The Use of Biotelemetry in Management of Areas of Concern in the Laurentian Great Lakes.

By

Jill L. Brooks

B.Sc., University of Wales, Bangor, 2006

A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements for the degree of

Master of Science

In

Biology

Carleton University,

Ottawa, Ontario

Abstract

Substantial efforts have been made to rehabilitate freshwater ecosystems and fish populations around the globe. In this thesis, I illustrate how biotelemetry can be used to complement traditional fish sampling methods to guide efforts to rehabilitate fish populations and habitat. I highlight several case studies within the Laurentian Great Lakes where biotelemetry is being used at various planning and monitoring stages, and used biotelemetry to monitor and inform the fish rehabilitation efforts in Hamilton Harbour, Lake Ontario. Walleye (*Sander vitreus*) have been reintroduced into the Harbour during 1992-2016. Biotelemetry revealed that mature walleye spent the majority of the study (October 2015-2016) within the Harbour, did not migrate out of the Harbour during spring spawning season, and that their home range extent was significantly reduced in the summer. These findings provided locations for future stocking and natural recruitment research and guided further research into the effects of summer hypoxia on walleye movements.

Acknowledgements

I would like to thank my supervisor Steven Cooke, my co-supervisor Susan Doka, my mentors Jon Midwood, Lee Gutowski, and Andrew Rous, and my committee Lenore Fahrig and Julie Morand- Ferron, for their guidance, support and incredible patience. I would also like to thank my collaborators (Cooke, Doka, Boston, Midwood, Gutowski, Hall) for helping with the development of the Hamilton Harbour project, and my collaborators (Boston, Doka, Gorsky, Gustavson, Hondorp, Isermann, Midwood, Pratt, Rous, Withers, Krueger, Cooke) for helping with the Areas Of Concern case studies. I would like to extend my sincerest appreciation to the employees at Fisheries and Oceans Canada and Environment and Climate Change Canada's Technical Operations team (Price, Reddick, Tang, Fern, Aguir, Benoit, Breedon, Chris) and volunteers from the Fish Ecology and Conservation Physiology Laboratory (William Twardek, Lisa Donaldson, Phil Harrison, and Jacqueline Chapman) for assistance in the field. Finally, I would like to thank my family and friends for the continuous encouragement, support, and care packages, even from thousands of miles away.

Co-Authorship

Chapter 2: Use of fish telemetry in rehabilitation planning, management, and monitoring in Areas of Concern in the Laurentian Great Lakes.

Brooks, J.L., C. Boston, S. Doka, D. Gorsky, K. Gustavson, D. Hondorp, D. Isermann, J. D. Midwood, T.C. Pratt, A. M. Rous, J. L. Withers, C.C. Krueger, & S. J. Cooke.

While the study was my own, the research was undertaken as part of a collaborative effort, and each co-author played a valuable role in its completion. The project was conceived by Brooks and Cooke. The majority of the writing was conducted by Brooks and individual co-authors contributed to their case studies. All co-authors provided comments and feedback on the manuscript. The manuscript has been submitted to the Journal of Environmental Management.

Chapter 3: Spatial ecology of a reintroduced fish (*Sander vitreus*) in an Area of Concern, Hamilton Harbour, Lake Ontario.

Brooks, J.L., J.D. Midwood, C. Boston, S. Doka, L.F.G Gutowsky, J. Hoyle, A. Todd, and S.J. Cooke.

While the study was my own, the research was undertaken as part of a collaborative effort, and each co-author played a valuable role in its completion. The project was conceived by Brooks, Cooke, Midwood and Doka. Field work was completed by Brooks, Midwood, and Boston and Gutowsky and Midwood provided analytical support. Hoyle and Todd provided technical advice regarding walleye stocking, fish sexual maturity and spawning surveys. All writing was conducted by Brooks.

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Glossary

AOC: Area of Concern

BUI: Beneficial Use Impairment

COA: Center Of Activity

Core range: 50 Percent Volume Contour

DFO: Fisheries and Oceans Canada

Home range: 95 Percent Volume Contour

IJC: International Joint Commission

GLATOS: Great Lakes Acoustic Telemetry Observation System

GLWQA: Great Lakes Water Quality Agreement

KDE: Kernel Density Estimate

KUD: Kernel Utilization Density

NSCIN: Near Shore Community Index Netting

OMNRF: Ontario Ministry of Natural Resources and Forestry

PES: Portable Electro-anesthesia Unit

PVC: Percent Volume Contour

RAMP: Reflex Action Mortality Predictors

RAP: Remedial Action Plan

RBG: Royal Botanical Gardens

Chapter 1: Introduction to fisheries and habitat management in the Laurentian Great Lakes.

Humans are continuing to transform the natural environment on local and global scales leading to dramatic changes in biodiversity (Vitousek et al., 1997). These effects are felt in aquatic ecosystems, and in particular, inland ecosystems. It has been suggested that rates of decline in freshwater biodiversity have been greater during the last few decades than that of their marine and terrestrial counterparts (Collen et al., 2014; Garcia-Moreno et al., 2014). Anthropogenic effects in inland ecosystems can be grouped into five major stressors; over-exploitation, water pollution, flow modification, destruction of habitats, and invasion of exotic species (Abell et al., 2008; Dudgeon et al., 2006). Inland ecosystems are perhaps more vulnerable than marine ecosystems as their catchment areas are often urbanized or altered for agriculture, and streams, rivers and lakes become repositories for human, agricultural, and industrial waste leading to sedimentation, eutrophication, and acidification. These stressors have the potential to influence the behaviour, physiology, fitness, health, and survival of wild animals. From an ecological perspective, it is now well known that the aforementioned stressors alter environmental conditions which through individual-, population- and species-level physiological tolerances and preferences (reviewed in Spicer and Gaston 2009) influence how animals are distributed in space and time (Candolin and Wong 2012).

The movement of animals is a characteristic of life and is driven by processes that act across multiple space and time scales (Nathan et al., 2008). Drivers of spatial ecology include short term activities like foraging and prey avoidance, to longer, and often larger scale movements such as spawning migrations. Migratory animals are often key players of complex food webs and the interruptions of migratory patterns can have cascading effects impacting other species (Lindstrom et al., 2014). The distribution and movement of aquatic animals is determined by a combination of species' interactions (notably the need to obtain food and avoid predators; Laundré et al., 2010) and their tolerance for a variety of biotic and abiotic factors. For aquatic ectotherms, however, water temperature is often regarded as one of the most influential factors. Indeed, Fry (1971) suggested that water temperature was the "master" environmental factor influencing fish. The increased temperatures and changes in precipitation as a result of changing climate (Ficke et al., 2007; Roessig et al., 2004) could lead to a loss of freshwater species from their refuges. The movement or expansion of animals into more suitable refuges will be increasingly difficult with the removal or destruction of suitable habitats and migration corridors (Turak et al., 2017).

Fish contribute in a variety of fundamental ways to aquatic ecosystems. Fish consume organisms regulating trophic structure and influence the stability, resilience, and food web dynamics; they recycle and transport nutrients and energy; and maintain sediment processes (via bioturbation) and genetic, species and biodiversity (Holmlund & Hammer, 1999). These ecological impacts are not limited to local scales for example migratory fishes like Pacific salmon (*Oncorhynchus* spp.) and alewife (*Alosa pseudoharengus*) transport energy and nutrients from distant ecosystems that support terrestrial food webs (Wipfli & Baxter, 2010). They also provide many ecosystem services to humans, including amongst others, production of food, control of algae and macrophytes, reduction of waste, and the supply of recreational activities (Holmlund & Hammer, 1999). Inland fish are an important food source, providing nutrition to billions of people worldwide (FAO, 2014), with the majority of reported harvests (80%) are by low-income, food deficit countries (Kapetsky, 2003). In addition to the income and livelihoods that fishing activities provide, inland fisheries generate substantial economic contributions in the form of secondary activities, such as processing and distribution (Welcomme et al., 2010).

Fish populations are intrinsically linked with the functioning and productivity of their surrounding ecosystem (Lapointe et al., 2014). Fisheries management is more recently focusing less on single species stock management, and moving towards more ecosystem and evidence-based policies (Pikitch et al., 2004). Traditional fisheries management techniques tend to regulate fishing mortality on a given stock in a way that produces near-maximum sustainable yields (Punt et al., 2014). This requires, however, an understanding of the spatial parameter of this stock unit, defined as all fish in an area that belong to the same reproductive process with no immigration or emigration (Begg & Waldman, 1999). Stock assessments enable the development of mathematical models of fisheries which in turn, allow managers to estimate the Maximum Sustainable Yield (MSY) and predict responses to various management processes (Lorenzen et al., 2016). Vital components of stock assessments include knowledge of the production of the water body, demographic parameters (e.g. lifespan, natural mortality rates, age and growth), population size, fish-habitat relationships and habitat (Cowx, 1999; Krueger and Decker 1999; King 2013). Tracking of fish is ideal for determining some of these components for effective ecosystem-based management, for example migratory pathways, home-ranges, core habitat utilization, and responses to physical habitat restoration (Lapointe et al., 2013; Cooke et al., 2016; Crossin et al., 2017).

The Laurentian Great Lakes (hereinafter referred to as the Great Lakes) is an example of a large, inland aquatic ecosystem that has experienced various anthropogenic stressors and is undergoing numerous efforts to rehabilitate fish habitat, and therefore fish populations. The Great Lakes contain one-fifth of the world's freshwater and their watershed covers 745,320 km^2 with the lakes themselves occupying 244,000 km^2 (Wetzel, 2001). The basin is home to about 10% of the U.S. population and 30% of the Canadian population (Danz et al., 2007). The watershed boasts a broad diversity of fish fauna due to their diversity of fish habitats, ranging from warm to very cold, from stagnant to fast–flowing, and small bog ponds through to deep seas (Lagler, 1964). Coastal wetlands provide critical spawning and nursery habitat for fish communities (Jude & Pappas, 1992; Wei et al., 2004). Human activities have led to drastic habitat alterations through activities such as shoreline modification, coastal wetland draining and filling (Chow-Fraser, 2006;Allan et al., 2015) and channelization of tributary streams (Jones et al., 2006). The influences of overexploitation, habitat loss, invasive species, and cultural eutrophication have led to a general reduction in fish productivity across all the lakes (Smith, 1972). Lake Ontario is the eastern most lake and as the first of the lakes to be inhabited by early immigrants and penetrated with transportation canals, had experienced the first of the major changes in the fish community during the 1800s. Improved water quality practices and well-informed fisheries management have led to substantial improvements to the health of Lake Ontario's ecosystem (Minns, 2014). Large-scale fisheries restoration projects in place, including controlling populations of the parasitic sea lamprey (*Petromyzon marinus*), persistent stocking of Salmonid fishes, habitat restoration, and local recreational and commercial fisheries management, have led to Lake Ontario boasting some of the world's best recreational fisheries for smallmouth bass (*Micropterus dolomieu*), largemouth bass (*M. salmoides*), and walleye (*Sander vitreus*).

Objectives

The goal of this thesis was to highlight the various ways that individual fish movement information can aid in the rehabilitation and management of fish populations. In Chapter 2, I introduce aquatic habitat restoration in the Great Lakes, including the U.S and Canadian governmental Area of Concern (AOC) program and discuss how radio and acoustic biotelemetry studies are informing restoration within AOCs. I describe several case studies where biotelemetry is being used as a data gathering tool within various planning and monitoring stages of the AOC Remedial Action Processes, and provide a critical review of the opportunities and limitations associated with biotelemetry technology. In Chapter 3, I use acoustic biotelemetry to track walleye to obtain knowledge of their residency and space use within a heavily urbanized and industrialized harbour at the western end of Lake Ontario. The harbour was listed as an AOC in 1985 and has undergone various rehabilitation efforts of both the terrestrial and aquatic habitats. In an effort to restore the generalist and benthic fish community, the Ontario Ministry of Natural Resources and Forestry (OMNRF) have reintroduced a previously extirpated apex piscivore, walleye. The first successful stocking event was in 2012 and the first stage of determining if natural recruitment will occur in the harbour is to determine the walleye residency and space use of the harbour, in particular during the springtime spawning period. Overall, this thesis provides guidance and examples of the use of biotelemetry technology in fisheries and habitat management, and provides pertinent biological information for the effective management of an ecologically, and economically-valuable fish species.

Chapter 2: Use of fish telemetry in rehabilitation planning, management, and monitoring in Areas of Concern in the Laurentian Great Lakes

Abstract

Freshwater ecosystems provide many ecosystem services; however, they are often degraded as a result of human activity. To address ecosystem degradation in the Laurentian Great Lakes, Canada and the United States of America established the Great Lakes Water Quality Agreement (GLWQA). In 1987, 43 highly polluted and impacted areas were identified under the GLWQA as having one or more of fourteen Beneficial Use Impairments (BUIs) to the physical and chemical habitat for fish, wildlife and humans, and were designated as Areas of Concern (AOC). Subnational jurisdictions combined with local stakeholders, with support from federal governments, developed plans to remediate and restore these sites. Restoration of fish habitats require prior information regarding habitat suitability, and post-project monitoring to determine restoration success. Biotelemetry (the tracking of animals using electronic tags) provides information on the spatial ecology of fish in the wild relevant to habitat management and stock assessment. Here, seven case studies are presented where biotelemetry data were directly incorporated within the AOC Remedial Action Plan (RAP) process. Specific applications include determining seasonal fish-habitat associations to inform habitat restoration plans, identifying the distribution of pollutant-indicator species to identify exposure risk to contamination sources, informing the development of fish passage facilities to enable fish to access fragmented upstream habitats, and assessing fish use of created or restored habitats. With growing capacity for fish biotelemetry research in the Great Lakes, I discuss the strengths and weaknesses of incorporating biotelemetry into AOC RAP processes to improve the science and practice of restoration and to facilitate the delisting of AOCs.

Introduction

Freshwater is essential to human survival, providing drinking water, irrigation, waste disposal, transportation, and a source of food (Falkenmark et al., 2009; Hoekstra and Mekonnen, 2012). After the accelerated growth of the human population over the past century, these uses of freshwater ecosystems grew with corresponding negative ecological effects (Carpenter et al., 1992; Strayer and Dudgeon, 2010). Anthropogenic stressors, including eutrophication, toxic chemical and waste loads, overexploitation, habitat destruction, loss of biodiversity, and exotic species, affected lotic and lentic systems (Dudgeon et al., 2006), large lakes in particular (Randall et al., 2009).

The Laurentian Great Lakes basin (herein referred to as the Great Lakes) encompasses more than 765,000 km² and 17,000 km of shoreline and is within one of the most industrialized regions in the world. The basin is home to about 10% of the U.S. population and 30% of the Canadian population (Danz et al., 2007). Throughout the Great Lakes basin, human activities have led to drastic physical habitat alterations through activities such as shoreline modification, coastal wetland draining and filling, and channelization of tributary streams (Jones et al., 2006). In addition, point source pollutants from industrial processes (largely from the 1800's and 1900's) and sewage outflows have caused localized sites (often harbours) to be severely contaminated. Non-point source pollution from activities that occur near tributaries (e.g., agriculture, stormwater management) deliver an excess of nutrients and other pollutants to the receiving waterbodies.

As a result of the degraded condition of certain areas of the Great Lakes, the International Joint Commission (IJC), which manages the boundary waters of Canada and the United States of America (IJC, 2017), drafted the Great Lakes Water Quality Agreement (GLWQA). The GLWQA was signed by both nations in 1972 to ensure commitment to the protection of the Great Lakes and St. Lawrence River drainage basin. As a result of implementation of the GLWQA, 43 highly degraded (and often contaminated) sites, known as Areas of Concern (AOC), were identified and designated in 1987. AOCs are locations where local human activities have impaired certain beneficial uses of the lakes and connecting rivers, such as water quality and fish consumption, dredging, and loss of fish and wildlife habitat, all categorized into 14

Beneficial Use Impairments (BUIs; Table 1). Upon designation as an AOC, federal government partners (e.g., US Environment Protection Agency, US Fish and Wildlife Service, Environment Canada and Climate Change, Fisheries and Oceans Canada) with assistance from subnational agencies are required to devise a Remedial Action Plan (RAP) representing a systematic and comprehensive ecosystem approach to restoring the AOC. The RAP is then submitted to the IJC over three stages; Stage 1: when a definition of the problem has been completed; Stage 2: when remedial and regulatory measures are selected; and Stage 3: when monitoring indicates that beneficial uses have been restored. AOCs are delisted when: i) a delisting target has been met through remedial actions, which demonstrates that the beneficial use has been restored; ii) it can be demonstrated that the impairment is not limited to the local geographic extent, but rather is typical of lake, region, or area-wide conditions, or; iii) that the impairment is caused by sources outside of the AOC (USPC, 2001). To date, seven AOCs have been delisted and two have been designated as in the recovery phase (http://ijc.org/en_/aoc).

When assessing aquatic ecosystem health, fish are often the focal point due to their important economic and ecological ecosystem services (Holmlund and Hammer, 1999; Lynch, 2006) including supporting commercial, recreational, and subsistence fisheries. Fish also can be used as bio-indicators of aquatic habitat condition (see Whitfield and Elliott, 2002, for full review). However, aquatic environments and fish in particular can be logistically difficult to study and observe directly. Therefore past monitoring efforts have often focused on endpoints such as changes in abundance and richness or community composition using sampling gear such as gillnets, trapnets, traps, trawls, and electrofishing to collect data (Ford, 1989; Murphy and Willis, 1996; Lorenzen et al., 2016). These surveying techniques each have unique bias and only record animals at single points in time and space, and yield relatively few sightings for rare species living in inaccessible environments (Aarts et al., 2008). Nonetheless, spatial ecology of fish and their habitat is an important component of freshwater fish management (Cooke et al., 2016). With technological advancements over the past several decades, biotelemetry (the use of animal-borne electronic tags) has allowed researchers to remotely track an animal's interactions with the ecosystem over scales of meters to thousands of kilometers, and over time frames of minutes to years (Cooke et al., 2013; Hussey et al., 2015). Numerous forms of biotelemetry can be used within freshwater fish research including radio, acoustic, and satellite, and include some with biologging capabilities that can record temperature, pressure (depth), dissolved oxygen, heart rate, predation events, and acceleration. Each has its unique benefits for answering specific questions, but also has constraints including costs, labour required, climate conditions, and battery size requirements (for full review see Cooke et al., 2013).

In this chapter I discuss how knowledge of spatial ecology emanating from radio and acoustic telemetry studies is being used in the restoration of AOCs and management of BUIs pertaining to fish and their habitats of the Great Lakes. To accomplish this, I describe seven case studies where biotelemetry is being used as a data gathering tool within various phases of AOC RAPs. Our purpose is to provide a critical review of the opportunities and limitations associated with biotelemetry for supporting AOC-related activities to inform future efforts given that biotelemetry is an emerging technology.

RAP Process

Environmental monitoring programs are developed to either measure the status and trends of specific chemical, physical, and biological characteristics over time, or to detect alterations in characteristics deemed to be indicators of a relevant change (Ekman et al., 2013). The RAP process can implement remedial actions effectively by using research and monitoring to track trends, promote adaptive management, develop interdisciplinary integration, and increase public accountability (Hall et al., 2006). Many AOCs have been exposed to anthropogenic disturbances for over one hundred years. Thus, rehabilitation of ecosystem services will likely take decades and maintaining momentum will be difficult. Monitoring programs essential for the RAP delisting process also serve to motivate local, regional, and national stakeholders for these long-term goals (USPC, 2001; Hall et al., 2006).

As already mentioned, the first stage of a RAP is to define and describe the environmental issues associated with an AOC, including the beneficial uses that are impaired, and the degree, causes, and geographical extent of the impairment. An ecosystem approach, integrating components of air, land, and water and all living organisms including humans, are considered in restoring beneficial uses (IJC, 2017). With regards to the fish BUIs, an understanding of the life history (including habitat requirements, migratory routes, foraging and reproductive sites, dispersal, and home range characteristics) of the impacted fish species is often needed when choosing remedial actions to implement, monitor, and restore a beneficial use. Traditionally, this information has been obtained from the measurement of endpoints, including changes in abundance, richness, or community composition (see Table 1) (Ford, 1989).

Currently, some monitoring programs exist within the Great Lakes, including the Mussel Survey and the Great Lakes Fish Monitoring Program (Carlson et al., 2006) that support RAP processes. Specific monitoring programs for various BUIs include sampling fish and wildlife populations, and their physical and chemical habitats (Table 1). Physical habitat sampling involves hydroacoustic surveys of submerged aquatic vegetation (Leisti et al., 2012; 2015) or substrate, plant, and water chemistry analysis (Grabas et al., 2012). Assessment of the water chemistry associated with fish habitat involves surface and water-column sampling for temperature, dissolved oxygen (DO), sediment, contaminants and metals. Current fish population monitoring schemes to quantify restoration success across multiple sites in the Great Lakes use local or regionally derived indices of biotic integrity, which consider the fish community trophic composition, including invasive species (Brousseau et al., 2011; Hoyle et al., 2012; Boston et al., 2016; Hoyle et al., 2016).

Biotelemetry in ecosystem management

Biotelemetry has typically been used to support ecosystem management with information on the spatial ecology of fish, including habitat requirements, migratory routes, foraging and reproductive sites, and dispersal characteristics (reviewed in Cooke et al., 2013). More specifically to habitat restoration, biotelemetry has provided a wealth of information on spatial and temporal habitat requirements for particular fish species, useful information for restoration design (Lucas and Baras, 2000; Lapointe et al., 2013). However, until recently biotelemetry has not often been used in pre and post restoration monitoring efforts in AOC. Some examples of the successful applications of biotelemetry in AOCs are outlined under the AOC case studies.

Biotelemetry systems employ battery-powered acoustic or radio tags that produce a coded transmission and are attached externally to the body or are surgically implanted into animals (see Cooke et al., 2011 for details). Animals can be actively located and tracked by foot, boat, or plane using hydrophones for acoustic transmitters or antennas for radio transmitters. Passive tracking involves autonomous fixed-position receivers that decode transmissions and store the tag identity, sensor data, time, and date for each transmission when tagged fish are within range (Kessel et al., 2015). Passive tracking allows long-term monitoring of multiple individuals throughout all seasons with relatively little labour (see Heupel et al., 2006). If acoustic receivers are positioned in a grid-like pattern close to each other (~750m), a fish's exact location can be determined for each acoustic transmission. Acoustic tags can also be equipped with sensors (Cooke et al., 2016) that measure environmental variables (e.g., depth, temperature, dissolved oxygen, pH), individual motion or activity (e.g., acceleration), or physiological status (e.g., heart rate). The combination of fish location, the surrounding environmental conditions, and internal status of the fish provides a more complete understanding of the fish's response to environmental conditions as well as drivers of fish movement. This integrated data is valuable to managers of freshwater ecosystem rehabilitation and compliments traditional fish community and habitat sampling techniques.

Case Studies

Progress towards delisting an AOC is dependent on managers' having access to accurate ecosystem models, and the ability to evaluate success of existing programs while identifying needs for new programs (Hall et al., 2006). Where used, biotelemetry provides important life history and habitat information for Great Lakes ecosystem models, and is used as a monitoring tool to provide data that contributes to the RAP adaptive management cycle. Here, I introduce seven case study examples (Figure 2.1) where biotelemetry data is being directly used by State, Provincial, and Federal managers to: 1) determine seasonal fish-habitat associations to inform habitat restoration plans; 2) identify the distribution of pollutant-indicator species to identify exposure risk to contamination sources; 3) inform the development of fish passage facilities to enable fish to access fragmented upstream habitats, and; 4) assess fish use of created or restored habitats. The presented biotelemetry projects have all been initiated, however they are at various stages of completion. I conclude by providing recommendations for scientists and managers that may consider the use of biotelemetry to inform AOC-RAP processes and beyond.

