Lake Sturgeon being a long standing concern at the base of the Seven Sisters spillway, it should be a high priority to maintain discharge between May and June when spawning and non-spawning Lake Sturgeon migrate towards the SSGS. Continuous flow is important for the downstream dispersal of juvenile Lake Sturgeon upon their swim-up period, which occurs 3-4 weeks after hatch (Randall 2008; Cleator 2010). Given that both species broadcast their eggs in shallow waters, alterations in spillway discharge should be minimized before, during, and after the spawning period to reduce dewatering spawning habitat, stranding spawning individuals, or restricting downstream dispersal upon larval swim-up. On the Winnipeg River, discharge rates are regulated both at the hydropower facilities and at the outflow of Lake of the Woods, ON, this determines flow rates based on the needs of multiple user groups. Regional management pertaining to Lake Sturgeon and Walleye can use this information to recommend discharge rates at hydropower GSs and at weirs that regulate lake outflows based on the findings for residency, depth use, and activity rates for these species within impoundments.

Habitat enhancements and conservation measures often commence outside of the scientific framework (Neuswanger and Bozek 2004; Bozek et al. 2011). Here, I utilize biotelemetry to collect information for prioritizing habitat augmentation and managing threatened and recreational fisheries with an impounded reach. Given the high site fidelity near the Seven Sisters GS for Walleye, there may be sub-populations that occur within impoundments. Walleye populations have been found to be overexploited by recreational fishing immediately downstream of hydropower facilities (Pegg et al. 1996, 1997) as these locations are congregation sites during spawning and can be easily accessible by anglers (Bozek et al. 2011). While there are closure to recreational fisheries during the Walleye spawning season in Manitoba, fisheries managers could consider additional measures such as catch-release restrictions or adjust catch-quotas on a temporal basis, considering that the tagged Walleye demonstrated high site fidelity to areas near the upstream hydropower stations and make them susceptible to recreational angling throughout the open water seasons. Future work needs to be implemented to investigate the movement and habitat use of Walleye that reside in different habitats to determine different life history strategies being employed within impoundments.

Conclusion

In this study, I addressed the multi-seasonal spatial ecology of Lake Sturgeon and Walleye relative to biologically relevant parameters. I first examined the general habitat use of Lake Sturgeon and Walleye by quantifying residency across habitat types. Relatively limited information has been documented for Lake Sturgeon and Walleye within impoundments on the Winnipeg River system (Barth et al. 2011) and across other areas of their range (Haxton et al. 2015). In addition, the movement and space-use in regulated and impounded systems are not fully understood both for Lake Sturgeon (McDougall et al. 2014) and Walleye (Bozek et al. 2011). This information reported here may be used to direct management actions for impounded reaches located on large river systems. Across North America, endangered Lake Sturgeon are thought to be sensitive to anthropogenic impacts as some populations continue to decline or are not recovering even after the significant historical cause of harm (i.e., commercial fishing) has been removed (Velez-Espino and Koops 2009). Because of their sensitivity, this information is important for specifying where and when Lake Sturgeon may be susceptible to harm within impounded systems. Walleye are also highly sought after by recreational fisheries in impoundments, so these results will help to inform managers focused on maintaining Walleye fisheries in impounded systems.

Figures

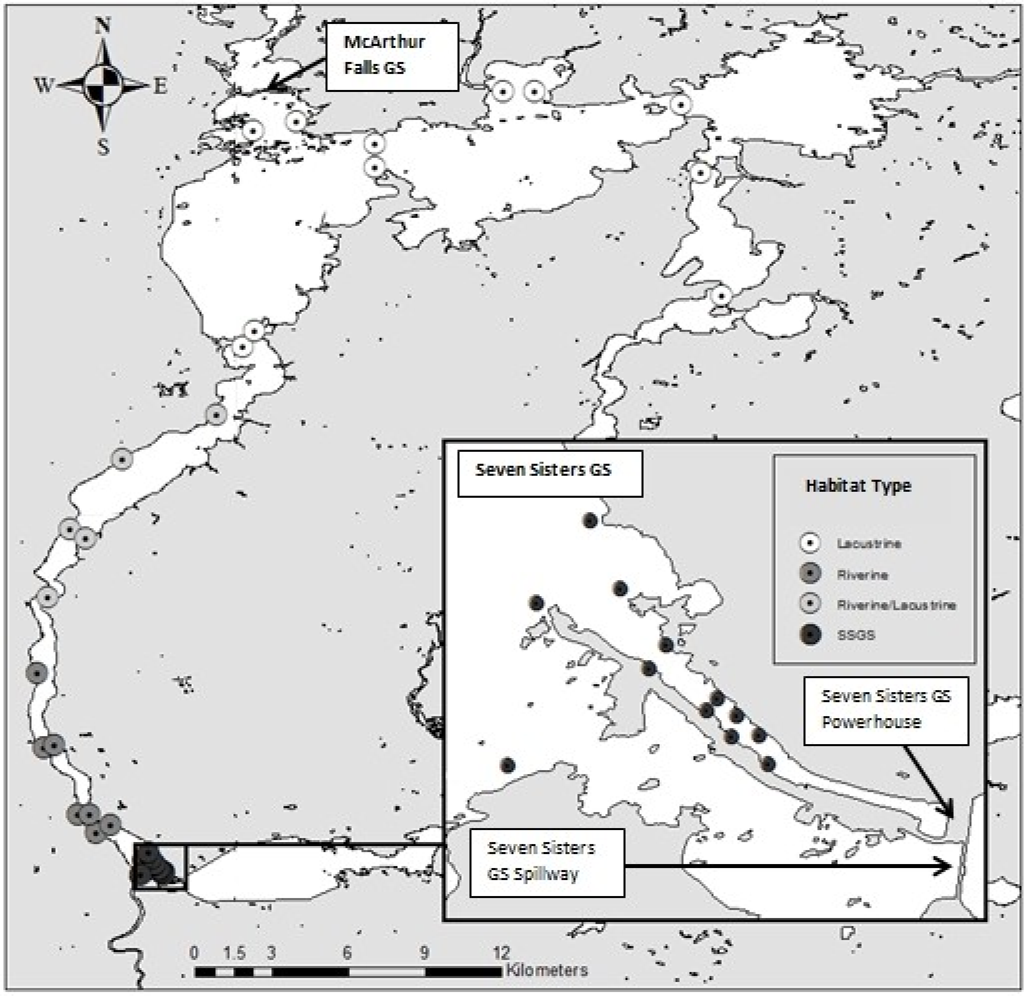

Figure 2.1. An overview of the VR2W acoustic receiver (Vemco, NS) array within the impounded reach situated between the Seven Sisters GS and McArthur Falls GS on the Winnipeg River, MB. The receivers are shaded by their habitat types. The map inset shows the acoustic receivers that are located in the SSGS habitat type. The riverine habitat type is situated downstream of the Seven Sisters GS (dark grey), followed by the riverine-lacustrine habitat type (light grey), and the lacustrine habitat type (white) that is associated with the backwatering area of the McArthur Falls GS.

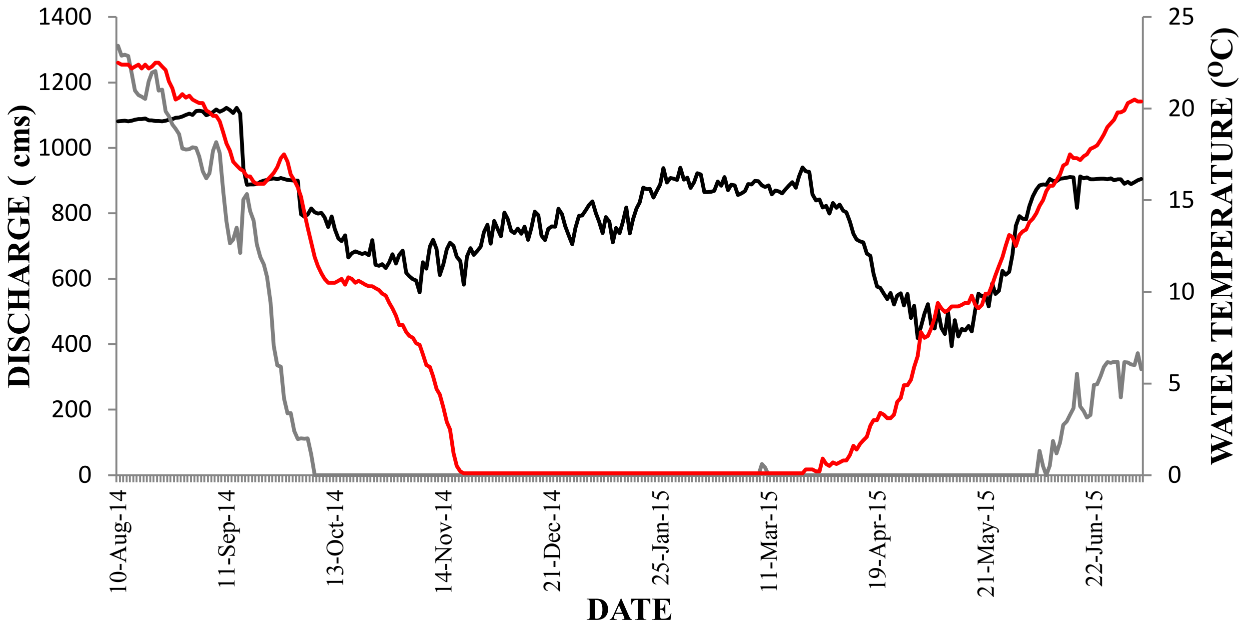

Figure 2.2. An overview of the daily water temperature (red) provided by the town of Powerview-Pine Falls, as well as the discharge from the SSGS tailrace (black) and SSGS spillway (grey) provided by Manitoba Hydro through the monitoring period (August 10, 2014 to July 6, 2015).

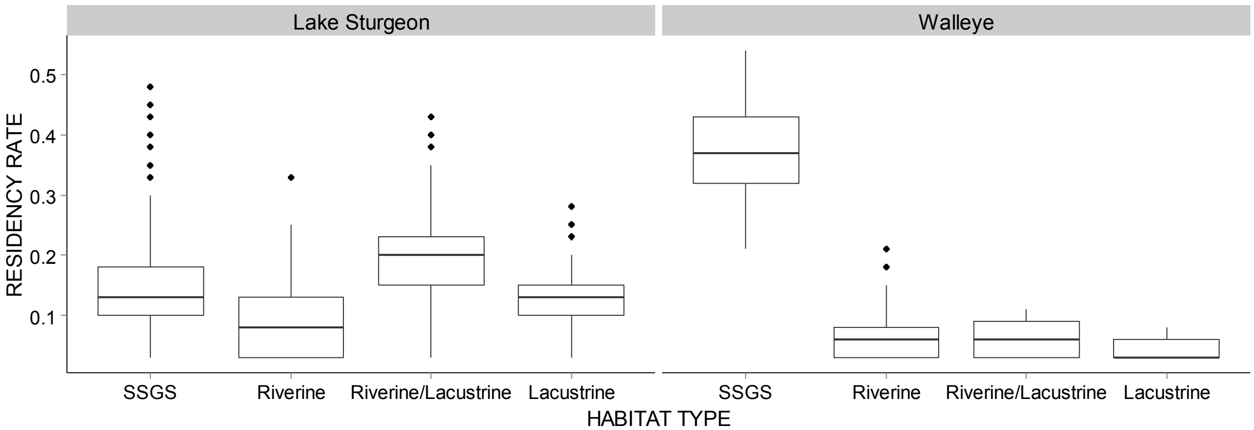

Figure 2.3. The residency for Lake Sturgeon and Walleye across four different habitat types within the impounded reach located on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

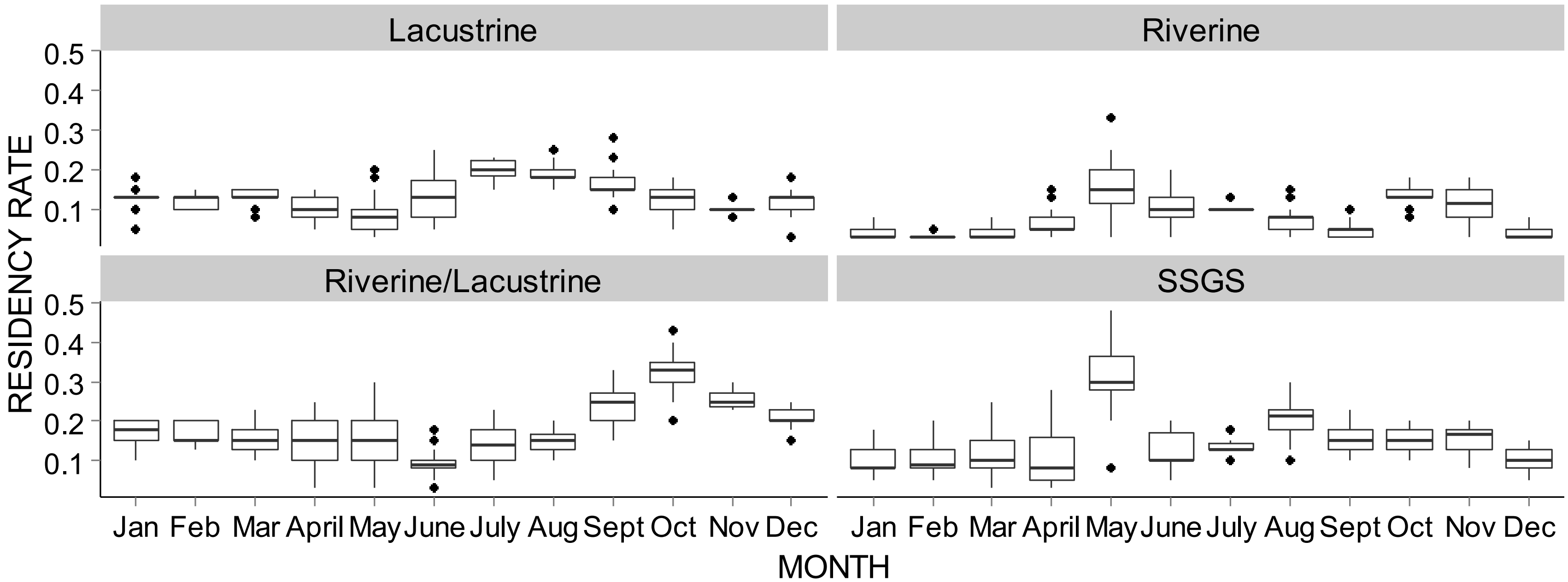

Figure 2.4. An overview of residency for Lake Sturgeon, which is summarized on a monthly basis in 2014 (August – December) and 2015 (January to July) across different habitat types within an impounded reach situated between the Seven Sisters GS and McArthur Falls GS on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

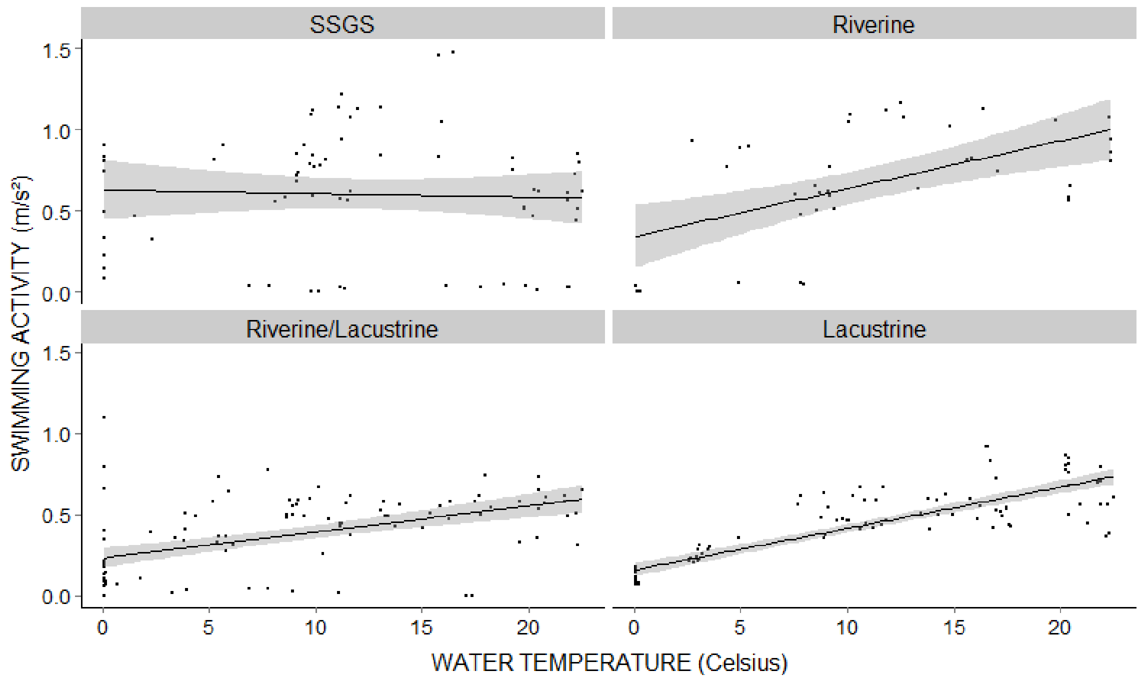

Figure 2.5. Swimming activity rates (tri-axial accelerometer sensors; m/s^2) for Lake Sturgeon relative to the water temperature range that was experienced during the multi-seasonal monitoring period (August 10, 2014 – July 6, 2015), which has been further summarized based on habitat type. The plot provides the raw data, the line of best fit, and 95% confidence intervals.