Lower Menominee River, USA (LMR)

Context

The Menominee River represents the boundary between northeast Wisconsin and the southern tip of Michigan's Upper Peninsula. The lower 4.8 km of the river and 5.0-km segments running north and south along the Green Bay (Lake Michigan) shoreline from the river's mouth were designated as an AOC in 1987 with six of 14 possible BUIs listed as impaired. Improper storage and disposal of arsenic combined with other industrial and municipal actions led to contamination of the lower river. Additionally, changes in habitat and lack of safe passage around dams limit access to important spawning and rearing habitat for fish species such as lake sturgeon (*Acipenser fulvescen*s). Park Mill and Menominee dams are within the AOC and serve as the initial upstream barriers to lake sturgeon passage from Green Bay, which contributes to the 'loss of fish and wildlife habitat' and 'populations' BUIs. The Menominee Fish Passage Partnership, comprised of state and federal agencies, non-profit conservation organizations, and a private energy company, is developing safe and effective passage for lake sturgeon around these two dams.

Biotelemetry Applications

The two BUIs being monitored with acoustic biotelemetry are: 'degradation of fish and wildlife populations' and 'loss of fish and wildlife habitat'. From 2014 to 2016, lake sturgeons were captured from below Menominee Dam using a fish elevator constructed within the dam and by electrofishing. Lake sturgeon (N = 120) ready to spawn were implanted with 10-year acoustic transmitters and released above the two lowest dams (Park Mill and Menominee) on the Menominee River. Fixed acoustic receivers located throughout the river are being used to determine if: 1) lake sturgeon remain above both dams to spawn at least once; 2) these fish eventually return downstream, and; 3) sturgeon use purpose-built downstream passage facilities. This work represents an important step in developing passage strategies that will enhance the lake sturgeon population in the lower Menominee River AOC, Green Bay, and Lake Michigan as a whole.

Manistique River and Harbour, Lake Michigan (MRH)

Context

The Manistique River and Harbour Area of Concern is a 2.7 km river reach and harbour on the northern shore of Lake Michigan in the Upper Peninsula of Michigan, USA. The site was designated an AOC in 1987 due to sediments contaminated with polychlorinated biphenyls (PCBs) and heavy metals, a fish consumption advisory, and impacted biota (Michigan DNR, 1987). The PCB contamination has been the subject of study and remediation since the 1980s, including large-scale sediment dredging efforts from 1996-2000 and again in 2016 and 2017. Two BUIs remain at this AOC: 'restrictions on dredging' and 'restrictions on the consumption of fish and wildlife', including a "do not eat" advisory on common carp (*Cyprinus carpio*).

Biotelemetry Applications

Radio and acoustic biotelemetry were used to inform the BUI of 'restrictions on fish and wildlife consumption'. At the site, common carp were the most contaminated fish species used to inform AOC BUIs. In 2015, adult common carp were captured from the AOC and implanted with integrated acoustic and radio transmitters with the objective of establishing their residency in the harbour and identifying their specific locations while in the harbour. A fixed array of receivers was in place from early June (pre-spawning) to late October 2015. The array was a hybrid design, intended to indicate the presence or absence of fish in some areas of the harbour and determine high-resolution 2-dimensional positions of fish in other areas, depending on harbour geometry. Additionally, aerial radio tracking was used to locate fish after they left the harbour, into Lake Michigan. The study showed that common carp were generally transient to the harbour, with residency ranging from only a few days to several months. Preferred locations of fish (while resident in the harbour) were also identified. Results have been used to establish that common carp were not a reliable indicator of the restriction on fish consumption BUI because their contaminant burdens cannot directly be attributed to the Manistique River and Harbour AOC.

St. Marys River, Lake Huron/Superior (SMR)

Context

The St. Marys River, the largest tributary to Lake Huron, is a 112 km long braided channel that connects Lake Superior and Lake Huron. This river contains a diversity of habitats (high energy rapids, fringing wetlands, and warm embayments) for fishes, yet a legacy of anthropogenic impacts resulted in the river being listed as an AOC in 1987 with 10 identified BUIs (Bray, 1996; Ripley et al., 2011). These impacts included extensive habitat loss in support of shipping and hydroelectric industries, high industrial discharges that continue to influence benthic communities, and water quality degradation from point sources such as water treatment facilities (Ripley et al., 2011). The fish community was originally listed as degraded in part due to concerns about habitat loss and aquatic invasive species, declines in native species, and high sea lamprey (*Petromyzon marinus*) abundance (Remedial Action Plan, 1992). Ongoing remediation efforts have included reductions in point source pollution, sediment remediation, and habitat restoration including the ongoing restoration of the Little Rapids area (Figure 2.1). Fish populations are generally healthier and more stable than most other AOCs, though reductions in the populations of some desired native fishes are suspected (Schaeffer et al., 2011; Pratt and O'Connor, 2011). Efforts to rehabilitate degraded walleye (*Sander vitreus*) and lake sturgeon and to combat sea lampreys are ongoing in the river.

Biotelemetry Applications

Acoustic biotelemetry is being used to address 'the degradation of fish and wildlife populations' and 'loss of fish and wildlife habitat' BUIs in the St. Marys River. Three recent studies examined how to limit the impacts or potential impacts of aquatic invasive species. Successfully controlling sea lampreys remains a critical management goal on the river, and two studies used acoustic biotelemetry to examine why sea lamprey trapping rates remain stubbornly low. The first study examined sea lamprey temporal and spatial migration dynamics, determining existing migration pathways and demonstrating that many sea lampreys were not vulnerable to traps (Holbrook, 2016). The second study used 3-D positioning to test if manipulation of discharge from a hydro-generating station could increase sea lamprey trap success at traps immediately downstream (Rous et al., 2017). The main finding identified a spatial (vertical) mismatch between the space use of sea lampreys and the locations of traps and increasing discharge did not alter space use in a manner that increased trap success (Rous et al., 2017). Another study examined the potential for invasive fishes (notably Asian carps) to use the shipping canals in the St. Marys River as a potential invasion pathway into Lake Superior (Kim et al., 2016). A number of acoustic biotelemetry studies examining walleye and lake sturgeon habitat use and movement are either completed (Gerig et al., 2011) or underway in the St. Marys River and will help address habitat loss concerns, and identify locations for protection or future remediation.

St. Clair & Detroit rivers (SCDR)

Context

The Detroit and St. Clair rivers together with Lake St. Clair form the connecting channel ecosystem that links Lakes Huron to Erie. The Detroit and St. Clair rivers once provided important spawning habitat for lake sturgeon, lake whitefish (*Coregonus clupeaformis*), cisco (*C. artedii*), and walleye, but after decades of navigational dredging, shoreline development, and pollution, spawning runs of these migratory species declined or ceased altogether (Bennion and Manny 2011; Roseman et al. 2011; Hondorp et al., 2014). Thus, in 1987, both rivers (but not Lake St. Clair) were listed as AOCs with the loss of fish habitat and degradation of fish populations as key beneficial use impairments. A primary emphasis of restoration efforts in both rivers has been the construction of rock-rubble spawning reefs that mimic natural spawning shoals that were the preferred spawning sites of migratory fish. To date, a total of six spawning reefs have been constructed in the main channels of the Detroit and St. Clair Rivers (Manny et al. 2015).

Biotelemetry Applications

Acoustic telemetry data is beginning to inform the site selection process for fish spawning reef construction in the St. Clair and Detroit rivers. Historically, candidate sites for reef construction were selected and prioritize using a biophysical model (Bennion and Manny 2014) that predicted spawning habitat quality from site-specific current velocities and bathymetry. More recently, however, a study using acoustic telemetry to describe lake sturgeon population structure in the Lake Huron-to-Lake Erie corridor has provided information on lake sturgeon movements in the vicinity of potential reef construction sites. The acoustic telemetry data enabled fishery managers to identify construction sites that would maximize lake sturgeon encounters with newly constructed reefs and to determine *a priori* which lake sturgeon populations would benefit from a spawning reef constructed at a given location. As an example, movements of acoustic-tagged lake sturgeon identified the North Channel of the St. Clair River between the Chenal a bot Rond confluence and Pte aux Tremble as an ideal location for the construction of spawning reefs due to heavy lake sturgeon use of this 5.0-km section of river. Similarly, acoustic telemetry data was used to confirm that lake sturgeon were likely to encounter man-made spawning reefs at a proposed site near Grassy Island in the Detroit River.

Hamilton Harbour, Lake Ontario (HH).

Context

Hamilton Harbour, a 21-km² embayment in the western end of Lake Ontario (Figure 2.1; Figure 2.2.C.), was Canada's largest contaminated site in the Great Lakes and designated as an AOC in 1985 with 11 BUIs. Historically, the harbour was a productive wetland area; however, it has lost 65% of available fish and wildlife habitat since industrialization in the early 1900s (Hamilton Harbour RAP, 2012). In nearshore zones, non-native species have become dominant, altering fish community composition and trophic balances such that benthic fish generalists are favoured over piscivores (Brousseau and Randall, 2008). The Hamilton and Burlington areas have five waste-water treatment plants introducing high levels of phosphorus and nitrogen into the harbour, leading to eutrophication and extremely low levels of dissolved oxygen in many areas (Gertzen, et al., 2014; Yerubandi, et al., 2016). Remediation efforts include 376 ha of restored fish and wildlife habitat, 12-km of new shoreline (Hamilton Harbour

RAP, 2012), and new and strict regulations on waste-water treatment outflows. Additionally, in an attempt to increase the levels of piscivores, Ontario Ministry of Natural Resources and Forestry (OMNRF) has over the last two decades stocked walleye, a previously extirpated native predator.

Biotelemetry Applications

The two BUIs being monitored with acoustic biotelemetry are: 'degradation of fish and wildlife populations'; and 'loss of fish and wildlife habitat'. Beginning in fall 2015, sexually mature walleye were captured and tagged with acoustic transmitters with pressure (depth) sensors. Fixed acoustic biotelemetry receivers were placed throughout and adjacent to the harbour to determine residency patterns of walleye, with a particular focus on identifying aggregation areas during the spawning season. Results will help assess whether stocking efforts have been effective and will also help to direct future habitat protection and enhancement efforts. In addition to walleye, fish from multiple trophic levels (e.g., channel catfish (*Ictalurus punctatus*), longnose gar (*Lepisosteus osseus*), and freshwater drum (*Aplodinotus grunniens*)) have been tagged to characterize seasonal habitat use with a particular emphasis on use of restored habitats. Pressure sensor data from these individuals will also help establish their seasonal depth distribution, which can be paired with extensive dissolved oxygen mapping and modeling efforts to evaluate changes in the amount of available habitat for fishes and whether fish are using anoxic zones. In the future, fish will be equipped with newly developed acoustic transmitters that have integrated dissolved oxygen sensors (see Svendson et al. 2006) to obtain more detailed information on use of anoxic or near-anoxia waters. Also, collaborations with researchers working in the nearby Toronto Harbour and Niagara River AOCs (see case studies) are planned to explore connectivity among these spatially distinct systems. Finally, efforts have been made to engage the public through social media activity, public events, and school visits because results from telemetry studies such as this can be easily understood and disseminated through mapping and fish movement visualization.

Toronto and Region, Lake Ontario (TH)

Context

Situated along the north shore of western Lake Ontario, the Greater Toronto Area is the most densely urbanized area in Canada (Figure 2.1; Figure 2.2). The watersheds and extensive coastal waters (42 km of shoreline) in and around the City of Toronto have a long history of agricultural and urban disturbance that led to this region being designated as an AOC in 1987 with 11 BUIs, eight of which are still listed as impaired. These BUIs are linked to stormwater and combined sewer overflows (e.g., excess nutrients, bacteria), contaminants related to industry and legacy pollutants (e.g., lead, PCBs, mercury), and changes to or a loss of habitat and biodiversity (Toronto Region RAP, 2009). Guided by the RAP, extensive restoration efforts have been undertaken throughout the AOC including: improvements to wastewater infrastructure (e.g., combined sewer separation), tree and riparian vegetation planting, removal of instream barriers to fish migration, addition of aquatic habitat structure to hardened slips and shorelines, and the creation and restoration of coastal wetland habitat (Toronto Region RAP, 2009). From a habitat perspective, the central waterfront of Toronto has experienced some of the largest changes in the AOC with a net loss of over 600 hectares of wetland habitat through infilling and shoreline hardening (Whillans, 1982). Restoration efforts to date have increased the amount and quality of aquatic habitat, but an understanding of how fish have responded to the increased habitat is needed to support RAP targets.

Biotelemetry Application

The acoustic biotelemetry project for the Toronto and Region AOC is focused on the central waterfront (Toronto Harbour) and aimed at supporting two BUIs, the ‘degradation of fish and wildlife populations’ and the ‘loss of fish and wildlife habitat’. The harbour has been the focus of many of the aquatic habitat creation and restoration efforts in the AOC, which have primarily occurred in the slips along the north shore, among the comparatively natural Toronto Islands, and at Tommy Thompson Park (created from surplus fill and dredged material). Starting in 2010, the acoustic biotelemetry project was implemented to help assess the efficacy of the restoration efforts completed in the harbour by evaluating the use and residency of native fishes (e.g., northern pike (*Esox lucius*), largemouth bass (*Micropterus salmoides*), walleye, yellow perch, white sucker (*Catostomus commersonii*), brown bullhead (*Ameiurus nebulosus*) and bowfin (*Amia calva*)) and the non-native common carp using a passive acoustic telemetry array. Clear evidence of use of restored areas by a subset of fishes has since been documented (Rous et al., 2017); however, increased use of restored areas relative to un-restored areas has been more challenging to confirm due to a lack of historical data. Results from the acoustic biotelemetry project will provide baseline data for restoration projects currently underway in the harbour. In addition to tracking residency and habitat use at the level of fish community, the biotelemetry project has provided more detailed insight into seasonal habitat preferences (depth, temperature, aquatic vegetation; Midwood et al., in sub; Peat et al., 2016) of tagged fishes as well as their behavioural responses to extreme events such as the frequent intrusions of cold Lake Ontario water into the harbour (Hlevca et al., 2015). This type of core fish ecology information has been used since to refine the design of habitat restoration projects. For example, for Cell 2 in Tommy Thompson Park (Figure 2.1), restoration plans were modified to include deeper water habitat (2-5 m) based on the telemetry-informed use of this depth by walleye and northern pike in the spring and by largemouth bass and northern pike in the winter. Moving forward with the Toronto Harbour project, tagging efforts and the array design will continue to support the assessment and refinement of restoration actions. Additional effort may also be directed towards an additional BUI, 'restrictions on fish and wildlife consumption'. White sucker continue to show elevated levels of PCBs in the AOC and in a similar manner as the Manistique River and Harbour AOC, and tracking their movements and residency within the harbour may help to determine whether the source of these contaminants is within the harbour and, if so, where more detailed sampling is required to isolate the source. This evaluation will partially be accomplished through the expansion of acoustic biotelemetry arrays in the Toronto and Region AOC and in the nearshore of western Lake Ontario as well as with support from collaborators managing acoustic arrays in the Hamilton Harbour and Niagara River AOCs.

Niagara River, Lakes Erie and Ontario (NR)

Context

The Niagara River is the connecting channel between Lake Erie and Lake Ontario (Figure 2.1). The river drains inputs from the upper Great Lakes basin into Lake Ontario. The availability of the water for transportation and power generation led to the industrialization within and around the major cities Buffalo, New York and Niagara Falls, Ontario. The upper Niagara River is generally a shallow and wide river system with high currents in the channels and slow water near several islands that split the waterway. The lower Niagara River has a large gorge section below the falls with fast flowing deep waters. Approximately 7.0 km below the falls, the river exits the gorge and opens into a wider sinuous river section before entering Lake Ontario. The upper Niagara River has been most impacted by industrialization. Contaminated sediment contributes to several BUIs in the Niagara River AOC (Niagara River RAP Stage 2 Addendum, 2012). Additionally, dredging and harbour development have removed or degraded many essential fish habitats within the AOC. Efforts to restore fish habitat are pending a resolution from the severe contamination from legacy chemicals. Considerable progress has been made in remediation of chemical contamination by reducing discharges and removal of contaminated sediments at multiple locations within the AOC.

Biotelemetry Applications

Two BUIs are currently being addressed with the use of acoustic telemetry: 'the degradation of fish and wildlife populations' and 'loss of fish and wildlife habitat'. The initial projects have tagged lake sturgeon to document habitat use during spawning and rearing. In the upper and lower Niagara River sections, acoustic receivers have been deployed over multiple years. These projects will help identify the duration of time lake sturgeon occupy habitats within the AOC with special consideration given to the site specific toxicity.

Synthesis

With recent improvements in technological capabilities, biotelemetry has seen a rapid increase in applications in aquatic habitats and has been used to support the management of fisheries and fish habitat in various forms (Donaldson et al., 2014). In this review, I presented several examples of how biotelemetry has and is being used to support the Great Lakes' AOC RAP process. Biotelemetry has been incorporated during both the planning (Stage 2) and monitoring (Stage 3) stages of the RAP management process for the BUIs involving fish and wildlife populations. I included biotelemetry projects funded specifically to support the Remedial Action Plans and cases where pre-existing but relevant animal movement data have also been incorporated.

During the planning stage of the RAP process (Stage 2), habitat preference information for various species of concern was incorporated into planning for physical habitat remediation. In Toronto Harbour, seasonal habitat and depth preferences for two focal species, northern pike and largemouth bass, were determined and then incorporated into the project designs of physical habitat restoration. In other AOCs, walleye and lake sturgeon movements will similarly be used to identify locations for further protection and remediation efforts. Biotelemetry was used during the post-restoration monitoring stage (Stage 3) for the majority of the case studies. In Lower Menominee River, lake sturgeon have been acoustically tagged to determine their upstream spawning habits, and the successful use of downstream passage facilities at the two dams within the AOC. In Manistique River and Harbour, common carp were traditionally used as bio-indicators for PCB contamination issues; however, radio and acoustic telemetry established that their residency times within the AOC boundary were too short and they were no longer considered a reliable indicator of the 'fish consumption' BUI. This application represents an important frontier in ecological risk assessment and begins to question the assumption that fish sampled in a given location are representative of contaminant burdens from that location (Van der Oost et al., 2003).

Biotelemetry includes a variety of technologies and methods of animal tracking, including radio, acoustic, and satellite, active and passive, archival and biologging, and provides fisheries biologists with the ability to study the behaviour and ecophysiology of individuals in their natural environment throughout various life stages (Lucas and Baras, 2001; Cooke et al., 2013). The ability to track individuals all year round (especially over the winter in temperate climates), and often over long time periods, are strengths of biotelemetry (see review by Cooke et al., 2013). In brief, tracking individual animals can often be less labour intensive than other fish and habitat monitoring techniques, such as electro-fishing, netting and trawling, and can often reduce sampling bias with the ability to obtain fish position data under environmental conditions when traditional techniques would be impossible to carry out, such as during inclement weather or under the ice (Lapointe et al., 2013).

Rapid advances in technology have also led to the miniaturization of tags enabling researchers to study earlier life stages of fishes (relevant for recruitment questions), and an increase in sensor capabilities has resulted in tags that can record acceleration, depth, temperature, and dissolved oxygen (Cooke et al., 2004; Hussey et al., 2015; Cooke et al., 2016). These sensor and biologging capabilities allow researchers to determine not only the location of fish but also the conditions of their local environment, potential drivers behind movements, and linking movement with physiology. Currently these technologies are being used to assess how fish in Hamilton Harbour use the water column in response to varying dissolved oxygen levels (pressure sensors). Results from pressure sensor tags have also led to deeper embayment construction based on depth preferences of several species in Toronto Harbour. Finally, also in Toronto Harbour, accelerometer sensors were used to determine the energy expenditure for fish in various habitat types, as animals that occupy sub-optimal habitats may experience increased expenditure of energy (Jeffrey et al., 2015).

Another additional benefit to biotelemetry is the possibility to engage with members of the public. As previously mentioned, with such long-term remediation projects, maintaining stakeholder momentum is an important aspect of the monitoring stage (Hall et al., 2006). Biotelemetry is an exciting tool to engage a broad public audience (McGowan et al., 2016) and can provide tangible and almost ‘real time’ proof that animals are surviving and using these newly restored habitats. Citizens of AOCs are ultimately affected by remedial efforts therefore, it is important that these stakeholders participate in the activities of research and monitoring (Hall, 2006). Several biotelemetry users surveyed by Nguyen et al., (In Press), mentioned an increase in public interest after they had shared their animal movement data online, leading to an increase in support and outreach opportunities. An example of this specific to the Great Lakes AOCs is a collaborative pilot project with the Great Lakes Fishery Commission, where walleye movement data from Hamilton Harbour were shared with local school groups as part of outreach efforts to involve the local community.

Constraints to biotelemetry use exist in the study of freshwater fish including problems with attaching devices to animals, the performance of electronic technology, and methods of analyzing data (Cooke et al., 2013). Biotelemetry is regarded as a relatively expensive technology and can vary in total system costs dependent on the equipment selected, the complexity required in the ecosystem, and scope of the study and may not be suitable for short-term management questions. However, a growing collaborative research community has developed and is willing to share resources (e.g., expertise and equipment) such that this approach may now be accessible even if a specific project is not well funded (e.g GLATOS; Ocean Tracking Network). Performance of biotelemetry equipment can be impaired by various environmental conditions, such as high flow and turbulent systems, depth (deep water is problematic for radio telemetry, shallow water can be problematic for acoustic telemetry), highly vegetated, and high traffic areas, all considerations required when choosing the type of technology for the project (Heupel et al., 2006; Kessel et al., 2014). Biotelemetry can also result in large datasets that require significant post-processing and analytical efforts, often beyond the capabilities of simple spreadsheet applications (Heupel et al., 2006).

Guidelines for using telemetry in RAPs

As with any study, the most important first step is to define clear project objectives and then to consider the best way to address the objectives. If biotelemetry is identified as a likely tool, defining the specific type of data required from a biotelemetry project will dictate the type of equipment required, and how best to deploy the selected technology (Heupel et al., 2006). Fine-scale habitat use on a scale of meters, either for habitat preference data, contaminated site use, or monitoring the use of restored habitats may be best served using active tracking or an acoustic fine-scale positioning array (Niezgoda et al., 2002; Roy et al., 2014). The addition of pressure sensor tags allows for a 3D position of the fish when combined with a Vemco Positioning System (VPS) array and high resolution bathymetry data, determining the use of water column in relation to known water quality conditions or contaminated sites. If data are required to determine the duration that an animal remains within a set region (e.g., a protected area, or an AOC boundary), fine-scale or 3D positioning may not be necessary and a simple set of receivers to monitor exit or return may suffice (Lacroix, 2005). Alternatively, in determining directed linear paths or migration routes requires a series of curtain or gate systems (Hayden et al., 2014). With the expanding use of biotelemetry in the Great Lakes, a collaborative group of researchers have formed the GLATOS allowing users of the same technology to share and exchange their data. Through this organized collaboration, tag detection coverage for individual projects is not limited to only the project's receivers. Managers can answer more broad-scale questions regarding the long-range migrations of fishes and the connectivity of AOC sites and other freshwater ecosystems, well beyond the geographic scope of individual projects.

For most research questions, a combination of telemetry and conventional research methods is recommended to ensure the desired level of population sample size and study power to achieve a complete picture of fish behaviour and physiology in relation to the environment (Bridger and Booth, 2003). Lapointe et al. (2013) noted several studies where telemetry was successfully combined with diet studies, mark-recapture, creel surveys, and underwater video analysis to strengthen the evaluation of restoration success. Well considered and planned experimental design is essential when using all forms of biotelemetry. Lapointe et al. (2013) reviewed habitat restoration success studies and determined an ideal design would include pre-restoration animal movement data, or a control site for "before and after" comparisons. This is, however, difficult to obtain at this point as many of the AOC restoration efforts are already underway.

Conclusion

Monitoring the success of habitat restoration is often difficult, in particular when little or no information exists on how fish used the site prior to restoration. However, when used in combination with other techniques, biotelemetry is proving useful in the AOC Remedial Action Plan process. It has allowed managers to answer questions important to the planning and monitoring of habitat restoration within the Great Lakes, as well as allowing researchers to ask broad scale questions, with potential relevance across AOCs and other freshwater habitat restoration efforts. Throughout these case studies, I have demonstrated that biotelemetry has been successfully incorporated into the RAP adaptive management process, with results from habitat preference studies directly integrated into further restoration designs. With consideration to the previously mentioned strengths and weaknesses to biotelemetry and the various technologies available, I recommend RAP managers consider including biotelemetry as an assessment tool and work to combine telemetry results from other AOC sites into their habitat management and restoration planning and monitoring processes.

Table 1. Current monitoring techniques for the 14 Beneficial Use Impairments and case studies where acoustic biotelemetry is being used to compliment these monitoring methods (Lower Menominee River (LMR); Manistique River and Harbour (MRH); St. Mary's River (SMR); St. Clair and Detroit Rivers (SCDR); Hamilton Harbour (HH); Toronto Harbour (TH); Niagara River (NR)).

Beneficial Use Impairment	Current monitoring techniques	Biotelemetry?
1. Restrictions on fish and wildlife consumption	Samples from edible-sized fish and Young of Year for PCB, mercury, lead etc.	Yes (HH, TH, MRH)
2. Tainting of fish and wildlife flavour	Samples from water column for volatile and semi-volatile organics and phenolics.	N/A
3. Degradation of fish wildlife populations	FISH: Electro-fishing, gillnet and trap net samples for species composition, abundance, size distribution and biomass. (IBI-Boston 2016) monitoring by RBG at the Cootes Paradise fishway WILDLIFE: Visual surveys	Yes (LMR, SCDR, HH, TH, NR)
4. Fish tumours or other deformities	E-fishing, gillnet for histological analysis from liver samples	N/A
5. Bird or animal deformities or reproduction problems	WILDLIFE: Whole body tissue concentrations of contaminants (eggs, blood, liver, brain, muscle, stomach samples) FISH: Fish of a size and species considered prey for the wildlife under consideration must be sampled.	N/A
6. Degradation of benthos (organisms living on lake bottoms)	Benthic macroinvertebrate communities (abundance, composition and size) & composite sediment samples/toxicity tests - Ponar grab	N/A

Beneficial Use Impairment	Current monitoring techniques	Biotelemetry?
7. Restrictions on dredging activities		Yes (MRH)
8. Eutrophication (undesirable algae)		N/A
9. Restrictions on drinking water consumption, or taste and odour problems		N/A
10. Beach closings		N/A
11. Degradation of aesthetics/visual appearance	Trash and contaminants, monitoring process?	N/A
12. Added costs to agriculture or industry		N/A
13. Degradation of phytoplankton and zooplankton populations		N/A
14. Loss of fish and wildlife habitat	PHYSICAL- increase habitat and further establish and protect critical connective corridors for wildlife; CHEMICAL: Dissolved Oxygen, current hypoxic and sometimes anaerobic conditions in AOC are primarily result of pollution, eutrophication and low flow.	Yes (LMR, SMR, HH, TH, NR)

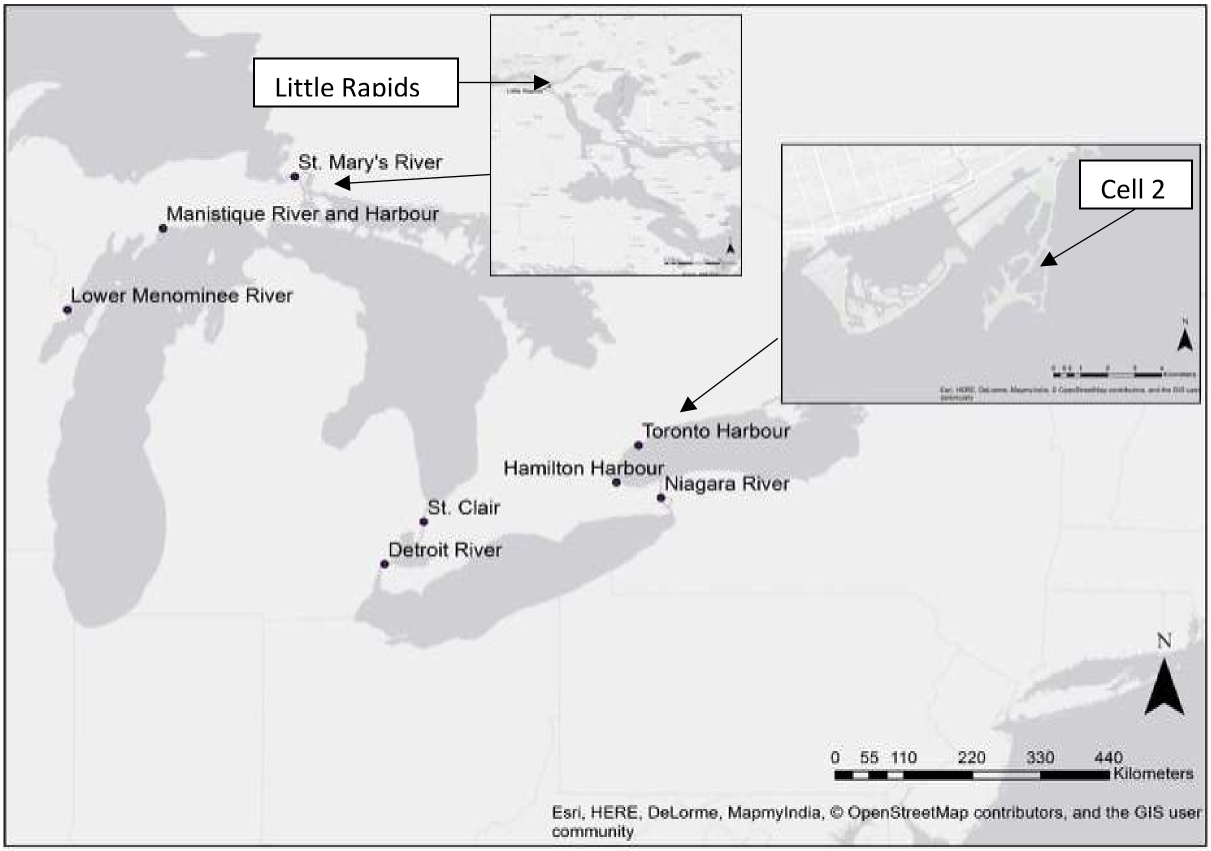

Figure 2.1. Map of the Laurentian Great Lakes, including seven Areas of Concern that are using biotelemetry in the Remedial Action Plans. Insets include Little Rapids section of the St. Mary's River, and the restored 'cell 2' site in the outer harbour of Toronto Harbour.

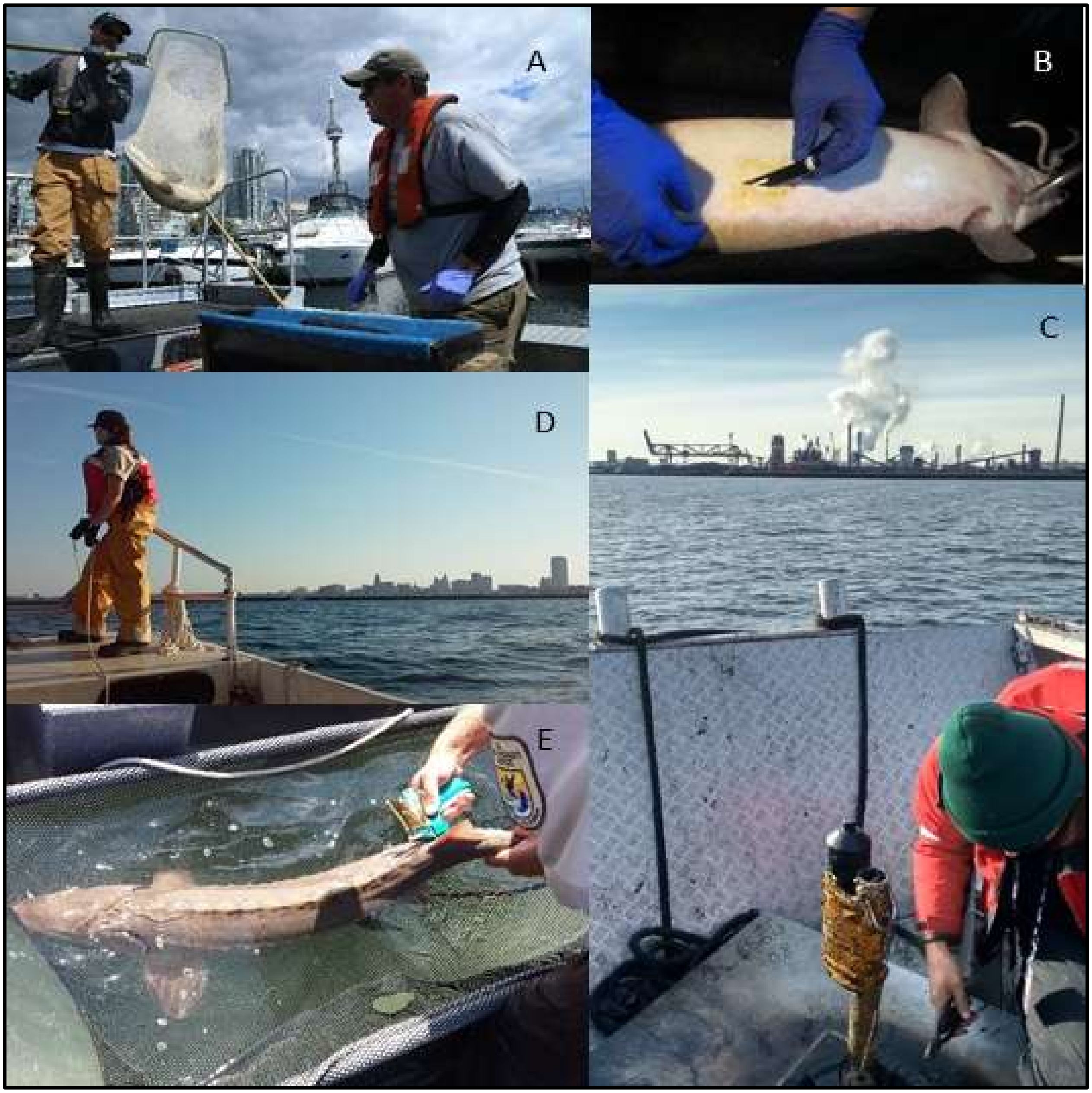

Figure 2.2. A. Electro-fishing a northern pike (*Esox lucius*) in Toronto Harbour, ON, for acoustic transmitter surgery (photo credit Jeff Dickie); Inserting an acoustic transmitter into a lake sturgeon (*Acipenser fulvescens*) in the Detroit River, MI C. Downloading an acoustic receiver near steel plant, Hamilton Harbour, ON (Photo credit Jill Brooks); D grappling for receivers near the city of Buffalo, NY (photo credit Jonah Withers); E. Inserting an external identification floy tag into a lake sturgeon (Photo credit D. Gorsky).

Chapter 3 – Spatial ecology of a reintroduced fish (*Sander vitreus*) in an Area of Concern, Hamilton Harbour, Lake Ontario.

Abstract

Many coastal embayments in the Laurentian Great Lakes have historically been subjected to extensive human physical modification (e.g., dredging, installation of hardened shorelines, infilling) and pollution (e.g., nutrients, heavy metals). For the last several decades there have been attempts to remediate degraded coastal ecosystems. Hamilton Harbour is an urbanized area at the western end of Lake Ontario and not unlike other coastal embayments in the Great Lakes it has been undergoing various forms of rehabilitation. In an effort to restore the fish community in Hamilton Harbour, several attempts have been made to increase the proportion of apex piscivores by reintroducing native walleye (*Sander vitreus*). Yet, the effectiveness of these reintroduction efforts remain unclear. The objectives of this study were to 1) determine the residency of this stocked population within the boundaries of the harbour, and 2) determine seasonal space use, with a particular focus on the spring spawning period. These objectives were achieved using acoustic telemetry to track walleye (n=15, mean length 517 mm, approximately age 3 years) and monitor movements between October 2015 and October 2016. To determine seasonal space use within the harbour, hourly Centers of Activity were used to calculate a Kernel Utilization Density map, and the 95 and 50 Percent Volume Contours produced from these estimates were compared for each individual across the four seasonal periods. Tagged fish spent an average of 323 days (standard deviation 73 days) within the harbour, and the remainder of the time in the main Lake Ontario. No walleye attempted to pass through the fishway into Cootes Paradise Marsh to the west of the harbour. Most individuals (n=12) remained within the harbour during the entire spring spawning period, and over half of the tagged fish departed (n=8) at the end of summer and beginning of fall. Areas of high use during the spring spawning period were identified, and spawning-phase fish presence during this time was also confirmed via electro-fishing. Tagging data revealed that walleye spent the majority of their time within the harbour and surprisingly did not migrate to either the Cootes Paradise marsh or Lake Ontario during the spawning period, a positive sign for natural recruitment within the Harbour. Walleye home range extent was significantly reduced in the summer. This information provides managers with

locations for further stocking efforts and egg and fry surveys, and enables further investigations into the effects of summer hypoxic conditions on the amount of habitat available to walleye.

Introduction

Freshwater fishes are vital elements of ecosystems. Through regulation of food web dynamics, recycling of nutrients, and transportation of energy, they play a major role in enhancing the biodiversity and integrity of aquatic ecosystems (Holmlund & Hammer, 1999; Lynch et al., 2016). Inland fishes and fisheries represent diverse economic, cultural, nutritional, and ecological values in North America (Malvestuto and Hudgins 1996). However, the degradation of water quality and modifications of physical habitat from urbanization, industrialization, and agriculture, combined with resource exploitation and invasive species have had substantial negative effects on freshwater ecosystems (Richter et al., 1997; Strayer & Dudgeon, 2010). Fishery professionals have been successful in addressing many of these threats and challenges by imposing regulations that restrict exploitation, enhance the conservation and restoration of fish habitat, and assist control of invasive species (Arlinghaus et al., 2016). The Laurentian Great Lakes are an example of a large freshwater ecosystem heavily affected by compounding anthropogenic stressors. Fisheries have undergone dramatic changes, with some near collapse (Christie 1974; Hansen, 1999). Ongoing, evidence-based management efforts are vital to safeguard long-term sustainability of the Great Lakes fisheries (Landsman et al., 2011).

The study of fish movement has been used to inform fisheries management within the Great Lakes by providing knowledge on both the target species and the surrounding ecosystem, including information about reproductive biology, environmental relations and disturbance, stocking, habitat use, invasive species, diet and trophic niches, barriers, and fish passage (Landsman et al., 2011). Methods for obtaining these types of information from fish include traditional mark-recapture techniques (anchor, jaw, wire-tags), and more increasingly, radio and acoustic biotelemetry (Landsman et al., 2011). Understanding the spatial ecology of a species is important to various aspects of management as it provides information about how fishes are distributed in space and time (Lucas & Baris, 2000; Cooke et al., 2016). Fisheries management is moving towards ecosystem management, a more effective and holistic approach that reverses the order of management priorities and starts with the ecosystem rather than the target species (Pikitch et al., 2004). Biotelemetry is ideal for assessing the behaviours that are fundamental to the spatial structure of a fish stock, such as core habitat use, home-ranges, and migratory pathways that all contribute to our understanding of how fish interact with their ecosystem (Crossin et al., 2016). Biotelemetry compliments traditional 'snapshot' fisheries sampling techniques by obtaining almost-continual fish locations, and therefore habitat and water quality preferences and requirements of individuals, throughout all weather conditions and seasons.

Walleye (*Sander vitreus*) are a perciform native to central North America (Billington et al., 2011), that have been described as a cool water species (Kitchell et al, 1977) and are found in both river and lake systems (Carlander et al, 1978). Walleye are an important recreational and commercial fish in North America, and are the most frequently caught species in Canadian recreational fisheries (Brownscombe et al., 2014). Within the Great Lakes, they rank second in target species behind black bass (*Micropterus* spp.) with approximately half a million anglers spending over 5.5 million days a year targeting them (USDOI et al., 2001) and Lake Erie boasts an estimated recreational angling value of US$600million (USDOI et al., 2008). In Lake Ontario, commercial harvest records date back to 1867, and up until 1917, annual harvests were as high as 0.2 million kg (Baldwin et al., 2002). Currently, there are 500 active commercial fishing licenses in Ontario (OMNRF unpublished data, obtained from Barton 2011).

Movement ecology of walleye has been studied using mark-recapture and biotelemetry throughout the Great Lakes in efforts to understand habitat use, reproductive biology (i.e. spawning sites, dispersal rates, homing tendencies), and stocking success (Crowe 1962; Todd & Haas 1993; Fielder & Thomas 2006; Thompson et al., 2009; Hayden et al., 2014). Walleye are known to travel long distances to spawn in deep, clear, gravel-bottomed, flowing tributaries or lake shoals, and return to their normal feeding grounds post spawning (Fielder, 2002; Hayden et al., 2014). They have high spawning site fidelity (Bozek et al., 2011; Hayden et al., 2017) and selection of spawning habits appear to be hereditary as such, there are lake resident walleye that spawn in lakes or migrate to river systems, and river residents that spawn in rivers. Spawning site imprinting and homing are behavioural mechanisms that are common to fish (Horrall 2011). It has also been hypothesized that walleye homing is an adult-learned behaviour rather than a natal-imprinted response (Olson et al., 1978), and that adults arriving at spawning sites first might produce odour trails for guiding recruit spawners to their natal grounds (Horrall, 1981). Spawning migration behaviour appears to be system-specific and further investigations are required to ascertain under which environmental conditions walleye will migrate or stay to spawn (Bozek et al., 2011).

Hamilton Harbour, a 21km² embayment in the western end of Lake Ontario (Figure 2.1), was Canada's largest contaminated site in the Great Lakes and designated as an Area Of Concern (AOC) in 1985 with eleven Beneficial Use Impairments (Hamilton Harbour RAP, 2012). Historically, the harbour was a productive wetland area, however, the infilling of the extensive marsh habitat along the south shore and rivers and streams, along with physical habitat modifications around the perimeter of the Harbour, has resulted in the loss of 22% of the open water area and a reduction of wetland area from approximately 500 hectares to less than 50 hectares (Smokorowski et al., 1998). The degradation of the remaining marshlands, in particular Cootes Paradise and the mouth of Grindstone Creek, stems from fluctuating water levels, nutrient enrichment, high suspended sediment load, and a large population of common carp (*Cyprinus carpio*; Whillans, 1996). The Harbour has been undergoing restoration for over 30 years with the bulk of the physical habitat enhancements constructed by 1992. This included 65 underwater structures (artificial reefs) that were offshore in water >2m deep, extensive shoreline work, as well as substrates (pea gravel, sand, rock rubble) for spawning, nursery and adult habitat (O'Connor, 2003). Additional restoration efforts include the control of the common carp population in Cootes Paradise with a two-way fishway and the replanting of native aquatic vegetation to provide important spawning and nursery habitat for northern pike (*Esox lucius*; O'Connor, 2003). Significant upgrades to waste water treatment plants have reduced the phosphorus loadings into the harbour, however, further reductions are required for progress towards Remedial Action Plan quality delisting objectives (O'Connor, 2003). As of 2006, after 15 years of restoration activities and improved water quality management, the state of the fish community had improved (Hall et al., 2006); however, Index of Biotic Integrity values, a metric that describes the condition of the fish community based on the composition of native, invasive, omnivorous, and piscivorous fishes, are still lower than other AOCs and the fish community continues to reflect an unhealthy ecosystem (Brousseau & Randall, 2008).

Dissolved oxygen is a limited resource in the cool, deep waters of lakes in the summer and can be depleted at an increased rate with nutrient input from agricultural and urban waste (Coutant, 1987). Hamilton harbour has been subject to contamination from municipal treated and untreated sewage input (26 streams, four Waste Water Treatment Plants and sewer outfalls), industrial effluent, and urban runoff resulting in extreme cultural eutrophication (Smokorowski et al., 1998; Gertzen et al., 2014). Increases in phosphorus concentrations leads to high primary production as these primary producers die, oxygen is used for their decomposition. During the summer stratification when the hypolimnion is isolated from oxygenated surface waters, it can experience hypoxic or even anoxic conditions (Gertzen et al., 2014) affecting the diversity or life and availability of suitable habitats for aquatic organisms. Preliminary monitoring and modeling of temperature and DO properties in the harbour have also shown cyclic upwelling events occurring due to seiche activity (Wells and Semcesen, unpublished data). Wind driven shifts in the thermocline position allow cool, hypoxic water to upwell close to the surface (Wells and Semcesen, unpublished data). Dissolved oxygen is essential to the metabolism and life history processes of aerobic aquatic organisms and therefore, an essential factor in maintaining life in aquatic ecosystems (Kramer, 1987).

Walleye were extirpated from Hamilton Harbour during the mid-20th century, and multiple efforts have been made to reintroduce this ecologically and economically valuable species into the harbour. Ontario Ministry of Natural Resources and Forestry (OMNRF) first attempted stocking adult and fingerling walleye of the nearby Bay of Quinte, Lake Ontario strain in the 1990s. Reintroduction programs, where individuals are translocated into a formerly occupied habitat, are an important conservation tool (IUCN, 2013), however, less than a quarter of reintroduction programs are successful at restoration (Fischer and Lindenmayer, 2000). There are numerous best practices for successful reintroduction which mainly focus on habitat quality and the demographics and logistics of translocation (Armstrong and Seddon, 2008), but the main consideration prior to any reintroduction program is to address the original reason(s) that led to extirpation of the species in the first place. There have been various improvements to the water quality and physical fish habitat in the Harbour prior to the stocking attempts. In addition, hatchery-rearing practices also contribute to the success of stocking programs. When hatchery-reared fish are released into the wild, they are placed in a novel and variable environment with exposure to predatory risks (Brown and Laland, 2001) and juveniles must be raised under conditions that enable them to learn the behaviours necessary for survival in the wild. The walleye were obtained from nearby Bay of Quinte, an AOC site further east of Hamilton in Lake Ontario, and had been reared at the nearby White Lake hatchery, and therefore were of a relatively local strain and genetically 'suitable' for typical Lake Ontario ecosystems, and were released at a young age, therefore reducing the chance of habituation to captive environments. Assessing the effectiveness of walleye stocking events has long been of interest to managers of fisheries (Hile 1937; Bozek et al., 2011). The abundance of these stocked walleye declined and were not evident between 2006 and 2012 (J. A. Hoyle, 2008). Stocking was reattempted in 2012, with further additions of fish in subsequent years (of the same genetic strain; Appendix Table A.1). OMNRF's Nearshore Fish Community Index Trap Netting (NSCIN) efforts in 2014 observed walleye catch rates 20% higher than their target catches (Hoyle, 2008). Furthermore, fingerling fish from 2012 were trapped in 2014, which is an early indication that the stocking has been successful in terms of survival and growth rates. Recently sampled walleye dissected for toxicity studies have shown the 2012 fingerlings have reached sexual maturity (Hoyle, unpublished data).