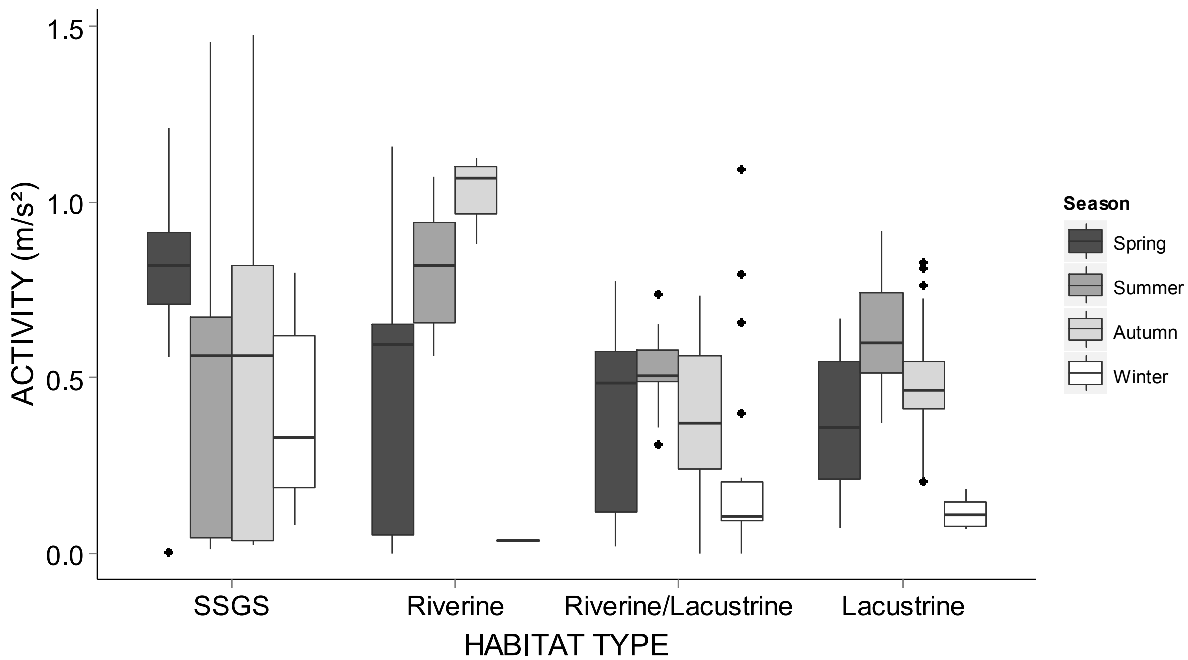

Figure 2.6. Swimming activity rates (tri-axial accelerometer sensors; m/s^2) that were generated by the tagged Lake Sturgeon across different habitat types and seasons within an impounded reach that is situated between Seven Sisters GS and McArthur Falls GS located on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

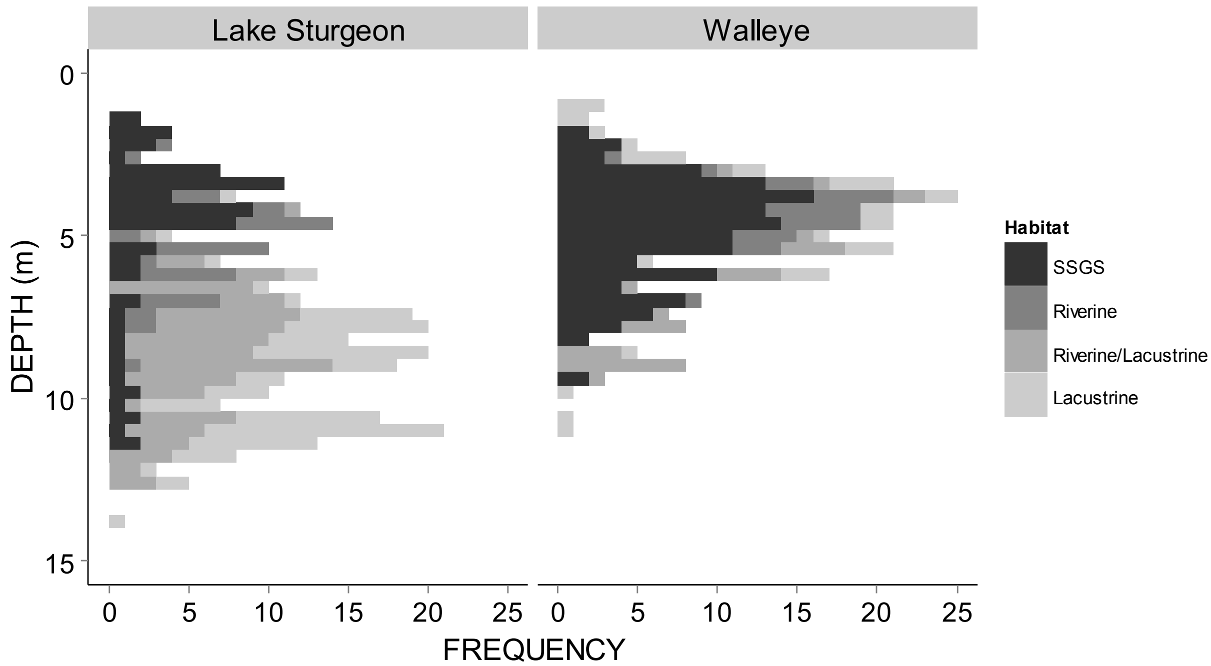

Figure 2.7. An overview for the frequency of depths selected (hydrostatic pressure sensors; m) by the tagged Lake Sturgeon (left) and Walleye (right) relative to the habitats types located in an impounded reach that situated between the Seven Sisters GS and McArthur Falls GS on the Winnipeg River, MB.

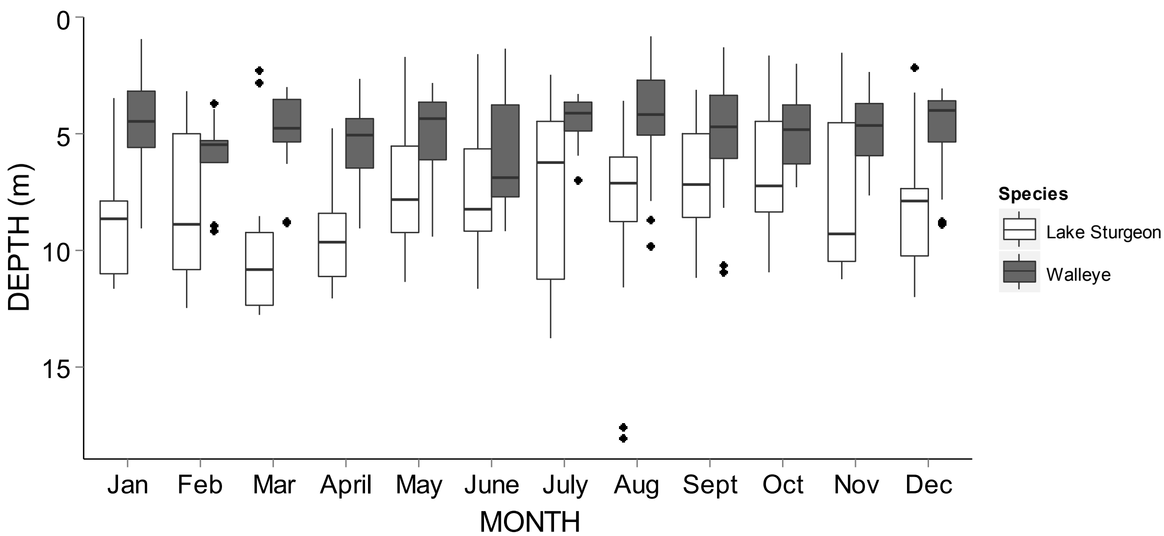

Figure 2.8. Depth use (hydrostatic pressure sensors; m) comparison between Lake Sturgeon (white) and Walleye (grey) across the months throughout the monitoring period within the impounded reach between the Seven Sisters GS and McArthur Falls GS on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

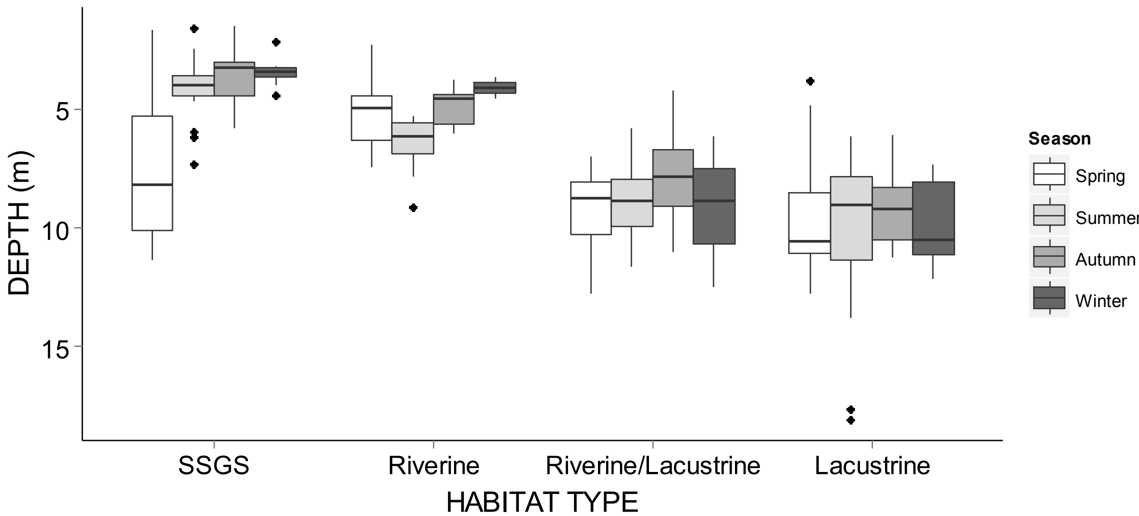

Figure 2.9. Depth use (hydrostatic pressure sensors; m) generated by the tagged Lake Sturgeon across the seasons and habitat types within the impounded reach that is situated between Seven Sisters GS and McArthur Falls GS located on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

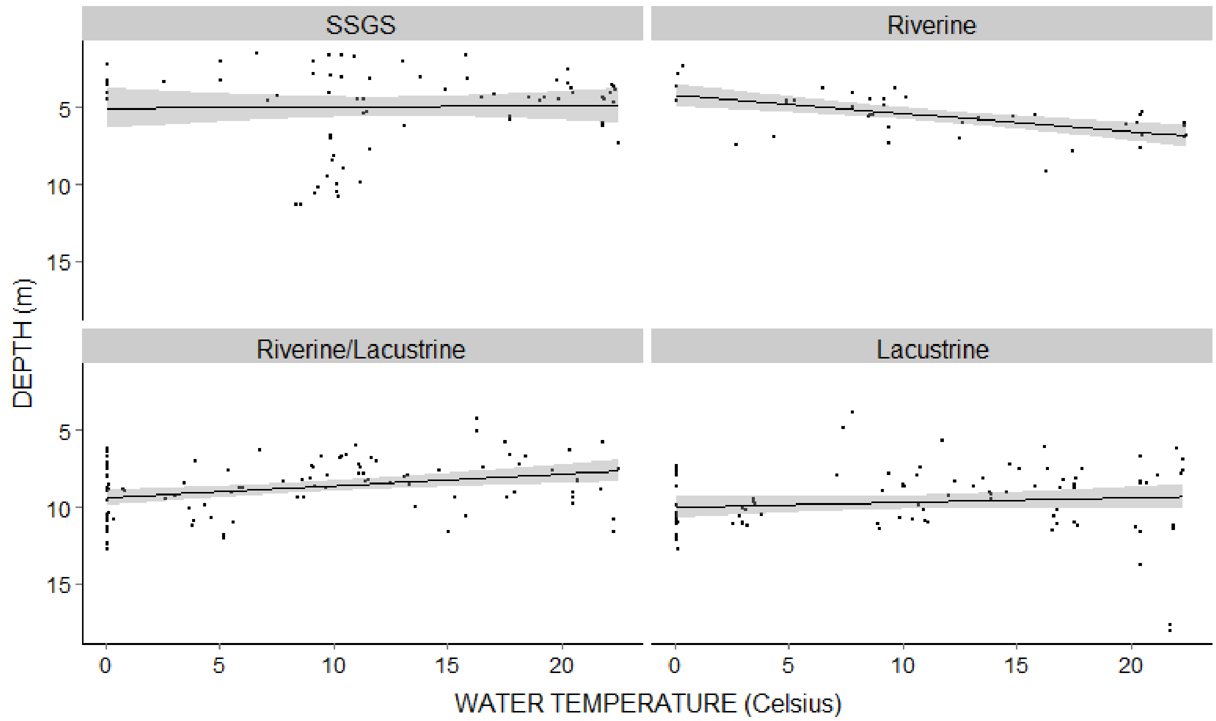

Figure 2.10. Depth use (hydrostatic pressure sensors; m) generated by Lake Sturgeon relative to the water temperature range that was experienced during the multi-seasonal monitoring period (August 10, 2014 – July 6, 2015), which has been further summarized based on habitat type. The plot provides the raw data, line of best fit, and 95% confidence intervals.

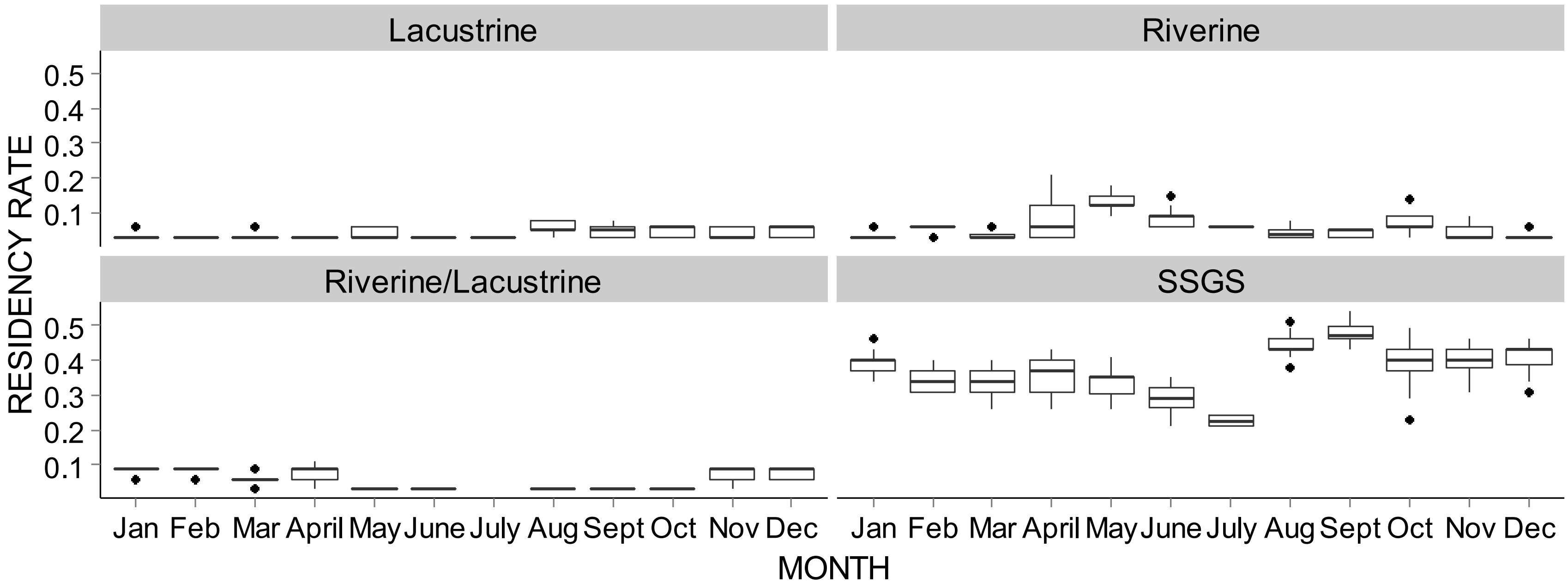

Figure 2.11. An overview of residency for Walleye, which is summarized on a monthly basis in 2014 (August – December) and 2015 (January to July) across different habitat types within an impounded reach situated between the Seven Sisters GS and McArthur Falls GS on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

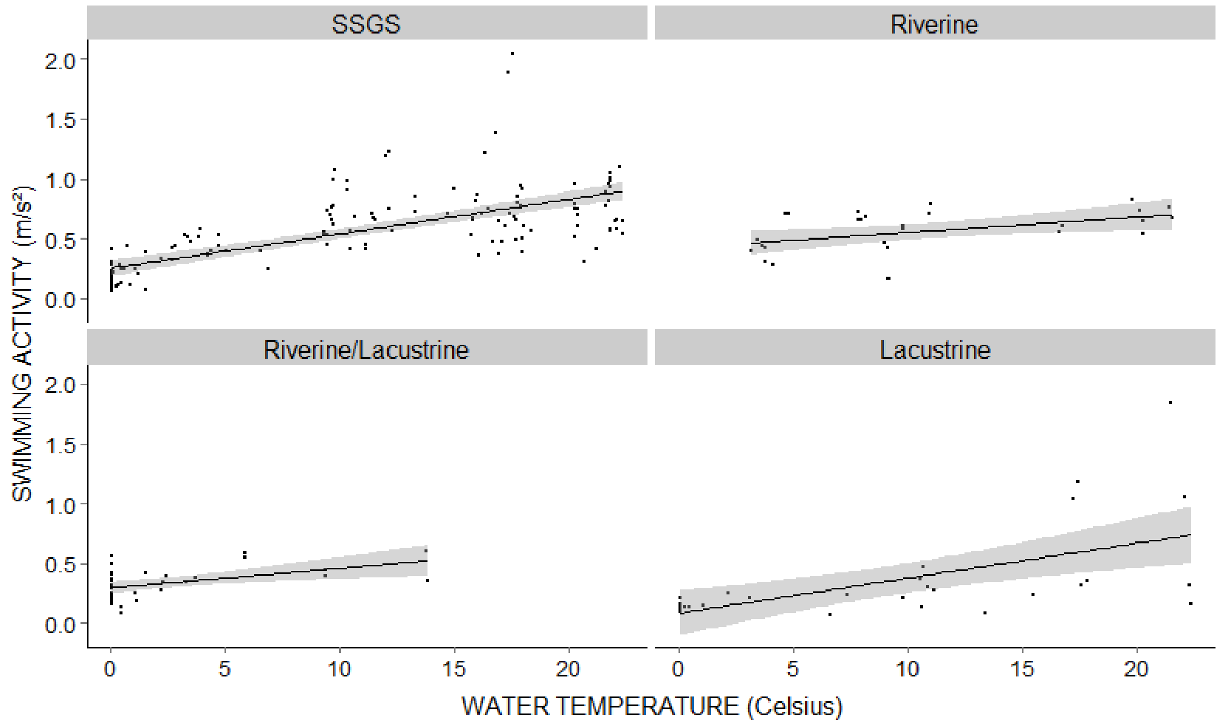

Figure 2.12. Swimming activity rates (tri-axial accelerometer sensors; m/s^2) generated by the Walleye relative to the water temperature range that was experienced during the multi-seasonal monitoring period (August 10, 2014 – July 6, 2015), which has been further summarized according to the habitat type. The plot provides the raw data, the line of best fit, and 95% confidence intervals.