Understanding Hamilton walleye movement, migration, and space-use throughout the year will allow fisheries managers to determine where natural recruitment may occur within the Harbour, what habitat features and environmental conditions stocked walleye are selecting, and provide guidance for future habitat restoration (for example physical habitat addition and addressing water quality issues), stocking and further studies into egg success. This chapter will use acoustic telemetry to address two of the US and Canadian government's Beneficial Use Impairments for the Great Lakes Area of Concern program, 'Degradation of Fish & Wildlife Populations' and 'Loss of Fish & Wildlife Habitat' to monitor what habitats walleye are using. With the highly turbid conditions in the harbour, the hatchery-origin of the fish, and without knowledge of the original Hamilton Harbour walleye spawning habits, the potential spawning locations of these stocked walleye are unknown. The objectives of this study were to 1) determine the extent and seasonal patterns of harbour residency for stocked walleye and 2) characterize seasonal patterns of habitat use and home range size, with a particular focus on the springtime spawning period. I hypothesized walleye residency and activity within the harbour was related to seasonal changes in biotic and abiotic factors. Walleye have been sampled during the summer months and occasionally caught by recreational anglers under the ice in the winter, therefore, I predicted that walleye will reside within the harbour for the majority of the year; however, with the highly turbid conditions and lack of typical walleye spawning habitat, I predicted that they will leave during the spring period for spawning. The harbour experiences hypoxia during the summer, with large volumes of water unsuitable for walleye's known preferred DO levels, therefore, I predicted that walleye home range extent will be lowest during the summer.

Methods

Overview

This study was conducted in Hamilton Harbour, an industrial shipping harbour at the western end of Lake Ontario (43.300 N, 79.806 W; Fig 2.1). Walleye were captured by either trap nets or electrofishing in August and October of 2015, equipped with acoustic transmitters and released almost immediately. After some initial range testing of typical habitats within the site, thirty acoustic receivers were positioned in Cootes Paradise marsh, Hamilton Harbour, and at either end of the canal connecting the harbour with Lake Ontario (Figure 3.1). Receivers were downloaded and serviced in April and October 2016. The data were filtered for dead fish, expelled tags and false detections, and hourly Centers of Activity were triangulated per individual (Simpfendorfer at al., 2002). These positions were divided into four equal, ecologically-relevant seasons based on the thermal properties of the harbour (summer stratification, fall turnover, winter ice cover, spring ice-off and spawning period; Appendix Figure A.1). Residency in the three 'zones' was determined using the receivers at the pinch points/gateways, and time spent within each zone was calculated per individual. Home ranges (both 95% and 50% core use areas) were calculated from Kernel Density Estimated distributions. Residency was compared across seasons using a binomial Generalized Linear Mixed effects Model (GLMM) and both home and core range areas were compared across seasons using a Generalized Linear Mixed effects Model, controlling for individual variability as a fixed effect. Individual home ranges were layered and combined per season to visualize areas of high usage. Centroids of these highly used areas were also calculated and plotted.

Study location

This study was completed in Hamilton Harbour, at the western end of Lake Ontario (43.30048 N, 79.80591 W). The western, northern and north-eastern shoreline are characterized by rocky shorelines, shallow vegetated areas, and man-made rocky islands and shoals. The southern shoreline, however, is characterized by harbour walls, two steel plants, and several marinas. The maximum depth in the Harbour is 24.9 meters in the center.

Range testing

The detection range for any acoustic receiving equipment is affected by the surrounding environmental conditions (i.e., wind, waves, turbidity, sounds, depth, vegetation; Kessel et al., 2014). It is therefore an important consideration when designing an array and interpreting detection data; preliminary and continual monitoring are essential. Approximate upper ranges for various habitat 'types' in Hamilton Harbour were assessed by lowering a range testing transmitter into the water column at known intervals from the receiver. As the conditions that allow this type of manual monitoring also typically equate to optimal acoustic conditions, this was considered the upper detection range for these locations. To assess the variation in ranges during the entire study period, two sites were selected for their opposing habitat and environmental conditions. Three fixed slow-emitting sentinel transmitters were placed at measured distances along a 100m receiver mooring line at the western end of the Harbour in between two receivers. This area was relatively shallow (~5 m), highly vegetated, sheltered from the prevailing wind and wave direction, and known to experience pulses of high turbidity that enter the Harbour from Grindstone Marsh and Cootes Paradise (Figure 3.2). Three sentinel transmitters were also secured to various points along the canal wall at the east of the Harbour. This location was selected due to the exposed conditions to wind and wave action, high levels of shipping traffic, relatively deep (~10 m) and the need to monitor detection efficiency at the 'gate' to Lake Ontario (Figure 3.3). The transmitters ping at a known frequency and the quality/variability of the acoustic signal can be observed every 20 minutes. These slow pinging rates are designed as to not fill the receivers' memory and reduce the chance of masking the detection of fish transmitters.

Receiver array

In the summer of 2015, 27 acoustic receivers (Vemco™ VR2W 69 kHz, Bedford, Nova Scotia) were deployed throughout the Harbour. Receivers were positioned to 1) maximize spatial coverage, 2) cover a variety of available types of habitat, and 3) determine whether tagged fish left the Harbour (Figure 3.1). Several of the receivers were attached to existing Fisheries and Oceans Canada and Environment and Climate Change Canada mooring lines and were co-located with temperature and/or dissolved oxygen loggers, and sediment traps (Figure 3.4.A). Receivers at the offshore locations were deployed with an anchor and a U-shaped mooring that could be retrieved with a grapple and a winch. Along the shore, receivers were secured to an anchored stand that was cabled to shore for easy retrieval (Figure 3.4.B). Receiver deployment commenced from August 6th to August 28th, 2015. They were downloaded and serviced in April (13th -22nd) 2016 and retrieved again October (22nd-29th) 2016. As such, the 12 month passive monitoring period commenced from October 21st, 2015, to October 20th, 2016, inclusively once all receivers and transmitters were in position. Receivers and sentinel transmitters at the western end of the harbour were stolen from the array April 24th, 2016. Data collected prior to installing the full array or from these two receivers were not used in the analyses to balance sampling effort throughout the study reach.

Fish capture and transmitters

The majority of the walleye (n=17) were captured in August, 2015, in trap nets set as part of the OMNRF's nearshore community survey. The remaining fish (n=8) were captured in

October, 2015, with either trap nets or using an electrofishing boat (Smith-Root electrofishing boat model SR 18.EH; 250 V and 7 A for intervals of ~1000 seconds)(Table 3.1). Upon capture, walleye were placed in holding tanks filled with ambient lake water prior to surgical procedures. During the capture period, no tagged walleye were recaptured while netting or electrofishing.

Fish were anaesthetized using either a Portable Electroanesthesia System (PES; Vandergoot et al., 2011; Rous et al., 2015; Figure 3.5.A) or using the boat's e-fishing electrodes. Both methods work by placing the fish in a state of electroanesthesia, which is commonly used during fish surgeries (Jennings and Looney 1998). Individuals were placed in a padded trough, oriented ventrally, and to maintain normal respiration during the surgeries, ambient lake water was poured into the trough to cover both the head and gills. Water was refreshed throughout each surgery and between individual surgeries. Transmitters fitted with pressure sensors to determine depth (Vemco™ V13P-1x-069k-1-0034m, 13mm diameter, dry mass 11g, battery life 1386 days) were inserted into the body cavity through a 2-3 cm mid-ventral incision. The acoustic transmitters were manufactured with a random delay range of 130-270 seconds to reduce transmitter collisions from multiple fish. Incisions were closed with 2-3 interrupted sutures (3-0 polydioxanone-II violet monofilament, 24mm; Ethicon USA), tied with a double surgeons knot (Figure 3.5.B). All surgical equipment and tags were cleaned with 10% povidone-iodine solution (Betadine®, USA) before each surgery. An external anchor tag (Floy Manufacturing Inc) printed with a unique identification number and Carleton University's phone number was then inserted into the muscle by the dorsal fin (Figure 3.5.C). The total lengths were measured for each fish and they were placed into the recovery live well containing fresh, recirculating lake water. The average processing time was 3.5 minutes and the fish typically recovered within 10 minutes. To ensure full recovery of fish prior to release, fish were tested for sufficient equilibrium, body flex, tail clamp, and eye movement (RAMP; Raby et al. 2012). Three fish died during the August surgeries, possibly because of warm water and their duration of holding in the trap nets, and potential exposure to hypoxic waters. Fish handling and surgical procedures were approved and followed a Canadian Council on Animal Care protocol administered by Carleton University.

Data preparation

Exported data were sorted and plotted on a "per fish" basis to visually check for dead fish or expelled tags. Any detections that remained on the same receiver(s) throughout the study period at a similar depth were presumed dead and removed from the database. False-positive detections can occur when multiple transmissions collide when detected by a receiver, resulting in erroneous tag IDs being recorded (Skalski et al., 2002; Pincock 2011). A residency analysis was then conducted in R Statistical Environment (R Core Development Team, 2017) to remove these false-positive detections by eliminating single detections and random tag IDs. Nine fish were removed from the analyses as they were either harvested, died at some point after tagging, or had expelled their transmitter. An additional fish was removed from formal analysis because it left the harbour shortly after release and only returned for two days within the study period (ID=754). Fifteen individuals were available for analyses within the 12 month study period.

Residency

Residency within the three zones (Cootes Paradise, Hamilton Harbour, and Lake Ontario) was determined using fish capture information obtained from the Royal Botanical Gardens fishway staff and the two receivers at both ends of the shipping canal into Lake Ontario (Figure 3.6, Figure 3.3). Fish that were detected at either of the canal receivers were isolated and the direction of travel was determined. There is no detection range overlap between the two receivers (Figure 3.3), therefore any fish recorded on the inside and then the outside receiver, with no immediate re-detection on the inside receiver, were recorded as exiting the harbour, and the same in reverse order for fish returning to the harbour. Number of days within the harbour was calculated as a proportion of the total number of days in the study and season; however, this does not mean that animals were detected on the array each individual day of the study period.

Spatial Analysis

After data filtering, the telemetry data were used to determine an individuals' Center of Activity (COA; Simpfendorfer et al., 2002). The COA algorithm produced a weighted, arithmetic mean position for each hour the fish was detected within the acoustic array. Hourly COAs were then imported into ArcMap (ESRI, 10.4.1) to calculate individual seasonal kernel-utilization distributions (KUD; Worton, 1989) from which 50 and 95 Percent Volume Contours (PVCs) were obtained to show home range (95% of predicted space use) and core ranges (50% of predicted space use), hereinafter referred to as home range and core range, respectively. A smoothing factor of 500m and grid size of 5 m^2 were used in all KUD estimations. Other methods for home range analysis are available (e.g., kernel Brownian bridges; Calenge 2006; LoCoH; Getz et al., 2007), however KUDs and PVCs are a simple and commonly used method for estimating animal home range from acoustic telemetry data (reviewed in Gutowsky et al., 2015; Kie et al., 2010; Lédée, Heupel, Tobin, & Simpfendorfer, 2015; Munroe, Simpfendorfer, & Heupel, 2014; Worton, 1989). Figure A.2 in the Appendices shows the process of obtaining the isopleths from the COA points. Individual 95 and 50 PVC raster files were compiled into a single layer to visualize the overlapping home and core ranges in ArcMap. This raster file was re-classified to show isopleths of the number of individuals using that area during that season. The central position of each season's most used area was calculated and plotted, and the area surrounding all four central points was calculated (Appendix A.3 & A.4).

Statistical modelling procedures

For both the residency and home-range size analyses, we examined the data at a seasonal level where seasons included fall (September-November), winter (December-February), spring (March-May), and summer (June-August). Seasons were classified to correspond with biologically meaningful thermal periods within the Harbour. Hamilton Harbour experiences thermal stratification and the 'summer' months of June, July, and August were selected as they were fully within the stratification period (Appendix A.1). Spawning behaviour for walleye is known to occur after ice-off in March and April, and spawning activity was corroborated in mid-April with opportunistic electro-fishing surveys by DFO (D. Reddick, pers. comm). Spring and fall periods represented the transition period between the comparatively stable cool temperatures in the winter and stratification in the summer (Appendix A.1). This classification ensured that the study period contained four biologically relevant seasons, which facilitated analyses.

Differences amongst seasons in the proportion of time spent within the harbour and both the 95% and 50% home range sizes were analyzed using Generalized Linear Mixed effects

Model (GLMM). All three models included fish identification number as a random effect, and season as a fixed effect. Data exploration was performed using standard tools including Cleveland dot plots (to identify outliers) and box and whisker plots (to identify relationships between continuous and categorical variables) (Zuur et al., 2009). Residency data were determined to be binomial and a GLMM with the 'binomial' family was generated with the 'lme4' package (Bates et al., 2015), with a 2-column matrix of days present and absent in the Harbour, using the 'cbind' function. Home range models were generated using the 'nlme' package (Pinheiro et al., 2017) and included a variance structure that accounted for residual heterogeneity (constant variance structure), as opposed to transforming the response variable, which can possibly alter the relationship with the predictor variable (Zuur et al., 2009). If the model indicated a significant result for seasonal effect, a Tukey post-hoc test using the 'multcomp' package (Hothorn et al., 2008) was used to make pairwise comparisons. Residuals were plotted as a dotplot to determine parametric assumptions, independence was determined by generating correlation lag plots, using the 'acf' function (Fox and Wiesberg, 2011), which indicates auto-correlation in observations. Normalized residuals were plotted against fitted values to check the assumption of residual homogeneity.

Results

Twenty five walleye were tagged in August and October, 2015, ranging from 430-700 mm (mean 518 mm) in total length. Data were collected from August 2015 to October 2016, yielding approximately 2.2 million walleye detections, with 152, 300 Center of Activity locations obtained within the study period, 21st October, 2015 to 20th October, 2016 (Figure 3.8). The COA locations were plotted per season prior to running through the Kernel Density Estimates tool in ArcMap (ESRI, 2017). Figure 3.10 shows an example of one individual's seasonal KUD plots (ID 774).

Residency

No walleye attempted to pass through the RBG fishway during the study period. Tagged walleye were present within the harbour for 135-365 days (mean ± s.e. = 323 ±19 days), including six walleye that never left the harbour (Figure 3.11). Seasonal average residency was converted to a percentage of time spent within the harbour, the lowest residency occurred in fall with 75% ±9%, then summer 89% ±7%, winter 91% ±6%, and spring 95% ±5%. Of the nine walleye that did leave the harbour, their residency was higher during spring, winter, and summer when compared to fall ($p<0.0001$), and they were more resident in spring than in both summer and winter ($p<0.0001$) (Table 3.2 and 3.3). Twelve individuals remained within the harbour for the entire spring period. Residency per individual across the 365 days of the study was plotted to visualize departures throughout the year (Figure 3.12). Several walleye departed towards the end of the summer, beginning of fall (n=8) prior to the turnover which occurred between 13^{th}-28^{th} September (Appendix Figure A.1).

Space use (extent)

Home range and core use areas were calculated for each individual per season (Figure 3.14 and 3.15) and plotted using boxplots per individual (Figures 3.16 and 3.17) and per season (Figures 3.18 and 3.19). Home range areas ranged from 0.4 km^2 to 10.2 km^2 (mean = 6.5 km^2 ±0.31) and core use ranged from 0.15 km^2 to 2.64 km^2 (mean = 1.05 km^2 ±0.08).Walleye had the largest home ranges in the fall (mean=7.76 km^2 ± 0.46), approximately double their home range in the summer (3.74 km^2± 0.45). There were no apparent differences in home range sizes between fall and winter ($p>0.05$; Table 3.5), fall and spring ($p>0.05$; Table 3.5), and winter and spring ($p>0.05$; Table 3.5), whereas all seasons had significantly larger home ranges than summer (in all cases, $P<0.0001$; Table 3.5). The proportion of core use area of their overall seasonal home range also varied across the seasons, with 11.3% for the summer, 14.1% for fall, 15.7% for spring, and 22% for winter. There was no significant difference between the area used by walleye that were fully resident, and those that left (t-test = 1.13855, p-value = 0.13772).

Space use (position)

Central positions of the polygons of the area used by the most individuals (Figure 3.20 and 3.21; fall n=14; winter and spring n=15; summer n=6) were calculated and plotted (Appendix, Figures A.3 and A.4). All four central positions were positioned within an area of

0.27 km² and 0.05 km² for home and core range respectively. Qualitatively, areas used in the spring and summer, both total home and core ranges, are more dispersed than in fall and winter. Walleye appeared to predominately use the western end of the harbour during the fall, spring and summer and were more concentrated in the central, deeper basin of the harbour during the winter. Core use areas appeared to gradually shift more easterly as the seasons progressed from summer towards winter. Areas used in the summer appear to be more coastal, i.e. most easterly and westerly shorelines with only one individual's core home range close to the central basin.

Discussion

In this study, residency and space use of walleye varied seasonably, presumably reflecting seasonal differences in environmental conditions (e.g., temperature, oxygen, food availability). While the results supported my general hypotheses that walleye residency and activity within the harbour was related to seasonal changes, predictions regarding residency of tagged walleye during the spring spawning season were not supported; walleye were the most resident to the harbour during this season. The areas most used by individuals also varied across seasons; however, the central positions of these were very close. Walleye home and core ranges were more isolated and coastal throughout the summer and spring when compared to fall and winter. As predicted, their winter and fall space use was contracted, presumably indicating their preference for offshore, more thermally-stable areas during cooler conditions.

Although there has not been genetic confirmation of the source of the captured walleye (hatchery or wild), walleye tagged in this study were presumed to be from the 2012 fingerling stocking event and therefore sexually mature (J. Hoyle, 2014). Walleye were not caught in the harbour during OMNRF's Nearshore Fish Community Index (NFCI) surveys for up to six years prior to the 2012 event, however, they have been captured and sampled annually since. Their Catch Per Unit Effort and age and growth data (LOA 2017; Appendix Figures A.5 and A.6) have shown the 2012 cohort's successful survival and growth rates over the preceding three years. Walleye mature at approximately 3-4 years in the Laurentian Great Lakes (Scott and Crossman, 1979) and generally at a total length larger than 300 mm (Colby et al., 1979). As such, stocked walleye were presumed to be sexually mature by time of sampling spring 2016. In addition, walleye dissected from the NFCI efforts in 2015 were of similar size range and were found to be sexually mature (Hoyle, pers. comm). Spawning activity was confirmed by DFO's electro-fishing surveys in April, 2016, with 49 ripe walleye (males = 47, females =2) observed and caught in aggregations along the coastlines (LOA 2017; Appendix Table A.2).

Home and core use data have shown sites used most frequently during spring, including areas thought to be unsuitable spawning habitat and therefore, not surveyed by DFO. The majority of the individuals remained within the harbour for the entire spring period, indicating a high chance that they attempted to spawn. These areas, however, may have been used in the periods prior or post spawning. Consequently, categorizing behaviour by season may have masked specific spawning sites. Typical walleye spawning habitat includes low turbidity, rocky shoals and reefs with little sediment deposition (Colby et al., 1979) as embryos require well-oxygenated water (Balon et al., 1977) and sedimentation can reduce the availability of oxygen (Benson 1968). Finer scale analysis may provide a more precise understanding of habitat used for spawning. Males tend to arrive at spawning sites first and stay longer than females (Bozek et al., 2011), and, although heavily dependent on water temperature fluctuations, can last between days and weeks (Priegal 1970). Unfortunately, sex of the tagged fish is unknown and therefore cannot be used to characterize variation amongst springtime home and core range use. Previous walleye home range studies have shown no difference between males and females during non-spawning seasons (Palmer et al., 2005). These data provide stocking managers with locations for further natural recruitment research, including egg collection and egg and fry survival studies, such as the shoals in the north-eastern corner and the rocky shorelines south of the canal entrance. Several fish (n=9) left the Harbour through the canal, and re-entered after days, weeks, or months. Other species of fish, including longnose gar (*Lepisosteus osseus*) and freshwater drum (*Aplodinotus grunniens*), that were tagged during the study period within the Harbour have also left and returned via the shipping canals on multiple occasions (Brooks, unpublished data). It is therefore unlikely that walleye remained within the Harbour during the spawning season because their attempts to migrate into Lake Ontario were halted because they could not 'find' the exit.

Unfortunately, we quickly lose track of individuals when they exit the canal into Lake Ontario and cannot determine if they are residing in the immediate areas near the harbour or travelling long distances. Walleye have been documented to travel up to 300 km from overwintering to spawning habitats (Hayden et al., 2014). The Hamilton acoustic array is part of a collaborative telemetry data sharing network, the Great Lakes Acoustic Telemetry Observation System (GLATOS), which enables researchers to share detections from fish outside of their own study, and thus expanding member's acoustic array coverage. There is a growing number of Vemco™ acoustic telemetry projects in Lake Ontario (n= 7; GLATOS) that will enable us to further determine broad-scale movements of walleye after leaving the harbour and connectivity between other AOCs. For example, a walleye from the Toronto Harbour telemetry group was detected on multiple receivers for a short period of time within Hamilton Harbour, indicating a broader scale connectivity between Hamilton and Toronto Harbour, and also that walleye not originating from Hamilton do enter the harbour. Walleye ID754 was removed from further analyses due to the lack of residency within the harbour during the study period (2 days; 0.54%). It is unclear if this fish was transient and from a different home site, simply visiting the harbour for a short period or if was one of the stocked fish that coincidentally departed immediately after tagging. Larger sample sizes and enhanced array coverage outside of the harbour will help to elucidate this in the future.

During warm water stratification (July to September) the areas mostly used by the walleye appear to be more coastal and patchy. This reduction and segregation in home range could have several explanations: 1) movement and activity is reduced during the summer so they are getting detected on fewer receivers and, therefore, the COA algorithm has positioned them closer to the receiver sites, resulting in a smaller home range; or 2) the harbour's hypoxic conditions (Gertzen et al., 2013) during the summer are restricting the amount of habitat available to walleye; 3) walleye are using locations that are not covered by receivers, i.e. they are using blind spots in the array; or 4) the acoustic range is more impaired during this season due to an increase in macrophyte growth. I will continue to explore these possibilities in more detail over the next few paragraphs.

Previous walleye telemetry studies have focused on spawning locations, habitats, and migration distances travelled (Crowe, 1962; Bunt 2000; Fielder, 2002; Einhouse, 2008). There has been little research conducted on summertime movements of walleye. Field studies of temperature preference and avoidance by fish indicate that the thermal structure of a waterbody is important to fish distribution (Coutant, 1987). When considering physiological parameters, temperature selection appears to place a fish in the temperature which generally maximized metabolic performance of physiological functions (e.g. growth; Coutant, 1987). In Lake Erie, walleye distributions have been linked to the availability of both thermal (optimal temperatures for walleye growth 18-22°C; Christie and Regier, 1988) and optical habitats, both of which seem ideal in the metalimnion or hypolimnion (Jones et al., 2006). Adults have been known to avoid temperatures exceeding 24°C, if possible (Fitz and Holbrook, 1978) with upper lethal temperatures reported at 29-32°C (Hokanson 1977) and 34-35° (Wrenn and Forsythe, 1978). However, in Toronto Harbour, preliminary analyses of walleye seasonal detections between 2012 and 2015 have shown a preference for shallow (mean depth 0.5-2.5m) and warm waters (mean 20-22°C, range 16- 27°C) (Midwood, unpublished data). Toronto Harbour is frequently flushed by Lake Ontario and the water column is mixed therefore does not have issues with hypoxia. Although these temperatures seem higher than their optimum, they could be potentially using these areas for foraging. Further study into thermal optimal preferences, depth use, and prey availability is required to determine this potential reduction in activity during the summer.

Depletion of DO in water (hypoxia) can have adverse effects on the diversity of life and the availability of suitable habitats for aquatic organisms. A reduction in available oxygen has the potential to affect fishes lethally, or sub lethally (Brandt et al., 2011). Sub lethal effects include altered feeding rates (Roberts et al., 2009), growth rates (Brandt et al., 2009), behaviour (Ludsin et al., 2009) and vulnerability to predation (Costantini et al., 2008). Although walleye can move horizontally or vertically in response to hypoxia, the temperature and light intensity in shallower waters might reach levels above what is optimal for foraging and growth (Lester et al., 2004). Preliminary monitoring and modeling of temperature and DO have shown cyclic fluctuations in water quality conditions in the shallow coastal zones and, when combined with fish depth data (Wells, unpublished data; Appendix Figures A.10 and A.11), has shown to be unsuitable for most species tagged in the larger telemetry study. Suitable habitat may be restricted and overcrowding can ensue in oxygen-rich refuges (Coutant, 1987). This required habitat shift could lead to various indirect negative effects for fish, for example reduced habitat quality, increased metabolic demands, and reduced consumption (Brandt et al., 2011). This could however, be a potential positive effect for fish, including the reduction of available habitat for prey species and therefore an increase in foraging efficiency (Rahel &Nutzman, 1994; Costantini et al., 2008). As mentioned previously, Hamilton Harbour suffers from hypoxia, in particular during stratification (Gertzen et al., 2014). Walleye in the harbour may be utilizing these concentrated zones for foraging, and therefore not needing to use large areas of habitat during the summer. Future research into their fine scale movements and depth use will help understand their activity during this summer period.