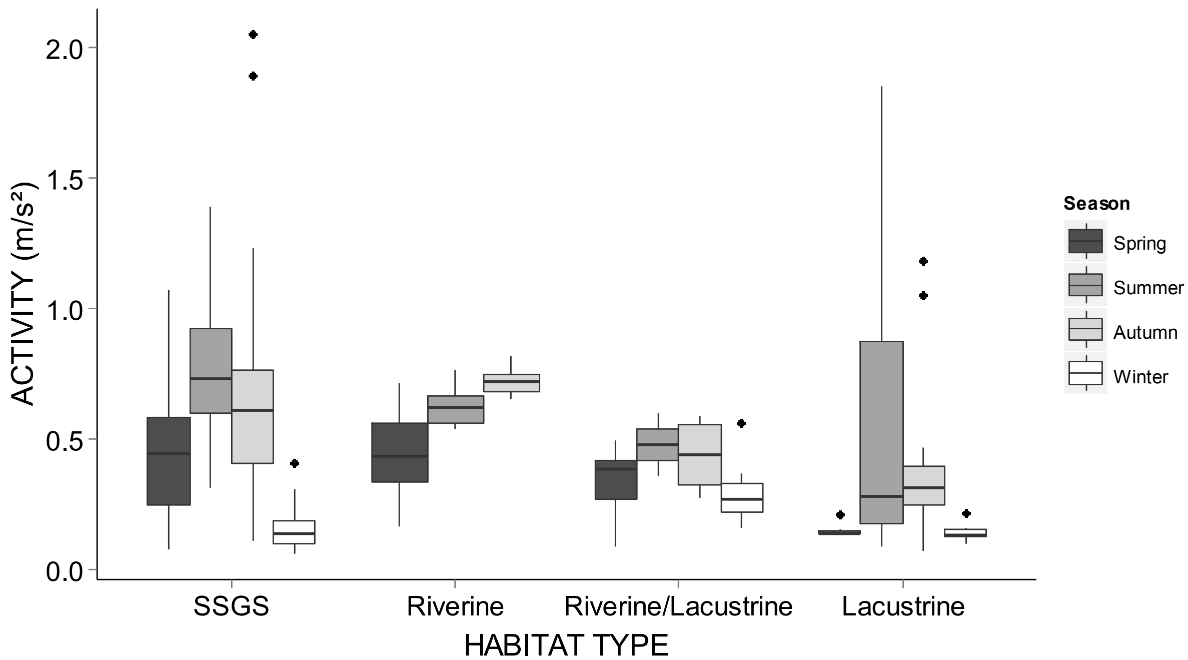

Figure 2.13. Swimming activity rates (tri-axial accelerometer sensors; m/s^2) that were generated by the tagged Walleye across the habitat types and seasons within the impounded reach that is situated between Seven Sisters GS and McArthur Falls GS located on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

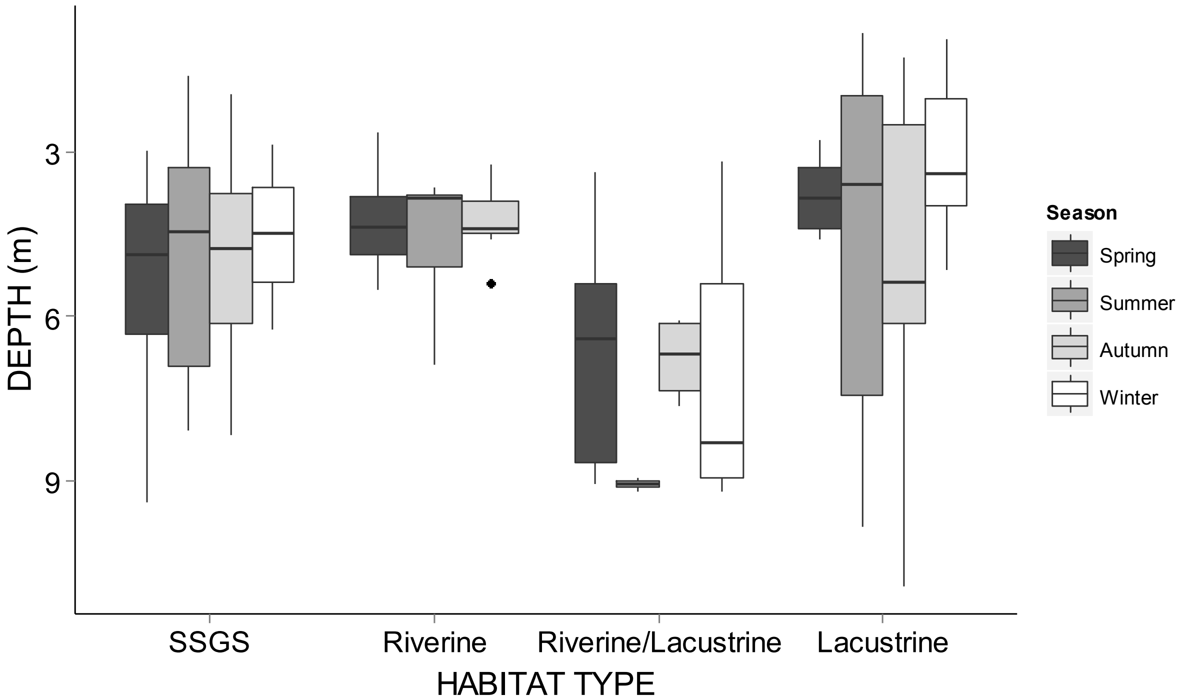

Figure 2.14. Depth use (hydrostatic pressure sensors; m) generated by the tagged Walleye relative to habitat types and across the seasons within the impounded reach that is situated between Seven Sisters GS and McArthur Falls GS on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

Tables

Table 2.1. An overview of the backwards model selection process for Lake Sturgeon (top) and Walleye (bottom) for swimming activity rates in an impoundment located between the Seven Sisters GS and McArthur Falls GS on the Winnipeg River system. The summary provides the degrees of freedom (d.f.), Akaike Information Criteria (AIC), Bayesian Information Criteria (BIC), and log-likelihood (Log-Lik) values.

Species	Model Terms	d.f.	AIC	BIC	Log-Lik
Lake Sturgeon	Habitat + Diel + Temperature + Season + Habitat*Temperature	25	-202.3	-108.7	126.2
	Habitat + Diel + Temperature + Season + Diel*Habitat + Habitat*Temperature	28	-201.2	-96.3	128.6
	Habitat + Diel + Temperature + Season	22	-167.1	-84.7	105.5
	Habitat + Diel + Temperature + Season + Diel*Habitat	25	-162.7	-69.1	106.4
	Model Terms	**d.f.**	**AIC**	**BIC**	**Log-Lik**
Walleye	Habitat + Temperature + Season + Habitat*Temperature	24	-142.3	-59.7	95.2
	Habitat + Diel + Temperature + Season + Habitat*Temperature	25	-140.3	-54.3	95.2
	Habitat + Diel + Temperature + Season + Diel*Habitat + Habitat*Temperature	28	-137.4	-41	96.7
	Habitat + Diel + Temperature + Season	22	-133.7	-58	88.9
	Habitat + Diel + Temperature + Season + Diel*Habitat	25	-131.2	-45.1	90.6

Table 2.2. Model summary for swimming activity for Lake Sturgeon (top) and Walleye (bottom) within the impounded reach situated between Seven Sisters GS and McArthur GS on the Winnipeg River, MB. The summary provides the species, model terms, the chi-square statistic (χ^2), degrees of freedom (d.f.), and the critical threshold (P-value), which are bolded if the pairwise comparison is found to be significant

Species	Model Term	χ^2	d.f.	P-value
Lake Sturgeon	(Intercept)	0	1	0.974
	Habitat Type	126.3	3	< **0.0001**
	Diel Period	3	1	0.083
	Water Temperature	216.3	1	< **0.0001**
	Season	60.1	3	< **0.0001**
	Habitat Type*Water Temperature	53.6	3	< **0.0001**
Walleye	(Intercept)	1.9	1	0.165
	Habitat Type	18.9	3	< **0.0001**
	Water Temperature	20.7	1	< **0.0001**
	Season	24.6	3	< **0.0001**
	Habitat Type*Water Temperature	15.1	3	**0.002**

Table 2.3. Pairwise comparisons between habitats types for the best fitted linear mixed-model that was generated for the swimming activity (m/s^2) of the tagged Lake Sturgeon and Walleye. The pairwise comparisons provide the slope estimate (ß), standard error (SE), the z statistic (z-value), and the statistical significance (P-value), which are bolded if the pairwise comparison is found to be significant

Species	Pairwise Comparison	ß	SE	z-value	P-value
	HABITAT TYPE				
Lake Sturgeon	Riverine - Lacustrine	-0.53	0.04	-11.91	< **0.0001**
	Riverine-Lacustrine - Lacustrine	0.47	0.04	13.32	< **0.0001**
	SSGS - Lacustrine	0.16	0.04	4.37	< **0.0001**
	Riverine-Lacustrine - Riverine	1.01	0.04	23.73	< **0.0001**
	SSGS - Riverine	0.7	0.04	15.89	< **0.0001**
	SSGS – Riverine-Lacustrine	-0.31	0.03	-9.07	< **0.0001**
	HABITAT TYPE				
Walleye	Riverine - Lacustrine	0.44	0.05	9.15	< **0.0001**
	Riverine-Lacustrine - Lacustrine	0.39	0.05	8.03	< **0.0001**
	SSGS - Lacustrine	2.63	0.04	65.24	< **0.0001**
	Riverine-Lacustrine - Riverine	-0.04	0.04	-1.05	0.711
	SSGS - Riverine	2.2	0.03	68.5	< **0.0001**
	SSGS – Riverine-Lacustrine	2.24	0.03	66.25	< **0.0001**

Table 2.4. An overview of the backwards model selection process Lake Sturgeon (top) and Walleye (bottom) for depth use in the impoundment located between the Seven Sisters GS and McArthur Falls GS on the Winnipeg River system. The models are ordered according to relative model fit to the data when moving from top to bottom of the table. The summary provides the degrees of freedom (d.f.), Akaike Information Criteria (AIC), Bayesian Information Criteria (BIC), and log-likelihood (Log-Lik) values.

	Lake Sturgeon				
Model No.	Model Terms	d.f.	AIC	BIC	log-Lik
5	Habitat Type + Temperature + Season + Habitat Type*Temperature	16	1215.2	1275.0	-591.6
2	Habitat Type + Diel + Temperature + Season + Habitat Type*Temperature	17	1217.2	1280.7	-591.6
4	Habitat Type + Diel + Temperature + Season	14	1221.6	1274.0	-596.8
1	Habitat Type + Diel + Temperature + Season + Diel*Habitat + Habitat Type*Temperature	20	1222.5	1297.3	-591.3
3	Habitat Type + Diel + Temperature + Season + Diel*Habitat Type	17	1227.2	1290.7	-596.6
	Walleye				
7	Habitat Type	9	850.4	881.5	-416.2
5	Habitat Type + Season	12	850.2	891.6	-413.1
4	Habitat Type + Diel + Season	13	851.0	895.8	-412.5
6	Habitat Type + Diel	10	851.2	885.7	-415.6
3	Habitat Type + Diel + Temperature + Season	14	852.7	901.0	-412.3
2	Habitat Type + Diel + Temperature + Season + Habitat Type *Temperature	17	856.5	915.2	-411.3
1	Habitat Type + Diel + Temperature + Season + Diel*Habitat + Habitat Type *Temperature	20	861.9	930.9	-411.0
8	Intercept Only	6	906.0	926.7	-447.0

Table 2.5. Model summary indicating the main terms that were retained in the final candidate model for explaining depth use for Lake Sturgeon (top) and Walleye (bottom) within the impounded reach situated between Seven Sisters GS and McArthur GS on the Winnipeg River, MB. The summary provides the species, model terms, the chi-square statistic (χ^2), degrees of freedom (d.f.), and the critical threshold (P-value), which are bolded if the pairwise comparison is found to be significant

Species	Model Terms	χ^2	d.f.	P-value
Lake Sturgeon	(Intercept)	96.5	1	**< 0.0001**
	Habitat	130.3	3	**< 0.0001**
	Temperature	0.9	1	0.338
	Season	17.2	3	**0.001**
	Habitat-Temperature	10.4	3	**0.015**
Walleye	(Intercept)	100.8	1	**< 0.0001**
	Habitat	71.8	3	**< 0.0001**

Table 2.6. Pairwise comparisons for habitats types and seasons for the fitted candidate models used to explain the depth use (m) for Lake Sturgeon (top) and Walleye (bottom) within the impounded reach on the Winnipeg River. The pairwise comparisons provide the slope estimate (ß), standard error (SE), the z statistic (z-value), and the statistical significance (P-value), which are bolded if the pairwise comparison is found to be significant

Species	Pairwise Comparison	ß	SE	z-value	P-value
	SEASON				
Lake Sturgeon	Summer - Spring	0.4	0.4	1.2	0.615
	Autumn - Spring	-0.6	0.2	-2.3	0.087
	Winter - Spring	-0.8	0.3	-2.5	0.052
	Autumn - Summer	-1	0.3	-3.3	**0.004**
	Winter - Summer	-1.2	0.5	-2.4	0.071
	Winter - Autumn	-0.2	0.4	-0.6	0.937
	HABITAT TYPE				
	Riverine - SSGS	-2.2	0.7	-3.2	**0.007**
	Riverine-Lacustrine - SSGS	1.9	0.7	2.9	**0.019**
	Lacustrine - SSGS	3	0.7	4.2	**< 0.001**
	Riverine-Lacustrine - Riverine	4.1	0.4	9.9	**< 0.001**
	Lacustrine - Riverine	5.2	0.5	10	**< 0.001**
	Lacustrine - Riverine-Lacustrine	1.1	0.5	2.3	0.084
	HABITAT TYPE				
Walleye	Riverine - SSGS	-1.5	0.4	-4	**< 0.001**
	Riverine-Lacustrine - SSGS	1.2	0.4	3.4	**0.004**
	Lacustrine - SSGS	-0.9	0.6	-1.6	0.382
	Riverine-Lacustrine - Riverine	2.7	0.3	8.3	**< 0.001**
	Lacustrine - Riverine	0.6	0.5	1.1	0.669
	Lacustrine - Riverine-Lacustrine	-2.2	0.5	-4.1	**< 0.001**

Investigating residency, movement, and depth use of wild fishes to assess exposure risk to hydrokinetic turbine infrastructure and operations in a large river

Abstract

Hydrokinetic Turbines (HTs) are being proposed for placement in riverine landscapes around the globe. While controlled experiments in flumes have found survival rates of fish entrained in HTs to be reasonably high, there is a lack of field-based assessment on wild fish. Here, I implanted 40 adult Lake Sturgeon and 40 adult Walleye with acoustic telemetry transmitters to monitor their space use (horizontal and vertical) at the *Canadian Hydrokinetic Turbine Testing Centre* (CHTTC) located in the Seven Sisters GS tailrace on the Winnipeg River, Manitoba. Specifically, I tested whether fish behaviour was influenced by the operation of HTs relative to control periods, and determined the relative risk of fish interaction with HTs across seasons. The telemetry data revealed that Walleye did not alter their behaviour or space-use when a singular substrate-mounted HT was operational. Walleye were neither attracted to nor deterred from the area where the HT was being tested. Walleye were more common during periods when the discharge rate was greater than 950 cms. Seasonal residency, movement, and depth use analyses indicated that Lake Sturgeon appear to be more susceptible to HTs during late-spring (i.e., May and June), whereas risk to Walleye would be highest throughout the summer and autumn seasons. Walleye utilized habitat at the CHTTC significantly more often than Lake Sturgeon. However, Lake Sturgeon utilized similar depths where HTs would be installed (i.e., $\geq$ 6.5 meters), while Walleye commonly occupied shallower depths at the HT testing centre. Collectively, these data provide the first insights on HT operations and wild fishes. I was able to

collect data necessary to conduct a risk assessment on HT exposure for two important fish species. The findings presented here will help guide best practices for commercial scale HT operations within river systems where Walleye and Lake Sturgeon reside. In addition, the approach used here serves as a template for studying potential consequences of HTs on wild fish in other systems.

Introduction

Hydrokinetic turbines generate electricity be garnering the kinetic energy of swift flows in marine and freshwater environments. Hydrokinetic Turbines (HTs) are a novel energy approach, with proposals steadily increasing for implementing riverine hydrokinetic turbine arrays in North America (Yuce and Muratoglu 2015), with tailraces of existing hydropower dams being an area of interest for installment (Cada and Bevelhimer 2011; Liu and Packey 2014). Developing hydrokinetic turbines may threaten wild fish populations (Cada et al. 2011; Seitz et al. 2011). When operational, the devices turn, creating noise and vibration and a potential source of physical injury or death to fish that interact with the devices. HTs normally include infrastructure (e.g., anchoring cables, electrical lines, anchoring blocks) that represent a footprint effect. Beyond the direct impacts, there is also the risk of pollution from petroleum constituents used as lubricants, as well as electromagnetic fields interacting negatively with wildlife (Cada et al. 2011). Collectively, hydrokinetic devices (including their presence and operation), support structures, and maintenance personnel may disrupt the natural behaviour and space-use of fish populations (Cada et al. 2011).

Environmental managers regulate hydropower activities that occur in aquatic ecosystems (Poff et al. 2003; Smokorowski and Pratt 2007). To do so, comprehensive ecological risk assessments involving novel hydropower developments are necessary for understanding potential negative consequences (Hart et al. 2002) and to inform siting, mitigation, or compensation activities (Smokorowski and Pratt 2007). In most jurisdictions, hydrokinetic turbine proponents are reviewed to investigate potential environmental impacts to fish and fish habitat arising from the installation and operation of hydrokinetic turbines. Energy proponents are optimistic for the development of commercial-scale HT arrays through large river systems (Arango 2011; Schwiezer et al. 2011), as well as being centred at existing hydropower facilities (Liu and Packey 2014). Currently, HT devices are understudied with regards to fish populations and aquatic habitat alteration (Cada et al. 2007; Seitz et al. 2011).

Of particular importance to both fisheries managers and energy developers is developing hydrokinetic turbine arrays that will minimize the risk of physical (i.e., entrainment, blade strike, and overpressure injuries), physiological, and behavioural impacts on fish populations (Cada 2011). Blade strike survival tests have been conducted in flumes (Amaral and Hecker 2008; EPRI 2011a; Schweizer et al. 2011) and in-situ testing sites (NAI 2009) for fish interacting with riverine hydrokinetic turbines. Certain fishes are positively rheotaxic and may be attracted to HTs, since flow is an important cue for spawning and movement behaviours (Schilt 2007; Loures and Pompen 2015). Aquatic habitats characterized by high flow (~ 2m/s) are ideal locations for placing HTs, thus overlapping with important habitats for some fish populations (Cada 2011). Assessing the movement and space-use of wild fishes will assist managers and the energy industry to adapt HT designs and operations to minimize ecological risk to fish (Linkov et al. 2006).

For this study, Lake Sturgeon (*Acipenser fulvescens*) and Walleye (*Sander vitreus*) are the focal species for investigating the ecological risk in association with HTs. Both species are relatively long lived, with Lake Sturgeon exceeding 80 years and Walleye 20 years in age (Scott and Crossman 1973; Auer 1996; Peterson 2007) and populate watersheds across central and eastern North America (Scott and Crossman 1973; Craig 2000). Lake Sturgeon populations are at risk of human-induced impacts, particularly as sub-adults and adults due to poaching, fishing, and hydropower development (Peterson et al. 2007; Auer et al. 2013). Through the 1800 -1900s, Lake Sturgeon populations were severely reduced in size across much of their geographic range due to overharvesting and habitat alteration (Houston 1987; Auer 1996; Peterson et al. 2007). In Canada, the Lake Sturgeon is considered endangered by the Committee on the Status of Wildlife in Canada (COSEWIC 2006) and recommended for federal protection in Canada. On the other hand, Walleye is a highly targeted commercial and recreational species in North America (Craig 2000; Fetherman et al. 2015). Although stocking and fishing restrictions are assisting their recovery and conservation (Zorn 2015), many Walleye populations in the Arctic, Hudson Bay, and Atlantic drainage basins have been severely reduced in size due to overfishing and habitat degradation (Post et al. 2002). Populations of Lake Sturgeon and Walleye are likely to face further environmental impacts associated with hydropower development, climate change, increased water consumption, and habitat degradation (Auer 1996; Post et al. 2002; Wilson and McKinley 2004).