Receivers were originally positioned to maximize coverage in the harbour and gain an understanding of broad scale movements. The harbour is a popular recreational boating area and there are limited areas in the coastal, shallower zones to position receivers free from risk of boat damage. Walleye use coastal, shallow areas in Toronto Harbour, it is therefore possible that walleye are moving into these marshy areas in Hamilton Harbour undetected and could explain the fewer detections and apparent smaller home ranges in the summer. The two receivers positioned to detect movements into the Grindstone Marsh area were unfortunately stolen prior to the summer period, therefore I will not be able to determine usage of these areas until the newly positioned receivers are downloaded in October, 2017. It has been documented, however, that walleye feed in 1-2 m Secchi depth, with a decrease in activity at less than 1 m or greater than 5 m (Ryder, 1977). Turbidity is high in these marsh areas, however, and Secchi disc depth is often less than 50 cm in the summer (Thomasen and Chow-Fraser, 2012), it is unlikely that walleye are inhabiting or foraging in these areas during this season. More receivers are to be positioned in the channel to the far west of the harbour, and closer to shore in the North East corner of the harbour near the small tributary to cover blind spots in these areas. Active tracking of walleye using a boat-based hydrophone during the summer may also help to locate these 'missing' fish. These may rule out the possibility that the fewer detections and smaller home ranges in summer are as a result of lack of acoustic detection coverage.

The detection range for any acoustic receiving equipment is affected by the surrounding environmental conditions (wind, wave, turbidity, sounds, depth, vegetation etc.; Kessel et al., 2014). An increase in submerged vegetation throughout the summer could possibly lead to a reduction in the acoustic performance of the receivers, and could explain the reduction in detections in summer. Three sentinel tags were placed along the receiver mooring line in front of the Grindstone Marsh/Cootes Paradise fish-way area and three were positioned around the canal exit at the eastern end of the harbour. Probability of detections were determined on a seasonal basis, however the three Grindstone Marsh sentinel tags were stolen in May 2016, so there was only the eastern tags for May, June, July and beginning of August. Preliminary analyses of the sentinel tag detections have shown no major seasonal reduction in acoustic detection efficiency (Appendix Figures A.7- A.9), however, further investigations into the environmental effects on the equipment are required.

Interestingly, walleye have been detected and caught during the month of August in the Ottawa Slip, and the effluent from an adjacent steel plant enters at the back of this slip. As a result, water temperatures in this area are generally higher and more stable than other areas of the harbour and ranged from a low of 21°C in October, to 30°C in August (C. McGinley, pers. comm.). Walleye were using habitat up to 8°C higher than their thermal optimum. Walleye were not detected in this area during the winter. Gonad maturation in female walleye requires minimum water temperatures of less than 10°C (Hokanson, 1977). A potential explanation for this unusual behaviour is that their acclimation temperatures are higher in the summer and they are able move in and out for foraging purposes and maybe in the winter, the thermal differential is too high. Another possible explanation is that there are no prey fish in this area during the winter and their movements are driven by prey movements. Future network analyses of individual fish paths will determine the duration and frequency that these walleye inhabit this area.

Study limitations

There were some limitations to this study, including site-specific issues with equipment, and general fish tagging, acoustic telemetry, and analyses. Indeed, these limitations are rather common in field telemetry studies. Hamilton Harbour is an active shipping harbour with large vessels commuting to and from the steel and grain plants on the south shore. The central basin is also used as an anchorage site during inclement weather in Lake Ontario. Although all efforts were taken to protect the moorings, including collaborating with and informing the harbour master, we still lost two receivers to ships. Surface markers are navigational hazards for large ships, therefore mooring techniques that involve subsurface floats and long mooing lines were used, however, these are still at risk of being dragged by anchors. This has been unavoidable and future deployments in the shipping channels will have acoustic 'pingers' to allow divers to locate and retrieve receiver equipment that have been dragged from their known position. Similarly, there are five marinas in the harbour for recreational sailing and boating.

Receivers in shallower waters are deployed on weighted bases with the intention of stabilizing them without the need for surface markers. It assumes, however, that these are sitting upright on the bottom but as the visibility in the harbour is so poor, we are never able to visually check. One receiver positioned outside of the shipping canal was dragged by either boat traffic or wave action and was retrieved by an Environment and Climate Change Canada technical diver, it was positioned on its side and there is no way of telling how long it had been like this.

Like all forms of aquatic biotelemetry equipment, the Vemco™ system has its own limitations. Vemco™ acoustic telemetry provides very large datasets that usually exceeds the capacity of generic spreadsheet software (Microsoft Excel 2013 is limited to 1.02 million rows of data). Hamilton Harbour's full database (8 species, 150 transmitters, 18 month period) is currently over 4 million rows of detections, therefore, data management and interpretation can be challenging. Interpreting passive acoustic telemetry data can be difficult as rows of data represent the repeated sampling of the same individual; therefore data are non-independent and suffer with issues of autocorrelation (Cooke et al., 2013). Fish detected on a receiver could be anywhere within the 360° dome of detection range and therefore, directionality cannot be determined by a single receiver. Using gates such as the canal array allows directionality to be determined. Here, there is no detection range overlap, therefore a detection on one and then the other provides a definite direction of the fish's movement. Using the COA (Simpfendorfer, 2002) to interpolate potential locations of fish allow the data to become more manageable and meaningful. For example, knowing a fish was within an approximate range of one receiver for twenty minutes, then at another nearby for one detection, then back again is quite difficult to both visualize and analyze. Having an average position for that individual for that hour provides an easier understanding of their broad scale habitat use. There are, however, limitations to the COA algorithm. Even though the detection range is 360°, fish will only ever be positioned within the outside perimeter of the receiver array as they are 'snapped' within the receiver 'lines of sight' for that hourly period, and gives the impression that fish are not using the coastal areas. Coastal deployments will avoid this and future, more complex network analyses will help determine finer-scale behaviours, for example actual paths taken by fish.

There are also inherent assumptions when using biotelemetry that tagged animals return to their natural behaviour post release. Studies in the field and in captivity have shown various lethal and sublethal effects from fish tagging (reviewed in Cooke et al., 2011), including increased mortality rates (Bunnel et al., 1999), increased predation (Jepson et al., 1998), decreased growth rates (Baras et al., 2000) and effects on social behaviour (Connors et al., 2002), however walleye have been studied frequently using biotelemetry in Lakes Huron and Erie with great success. It is more difficult, however, to assess the tagging effects on long term, post release movement behaviours, and there were concerns of fish not returning to their capture sites, an issue well documented in bird tagging studies (reviewed in Calvo and Furness, 1992), however detection data showed that walleye returned to sites of capture and release, and other species of fish in the study were recaptured by anglers in their exact original capture location.

Management Relevance

The reintroduction of walleye into the Harbour has been attempted on several occasions over the previous thirty years and has shown little success until 2012 (Appendix Table A.1). A common goal of species reintroduction programs is for natural recruitment to occur, enabling a self-sustaining population without the requirement of further stocking. The OMNRF's summer trapnetting surveys have provided an indication that the stocked population of walleye are surviving and growing at comparable rates to natural populations and have reached sexual maturity, however, they have been limited to four days of sampling during August each year and had little indication of their year-round presence in the harbour (LOA, 2016). Telemetry data from this study has provided knowledge that the walleye remain within the harbour for the majority of the year, including and more importantly, during the springtime spawning period. Although residency and spawning behaviour does not indicate spawning or natural recruitment success, it provides managers with answers to the first step in this process. Core use area data have also provided them with starting locations for their upcoming egg and fry surveys and information for further habitat restoration, such as the south east shoreline below the shipping canal, the north east rocky islands, and potentially the north shoreline west of the LaSalle marina.

This study suffered from an unusual high mortality rate during the August trapnetting efforts. Three fish died during the surgeries, and nine of the tagged and released fish either expelled their tag or died post-release. This high mortality rate could have been attributed to the method of capture, the water quality, or the expertise of the surgeon. Trap nets were set overnight, therefore there is potential for walleye to be held in nets for up to 20 hours. If these nets are positioned in or near areas with fluctuating DO levels, this could further add to the stress of the capture and tagging procedures. I was sufficiently trained in surgical procedures and had experienced low post-release mortality in the October tagging period and other projects outside of Hamilton Harbour, therefore, I would could rule out poor surgical training as a factor for the high mortality rate. I therefore recommend that OMNRF consider water quality, in particular DO levels, in their net setting locations prior to deployments to ensure their sampling does not impact the survival of their study species, and also to consider the patchy use of these coastal areas during the summer period when extrapolating their population estimates. We refrained from using netting methods to obtain further fish for our study, and I also recommend to use electrofishing as an almost-immediate capture method, and to focus future fishing efforts during the cooler spring and fall periods.

Future research

Further investigations into the fine-scale movements of walleye will determine a more accurate use of spawning sites and also habitat, thermal, and DO preferences within the Harbour. Combining depth and spatial use with environmental data such as vegetation cover, bottom type, slope, wind fetch, and available depth will help further understand the seasonal habitat requirements of adult walleye in a rehabilitated area. Managing fisheries in a changing climate requires accurate information regarding current habitat and water quality requirements and availability of these within an ecosystem. Biotelemetry, when combined with other habitat monitoring information, can help ensure effective management of fisheries in the future.

Tables

Table 3.1. Individual walleye identification number, tagging date, Vemco™ transmitter number, fish total length (TL), the percentage of study spent within the harbour, and the minimum and maximum seasonal 95 and 50 Percent Volume Contour area (km²).

Walleye ID	Tagging Date	Transmitter Number	TL (mm)	Residency in Harbour (%)	95PVC Range (km²)	50PVC Range (km²)
754	12-Aug-15	15754	521	0.55	N/A	N/A
755	12-Aug-15	15755	490	100	2.23 – 9.01	0.26 – 1.84
756	13-Aug-15	15756	700	68.2	0.41 – 9.39	0.02 – 1.96
759	13-Aug-15	15759	471	100	6.49 – 9.01	0.74 – 2.64
760	13-Aug-15	15760	512	85	2.57 – 7.76	0.19 – 1.17
761	13-Aug-15	15761	485	36.99	*7.83 – 9.04	*1.0 – 2.31
766	13-Aug-15	15766	430	52.33	3.63 – 9.61	0.34 – 2.05
769	13-Aug-15	15769	513	93.7	3.58 – 10.20	0.41 – 2.30
79	20-Oct-15	79	520	100	2.12 - 8.92	0.44 - 1.99
83	20-Oct-15	83	515	99.45	5.42 – 9.01	0.81 – 1.36
763	20-Oct-15	15763	506	97.81	4.45 – 7.52	0.24 – 1.18
764	20-Oct-15	15764	570	97.53	2.46 – 6.36	0.28 – 0.76
765	20-Oct-15	15765	521	86.58	3.29 – 8.08	0.32 – 1.19
771	20-Oct-15	15771	562	100	3.56 – 8.88	0.04 – 0.71
772	20-Oct-15	15772	555	100	5.08 – 9.83	0.77 – 1.82
774	20-Oct-15	15774	525	95.89	5.58 – 10.19	0.87 – 1.76

*ID761 was not present during the summer.

Table 3.2. Generalized linear mixed effects model (family = binomial) outcome for seasonal residency. Model summary provides the response term, value, standard error (SE), Z-value and the P value (bolded if found to be significant).

Model Term	Value	SE	*Z* value	*P* value
Intercept	0.9235	0.7319	1.262	0.207
Spring	3.1123	0.1853	16.794	**<0.0001**
Summer	2.0331	0.1581	12.859	**<0.0001**
Winter	2.3384	0.1650	14.168	**<0.0001**

Table 3.3. Post Hoc Tukey Pairwise comparison for seasonal residency for the fitted model. The pairwise comparisons provide the slope estimate, 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.

Season pair	Estimate	SE	*Z* value	*P* value
Spring – Fall	3.1123	0.1853	16.794	**<0.0001**
Summer – Fall	2.0331	0.1581	12.859	**<0.0001**
Winter - Fall	2.3384	0.1650	14.168	**<0.0001**
Summer - Spring	-1.0791	0.1778	-6.070	**<0.0001**
Winter - Spring	-0.7739	0.1807	-4.282	**<0.0001**
Winter - Summer	0.3053	0.1612	1.894	0.2295

Table 3.4. Generalized linear mixed effects regression model outcome for seasonal home range (95Percent Volume Contour). Model summary provides the response term, value, standard error (SE), t-value and the P value (bolded if found to be significant).

Model Term	Value	SE	df	*t*	P value
Intercept	7760605	493178.5	41	15.735896	**<0.0001**
Spring	-201454	599649.6	41	-0.335952	0.7386
Summer	-3995177	590729.6	41	-0.6763123	**<0.0001**
Winter	-1080134	655500.3	41	-1.647801	0.1070

Table 3.5. Post Hoc Tukey Pairwise comparison for seasonal home range (95 Percent Volume Contour) for the fitted model. The pairwise comparisons provide the slope estimate, 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.

Season Pair	Value	SE	Z value	P value
Spring – Fall	-201454	599650	-0.336	0.987
Summer – Fall	-3995177	590730	-6.763	**<0.0001**
Winter - Fall	-1080134	655500	-1.648	0.351
Summer - Spring	-3793723	549761	-6.901	**<0.0001**
Winter - Spring	-878680	618835	-1.420	0.486
Winter - Summer	2915043	610195	4.777	**<0.0001**

Table 3.6. Generalized linear mixed effects regression model outcome for seasonal core range (50 Percent Volume Contour). Model summary provides the response term, value, standard error (SE), t-value and the P value (bolded if found to be significant).

Model Term	Value	SE	df	*t*	P value
Intercept	1091690.0	131667.8	41	8.2912	**<0.0001**
Spring	94306.7	182742.2	41	0.516064	0.6086
Summer	-662441.4	132719.6	41	-4.991285	**<0.0001**
Winter	374901.7	201867.0	41	1.857172	0.0705

Table 3.7. Post Hoc Tukey Pairwise comparison for seasonal home range (50 Percent Volume Contour) for the fitted model. The pairwise comparisons provide the slope estimate, 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.

Season Pair	Value	SE	Z value	P value
Spring – Fall	94307	182742	0.516	0.953
Summer – Fall	-662441	132720	-4.991	**<0.0001**
Winter - Fall	374902	201867	1.857	0.236
Summer - Spring	-756748	147149	-5.143	**<0.0001**
Winter - Spring	280595	211634	1.326	0.533
Winter - Summer	1037343	170319	6.091	**<0.0001**

Figures

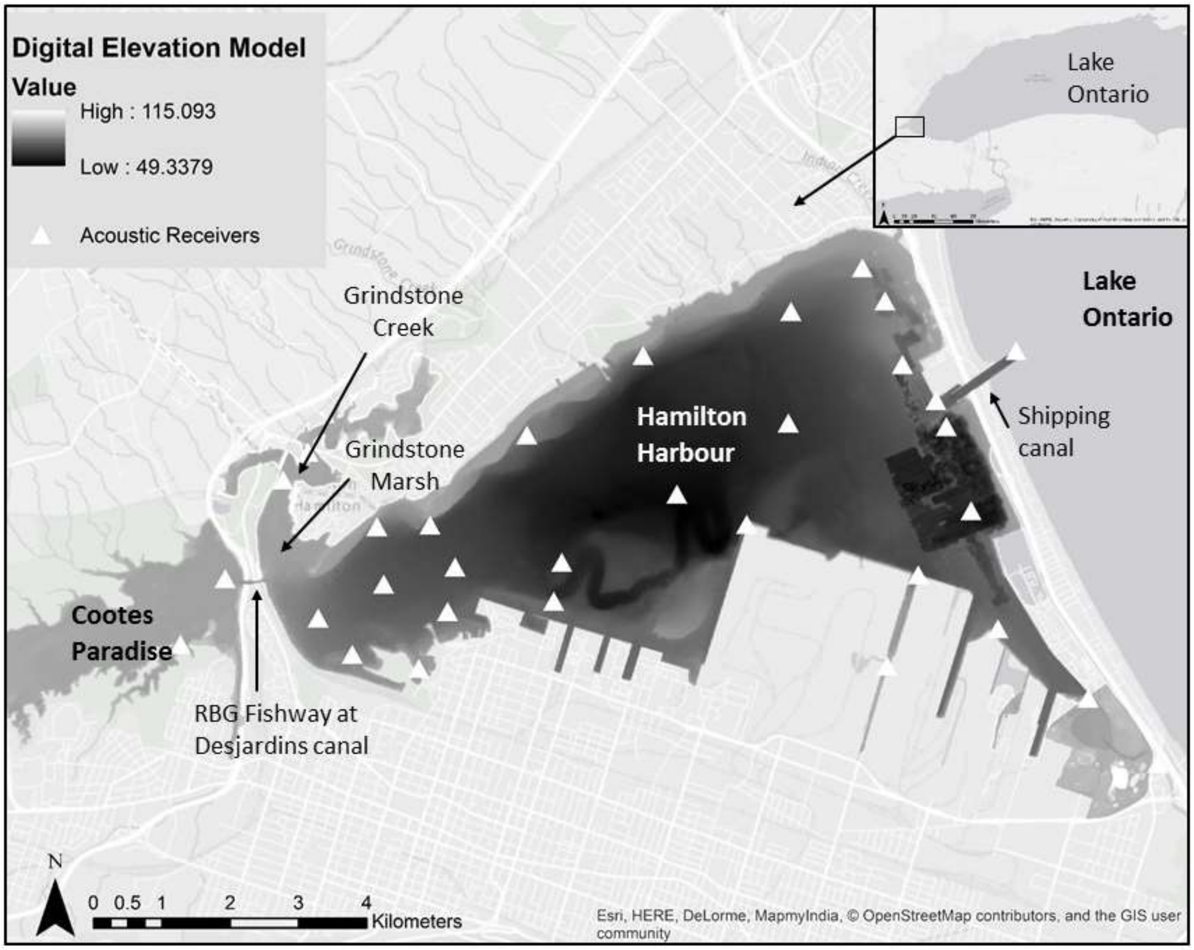

Figure 3.1. Digital elevation model of Hamilton Harbour, at the western end of Lake Ontario (inset). Receivers indicated by white triangles. Available entrance points to the Harbour include the shipping canal from Lake Ontario at the eastern end and the Desjardins canal from Cootes Paradise at the western end. Fish passage into Cootes Paradise is regulated and monitored via the Royal Botanical Gardens fishway.

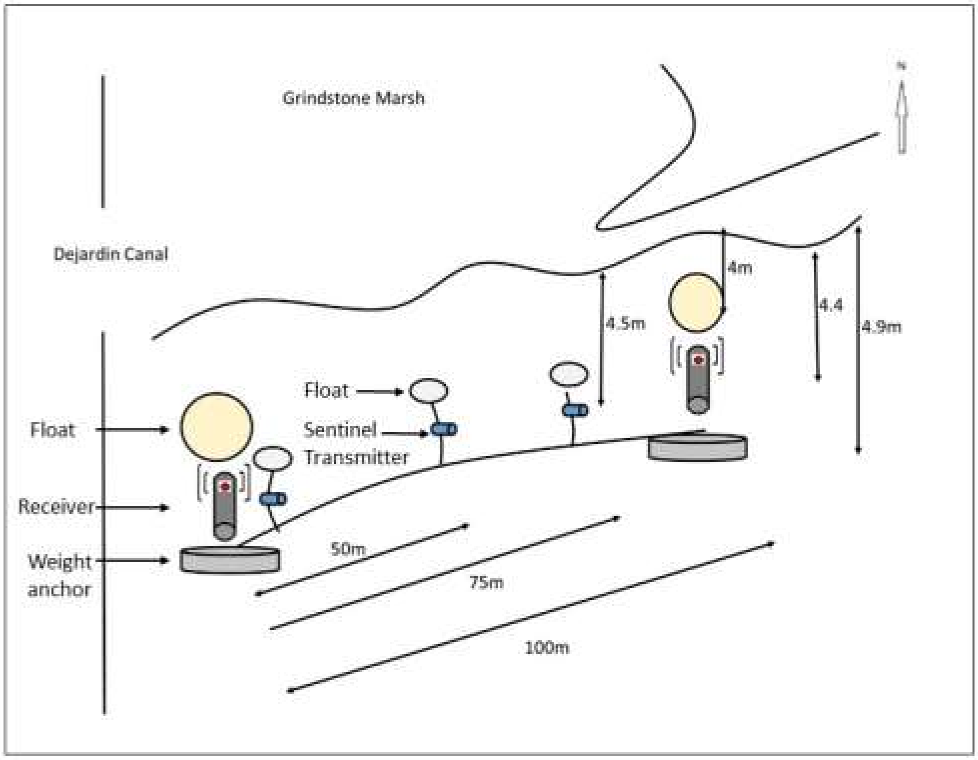

Figure 3.2. Sentinel transmitter and acoustic receiver mooring line placed at the mouth of the Grindstone Marsh and the Desjardins canal (to Cootes Paradise).

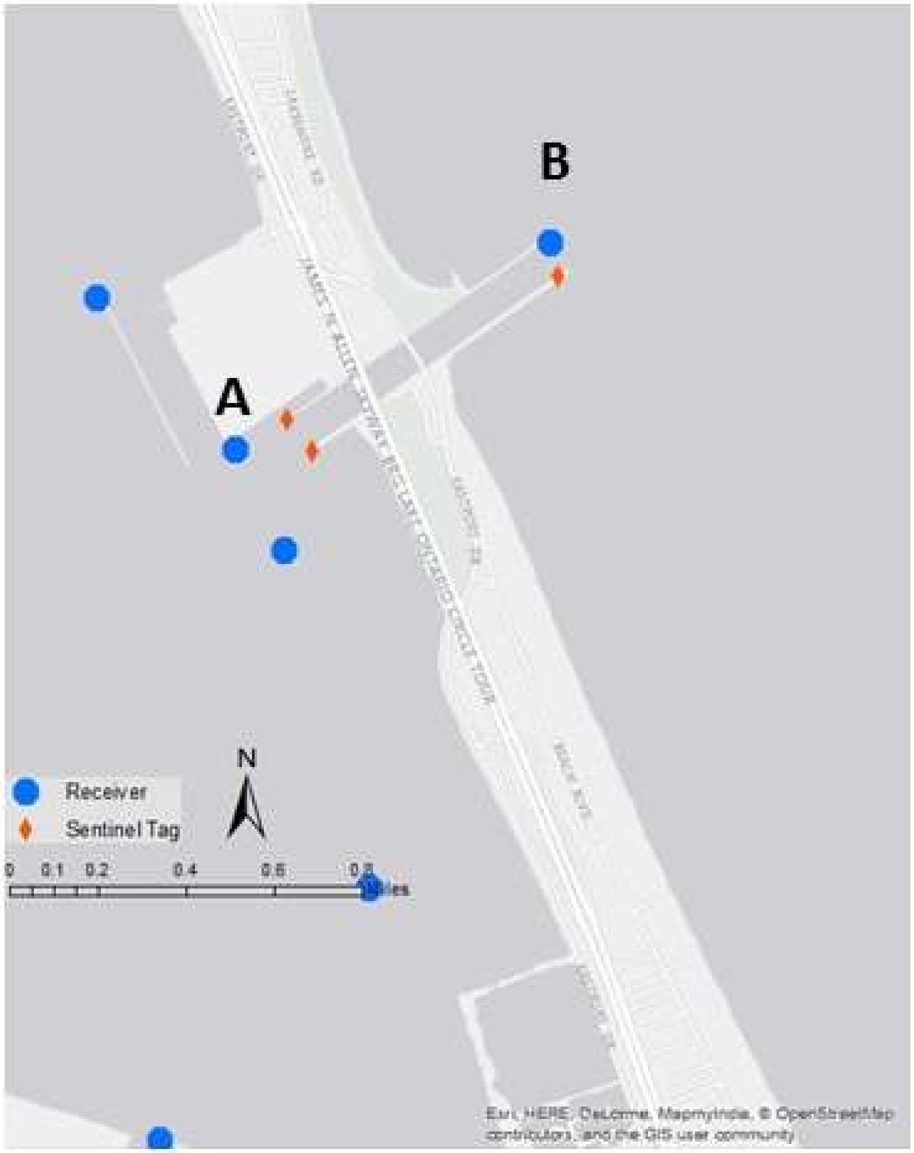

Figure 3.3. Sentinel transmitter and acoustic receiver placement at each side of the canal to Lake Ontario. No detection overlap between receiver A and B.