The risk towards aquatic animals and habitat is a complex problem to address with regards to hydrokinetic turbine operations (VanZweiten et al. 2014). Both Lake Sturgeon and Walleye populations reside in close proximity to the *Canadian Hydrokinetic Turbine Testing Centre* (CHTTC) where HTs are undergoing pre-commercial testing. These populations may be susceptible to blade strike, noise, EMF, chemicals contamination that may affect survival, behaviour, and movements (USDOE 2009; Cada et al. 2011; VanZweiten et al. 2014). This study investigates Lake Sturgeon and Walleye in proximity to where HTs are being tested (i.e., CHTTC) located on the Winnipeg River, Manitoba. To do so, this project applies acoustic biotelemetry equipment to monitor free-ranging Lake Sturgeon and Walleye to investigate the spatial ecology and biological responses to measure risk from hydrokinetic turbines. Acoustic telemetry facilitates the study of spatial ecology of aquatic species that otherwise would not be possible with traditional approaches (i.e., mark-recapture, direct observations; Cooke et al. 2004a; Hussey et al. 2015).

The principal goal of this study is assisting energy developers to adapt operations of hydrokinetic devices to minimize risk for wild fish populations. For this study, there are two specific objectives that were addressed: (1) determine if the spatial ecology of wild fish is affected when HTs are operational in aquatic systems, and (2) execute a risk assessment of HT exposure to wild fishes by quantifying seasonal residency, movement, and depth distribution at the CHTTC. Answering these questions will assist environmental managers and HT proponents with siting considerations and operational guidance to help minimize the risk of negative interactions between fish and HTs.

Methods

Study Location

This study was conducted at the *Canadian Hydrokinetic Turbine Testing Centre* that is situated 400-1200 meters downstream of the Seven Sisters Generating Station (SSGS) powerhouse (50° 07' 14”N; 96° 01' 02”W). The SSGS tailrace extends downstream ~1.2 km with an average width of ~50 meters (Figure 3.1). Flow velocity at the CHTTC measured ≥ 2 m/s (data obtained from University of Manitoba) throughout the water column during the study period (June 9, 2014 –

July 6, 2015), with an average discharge rate of 1029 cms (± 12.4) from the SSGS powerhouse throughout the acoustic monitoring period (Data obtained from Manitoba hydro). The thalweg depth within the SSGS tailrace ranges between 9-15 meters, accounting for bathymetry and powerhouse discharge fluctuations.

Fish Capture and Transmitters

Recent stock assessments completed within this impounded reach have found all age classes of Lake Sturgeon currently reside within this river reach, with recruitment occurring (Hrenchuk et al. 2009; Manitoba Fisheries Branch 2012). Past research at this study location found that Lake Sturgeon utilize the Seven Sisters GS tailrace and spillway in late spring to spawn, and also documented relatively high numbers of Walleye residing downstream of the Seven Sisters GS (Hrenchuk 2009).

Fish capture and surgical implantation procedures were conducted during the period of May 20 – June 2, 2014. Multi-panel multifilament gill nets with large mesh size (200 mm to 300 mm) and boat electrofishing were used to capture Lake Sturgeon. Gill net panels were placed in deep pools situated downstream of the Seven Sisters GS tailrace. The gill nets were set at dusk (~1700-2100 CDT) and pulled at dawn (soak time of ~12 hours). Lake Sturgeon are resilient to gill net capture, with minimal physiological stress or bodily harm occurring (Baker et al. 2008; Thiem et al. 2011), and no immediate mortality or severe injury was observed for the tagged Lake Sturgeon from the capture efforts. Walleye were also captured with a combination of fine- (10-20 mm) and large- (200-300 mm) meshed multi-paneled gillnets, as well as with boat electrofishing during the crepuscular and nocturnal periods. Upon capture, the Lake Sturgeon and Walleye were placed in holding tanks filled with ambient river water prior to surgical procedures. The total length (TL, measured to the nearest mm) and weight (kg, to the nearest g) was recorded for each individual during the tagging procedure. During the capture period, no individual Lake Sturgeon or Walleye were recaptured while netting or boat electrofishing.

Acoustic biotelemetry was used to passively-monitor Lake Sturgeon and Walleye throughout the impounded reach during the monitoring period. This study implanted positional transmitters (n = 40; V13-1L; lifespan: 818 days; Vemco, Halifax, NS), as well as sensor transmitters (n = 40; V13AP-1L; lifespan: 649 days; Vemco, Halifax, NS) that provided a 1:1 ratio of depth (i.e., hydrostatic pressure; maximum depth of 68 meters) and swimming activity (i.e., tri-axial accelerometers; maximum range of 3.43 m/s^2). The transmitters were divided equally between Lake Sturgeon (n = 40) and Walleye (n = 40) for both transmitter models (i.e., 20 V13-1L and 20 V13AP-1L per species). All transmitters have a unique coded ID and a transmission frequency of 69 kHz. The acoustic transmitters were manufactured with a random delay range of 50-130 s, with a nominal average delay of 90 s, to reduce transmission collisions from multiple tagged fish residing within detection range of the acoustic receivers.

Lake Sturgeon Tagging Procedures

Individuals were held in a fine-mesh cradle that was submerged in ambient river water, and were ventrally-orientated to immobilize and access the incision location. The head and gills remained submerged in a trough filled with river water, which was refreshed between capture events, to maintain normal respiration during the surgeries. All surgical tools and acoustic transmitters were disinfected using a 10% povidone-iodine solution (Betadine®, USA), and nitrile gloves were worn while performing surgical procedures. A small incision (~2cm) was made with a scalpel on the midline positioned slightly posterior to the pectoral girdle. Either a V13-1L or

V13AP-1L acoustic transmitter was inserted posteriorly into the coelom cavity, followed by 3 interrupted sutures (3-0 polydioxanone-II violet monofilament; Ethicon USA) to close the wound. No anesthetic was used on Lake Sturgeon, and all surgeries took less than 5 minutes to complete. Each Lake Sturgeon was returned to a holding tank and released 10-15 minutes post-surgery below the netting site (~0.5 km).

Walleye Tagging Procedures

Similarly, individual Walleye (n = 40) were intra-coelomically implanted with either a V13-1L or V13AP-1L acoustic transmitter. Certain aspects of the surgical procedure (i.e., tool disinfection, gloves worn, and incision closure procedure) were identical to the methods used on Lake Sturgeon. However, there were some modifications with administering an anesthetic and immobilization technique. Stage-4 electroanesthesia (Summerfelt and Smith 1990) was administered using a Portable Electrosedation Unit (PES; Smith-Root, USA; Vandergroot et al. 2011) prior to surgical implantation to immobilize fish during surgery. The PES was set to 100 hz, 25% duty cycle, and 40 volts. Pulsed detect current is an appropriate anesthetic for adult Walleye because it provides a surgery window of 250-350 s, fish recover quickly with minimally impact to vertebral integrity (Vandergroot et al. 2011). Upon stage-4 anesthesia, Walleye were placed supine in a padded v-shaped trough. Ambient river water was continuously pumped over the gills (using a recirculating flow-through pump system) to maintain normal respiration during the surgical period (< 5 minutes). A small incision was made slightly posterior to the pectoral girdle on the ventral mid-line, and a transmitter was inserted posteriorly into the coelomic cavity, followed by 3 interrupted sutures to close the wound. Each fish was given 5-10 minutes to recover from surgery by being placed in a container filled with ambient river water, then subsequently released downstream of the Seven Sisters GS.

No Lake Sturgeon or Walleye died during surgical procedures. All tagged fish were below the 2% tag to fish weight ratio as a means to minimize the chance of altering their natural movement behaviour due to transmitter presence (Gallepp and Magnuson 1972; Ross and McCormick 1981; Rogers and White 2007). Fish handling and surgical procedures were approved and followed the Canadian Council on Animal Care protocol (AUP #101065). This research project was approved by Manitoba Water Stewardship, Fisheries Branch under Scientific Collection Permit No 14-14.

Acoustic Receiver Array

Passive monitoring of free-ranging Lake Sturgeon and Walleye individuals was completed with an array of 8 acoustic monitoring receivers (VR2W; Vemco, NS, Canada) that were positioned at the CHTTC (50° 07’ 25”N; 96° 01’ 31”W; Figure 3.1). Each receiver was substrate-anchored using 36 kg granite blocks, which were shore-tethered using 1/4” galvanized steel cable to securely fasten the receivers within the swift environment. The receivers were affixed to 3/8” multi-strand braided line that was positioned between the granite block and a sub-surface buoy that was placed ~1-2 meters above the substrate in 3-6 meters of water. Stationary range testing (Webber 2009; Kessel et al. 2013) was completed in the tailrace to determine the maximum detection radius of the VR2Ws situated within the tailrace prior to mooring the VR2W receiver array. The detection range was found to be between 50-75m due to ambient noise and turbulent environment.

Upon finding the optimal detection range of the VR2Ws, the receivers were spaced throughout the CHTTC at various distances away from the substrate-mounted HT to maximize the detection coverage within the testing area. For each receiver, a river distance in kilometers (rkm) was measured using the path tool in Google Earth (distance range: 30-310 meters). The measurements were determined by the sum of linear distances taken mid-channel from the substrate-mounted HT to each receiver located at the CHTTC. The rkm position was used to evaluate movement frequency of the tagged fish in the area where turbines were being tested. The listening stations recorded transmitted data from the tags, which provided horizontal positioning, depth information (i.e., hydrostatic pressure sensors), and locomotory activity (i.e., tri-axial accelerometer sensors). Data were offloaded from all receivers in August 10th 2014, April 10th 2015, and July 6th 2015. After each data offload, each receiver was immediately placed within 2 m of the initial anchoring site. Five of the 8 receivers included collocated sentinel tags (V16; 500-700s delay) to measure detection efficiency (*DE*) across turbine operational periods to assess array performance during the monitoring period (Melynchuk 2012; Kessell et al. 2013). Here, *DE* was assessed by calculating the proportion of expected daily transmissions based on the nominal average delay (600s) from the sentinel tags that were received by the collocated receivers. This data was further summarized according to each month and season. With examining HT exposure measures (i.e., residency, movement, and depth use) on a seasonal scale, I compared *DE* on a monthly and seasonal basis using analysis of variance (ANOVA).

Database Management

Surgical procedures may potentially influence behaviour of tagged fish, which can bias movement and behavioural ecology (Rogers and White 2007; Cooke et al. 2011). To minimize the probability of including biased biological information, the first week of all acoustic telemetry data was omitted from the database (Cooke et al. 2011). As such, the monitoring period was June 9, 2014 through July 6, 2015. Additionally, false-positive transmissions are common in large scale arrays and need to be filtered prior to summarizing and analysing telemetry datasets. These can occur when multiple transmissions collide as they are simultaneously detected by a receiver that results in an erroneous tag ID being recorded (Skalski et al. 2002; Pincock 2008). False-positives were assessed in the Vemco User Environment (VUE) as single detections from unidentifiable coded transmitters. The database was further filtered by assessing spatiotemporal order of detections. Distance and time between consecutive detections was calculated. If a fish was detected at an unrealistic speed between two consecutive detections (i.e., movement velocity of >5m/s), they were further investigated and removed if deemed erroneous (Skalski et al. 2002; Pincock 2008). Occasionally, the sensor tags can transmit false detections that result in negative values. As such, sensor transmissions that were less than zero were filtered from the database prior to performing analyses.

Additionally, because the VR2Ws were relatively close to one another, a single transmission could be detected by two or more listening stations. These duplicate detections were filtered from the database by removing consecutive detections from each individual fish that was detected less than the minimal tag delay (i.e., <50 s). If a fish suddenly stopped moving (i.e., no change horizontally, vertically, or swimming speed), then the data was further inspected and removed if considered to be erroneous (i.e., fish had expelled the tag, dead fish). Data filtration was completed using the R Statistical Environment (R Core Development Team, 2014), MS Access (2010), and VUE software (Vemco; version 2.0.6). The internal clocks of the VR2Ws drift over time, therefore time of arrival for detections were corrected using the VUE software prior to implementing the data filter queries.

Detection data was then summarized according to the seasons (i.e., based on month), species, turbine operational status (i.e., on, off). Daily discharge data (cms [$m^3 \cdot s^{-1}$]) were provided by Manitoba Hydro, and water temperature readings were provided by the town of Powerview-Pine Falls. Daily solar information was acquired online (www.ptaff.ca) for the study area and was used to determine day (> local sunrise and < local sunset) and night (> sunset and < sunrise) diel periods.

Fish Presence and HT Testing

Because the hydrokinetic turbines at the CHTTC had been installed prior to this study, it was not possible to complete a “before-after control-impact” (BACI) experimental design for quantifying changes in movement behaviour relative to HT operations. An HT was installed in September 2013 and has been intermittently tested by Clean Current Power Systems Inc. (Vancouver, BC, Canada; Figure 3.3) at the CHTTC. It was substrate-anchored within the Seven Sisters GS tailrace (~400 meters from the powerhouse) at a depth of 11 meters and positioned 4.5 meters above the substrate (i.e., a nominal depth of 6.5 meters). The turbine has a shrouded horizontal axial-flow design, which is intended for sub-surface deployments. Three distinct testing periods were selected to investigate fish residency patterns at the CHTTC: (1) July 30, 2014 to Aug 24, 2014; (2) Sept 9, 2014 to Sept 12, 2014; (3) Nov 16, 2014 to Nov 20, 2014. Each of these testing periods was preceded by an equal period of non-operational status to make comparisons between operational regimes (i.e., operational vs. non-operational). Several days (7-59 days) separated each operational period to minimize temporal autocorrelation occurring for fish presence across HT testing periods.

The daily count of fish in proximity to the substrate-anchored HT was used to quantify residency. Data were first examined for influential observations, collinearity, and relationships between the response and explanatory variables using a variety of visualisation options including Cleveland dotplots, scatterplots, and conditional box and whisker plots. Lake Sturgeon were not included in the analysis here due to low sample sizes (≤3 individuals) detected daily across all monitoring periods. Explanatory variables included distance from the tested HT (DST, continuous), and turbine status (Operating: Yes/No over three time periods). In addition, because there were two generally distinct daily mean dam discharge rates (high: > 950 m^3/s; low: < 750 m^3/s), dam discharge was coded as a fixed categorical factor (DISC). Continuous covariates were centered [i.e., value-(mean/standard deviation)] to help ensure model convergence. Because turbine status was a paired variable (i.e., before and during) with temporal dependency, I included an additional nested variable, turbine operating regime (three before and after periods), as a random effect.

For the analysis, the response variable (proportion of unique Walleye detected/day) was modelled using generalized linear mixed-models (GLMM) that were fitted with a binomial distribution and restricted maximum likelihood estimation (Zuur et al. 2009). The importance and therefore inclusion of the random effect was evaluated using AIC model selection (Akaike 1998). To identify the factors that best explained the proportion of tagged Walleye detected at any given time, a set of candidate models (n = 7) were hypothesized and compared using second-order AIC (Mazerolle 2015). Model averaging was performed if ΔAICc was < 2 (Symonds and Moussalli 2011; Barton 2014). Model coefficients were plotted using the 'coefplot2' package (Bolker and Yu-Sung 2011). The relative importance (RI) of the predictor variables in the top models was assessed by taking the sum of the Akaike weights over all of the models in which the parameter of interest appeared (Barton 2014). All candidate models were validated by plotting the residuals and testing for overdispersion (i.e., the occurrence of more variance in the data than predicted by a statistical model; Bolker et al. 2009) using methods described by Zuur et al. (2009).

Seasonal Residency

The risk of exposure to HTs can be quantified by investigating the amount of time that fish reside in the areas where HTs are operational. Managers may adjust operation schedules according to periods of high and low residency for wild fish. Residency indices according to solar seasons were calculated for each tagged Lake Sturgeon and Walleye to investigate residency patterns for distinct periods across the monitoring period. As such, a seasonal residency index (SR_I) was calculated as the proportion of days a fish was detected over the number of days in a given season. The monitoring period (June 9, 2014- July 6, 2015) was categorized into four seasons based on the calendar month: (1) *spring* (March-May), (2) *summer* (June-August), (3) *autumn* (September-November), and (4) *winter* (December-February). Prior to calculating SR_I, a tagged fish was considered present at the CHTTC only if it was detected two or more times on a given monitoring day. Once the SR_I was calculated, these results were grouped by diel periods to determine if fish were more likely to be present at the CHTTC during the day or night. Fish size (TL) was standardized prior to model selection (value-[mean/standard deviation]) to make meaningful comparisons between the two species.

Linear mixed-modelling (LMM) with restricted maximum likelihood estimation was fitted to the data to investigate trends in SR_I relative to environmental cues (diel periods, seasons) and biological parameters (fish size, species), and with selected two-way interactions that were considered to be biologically relevant. A covariance structure that included both season and species was added to the model to improve residual homogeneity of variance for these parameters. Due to the nested data structure from repeatedly sampling the same fish, a random intercept for fish ID was included in the candidate models. The fit of the random effect was assessed using AIC model selection (Zuur et al. 2009). Backwards model selection was completed using the information-theoretic approach (i.e., AIC; BIC; log-likelihood). Three-way interactions were not included because they would be difficult to visualize and interpret.

Movements Frequency

The probability of entrainment and blade strike would likely increase with higher occurrences of upstream and downstream movements past the area where the HTs have been installed and tested. Movement events were calculated as sequential detections from an upstream river position (rkm) position to a downstream position, or vice versa, within the area where HTs were being tested. Movement events at the CHTTC were calculated for each tagged fish and summarized according to species, diel period, and across the months of the monitoring period. The frequency of movements in the area where HT testing occurred was investigated using LMM with backwards model selection. Lake Sturgeon were not included in the modelling process because of low sample sizes on a daily and seasonal basis (≤ 5 individuals). The explanatory model terms included month, fish size (TL), diel period, and the interaction between month and fish size. To improve normality in the data, a square-root transformation was applied to the response variable. Fish ID was included as a random effect and assessed for importance using AIC model selection. A variance covariate for month was included in the model to improve homogeneity of variance. Water temperature, discharge and months were found to be collinear. As such, water temperature and discharge were not included, while retaining the month as an explanatory term in the model because this parameter was considered more relevant for management purposes regarding HT operations.

Depth Use

Depth use for Lake Sturgeon and Walleye (i.e., hydrostatic pressure sensors; Vemco, NS) was used as a measure for HT exposure risk. Investigating depth distribution across various temporal scales (i.e., months, diel periods) provides an understanding of when and if different sized fish are susceptible to negative interactions with HTs in tailraces. At the CHTTC, the substrate-anchored hydrokinetic turbine was positioned at a nominal depth of 6.5 meters during the acoustic monitoring period. Fish that frequented these depths may be at greater risk of interacting with substrate-anchored HTs and their associated anchoring structure. Mean daily depth was calculated for each individual when a minimum of 10 valid detections for each given monitoring day were provided by each tagged fish. Depth sensor data were then summarised across seasons and diel periods at the CHTTC. Fish size (TL) and discharge from the SSGS powerhouse were included in the analysis. For this analysis, LMM with restricted maximum likelihood estimation and backwards model selection was used to investigate the explanatory parameters for the depth use response at the CHTTC. The full model included month, diel period, fish size, species, as well as the interaction between diel period and species. The model terms for diel period and month were assessed for inclusion as a variance covariates using AIC model selection (Zuur et al. 2009). With the nested data structure, Fish ID was included as a random effect and assessed for its importance with model fit using AIC model selection (Zuur et al. 2009).

General Modeling Procedures

Data exploration and analyses were carried out in the R statistical environment (R Core Development Team, 2014). Model selection for all analyses was implemented using the 'nlme' package (Pinheiro et al. 2015). The presented group comparisons provide the mean ± standard error. Statistical significance was assessed at the 0.05 threshold using type III sum of squares as implemented in the “car” package (Fox and Weisberg 2011). Collinearity between explanatory variables was assessed with variance inflation factor (VIF) within the “car” package (Fox and Weisberg 2011). Each model was examined for residual heteroscedasticity and non-normality using QQ-Plots, plotting histograms for normalized residuals, and plotting normalized residuals against fitted values for terms that were either included or dropped during model selection. Independence was assessed with using correlation lag-plots as implemented with the *acf* function.

Results

Forty each of Walleye and Lake Sturgeon were tagged from May 22 to June 2, 2014. Tagged Walleye ranged in size from 175 to 724 mm TL, whereas the Lake Sturgeon ranged from 710 to 1785mm TL. These fish were passively monitored by 8 autonomous VR2Ws, which provided 2,255,111 valid detections at the CHTTC site from June 9, 2014 to July 6, 2015 for Lake Sturgeon (Figure 3.2) and Walleye (Figure 3.3).Two Walleye (Walleye 05, 18) were reported as retained by anglers (last detected at Station 30, July 2014; last detected at Station 15, May 2015). Seven additional Walleye (Walleye 26, 08, 10, 11, 15, 34, and 40) were determined to have either died or expelled their tags during the monitoring period. No individual Lake Sturgeon were found to have died or expelled the internal transmitter. Detection efficiency of the VR2W array was similar across all months (d.f. = 11, F = 0.97, P = 0.486) and seasons (d.f. = 3, F = 1.14, P = 0.339), with an average *DE* of 0.44 (± 0.02) across the monitoring period (figure 3.4). Comparisons could be made across the months and seasons at the CHTTC for the HT exposure measures since there was not a significant difference with detection efficiency among the seasons of the monitoring period.

Fish Presence and HT Testing

The top models (where ΔAIC_c was < 2) included discharge (M1), discharge and turbine status (M5), and an interaction between discharge and turbine status (M6, Figure 3.1). These three models differed little in the ability to describe the proportion of Walleye at the CHTTC (Table 3.1). Using AIC, the random effect (i.e., turbine operating regime) was found to be important (ΔAIC = 56.9) and therefore was included in the set of candidate models. The proportion of tagged Walleye that were detected in the system decreased when discharge was less than 750 cms (Figure 3.5). Discharge was the most important factor in the candidate set (RI = 1.00), followed by turbine status (RI = 0.53) and discharge × turbine interaction (RI = 0.23; Figure 3.6). Although an important factor in the top candidate models (see Table 3.1), turbine operating status posed no significant effect on the proportion of Walleye detected in the system based on the model averaging regression coefficient (Figure 3.6) and the plotted data (Figure 3.7). Walleye were not attracted or deterred from the CHTTC during HT operations, because there was a marginal difference in distance from the HT when it was operating versus not operating (Figure 3.8).

Seasonal Residency

The top model for Seasonal Residency (SR_I) included species, season, and species × season interaction (Table 3.2, 3.3). SR_I was considerably higher for Walleye than Lake Sturgeon during the spring, summer, autumn, but both were almost non-existent at the CHTTC in the winter (t = 3.48, P < 0.001). The interaction between species and seasons was an important predictor for explaining SR_I at the CHTTC (χ^2 = 24.2, D.F. = 3, P < 0.0001). Overall, Walleye spent much more time at the CHTTC than Lake Sturgeon during the monitoring period ($\chi^2 = 12.1$, D.F. = 1, P < 0.001). Residency was relatively similar for Walleye and Lake Sturgeon during the winter season (Figure 3.9), with Lake Sturgeon demonstrating somewhat higher residency during the winter. For Walleye, the highest rates of residency occurred in summer (SR_I: $\bar{x} = 0.24 \pm 0.3$) and autumn (SR_I: $\bar{x} = 0.23 \pm 0.2$), whereas residency was lower in spring (SR_I: $\bar{x} = 0.18 \pm 0.16$) and lowest in winter (SR_I: $\bar{x} = 0.05 \pm 0.04$). Although there was no significant difference in residency across the seasons at the CHTTC, there was somewhat higher SR_I in the spring season for Lake Sturgeon (Figure 3.9). Interestingly, a large proportion (~50%) of the tagged Lake Sturgeon returned to the CHTTC between May and June 2015 (Figure 3.2, 3.9), which corresponds with the spawning season (Hrenchuk 2009). Lake Sturgeon residency was relatively low throughout the entire monitoring year at the CHTTC ($\bar{x} = 0.06 \pm 0.06$; range = 0.01 – 0.27).

Movement Frequency

When modeling the response of movement frequency, Fish ID was found to improve the model fit when included as a random effect (ΔAIC = -25.7), and inclusion of a variance structure for month improved homogeneity of variance for the model residuals (ΔAIC = -42.9). The best fitting model included fish size (TL), month, and the interaction between these two model terms (Table 3.3, 3.4). Movement frequency did not change considerably between day (9.6 ± 0.8) and night (8.9 ± 0.7) for Walleye. Fish size was not a significant predictor for movement frequency at the CHTTC (table 3.6), however there was an important interaction between fish size and the month of the monitoring period ($\chi^2 = 56$, d.f. = 7, P < 0.0001). Larger Walleye moved throughout the CHTTC more frequently in September and October, while smaller individuals moved more frequently throughout the CHTTC in the months of April and June (Figure 3.10), while all other months had similar movement frequency across the range in fish size. The calendar month was considerably important for explaining movement frequency of Walleye at the CHTTC ($\chi^2 = 45.9$, d.f. = 7, $P < 0.0001$). Walleye moved more frequently throughout the CHTTC during July (12.4 ± 2), September (10.1 ± 1), October (12.4 ± 1.9), and November (12.9 ± 2.8), while considerably less in other months. According to the telemetry results, no tagged Walleye were found to make any upstream or downstream movements at the CHTTC between December and March. Lake Sturgeon were found to make minimal movements at the CHTTC across the monitoring period, with movements only generated in May (3.8 ± 0.53) and June (8.9 ± 3.4).

Depth Selection

The final model for explaining depth use at the CHTTC included month, diel, and species (Table 3.5, 3.3). Fish ID was included in all models during the backwards model selection process (ΔAIC = -701.7). The terms for discharge and months were found to be collinear, so the discharge variable was dropped while including month in the model selection process because seasonality in depth use was of particular interest for assessing HT exposure risk. The interaction between diel period and species was not significant and was dropped during the model selection process. Walleye were found to reside in shallower water (5.6 m ± 0.17) depths than Lake Sturgeon (10.6 m ± 0.23) at the CHTTC (Figure 3.11). Depth use varied through the calendar months, with Walleye moving deeper into the water column at the CHTTC through May (6.9 m ± 0.15) and June (6.7 m ± 0.11), while residing in relatively shallower depths in August (4.3 m ± 0.10) and September (5.1 m ± 0.13; Figure 3.12). Lake Sturgeon only generated depth data in May, June, and July, with greatest variation in depth use for Lake Sturgeon in the month of June (Figure 3.11), while selecting shallower depths in July (8.9 m ± 0.27) and residing deeper in May

(11.1 m ± 0.18). There were differences in depth-use between diel periods ($\chi^2 = 34.5$, d.f. = 1, P < 0.0001), with both species residing at greater depths during the day while shallower at night (Figure 3.13).

Discussion

Hydrokinetic turbines are the next frontier of green energy, harnessing the kinetic energy potential of freshwater flows to generate kilowatts of electricity (Khan et al. 2008; Lago et al. 2010). By tracking wild fish with biotelemetry and using mixed-modelling, I examined the effects of several putative parameters on the response of residency, movement frequency, and depth use as measures for assessing risk of exposure to HT operations at the CHTTC. To my knowledge, this is one of the first projects to assess ecological risk for wild fishes using biotelemetry in proximity of riverine HTs installed at an existing hydropower facility. This testing centre is the only one of its kind on a Canadian river system with pre-commercial operational tests are anticipated to continue at this site in partnership with several private energy companies.

Fish Presence and HT Testing

Particularly concerning with HT operations is that they may interfere with the spatial ecology (e.g., movement behaviors, habitat use, foraging) of wild fish populations residing where operations take place. Given that the tagged Walleye were neither more nor less present at the CHTTC and did not alter their distances while an HT was operational, this suggests that the normal operation of singular substrate-HTs located in tailrace environments would not impede the habitat use for Walleye. The tagged Lake Sturgeon were minimally present (≤ 3 individuals) during the experimental operations, making inferences negligible for this species relative to the HT testing periods (*Test 1*: July 30, 2014 to Aug 24, 2014; *Test 2*: Sept 9, 2014 to Sept 12, 2014; *Test 3*: Nov 16, 2014 to Nov 20, 2014). Lake Sturgeon may respond to the HTs if tests occurred during their spawning season that occurs in spring. However, testing operations did not occur during the spawning period, so inferences could not be made regarding how Lake Sturgeon respond to a substrate-anchored HT.

The number of Walleye residing in proximity of the HT was related to discharge rates from the SSGS powerhouse (see Figure 3.14), with more fish residing at the CHTTC when discharge was above 950 cms (Figure 3.5). Relationships between discharge and Walleye activity have also been documented in relation to hydropower tailraces. For example, Murchie and Smokorowski (2004) found peak activity of Walleye corresponded with peak discharge rates from a hydropower facility as fish were likely at greater exposure to flow and refugia areas were reduced. Additionally, DiStefano and Hiebert (2000) found that Walleye moved upstream into the tailwaters of a peaking generating station when water is released during the spawning season (March 4^{th} to April 24^{th}). To minimize the risk of negative interactions with HT infrastructure, adjustments to operational schedules should be considered during high flow periods when placing HTs in tailraces as Walleye appear to be attracted to tailraces during periods of high flow, particularly during the spawning period in the spring.

Ecological Risk Assessment

The study was limited to comparing fish presence across three discrete HT testing and non-testing periods. However, this testing schedule lacked seasonal representation of fish presence relative to hydrokinetic operations. In an effort to further investigate potential risk of negative interaction with HTs situated in hydropower tailraces, I used acoustic telemetry to also investigate the seasonal residency, movement frequency, and depth-use of Lake Sturgeon and Walleye, to make inferences for the potential risk from negative interactions with HTs for the populations within this river system.

Lake Sturgeon

For the tagged Lake Sturgeon, the seasonal residency index was minimal across all seasons (Figure 3.7). However, seasonal residency was somewhat higher in the spring, which coincides with a brief period in late-May and early-June when a large proportion (55%) of individuals were detected at the CHTTC (Figure 3.2, 3.8). This is likely because of the spawning periodicity that occurs between late-April and early-June, and is linked to the water temperature and discharge rates experienced by the tagged individuals (Peterson et al. 2007; Forsythe et al. 2012). Past research found that upstream migration towards spawning habitat occurs when temperatures range between 5-14^{o} Celsius (Rusak and Mosindy 1997). A number of the Lake Sturgeon were detected at the CHTTC in May and June when water temperatures ranged between 9.8 - 16^{o} Celsius. Spawning and non-spawning cohorts may home to the same location during the spawning season (Auer 1996, 1999), which are usually characterized by high-velocity flow in the upper reaches of river systems (Peterson et al. 2007; Thiem et al. 2013). HT operation schedules could be adjusted (e.g., number of HTs operating, reduce maintenance activities) according to water temperatures. Lake Sturgeon move into the SSGS tailrace during a small window of time based on favourable water temperatures.

Substrate-anchored HTs will likely be placed at the CHTTC and in other tailraces in the coming years where Lake Sturgeon populations reside. However, depth and movement events were notably detected from the tagged Lake Sturgeon in May and June. During the spawning period, the Lake Sturgeon appear to demonstrate porpoising behaviour (i.e., variation in depth-use; Figure 3.12) and move more frequently throughout the CHTTC in the month of June, this is likely male fish searching for ovulating females (Bruch and Binkowski 2002). When residing at the CHTTC, Lake Sturgeon frequent depths where HTs and anchoring structures are positioned (i.e., $\geq$ 6.5 m). Environmental managers could consider adjusting operations and maintenance activities at this time of the year to reduce the risk of deleterious harm or altering natural spawning behaviours of Lake Sturgeon. However, Lake Sturgeon would be at lower risk in the summer, autumn and winter months as tagged individuals marginally utilized or moved throughout the habitat at the CHTTC during these seasons.

Walleye

The tagged Walleye utilized habitat at the CHTTC considerably more than Lake Sturgeon during the monitoring period (Figure 3.9). Walleye are known to have site fidelity below hydropower facilities (McConville and Fossum 1981; Murchie and Smokorowski 2004) and to make minimal movements downstream from hydropower stations (Murchie and Smokorowski 2004). The tagged Walleye are likely utilizing the SSGS tailrace to forage in the open-water season as they are likely attracted to the swift environment, the SSGS powerhouse restricted any further upstream movement, and opportunistically feeding on fish that are entrained through the Seven Sisters powerhouse. Based on seasonal residency, Walleye may be more likely to be at risk of HT impacts (i.e., blade strike, electromagnetic fields, chemical leaking; Yuce and Muratoglu 2015) during the spring, summer, and autumn, while at low risk in winter season. Highest residency occurred during the summer and autumn seasons (i.e., June to November;

Figure 3.9), indicating that this area is favourable for Walleye during the open-water period, but were marginally present here during winter. The tagged fish likely move downstream in search of deeper, slower refugia areas when discharge and water temperatures are not optimal for energetic costs associated with foraging as water temperature drops below 5^{o} Celsius (Paragamian 1989).

Across the monitoring period, Walleye moved more frequently within the CHTTC compared to Lake Sturgeon. Movement frequency was elevated during July, October, and November throughout the area where HTs have been installed and tested. This is similar with previous studies that have shown that Walleye movement is highest in autumn and spring (Schupp 1972; Holt et al. 1977). Interestingly, movements past the testing area were not documented from the tagged Walleye from December 2014 to March 2015. This trend in greater movement in the summer and autumn months and lower in the winter and spring is likely related to water temperature (Holt et al. 1977; Paragamian 1989), foraging behaviour (Bozek et al. 2005), and/or discharge (DiStefano and Hiebert 2000; Murchie and Smokorowski 2004).

Diel period did not significantly influence movement frequency at the CHTTC. This is a variable for which the Walleye movement literature is inconsistent, with some studies finding no differences in movement (Ager 1976; Holt et al. 1977) and others finding greater movement frequency during the nocturnal period (Prophet et al. 1989; DiStefano and Hiebert 2000). This is likely because Walleye are a photophobic species (Ryder 1977; Einfalt et al. 2012). However, differences in movement between diel periods can be confounded by environmental parameters that change ambient light conditions, such as water clarity and depth availability (Ryder 1977; DiStefano and Hiebert 2000). Water passing through the CHTTC is swift, which may have resulted in similar movement frequency between day and night periods.

Although Walleye frequently move and reside at the CHTTC across the spring, summer, and autumn seasons, their average depth-use (5.6 meters) was not within the range where the HT and anchoring structures were positioned (≥ 6.5 meters). In addition, there were no depth positioning data provided from December to March, which corresponds with their lower residency rate (SR_I) and lack of movements during this period. However, Walleye do occasionally utilize depths where the substrate HT was positioned, particularly in the months of May (6.9 m), June (6.7 m), October (6.4 m), and November (6.7 m; Figure 3.12). These months were also characterized by high rates of movement and residency. As such, Walleye would be at higher risk from substrate-HTs and anchoring structure during these months when collectively considering residency, movement frequency, and depth use. However, the telemetry data revealed that no fatalities occurred and space-use was not altered when the HT was operational. Overall, the concern of entrainment, blade strike, ambient noise and EMF is likely a low threat for Walleye relative to singular HTs situated in hydropower tailraces. Walleye are either able to avoid the HT when moving upstream and downstream, or are utilizing flow boundary areas at these depths to balance energy expenditure and foraging success when located in the tailrace. Although noise and turbulence were not measured here, these factors are not likely to affect Walleye since the tailrace environment is already turbulent and noisy.

Study Limitations

This research represents the first assessment for the biological responses of wild fish relative to hydrokinetic turbines in tailrace environments. Based on the intermittent and ad-hoc testing schedule for HTs at the CHTTC, an orthogonal design was not possible to compare the spatial ecology of fish across the all seasons. The investigation for HT operational regimes and fish presence was limited to 34 days of operational data that occurred during late-summer and autumn. This was insufficient to assess the full range of behaviour and movement ecology for Lake Sturgeon and Walleye relative to HT operations due to the lack of seasonal representation. There are seasonal differences with the spatial ecology and general biology of Walleye and Lake Sturgeon that need to be considered when evaluating HT operational regimes. Balancing the testing schedule across a full monitoring year would provide greater insights into potential behavioural alterations due to HT operations.

Investigating risk can be a complex undertaking due to the number of variables when implementing ecological risk assessments for HT devices (VanZweiter et al. 2014). Here, the investigation was limited to two species because of their prevalence in this system, their significance to recreational fisheries, and the risk of extirpation for Lake Sturgeon. The entire fish community was not assessed due to logistical reasons, but other species could be impacted by HTs in tailrace environments. While I investigated general risk of HT exposure here, the potential indirect impacts from HTs, such as noise, chemical leaching, EMF, or hydraulic alterations. These factors may affect the behaviour, physiology, and spatial ecology of wild fishes in riverine systems, and should be investigated for HTs placed in river systems.