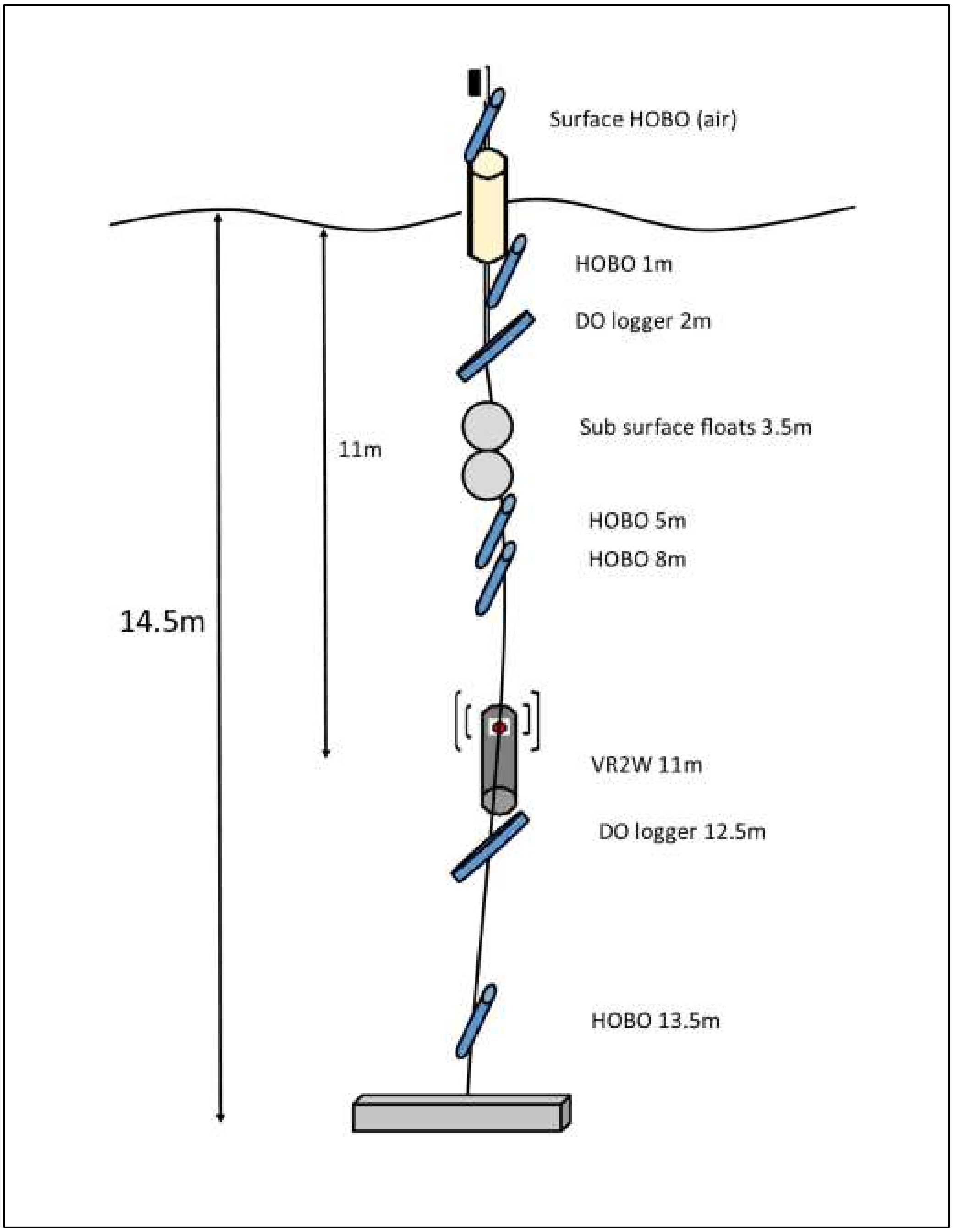

Figure 3.4.A. Summer season Fisheries and Oceans Canada and Environment and Climate Change Canada mooring line including VR2W acoustic receiver, temperature (HOBO) and dissolved oxygen (DO) loggers. Surface buoys detached and second mooring lines attached prior to winter.

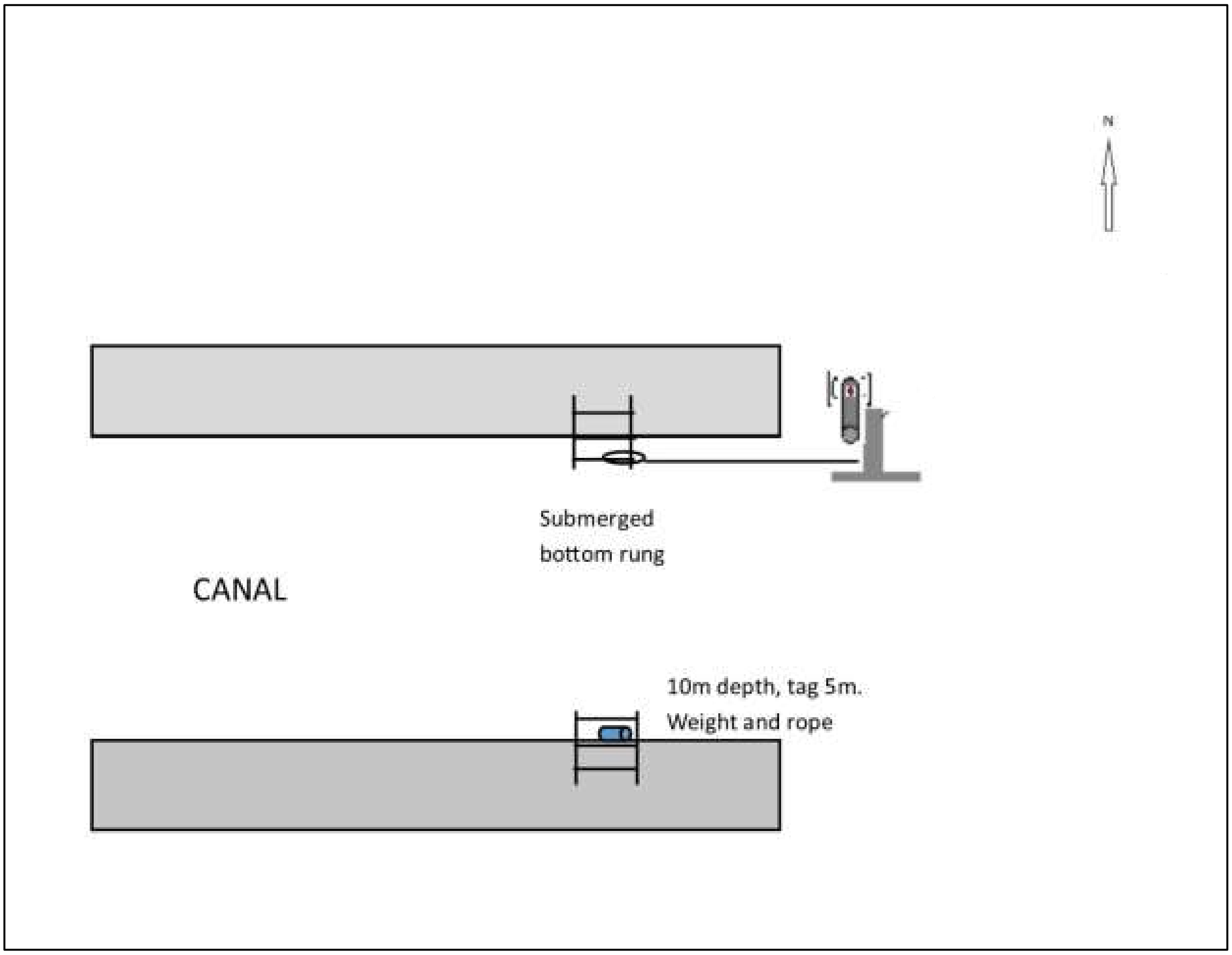

Figure 3.4.B. Aerial view of east of the canal exit into Lake Ontario. Receivers are secured to a weighted anchor base and cabled to the concrete canal wall (positioned upright on the lake bed outside of the harbour wall). Sentinel transmitter is secured to the opposite wall.

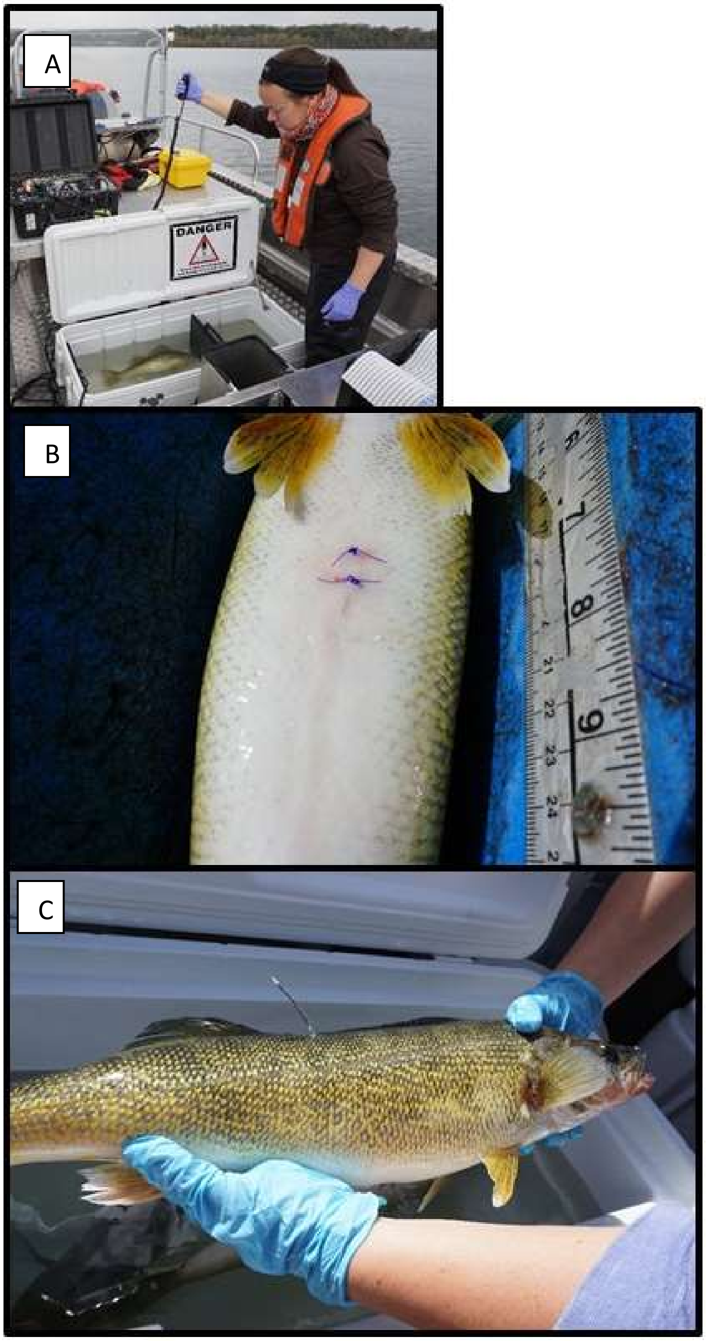

Figure 3.5. A. Fish anesthesia prior to surgery using Portable Electro-anesthesia System; B. Ventral abdominal surgical implantation of transmitters; C. Dorsal external identifying dart tag on a tagged walleye (*S. vitreus*).

Figure 3.6. Royal Botanical Garden’s two-way fishway preventing invasive species entering Cootes Paradise marsh area. Fish trap baskets are raised and sorted twice per day.

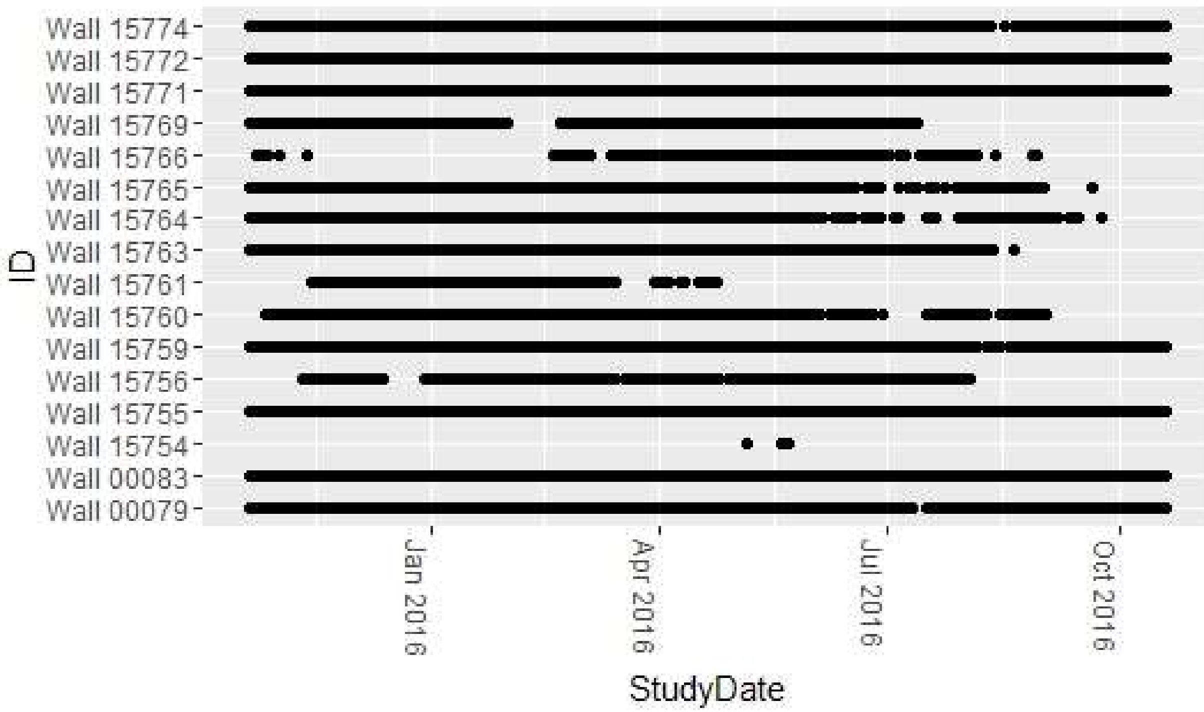

Figure 3.7. All array detections of walleye across the study period (including within harbour and the canal).

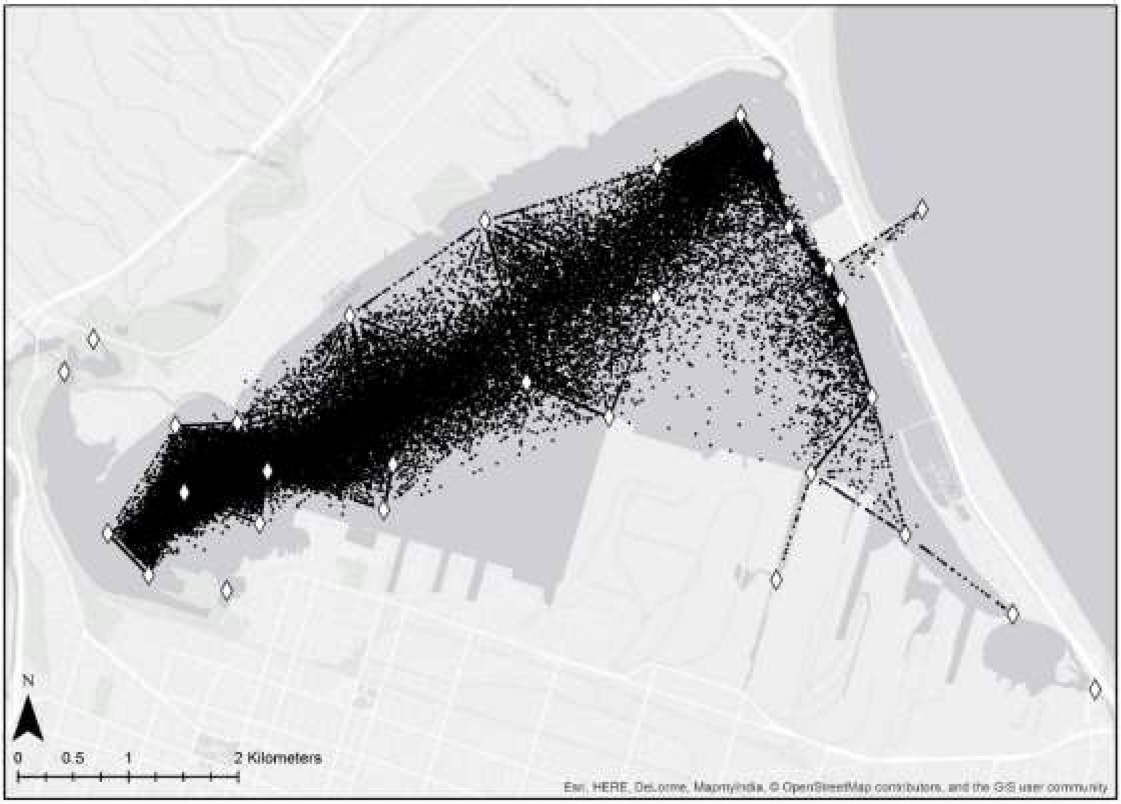

Figure 3.8. Hourly Center of Activity (Simpfendorfer, 2002) positions of walleye (*S. vitreus*) for the study period 21st, October 2015 to 20th, October 2016 within Hamilton Harbour. White diamonds indicate receiver positions.

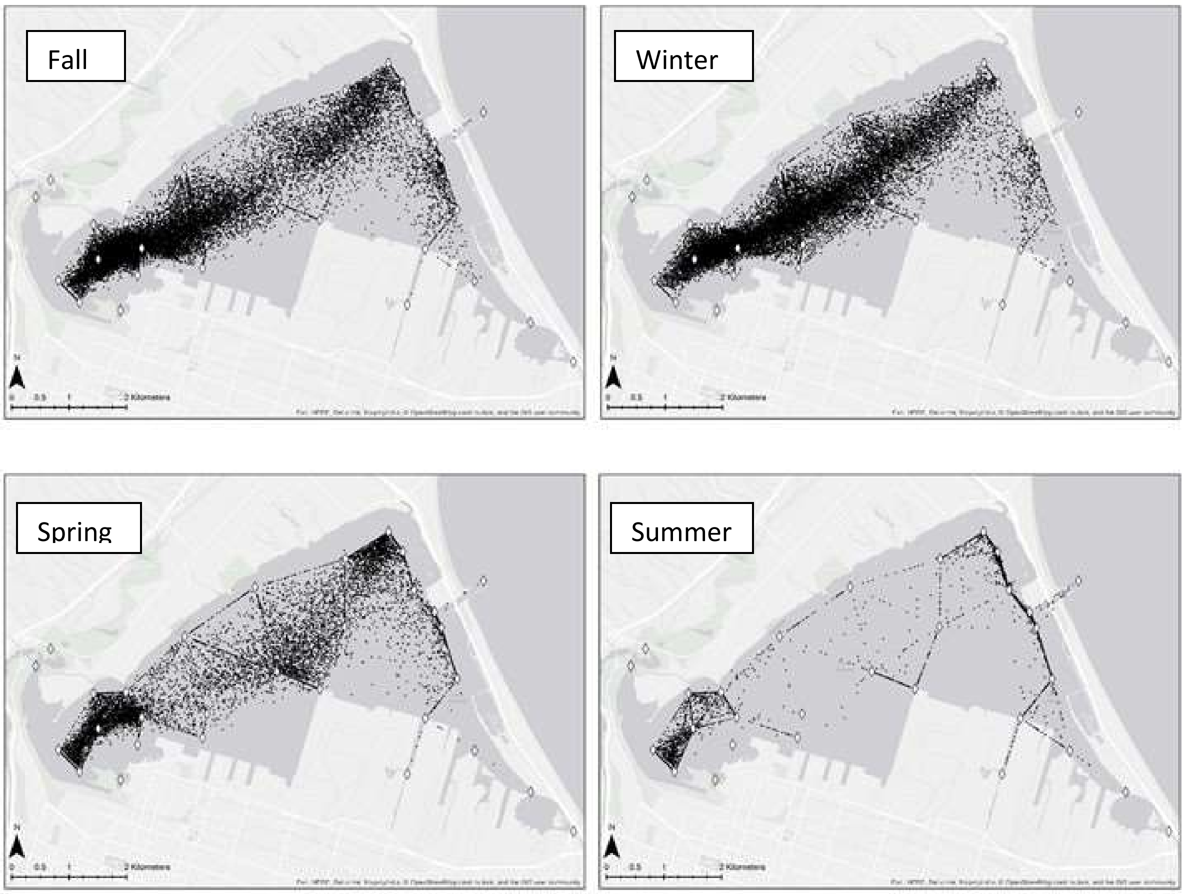

Figure 3.9. Hourly Center of Activity (Simpfendorfer, 2002) locations per season for tagged walleye (*S. vitreus*) in Hamilton Harbour. White diamonds indicate receiver positions.