Management Implications

This risk assessment at the CHTTC provides timely and relevant information to hydrokinetic energy developers and regulators. This research provides one of the first studies to address HT operations and ecological risk for wild fish populations in a riverine environment. However, a considerable amount of impact assessments are still required before commencing commercial-scale HT operations within river systems. Future studies can use this risk assessment approach as a template for future research regarding riverine-based HT arrays. Research addressing HTs and responses from wild fishes should focus on the importance of collaboration with operators to develop before-after-control-impact (BACI) experimental designs. Implementing BACI designs will help to facilitate comparisons of fish behaviour and ecology before, during, and after HT operations. Additionally, collaboration with operators is critical for commencing operations and monitoring programs in tandem. In this study, there is potential that the tagged individuals were predisposed to HT operations at the CHTTC as pre-commercial operations had commenced prior to biotelemetry monitoring. This may have altered fish behaviour and habitat use prior to implementing the risk assessment.

The tested HTs at the CHTTC are representative of commercial-level operations. As such, this study will help to guide best management practices for commercial operations for in-stream hydrokinetic projects that are expected to be implemented at existing hydropower stations in the coming years. Riverine hydrokinetic devices installed at existing hydropower stations will likely be deployed as arrays that include multiple HT devices operated in series. In this study, I investigated a single substrate-mounted HT. However, there are current proposals for commercial hydrokinetic energy projects consisting of large arrays of HTs (Schweizer et al. 2011). The behavioural responses from wild fishes would likely be related to the HT array size, as well as, the quantity of ambient turbulence, noise, and EMF that is generated. Additionally, the risk of blade strike is directly proportional the size of fishes and the density of HTs installed (Cada et al. 2011). HT operators need to consider the entire fish community and how they may be affected by HT operations, particularly if there are rheotaxic and migratory species present in the area, as in the case with this risk assessment. Furthermore, the question regarding several small or a single large turbine needs to be investigated relative to the wellbeing of fish populations and fish habitat. Lake Sturgeon and Walleye are both large-bodied and migratory, making them susceptible to harm from blade strike and more likely to come into contact with HTs.

As indicated here and with other preliminary assessments (Hammar et al. 2013), singular HTs are unlikely to be hazardous to wild fishes (NAI 2009; EPRI 2012). However, environmental managers should use the precautionary approach before and during full-scale operations occur for HTs in river systems. While operational schedules may not be flexible for commercial-scale operations, energy companies can minimize scheduled maintenance and pre-commercial testing activities during periods when fish are most likely to be present at the testing site. Similar with conventional hydropower stations, research could be directed at assessing deterrent and monitoring systems designed for HT devices. Such devices may reduce the risk of entrainment by deterring fish from passing through the turbines, or being able to halt operations if large-bodied fish are detected in close proximity of an HT. Overall, singular HTs likely have a minimal impact on large-bodied fishes, such as Lake Sturgeon and Walleye. However, this is a complex question with many variables and unknowns that come into question. Further research is warranted to continue investigating HTs within tailraces for other species, across seasons, and with different anchoring systems, but provides important first insights into the spatial ecology of wild fish where riverine hydrokinetic turbines are operational.

Figures

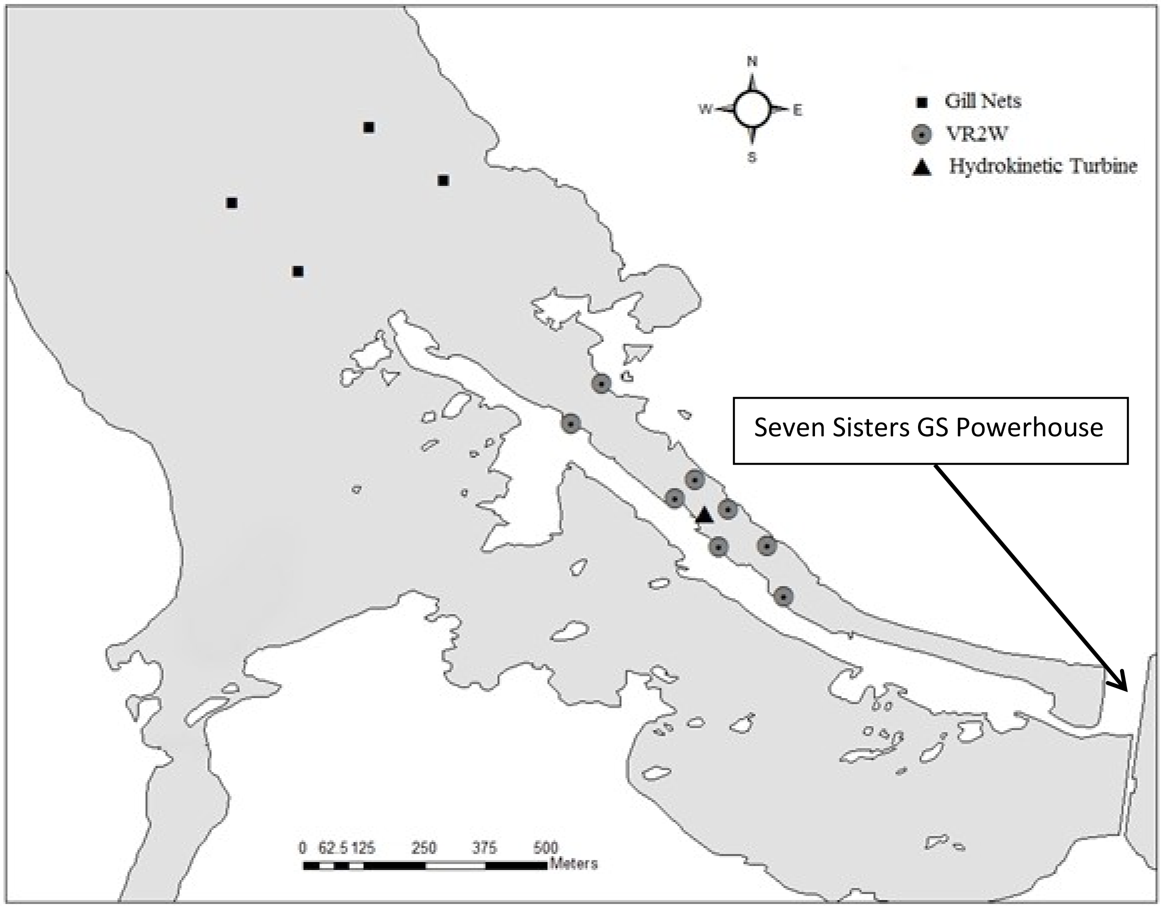

Figure 3.1. Overview of the receiver array located at the HT testing centre (CHTTC) located in the tailrace of the Seven Sisters GS on the Winnipeg River, MB. The map illustrates (A) the 8 VR2Ws that were used to passively-monitor Lake Sturgeon and Walleye, (B) the location of the substrate-anchored HT, and (C) the locations where fish were captured with gill nets.

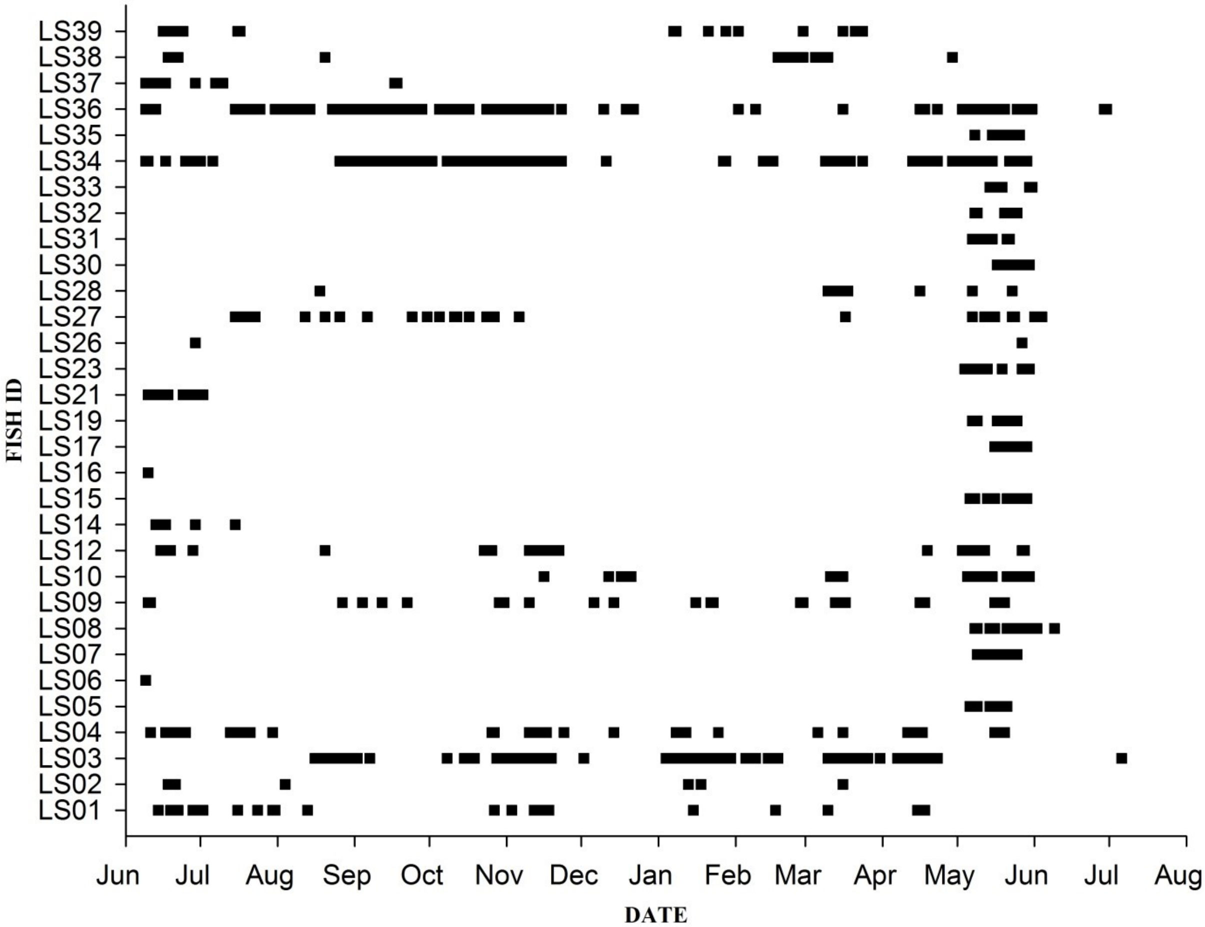

Figure 3.2. Detection summary for the tagged Lake Sturgeon during the acoustic monitoring period (June 9, 2014 to July 6, 2015) at the *Canadian Hydrokinetic Turbine Testing Centre*, which is located in the tailrace of the Seven Sisters GS on the Winnipeg River, MB.

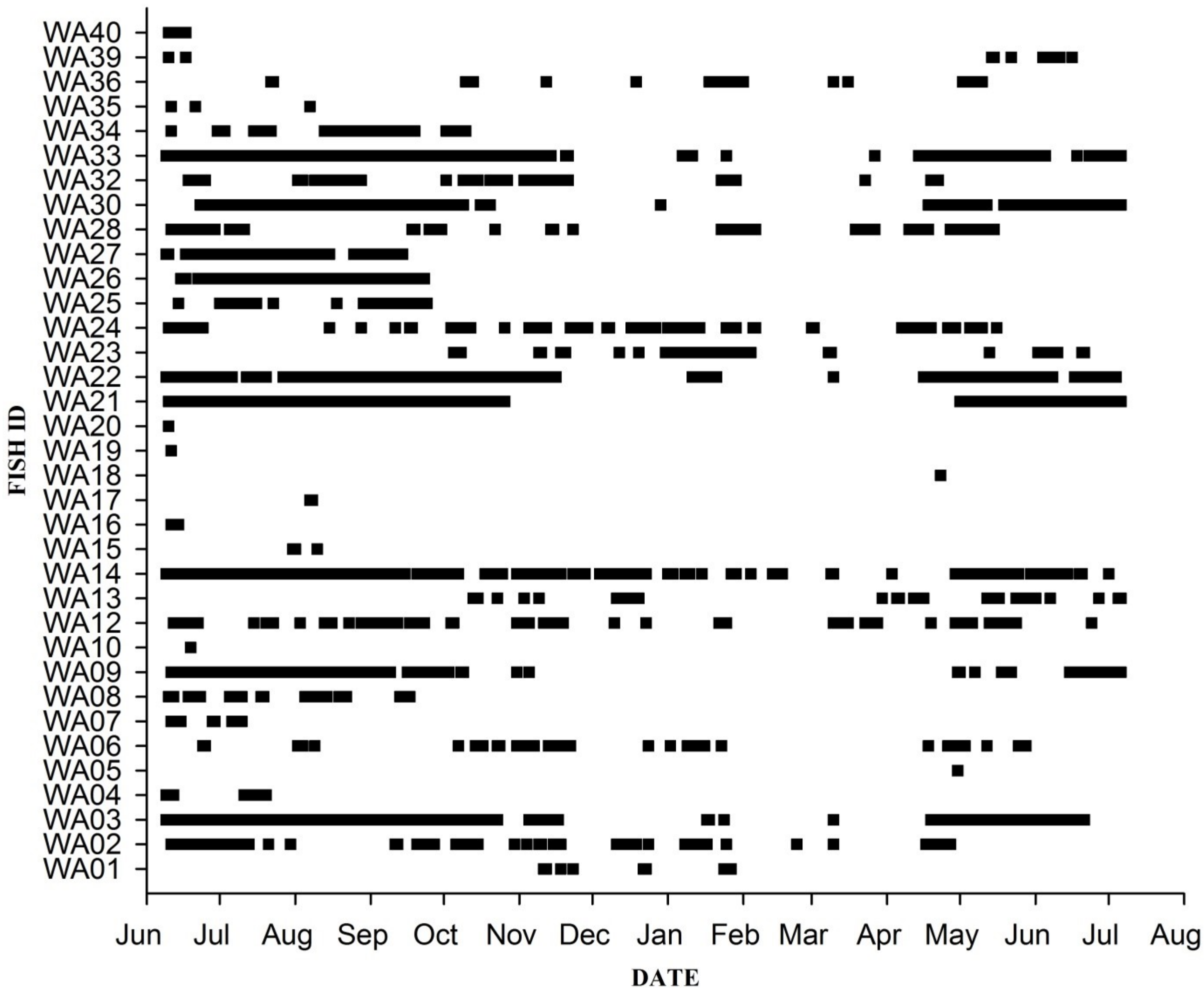

Figure 3.3. Detection summary for the tagged Walleye during the acoustic monitoring period (June 9, 2014 to July 6, 2015) at the *Canadian Hydrokinetic Turbine Testing Centre*, which is located in the tailrace of the Seven Sisters GS on the Winnipeg River, MB.

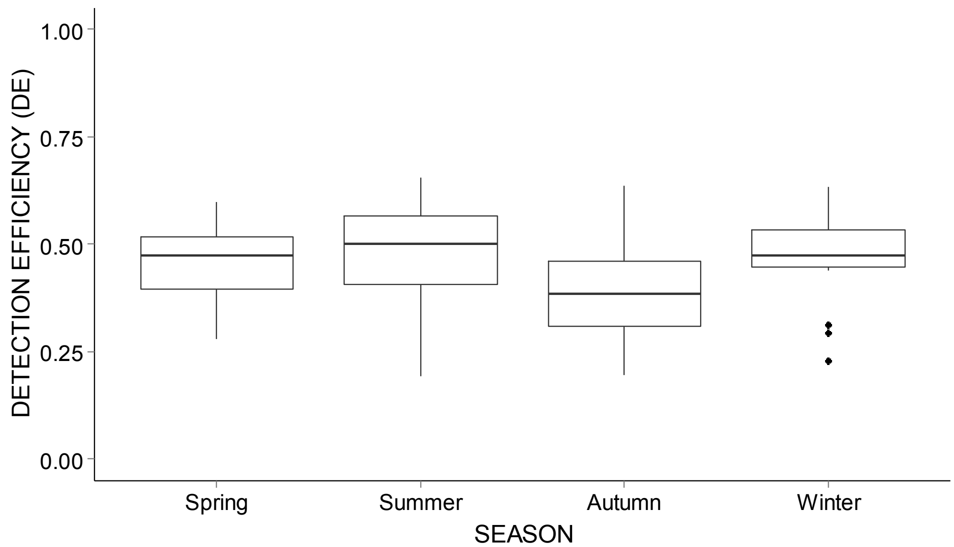

Figure 3.4. Detection efficiency (*DE*) on a seasonal basis for the stationary tags that were collocated to 5 of the VR2W receivers located at the CHTTC. The 1-way ANOVA found no difference in DE across the months or seasons of the monitoring period. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

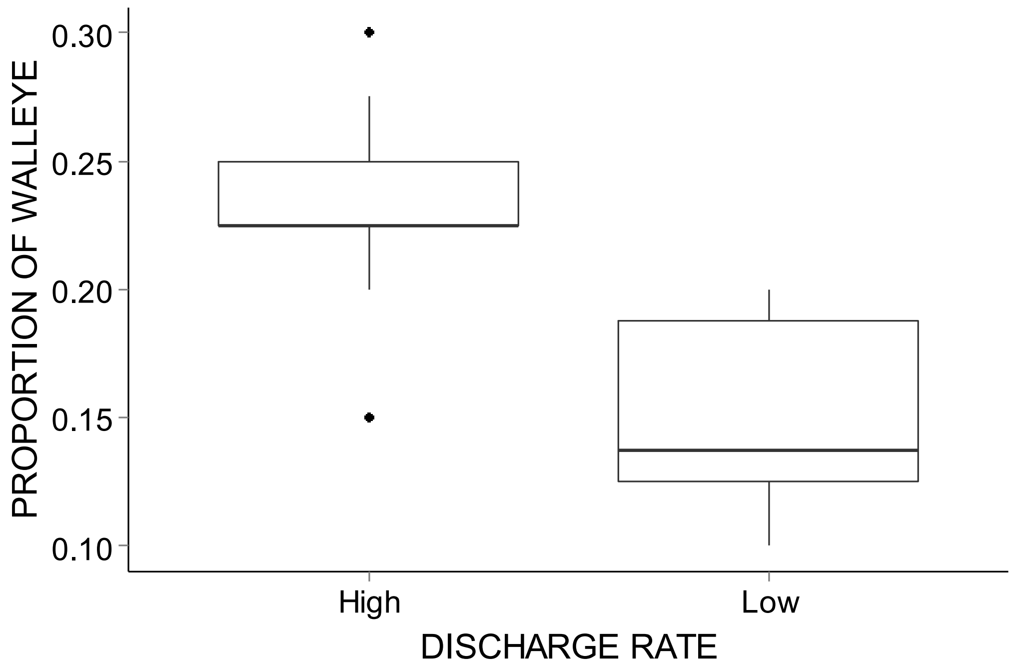

Figure 3.5. The proportion of tagged Walleye that were residing at the *Canadian Hydrokinetic Turbine Testing Centre* (Seven Sisters GS tailrace; Winnipeg River, MB) when discharge rates were high (>950 cms) and low (<750 cms). The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