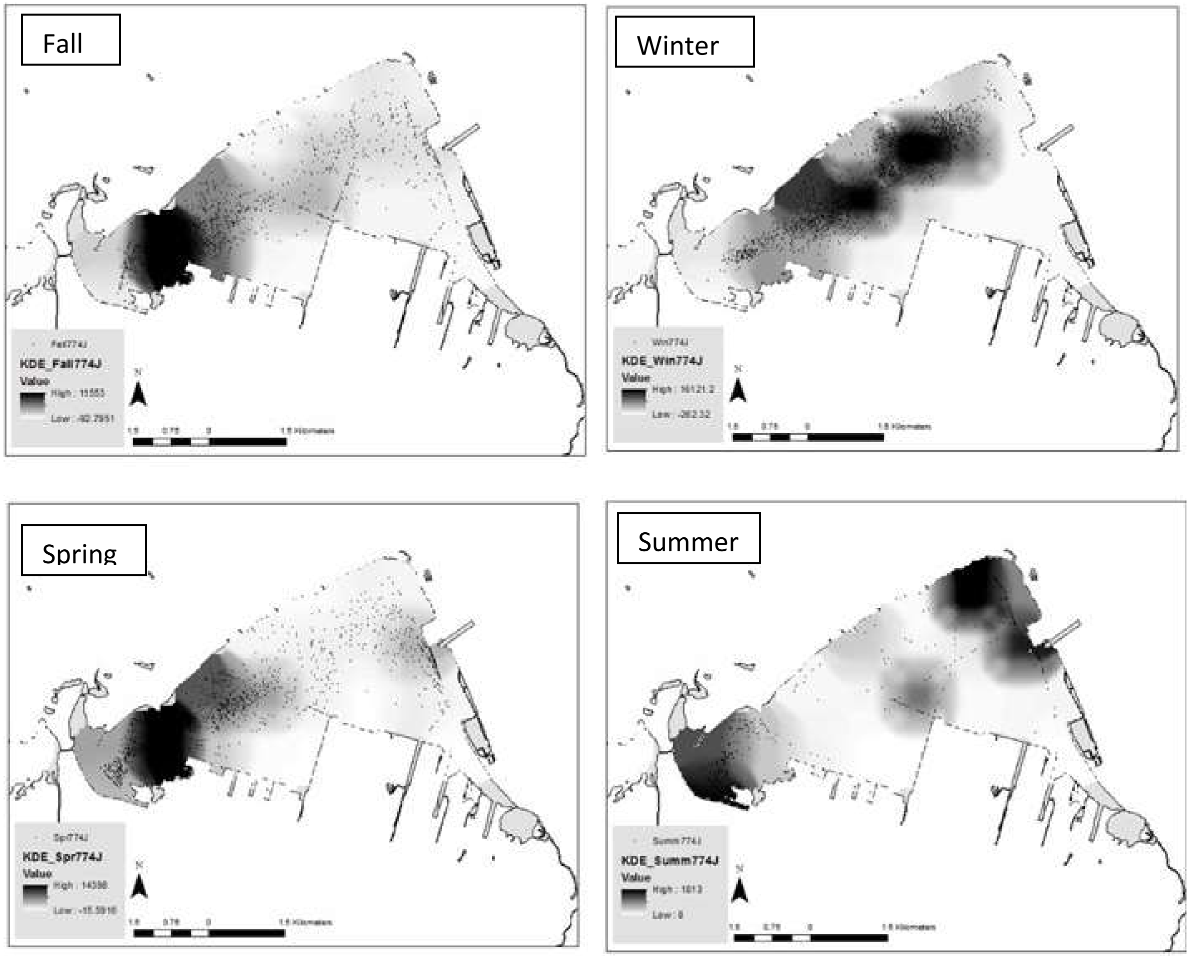

Figure 3.10. An example of seasonal Kernel Utilization Density for walleye ID774 in Hamilton Harbour, produced in ArcGIS (ESRI, 2017).

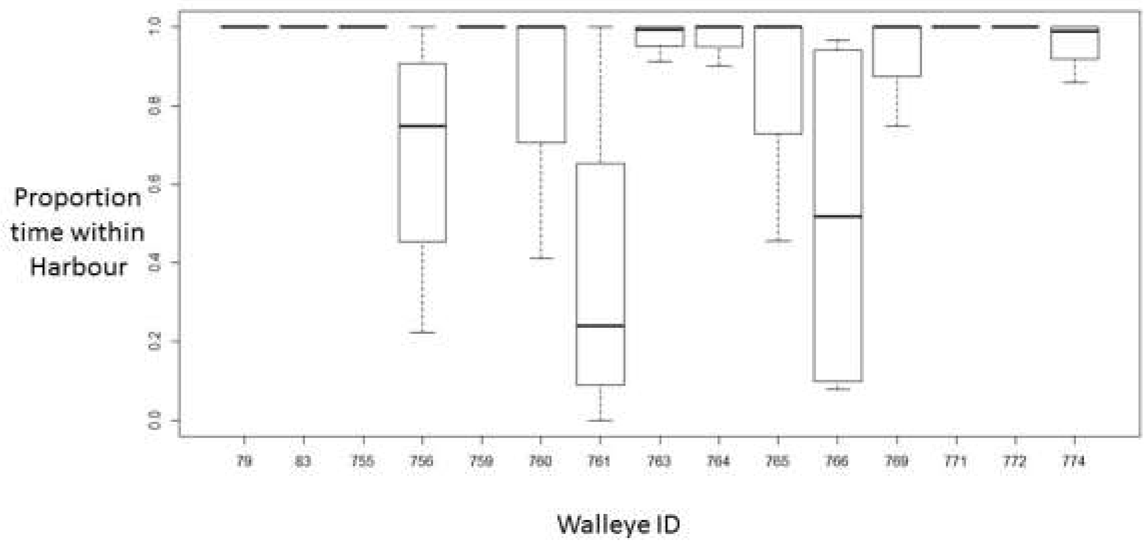

Figure 3.11. Proportion of residency boxplot for each individual walleye. A residency value of 1 indicates 100% residency within Hamilton Harbour. Six individuals did not leave the harbour.

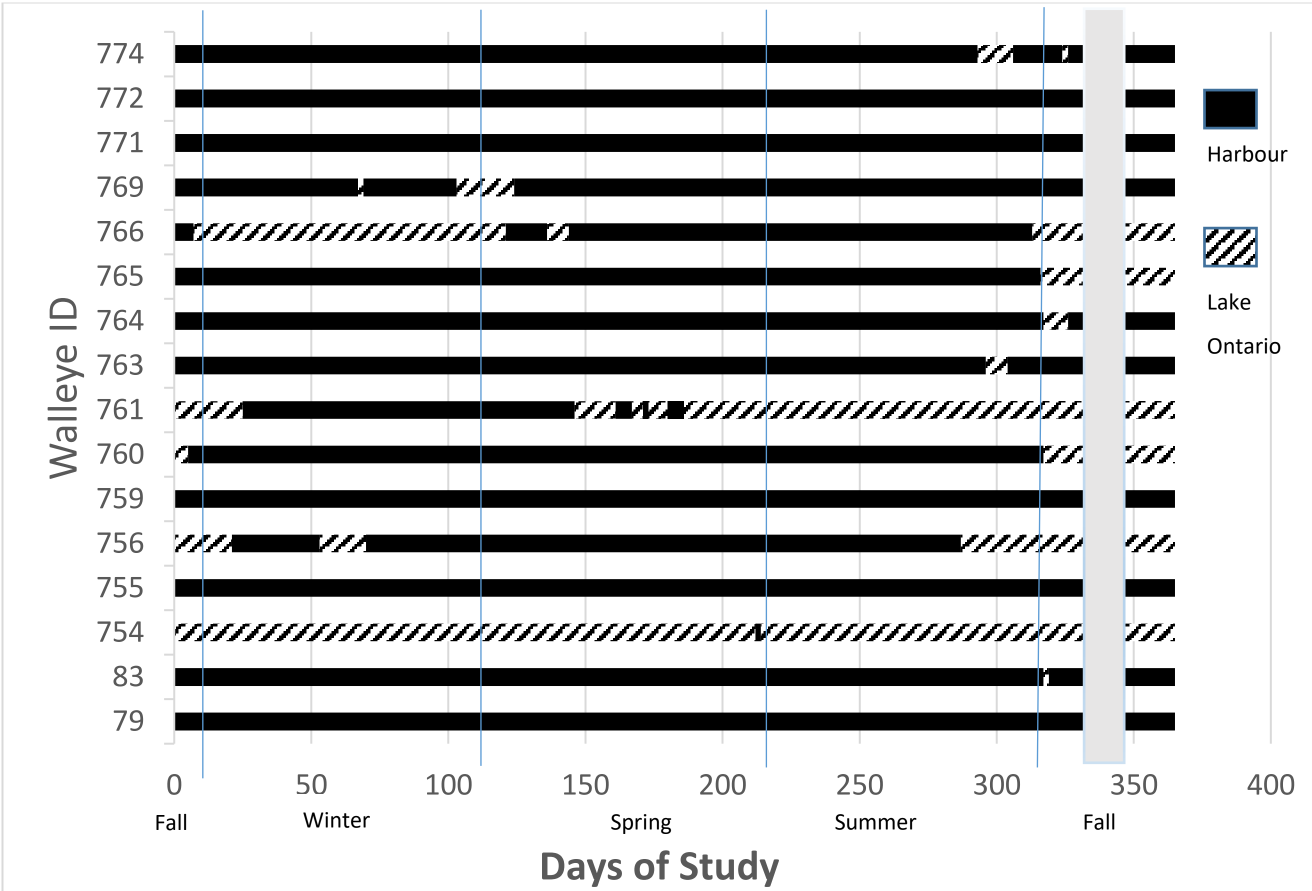

Figure 3.12. Walleye (*S. vitreus*) residency within Hamilton Harbour (solid bars) and Lake Ontario (hashed bars). The light grey rectangle depicts the days of the year that the harbour thermocline turned over, i.e. surface and bottom temperatures were mixed and no longer stratified.

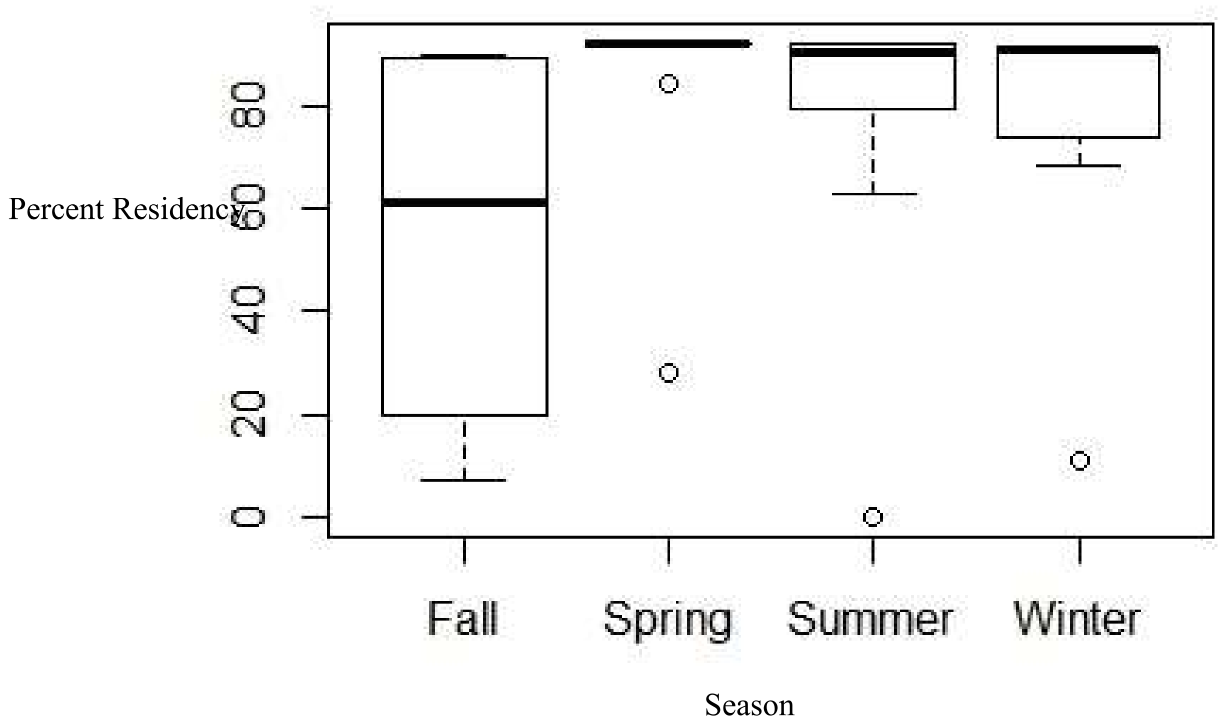

Figure 3.13. Residency proportions of all individuals by season of walleye (*S. vitreus*) in Hamilton Harbour.

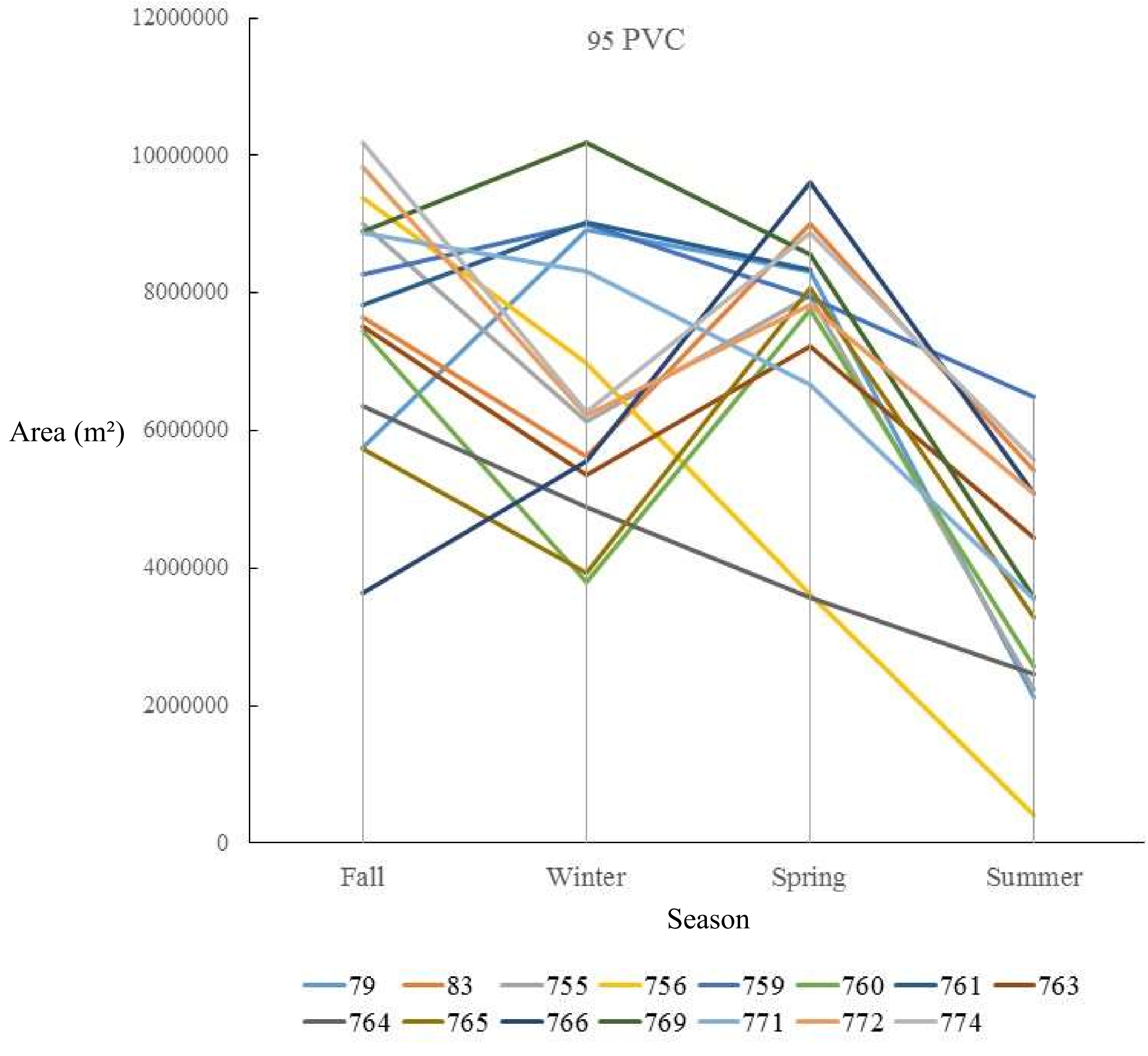

Figure 3.14. Home range size (95PVC) of individual walleye (*S. vitreus*) across four seasons in Hamilton Harbour.

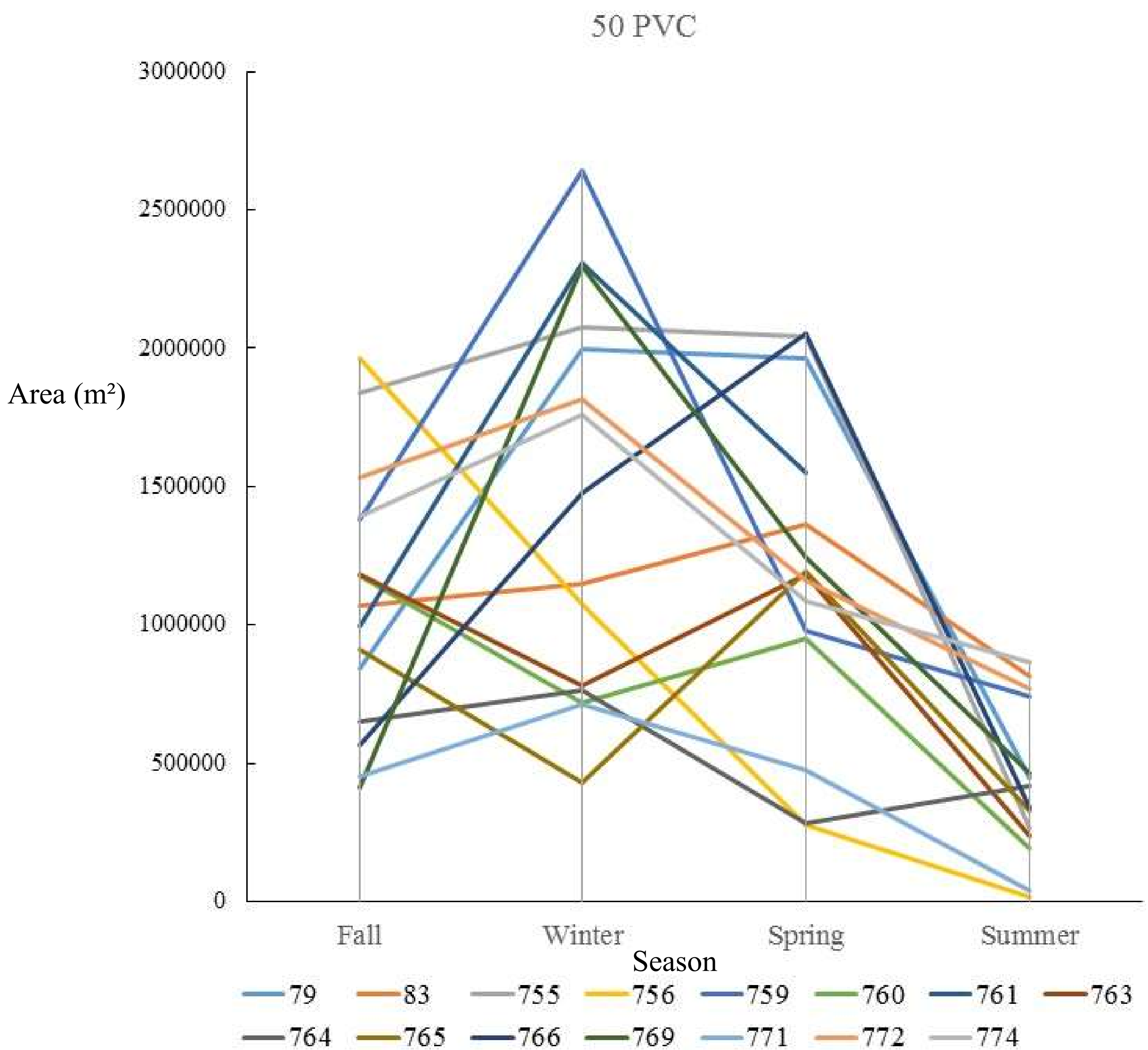

Figure 3.15. Core range size (50PVC) of individual walleye (*S. vitreus*) across four seasons in Hamilton Harbour.

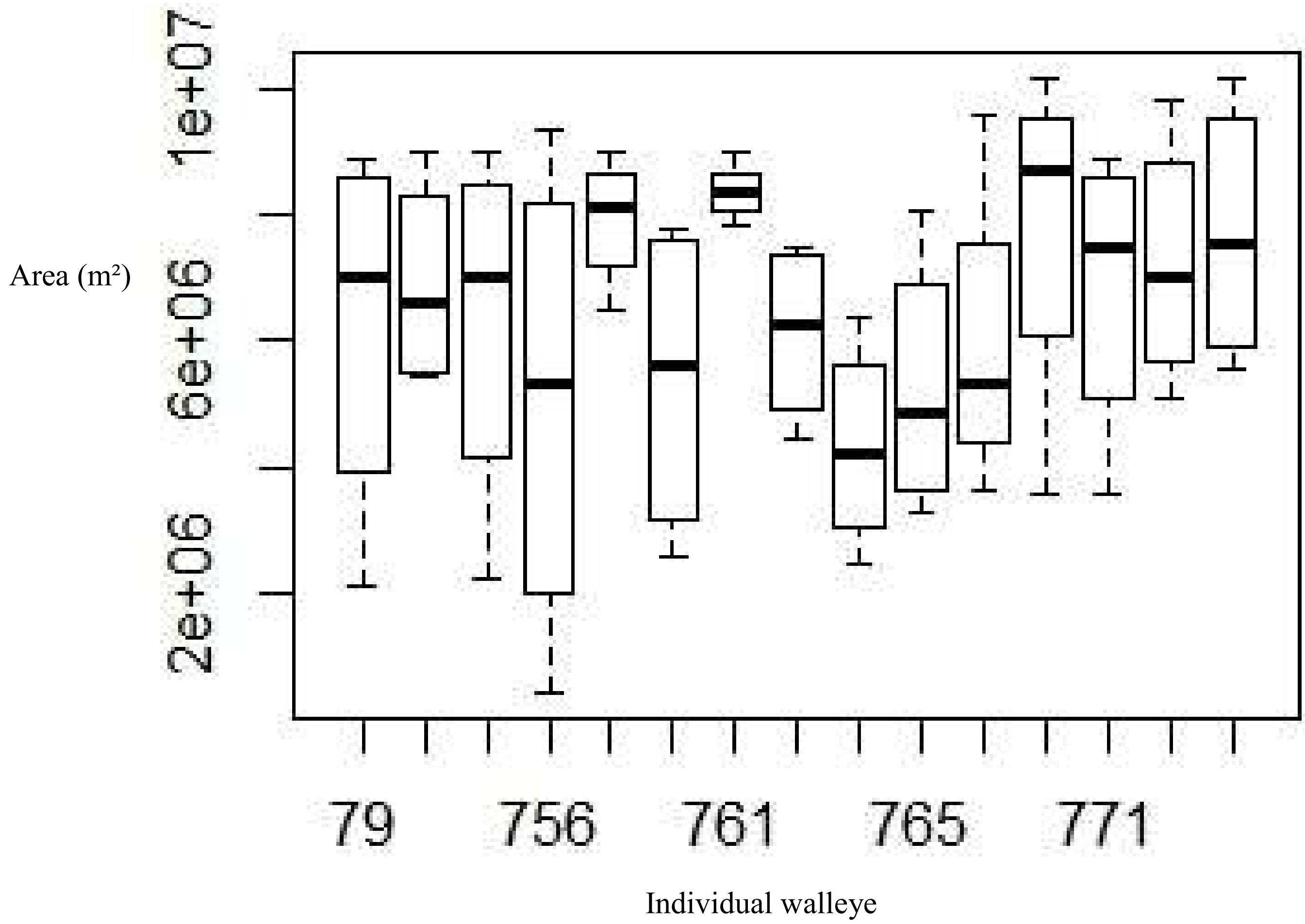

Figure 3.16. Individual walleye (*S. vitreus*) home range size (95PVC) for all seasons.