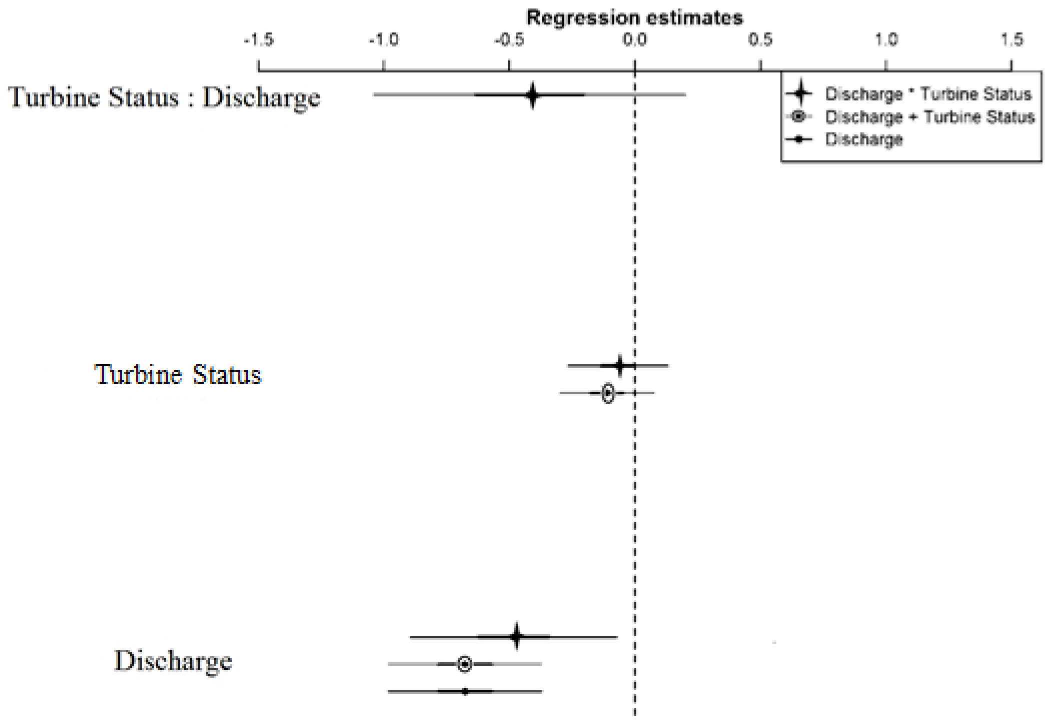

Figure 3.6. The Results of the model averaging for 3 different models (1. Discharge:Turbine Status; 2. Discharge + Turbine Status; 3. Discharge) that indicates relative importance (RI) of model parameters for fish presence at the CHTTC. Based on regression estimates, discharge was the most important term in all three models, whereas turbine status (i.e., operational vs non-operational) was of little importance for predicting Walleye residency.

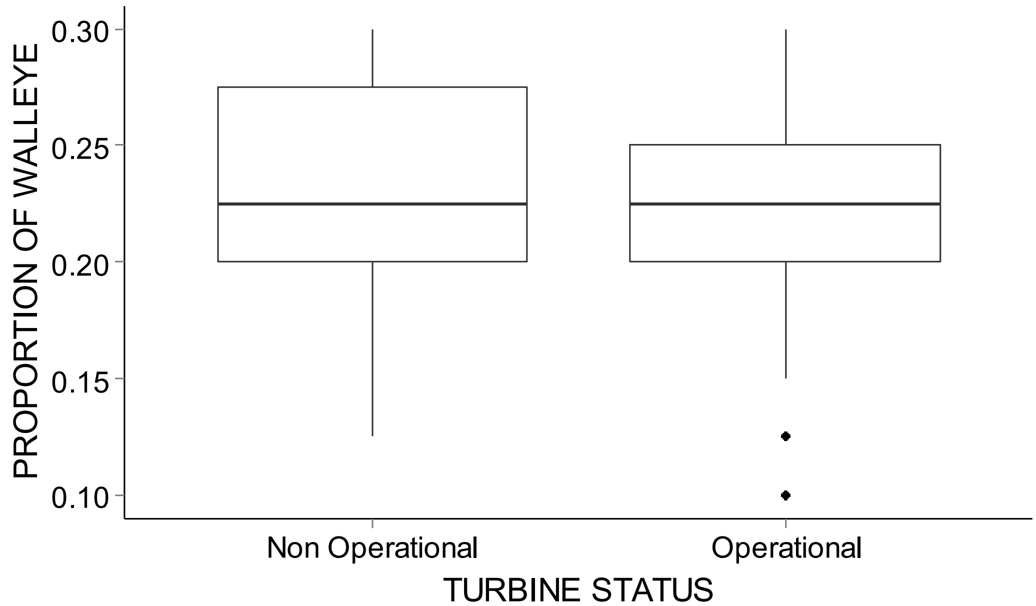

Figure 3.7. The proportion of tagged Walleye that were residing at the *Canadian Hydrokinetic Turbine Testing Centre* (Seven Sisters GS tailrace; Winnipeg River, MB) when a hydrokinetic turbine was either non-operational (left) and operational (right). The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

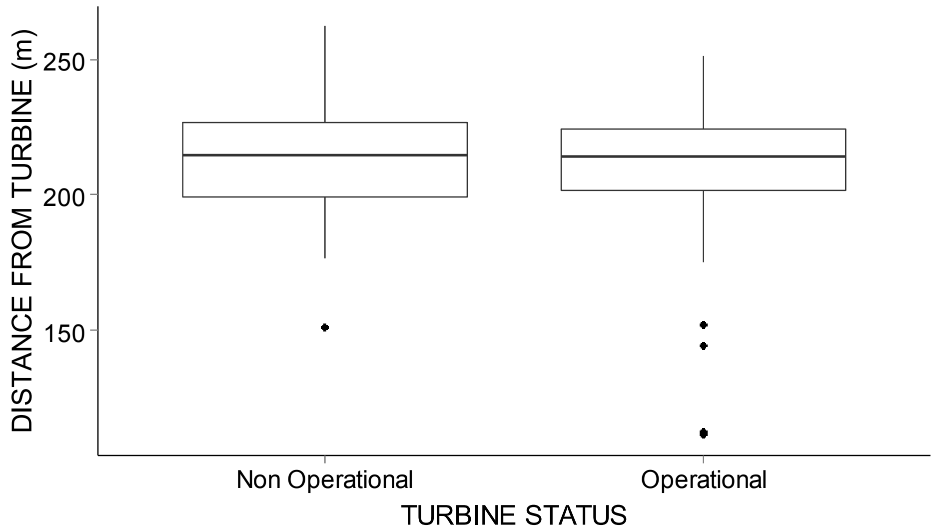

Figure 3.8. The distance that Walleye were residing in proximity to where a hydrokinetic turbine was being tested at the *Canadian Hydrokinetic Turbine Testing Centre* (Seven Sisters GS tailrace, Winnipeg River, MB). The plot shows the number of Walleye at the CHTTC when the turbine was non-operational (left) and operational (right). The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

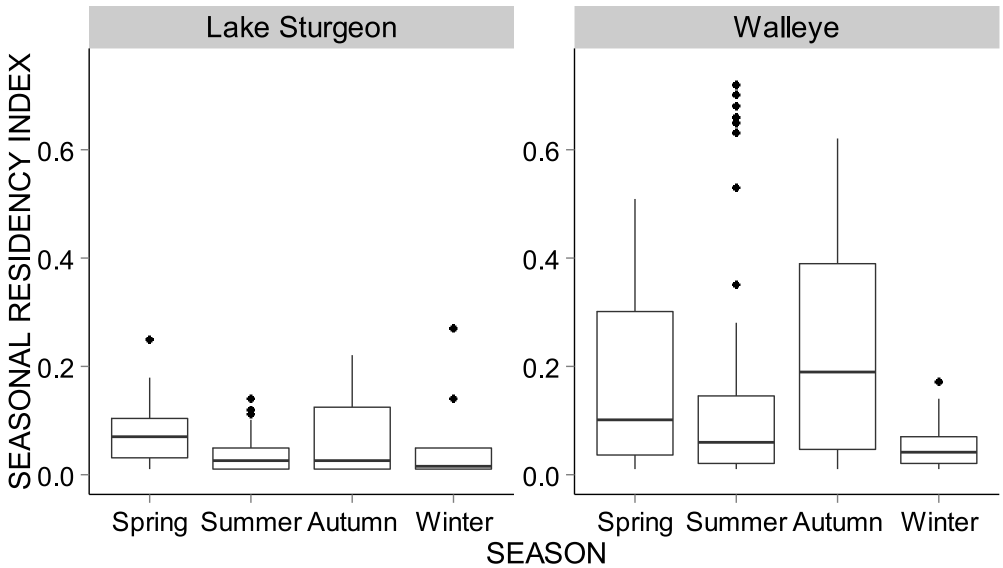

Figure 3.9. Seasonal Residency Indices (SR_I) for Lake Sturgeon and Walleye for *autumn* (Sept – Nov), *spring* (March-May), *summer* (June-Aug), and *winter* (Dec – Feb) at the *Canadian Hydrokinetic Turbine Testing Centre* located on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

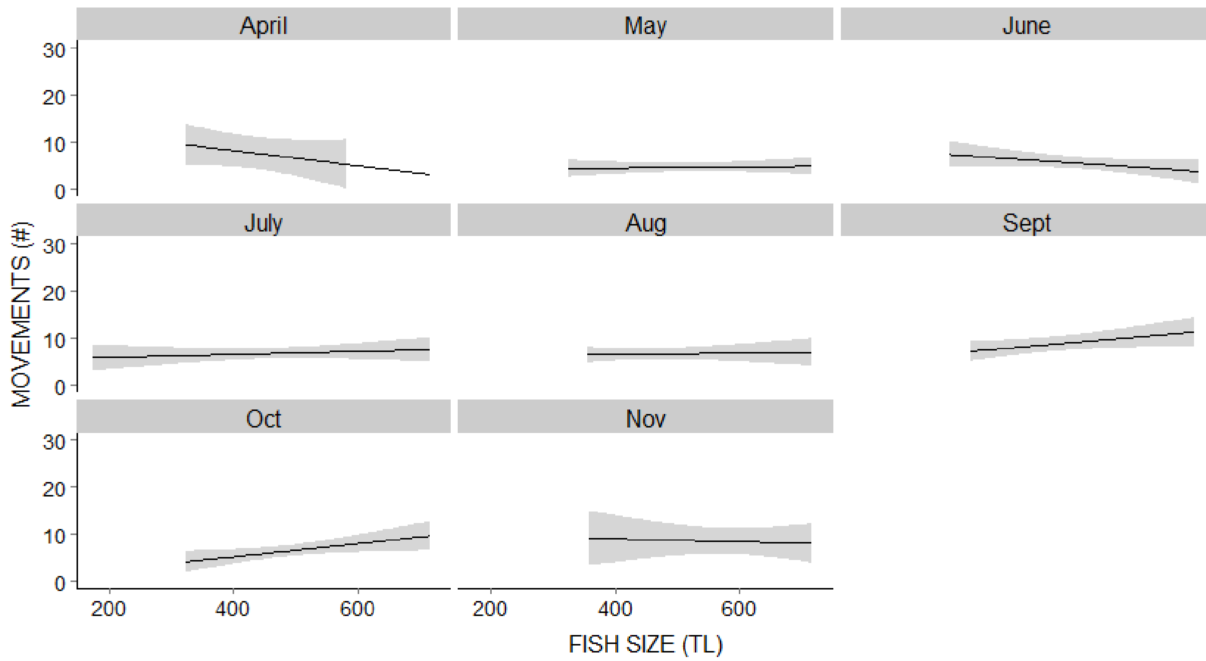

Figure 3.10. The movement frequency of Walleye throughout the calendar months at the Canadian Hydrokinetic Turbine Testing Centre (CHTTC) across the size range (TL). No movement events occurred during the winter and early-spring seasons (Dec-Mar). The plots provide the line of best fit and 95% confidence intervals.

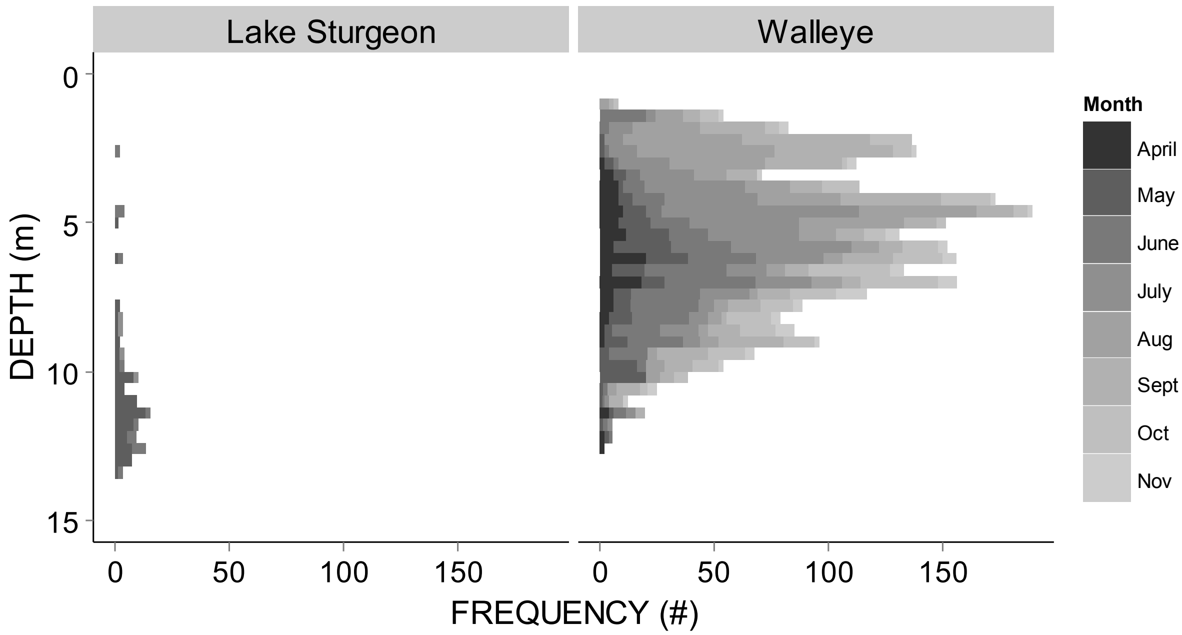

Figure 3.11. An overview for the depths frequented by Lake Sturgeon (left) and Walleye (right) at the *Canadian Hydrokinetic Turbine Testing Centre* (CHTTC) located on the Winnipeg River, MB.

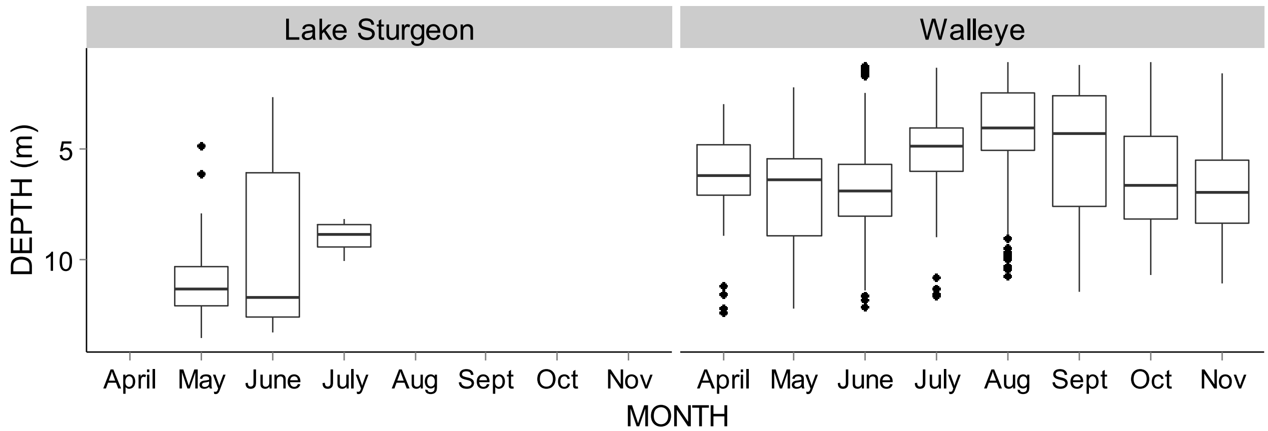

Figure 3.12. An overview of the depth use across the calendar months for Lake Sturgeon (left) and Walleye (right) at the *Canadian Hydrokinetic Turbine Testing Centre* (CHTTC) located on the Winnipeg River, MB. The boxplot provides the median, the 50% quantile, the 75% quantile, and outlying data points.

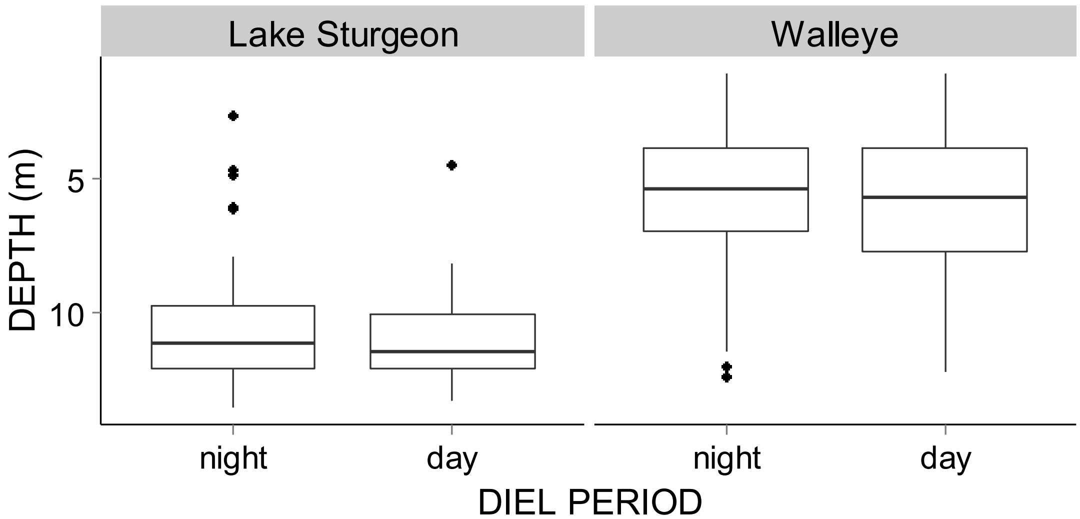

Figure 3.13. An overview of the depth use by Lake Sturgeon (left) and Walleye (right) between diel periods (i.e., day and night) at the *Canadian Hydrokinetic Turbine Testing Centre* (CHTTC) located on the Winnipeg River, MB.

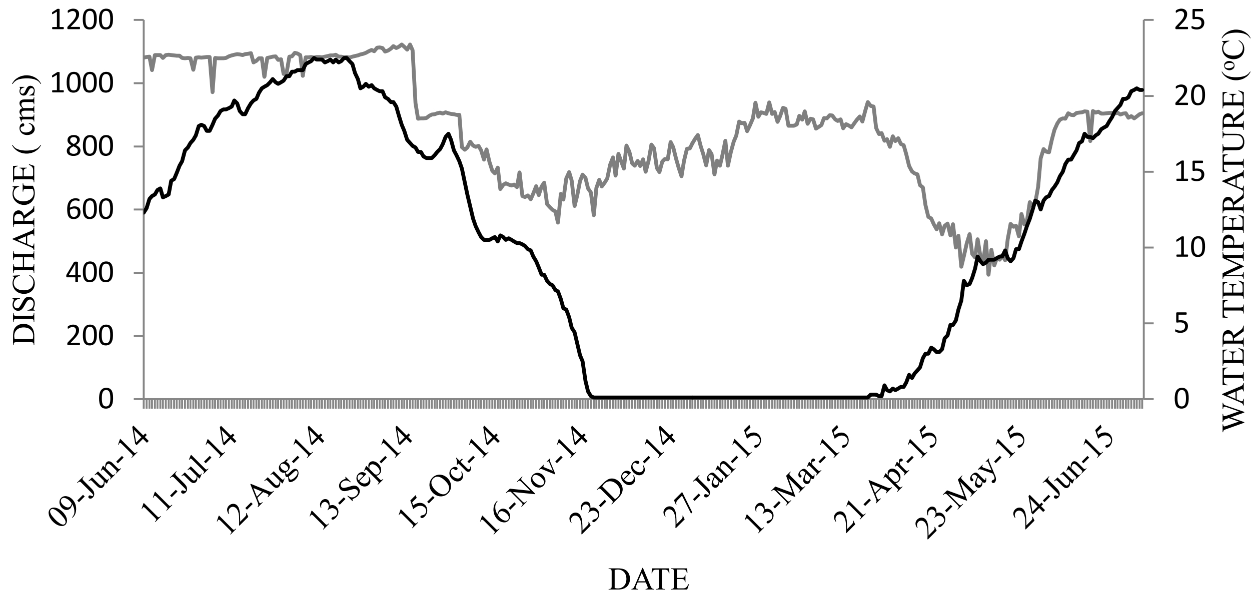

Figure 3.14. Daily discharge rates (cms; grey) measured at the Seven Sisters GS powerhouse and water temperature readings (°C; black) provided by town of Powerview-Pine Falls, MB throughout the acoustic monitoring period (June 9th 2014 to July 6th 2015) on the Winnipeg River, MB.

Tables

Table 3.1. Model selection statistics from binomial GLMMs on the proportion of tagged Walleye detected in the Winnipeg River, MB. Fixed terms included discharge (DISC), distance from turbine (DST), and turbine status (ST). K is the number of parameters; AICc is the bias-corrected Akaike Information Criterion; ΔAICc is the difference in bias-corrected AIC between a given model and the top ranked model; wAICc is the relative weight of the bias-corrected AIC; Cumul.Wt is the cumulative Akaike weights and; L-Lik is the log-likelihood of the models. All models contain turbine operating regime as a random effect.

Model No.	Fixed terms	K	AICc	ΔAICc	wAICc	Cumul.Wt	*L*-Lik
M1	DISC	3	293.53	0	0.47	0.47	-143.6
M5	DISC + ST	4	294.44	0.9	0.3	0.77	-142.93
M6	DISC * ST	5	294.97	1.44	0.23	0.99	-142.04
M4	DST * ST	5	304.09	10.56	0	1	-146.61
M2	DST	3	304.46	10.92	0	1	-149.06
M3	ST	3	305.68	12.15	0	1	-149.67
M7	DST + ST	4	306.27	12.73	0	1	-148.84

Table 3.2. Set of candidate models using backwards model selection for Seasonal Residency Index (SR_I) for Walleye at the CHTTC. The degrees of freedom (d.f.) are given for each candidate model; Models were ranked using Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and log-likelihood (log-Lik) for each candidate model. All models contain Fish ID as a random effect. The models are ranked in order from top to bottom.

Model No.	Model Terms	d.f.	AIC	BIC	log-Lik
M6	Season + Species + Season*Species	17	408.568	468.77	-187.28
M4	Season + Species + Diel + Season*Species	18	410.394	474.137	-187.2
M5	Season + Species + TL + Season*Species	18	410.564	474.307	-187.28
M2	Season + Species + Diel + TL + Season*Species + Diel*Species	20	411.696	482.522	-185.85
M1	Season + Species + Diel + TL + Season*TL + Season*Species + Diel*Species	23	411.947	493.396	-182.97
M3	Season + Species + Diel + TL + Season*Species	19	412.388	479.672	-187.19

Table 3.3. Model outcomes for type III sum of squares for seasonal residency, movement frequency, and depth use at the CHTTC located on the Winnipeg River, MB. Model summary provides the response term, model terms, the chi-square statistic (χ^2), degrees of freedom (d.f.), and the critical value (P-value) is bolded if found to be significant at the 5% threshold.

Response	Model Term	χ^2	d.f.	P-value
Seasonal Residency Index (SR_I)	(Intercept)	8.7453	1	**0.003**
	Season	3.7958	3	0.284
	Species	12.1284	1	**< 0.001**
	Season*Species	24.2104	3	**< 0.0001**
Movement Frequency (#)	(Intercept)	17.7038	1	**< 0.0001**
	Month	45.8516	7	**< 0.0001**
	TL	3.6373	1	0.057
	Month*TL	56.5876	7	**< 0.0001**
Depth Use (m)	Month	531.631	7	**< 0.0001**
	Diel	34.462	1	**< 0.0001**
	Species	24.88	1	**< 0.0001**

Table 3.4. Set of candidate models using backwards model selection for movement frequency at the CHTTC. The degrees of freedom (d.f.) are given for each model. The models were ranked using Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and log-likelihood (log-Lik) for each candidate model. All models contain Fish ID as a random effect. The models are ranked in order from top to bottom.

Model No.	Model Terms	d.f.	AIC	BIC	Log-Lik
M3	Month + TL + Month*TL	25	2105.93	2216.06	-1028
M1	Month + Diel + TL + Month*TL	26	2107.93	2222.46	-1028
M2	Month + Diel + TL	19	2145.24	2228.94	-1053.6

Table 3.5. Set of candidate models using backwards model selection for explaining depth use at the CHTTC. d.f. is the degrees of freedom for the given model; Models were ranked using Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and log-likelihood (log-Lik) for each candidate model. All models contain Fish ID as a random effect. The models are ranked in order from top to bottom.

Model No.	Model Terms	d.f.	AIC	BIC	Log-Lik
Model 2	Month + Diel + Species	19	11281.1	11393.6	-5621.5
Model 1	Month + Diel + Species + Diel*Species	20	11281.9	11400.3	-5620.9
Model 5	Month + Diel	18	11297.2	11403.7	-5630.6
Model 4	Month + Species	18	11313.2	11419.8	-5638.6
Model 3	Diel + Species	12	11720.3	11791.4	-5848.2

Chapter 4: General Discussion

Research Significance

Large river systems across the globe have been reshaped by anthropogenic developments, particularly due to hydropower facilities (Poff et al. 1997; Rosenberg et al. 1997). Hydropower dams can restrict the upstream and downstream migration of fish that can lead to genetic structuring due to the lack of gene flow between fragmented reaches (Haxton et al. 2015), as well as limiting population growth and biodiversity loss due to the lack of available habitat (Beamesderfer 1998). Hydropower facilities regulate flow on a seasonal and diel basis, this can cause stranding events due to abrupt dewatering or drawdown (Nagrodski et al. 2012). The Winnipeg River has been extensively developed for run-of-river hydropower production, with eight facilities located on the river system. Discharge is regulated at the hydroelectric facilities to meet daily and seasonal energy demands, and at the outflow from Lake of the Woods, ON, to manage water demands from multiple user groups within this watershed.

Hydropower developments, which cause habitat alterations, and are thought to impact Lake Sturgeon (Barth et al. 2011) and Walleye (Haxton et al. 2015) populations that are confined within fragmented systems. The potential development of hydrokinetic turbine arrays in tailraces and forebays at existing hydropower stations to augment supply to the power grid (Khan et al. 2009; Liu and Packey 2014) pose a possible additional threat. Indeed, such devices are undergoing pre-commercial testing in this impounded reach, situated within the tailrace of the Seven Sisters GS. There were two study objectives addressed in this thesis. First, an acoustic telemetry array was used in chapter 2 to investigate how Lake Sturgeon and Walleye utilize impounded reaches, as well as their responses to the abiotic environment. For chapter 3, the seasonal risk of exposure to HTs was addressed for Lake Sturgeon and Walleye at the *Canadian Hydrokinetic Turbine Testing Centre (CHTTC)*. The generated information from these chapters will help to inform fisheries managers of Lake Sturgeon and Walleye with regards to hydropower developments on large river systems.

Findings and Implications

Impoundments

Positional and sensor transmitters are reliable methods for examining the physiology and behavioural responses of fish to anthropogenic development and the abiotic environment as a means to enhance fundamental understanding and guide conservation actions (Cooke et al. 2004b; Wilson et al. 2015). I used tri-axial accelerometers that provided activity information, while hydrostatic pressure sensors provided data on depth use. Using sensor transmitters is a practical and effective tool for assessing temporal patterns in physiology, behaviour, and energetics, particularly during the winter period when field data collection would be unfeasible using other means (Cooke et al. 2004a, b).

To examine how these species utilized habitat and respond to the abiotic environment within impoundments caused by hydropower developments, I tagged 40 Lake Sturgeon and 40 Walleye with acoustic transmitters. Almost half of the tagged Lake Sturgeon returned to the vicinity of the Seven Sisters GS, either to spawn or moving with spawning conspecifics, the following spring after tagged commenced. The upstream habitat of this impoundment is likely a critical spawning location for this population. Similar results have been found in adjacent reaches on the Winnipeg River system (McDougall et al. 2013b, 2014) and elsewhere (McKinley et al.

1998), where migration is thought to be initiated with rising water temperature and discharge rates in the spring season (Peterson et al. 2007).

Adult Lake Sturgeon have larger home ranges compared to juveniles and sub-adults (Peterson et al. 2007; Auer et al. 2013; McDougall et al. 2013a). In recent research, Barth et al. (2011) concluded that juvenile Lake Sturgeon generally have small ranges that meet their seasonal habitat requirements. Conversely, sub-adult and adult Lake Sturgeon normally utilize larger home ranges and seasonally select different habitats throughout their range for spawning, foraging, and overwintering needs. My results indicate that a proportion of the tagged Lake Sturgeon remained near the upstream hydropower facility, while others utilized the downstream area of the impoundment that is characterized by a transition from riverine to lacustrine habitat. This information is important for managers as it identifies that upstream habitat within impoundments is utilized by Lake Sturgeon not just for spawning purposes, but also to forage and overwinter to some extent.

Walleye heavily utilized a small section of river and tailrace located below the Seven Sisters GS. Walleye are known to adapt reproductive and life histories to improve fitness and take advantage of the local environment (Priegel 1970; Minor 1980). The individuals were captured and tagged near the Seven Sisters GS. They generally remained near the Seven Sisters GS throughout all seasons, so it is likely that the majority of the tagged Walleye were employing a “river resident-river spawning” reproductive life history (Bozek et al. 2011). This area is likely a critical spawning, foraging, and overwintering habitat within this impoundment for sub-populations of Walleye.

Lake Sturgeon utilized deeper and a larger range in depth use across the study reach, while Walleye appear to prefer depths between 4-7 meters across all habitat areas and seasons. This is likely due to differences in foraging strategies. Interestingly, swimming activity rates for Walleye were similar to that demonstrated by Lake Sturgeon. Both species were highly active during the open-water period, while inactive in the winter months. Water temperature is likely the controlling factor for the activity responses for these fishes. Energetically, fish are less likely to move when temperature are sub-optimal for foraging purposes. However, Lake Sturgeon activity rates were somewhat higher than Walleye during the open-water period, and is another indication of different foraging strategies in the open-water periods. Additionally, Lake Sturgeon move throughout the impounded system on a seasonal basis, while the tagged Walleye remain in the upstream area near the SSGS. This is likely due to foraging behaviour as Lake Sturgeon actively search for food items, while Walleye likely employ a "sit-and-wait" feeding tactic to ambush prey and intercept entrained fish as they pass through the spillway and powerhouse of the Seven Sisters GS.

Hydrokinetic Turbines

In chapter 3, I explored seasonal residency, movement frequency, and depth use of Lake Sturgeon and Walleye at the *Canadian Hydrokinetic Turbine Testing Centre.* The research outlined in chapter 3 is one of the first to address seasonal movement and space-use of free-ranging fishes in relation to pre-commercial tests for riverine hydrokinetic technology. Based on the seasonal residency index (SR_I), Lake Sturgeon would generally be at higher risk in May and June during the spawning season, while at lower risk throughout all other periods. While Lake Sturgeon were minimally present at the CHTTC when the HTs were being tested, the adult population would be at greater risk from HT impacts (e.g., blade strike, EMF, collision with sub-surface anchoring apparatus) than Walleye because they were often found in depths where the substrate-mounted HT was being tested. Lake Sturgeon are known to demonstrate porpoising behaviour during the spawning season, characterized by abrupt movements from a deep holding position to breaching the surface. This may be what the depth sensor data is demonstrating that was attained from the tagged Lake Sturgeon. With the abrupt and frequent changes in depth-use, there would be a greater chance of striking HTs and the associated anchors and cables that could lead to injury or mortality. In general, the Lake Sturgeon spawning period occurs over a short period (~3 or 4 days; McKinley et al. 1998) when water temperature approach 10-15^{o} Celsius (Harkness and Dymond 1961; Kempinger 1988). HT operations could be minimized for a brief period of time in the spring based on water temperature. This would allow the Lake Sturgeon spawn to occur uninhibited by the risk of exposure to blade strike, noise, or EMF when residing at the spawning site.

The tagged Walleye appeared to reside at the CHTTC at greater rates than Lake Sturgeon throughout the year. This area is likely a productive foraging area with prey being entrained through the turbines of the Seven Sisters GS and a barrier to upstream movement of all fishes here. However, the tagged Walleye were not attracted nor deterred from the turbine testing berth while the HT was operational. Interestingly, discharge played a role in Walleye presence during the HT testing operations. When discharge was high (>950 cms), there was a greater proportion of the tagged Walleye residing in the area where HTs are being tested. Singular HTs in tailraces would likely not interfere with the behaviour of Walleye, but the population may be at greater risk from turbine effects (EMF, noise, chemical leaching) with greater densities of Walleye residing at the testing centre when discharge is elevated.

Based on these results, operations and maintenance schedules could be adjusted to minimize risks. The period between May and June should be a priority to make operational adjustments to protect Lake Sturgeon populations. Hydrokinetic developments are expected to be set up in large arrays that may consist of 50 or more devices (Schweizer et al. 2011). HT impacts, particularly blade strike induced injury and mortality is proportional to the number of devices that are operational (Cada et al. 2011). The number of devices that are operational could be reduced during peak residency periods for Lake Sturgeon and Walleye. Additionally, planned maintenance activities and testing schedules could be minimized during periods of peak residency and movement for Lake Sturgeon and Walleye. The winter season appears to be a low risk period for Lake Sturgeon and Walleye, since the tagged fish were rarely located at the CHTTC during this period. The tagged fish likely moved downstream to overwinter in deeper, lower velocity waters to minimize energy expenditure in the winter months. When collectively evaluating the results for all HT exposure risk measures, the months from December to March would be the safest for HT operations in tailraces given that risk of exposure would be lowest during these months.

Future Directions

Building upon the framework set out in chapter 2, there are specific applied and theoretic questions that could be addressed within impounded reaches. In particular, entrainment risk and stranding events are concerning for wild fishes within impounded reaches. Previous work has addressed this question in adjacent impoundments on the Winnipeg River, finding an entrainment rate of 8.3% for Lake Sturgeon (McDougall et al. 2013a). However, the study system was a relatively small impoundment (~10 km long), mainly characterised as riverine habitat, and had a shallow narrow section that restricted movements of juvenile and sub-adult

Lake Sturgeon. Fish are likely to utilize and move differently through impoundments that are relatively larger, characterized both by riverine and lacustrine habitat types, and do not have any natural barriers that restrict movements. Furthermore, the occurrence of stranding wild fish due to rapid dewatering merits further investigation for impounded rivers. Stranding events have been reported at the spillway of the Seven Sisters GS (K. Kansas, Fisheries Branch, Pers. Comm.), but have not been directly addressed in the literature for determining the seasonal occurrence for Lake Sturgeon, Walleye, or other relevant fish populations in impoundments. Overall, stranding events have not been extensively studied for Lake Sturgeon and Walleye, but could be important to address as a measure for protecting fish populations residing in impounded reaches.

Sensor transmitters also proved to be an effective tool for examining how wild fishes respond to the abiotic environment. These tags could be used to further address fundamental and applied questions within impoundments. For example, tri-axial accelerometers could be calibrated in closed flumes to determine swimming speeds and metabolic oxygen demands as bioenergetics metrics. Once calibrations have been completed, energy expenditure within impounded reaches and relative to HT operations could be investigated. Additionally, depth and activity sensor data could be paired with fine-scale positioning data (e.g., VPS; Vemco, NS) and habitat information, such as bathymetry, substrate type, and velocity profiles, to test hypothesis for movement behaviour and ecology.

Chapter 3 solely focused on HT development in tailrace environments. However, further research is warranted for river in-stream hydrokinetic turbines (RIHTs) that may be placed within the main channel of river systems to generate energy in remote communities (Previsic et la. 2008; Sornes 2010; Liu and Packey 2014). Fish movement ecology and behaviour should differ from those demonstrated in tailrace environments. Recent research has addressed fish behaviour and movement in flumes (EPRI 2011a; Castro-Santos and Haro 2015) and controlled field conditions (NAI 2009), but not in riverine setting where wild fish population would be at risk of HT exposure. Furthermore, there are various designs for HTs (e.g., axial-flow, Darrius, helical) that may affect the movement, habitat use, and behaviour of wild fish in open systems differently than the system studied here. Additionally, HTs can be shrouded or unshrouded, which could alter the rate of entrainment or blade strike for wild fish. There are also deterrent devices (e.g., lighting, noise) and monitoring systems that could be tested in conjunction with hydrokinetic turbines to determine if they are effective for minimizing blade strike or behaviour impairment in wild fishes. The risk of negative HT interactions or altering fish behaviour is likely dependent on seasonality, ontogeny, and the density of HT devices that are installed in river systems. When performing risk assessments for wild fishes, future studies should not only consider a BACI design, but also examine all stages of maturity, seasonality, and adjusting the number of HTs being tested.

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