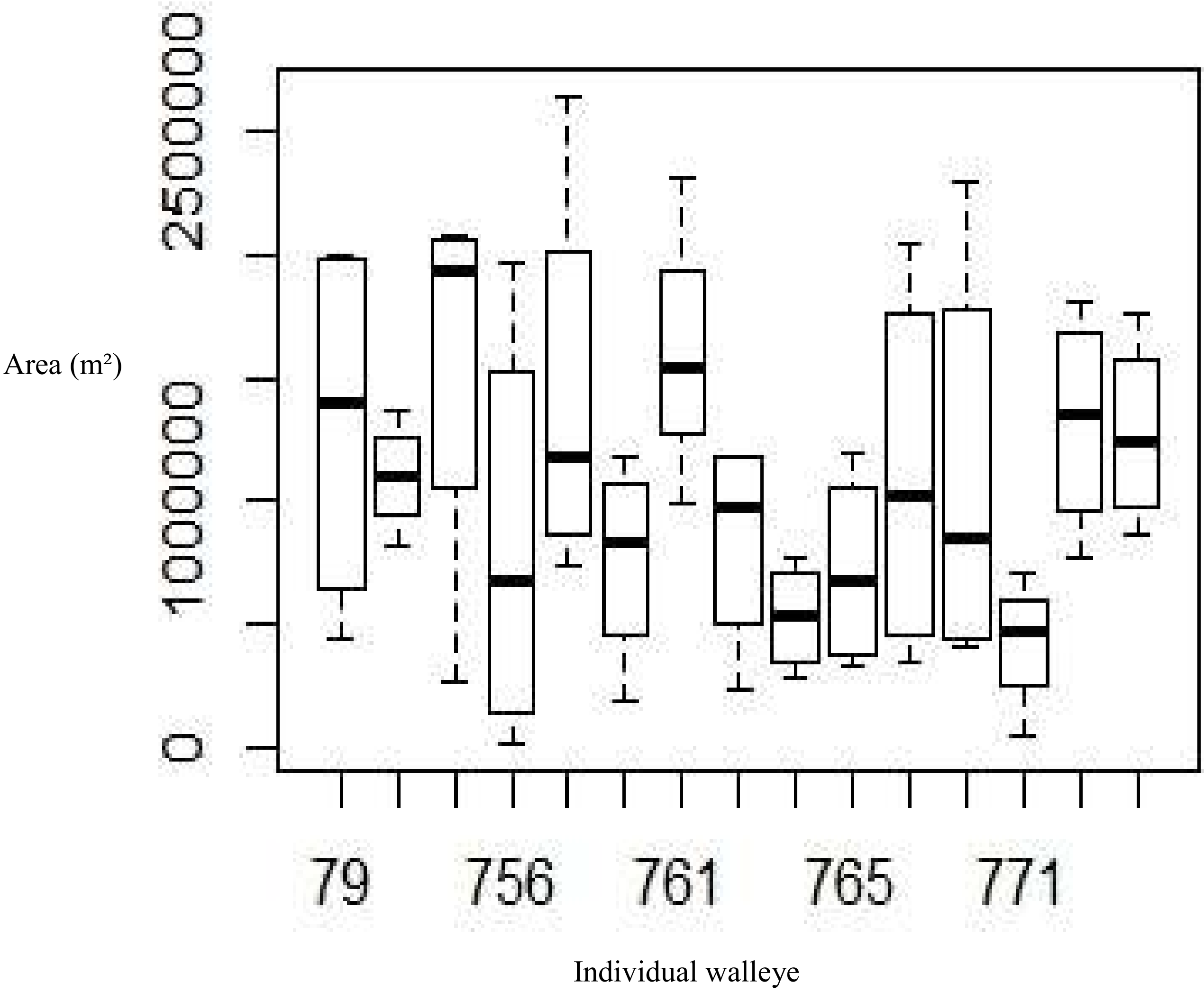

Figure 3.17. Individual walleye (*S. vitreus*) core range size (50PVC) for all seasons.

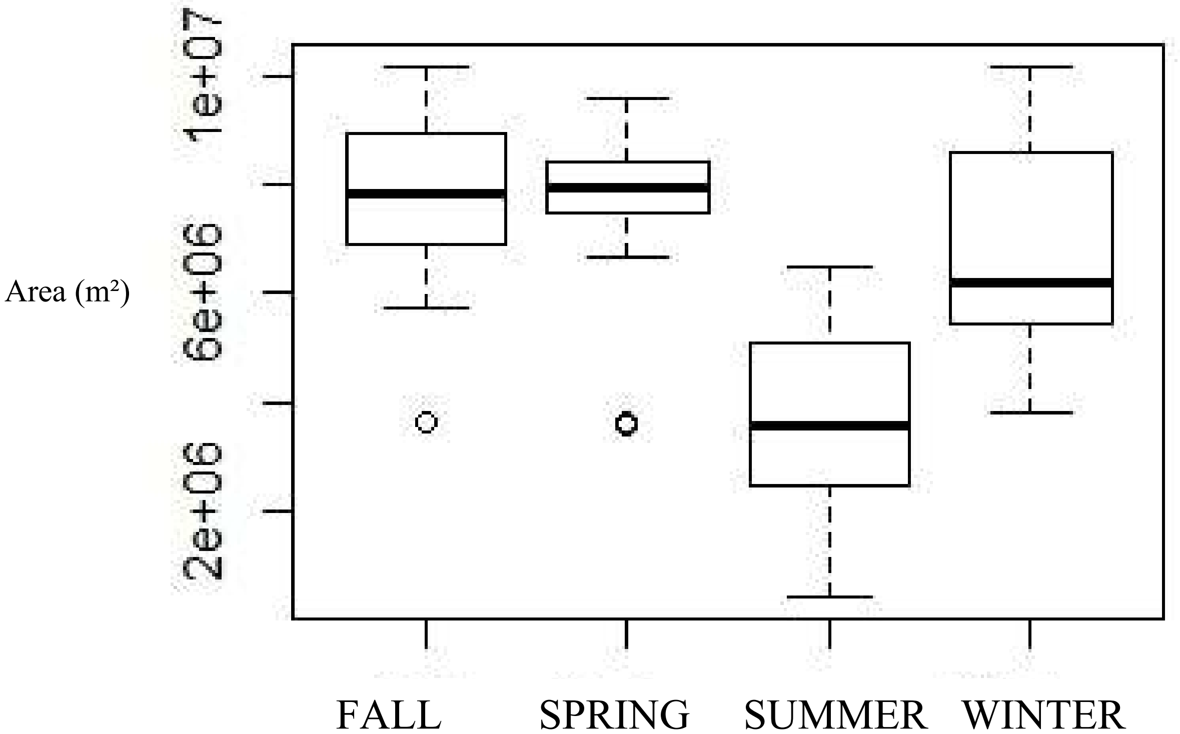

Figure 3.18. Walleye (*S. vitreus*) home range (95PVC) size per season.

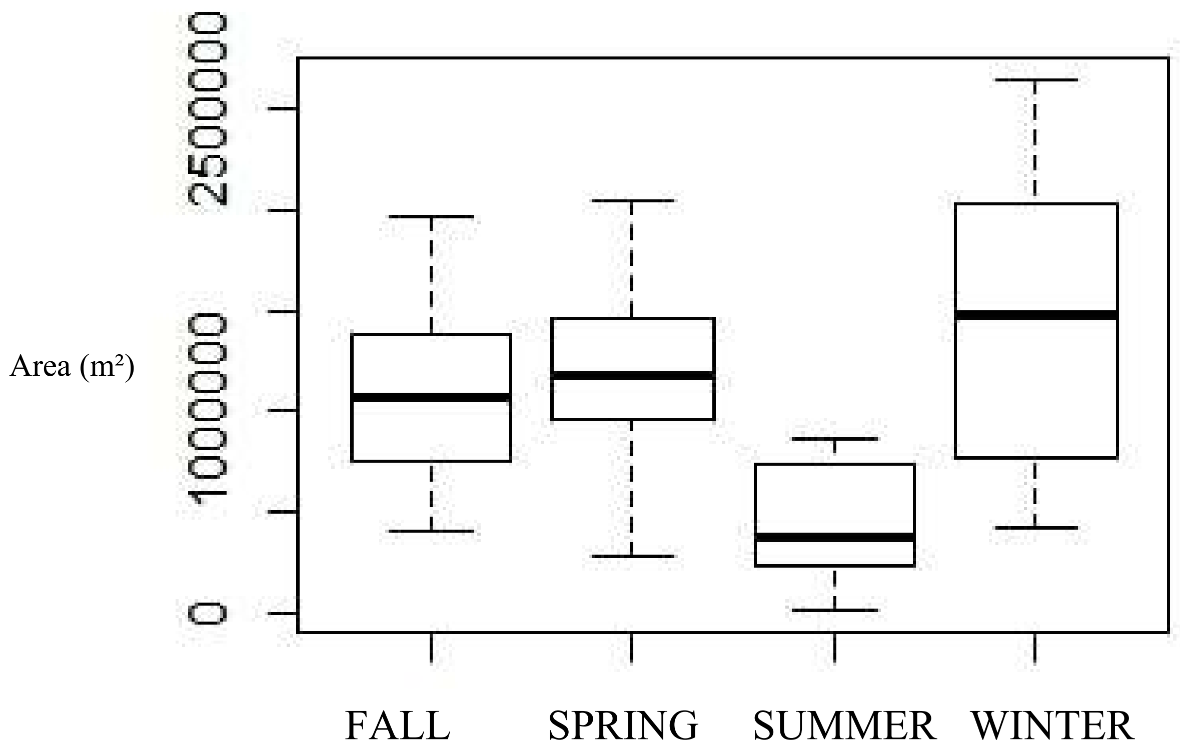

Figure 3.19. Walleye (*S. vitreus*) core range (50PVC) size per season.

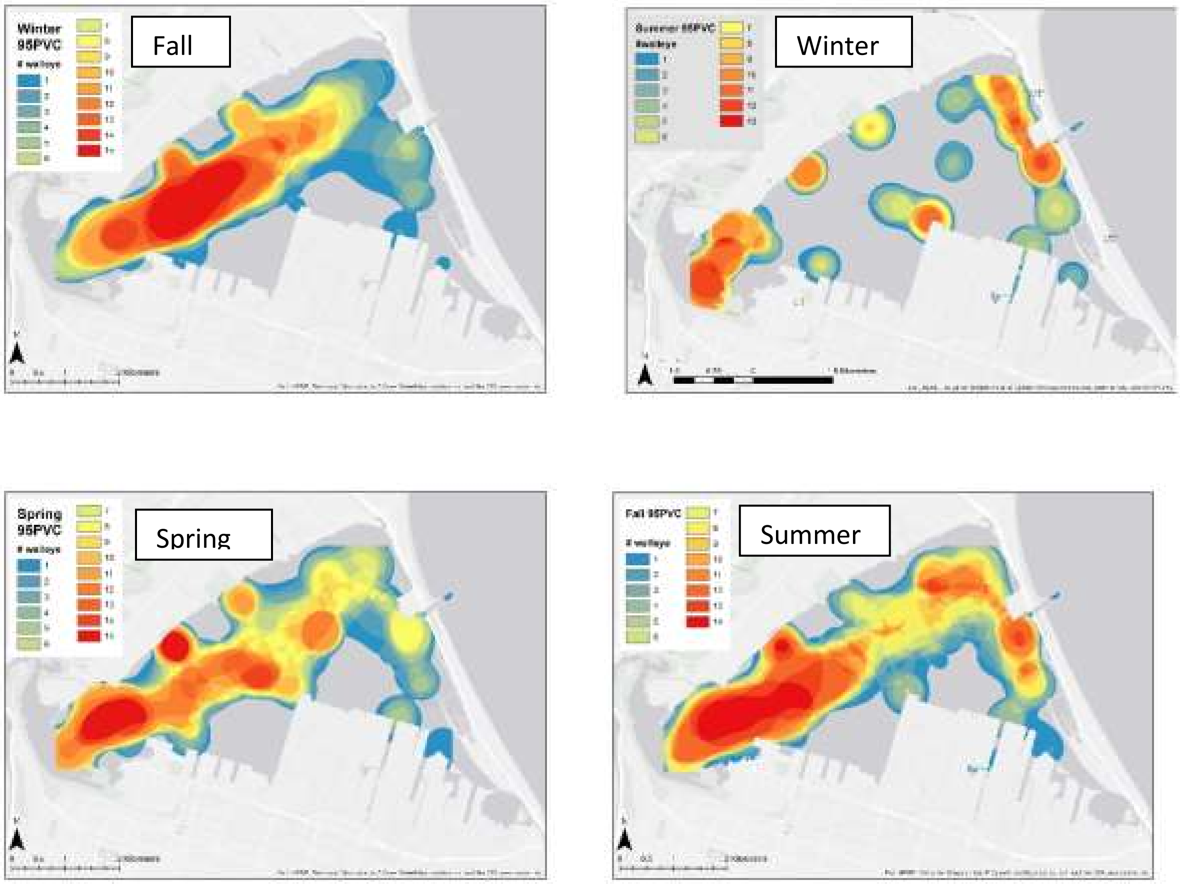

Figure 3.20. Estimated seasonal home range (95PVC) plots. Red shades indicate areas of high use of individuals.

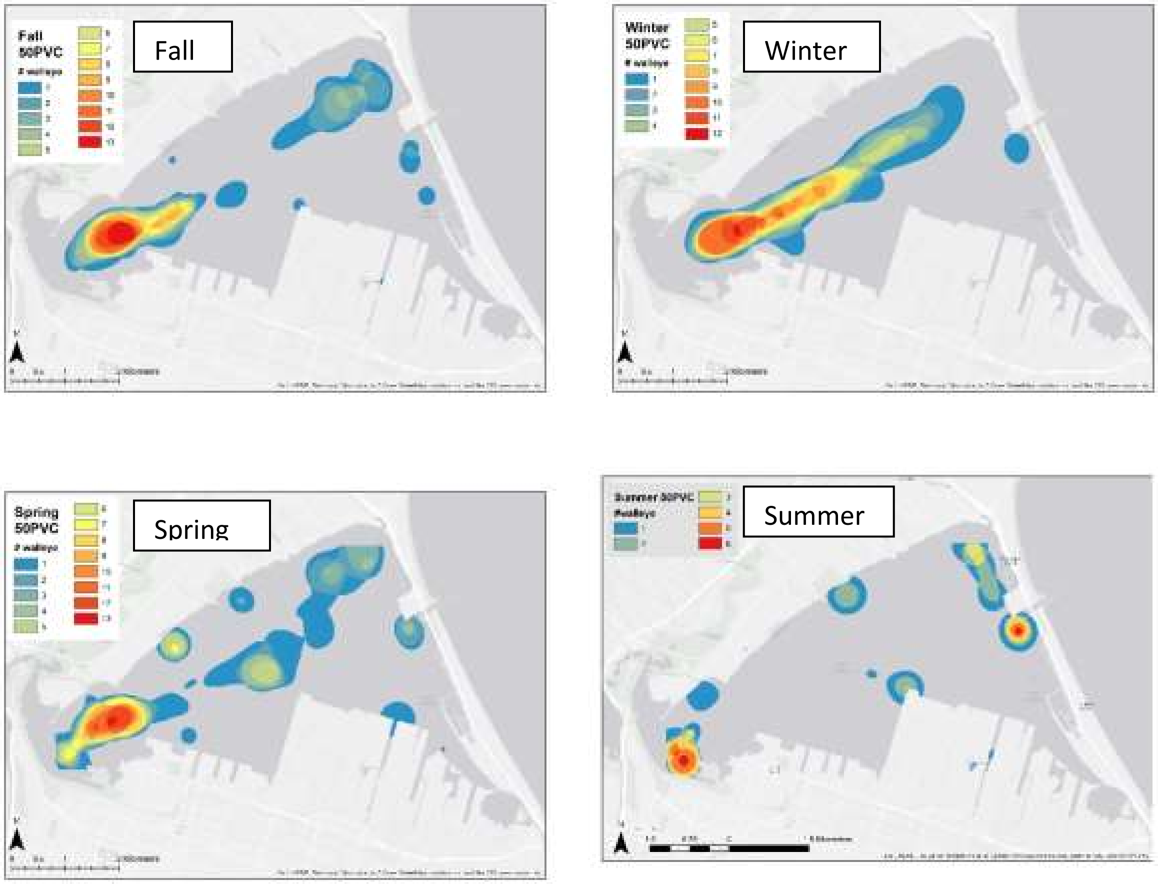

Figure 3.21. Estimated seasonal core range (50PVC) plots. Red shades indicate areas of high use of individuals.

Chapter 4: General Discussion

The Canadian and US governments have long had an understanding of the value of their shared freshwater resources, the Laurentian Great Lakes, and have been attempting to rehabilitate these ecosystems through their Area of Concern (AOC) program (IJC, 2012). Fish are important to enhancing the biodiversity and integrity of aquatic ecosystems by providing various ecosystem services, including regulation of food web dynamics, recycling of nutrients, and transportation of energy (Holmlund & Hammer, 1999; Lynch et al., 2016). Overfishing, eutrophication, loss of spawning and nursery habitat, pollution, exotic species, and declines in native fish populations have all had substantial effects on fish populations in the Great Lakes and continued research is required to ensure the long-term sustainability of fisheries (Smith et al., 2015). Effectively managing freshwater fisheries involves an understanding of how fish use their habitat, and their behavioural responses to these environmental and anthropogenic changes.

The purpose of this thesis was to provide insight on how biotelemetry is being used to inform fisheries and habitat rehabilitation in the Great Lakes. Chapter 2 summarized the history of the AOC program and the Beneficial Use Impairments to aquatic ecosystems that are used to classify AOC sites, discussed the rehabilitation processes, including the various planning and monitoring and importance of monitoring rehabilitation projects, and the benefits of spatial ecology knowledge in the planning and monitoring stages of the Remedial Action Plan. I highlighted seven case studies that are currently using radio and acoustic biotelemetry to plan and monitor restoration projects in AOCs. These include restoration of physical fish habitat such as spawning reefs and shoals, fish passageways at fragmented migration corridors, and reintroduction programs. I discussed the benefits and limitations of biotelemetry technology and provided guidelines to AOC managers on how it can complement current fisheries and habitat restoration management. In Chapter 3, I used acoustic biotelemetry to track fifteen individuals from a reintroduced population of walleye (*Sander vitreus*) in an AOC undergoing various forms of rehabilitation to the water quality, physical fish habitat, and fish community. I monitored fish movements between October, 2015 and October, 2016, to determine their residency within the harbour, and their home range extent and locations when within the harbour.

Findings and Implications

Biotelemetry, when combined with conventional research techniques, has been useful in various stages of fisheries and habitat rehabilitation planning and monitoring (Crossin et al., 2017). Specific applications of biotelemetry to fisheries management in the Great Lakes' AOC program include: determining seasonal fish habitat associations to inform habitat restoration design; identifying the distribution and residency within an AOC boundary of a pollutant-indicator species to identify exposure risk to contamination sources; informing the development of fish passage facilities to allow fish to use fragmented upstream habitats; and finally, monitored the use of created fish habitats. As with any technology, there are limitations that are discussed in detail in Chapter 2 and 3, including equipment lifespan, the management of large datasets - requiring advanced database and analytical expertise - and monetary costs (reviewed in Cooke et al., 2013). However, technological capabilities are advancing; batteries and transmitters are getting smaller, analytical and statistical tools are being developed for handling and using such large, complex datasets, and finally, collaboration networks are becoming more established to allow researchers to ask smaller scale, shorter term research questions without the significant costs of infrastructure (Crossin et al., 2017; GLATOS). Maintaining stakeholder momentum in these long-term restoration processes is also important, therefore monitoring successes and communicating these results is also beneficial (Hall, 2006). Biotelemetry allows almost 'real time' tracking of fish in these imperiled ecosystems and provides opportunities for outreach and stakeholder involvement, which other telemetry users have found beneficial (Nguyen et al., 2017).

In Chapter 3, I assessed the residency and space use of individuals from a reintroduced population of walleye that were approaching their first year of sexual maturity. I was able to demonstrate that individuals spent the majority of the year within the harbour, including the spring spawning season, and that their space use varied on a seasonal basis. I determined that the majority of departures from the harbour occurred late in the summer and early fall. This timing coincided with the turnover of the harbour and the breakdown of the stratification. As the summer progresses, dissolved oxygen beneath the thermocline is depleted and conditions are increasingly unsuitable for walleye optimal dissolved oxygen consumption (Brandt at al., 2009).

I speculate that walleye are leaving the harbour during the late summer period during periods of low DO and returning after the harbour has mixed and DO returns to more optimal levels. I was also able to demonstrate that summer home ranges were smaller, coastal, and more isolated when compared to the rest of the year. Preliminary graphing of the depth movements compared to modelled thermal and DO characteristics of the harbour have shown that fish alter their position in the water column in response to the cyclic upwelling events. It is unclear if these small, patchy home ranges used by walleye are a result of the unsuitable water quality conditions, prey re-distribution into smaller areas compared to other seasons, or general activity reduction during warmer conditions.

Collectively, this thesis revealed the numerous ways that biotelemetry, when combined with traditional fisheries and habitat monitoring techniques, is a valuable tool to the Great Lakes AOC rehabilitation program. More broadly, the technology and findings from these projects can assist with the planning and monitoring of other aquatic ecosystem restoration. This work demonstrated that the reintroduced walleye population are using Hamilton Harbour throughout the year and are not migrating out of the canal into Lake Ontario for spawning purposes, providing a better understanding of how a reintroduced population of fish use a novel system. Residency within the harbour during spawning season is a promising first sign that natural recruitment may occur within Hamilton Harbour and provides fisheries managers with locations for the next step in their egg and fry success surveys.

Future research

I have determined that walleye home ranges and activity in the summer appear to be smaller and patchier than during other seasons. However, through this research I was not able to determine the drivers behind this behaviour. Further tracking of these individuals and other species of fish within the harbour will facilitate further characterization of the environmental and/or ecological drivers. Increasing receiver coverage, both inside the harbour and in Lake Ontario, will define larger movement patterns of Hamilton-tagged fish species, and therefore broader, lake-wide impacts of restoration efforts within the Harbour. In addition to more receiver coverage, more range testing would help determine seasonal effects on the performance of acoustic telemetry equipment.

Low levels of DO are prevalent in aquatic ecosystems throughout the world, and while observed levels may not reach lethal limits, it is important to understand the sublethal effects of this stressor and the impacts on the physiology and behaviour of fishes, which in turn can greatly impact community ecology (Pollock et al., 2007). The adverse effects of hypoxia on aquatic life have been well studied in controlled lab settings (Kramer 1987; Pollock et al, 2007); however, the responses of organisms to hypoxia and combined sewer outflows in field situations are lacking due to the complex physical and chemical interactions and site-specific conditions (Gaulke et al., 2015). Further biotelemetry research of fish in Hamilton Harbour will increase our understanding of the types of habitats that wild fish (native and reintroduced) use during varying environmental conditions (including any restored physical habitat), their behaviours within these habitats, and how they are responding to the dynamic hypoxic, and sometimes anoxic, environments.

Fine scale behaviour and network analyses of these tagged fish will also provide a better understanding of chemical and physical habitat preference. There appears to be a trade-off between suitable oxygen, thermal, and optical level habitats for walleye (Brandt et al., 2009). Modelling fish positioning and depth in the water column with thermal and DO parameters will provide a holistic understanding of how walleye use this fluctuating habitat. Habitat suitability models, often used by fisheries managers, require data of the abovementioned habitat preferences. For example, in Lake Erie, the annual walleye harvesting quotas are allocated across three US State and Canadian Provinces according to their proportions of areas deemed as suitable walleye habitat (areas <13m deep; STC, 2007). Effective management of these quotas and availability of predicted suitable habitats are contingent on accurate preferences of the fish that inhabit them.

On a broader scale, there are uncertainties in the literature on how a warming climate may affect cool water species such as walleye (Plumb & Blanchfield, 2009). Warming waters often lead to an increased frequency and intensity of hypoxia events. Further research into how walleye, and other local fish species, respond to hypoxia, will provide a better understanding of the effects of warming water temperatures on suitable habitat availability.

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Appendices

Table A.1. Walleye stocked into Hamilton Harbour, 1993-2015 and target for 2016. (Obtained from Hoyle et al., 2015)

Year	Month	Life-Stage	Mean weight (g)	Number of fish	Source
1993	October	adult	600	185	transferred from Bay of Quinte
1994	October	adult	1,500	129	transferred from Bay of Quinte
1997	October	adult	900	130	transferred from Bay of Quinte
1998	September	adult	1,364	120	transferred from Bay of Quinte
1999	July	3-months	0.5	6,000	White Lake FCS (Bay of Quinte strain)
2012	July	3-months	1.0	100,000	White Lake FCS (Bay of Quinte strain)
2012	November	adult	1,500	74	White Lake FCS (Bay of Quinte strain)
2013	July	3-months	0.5	10,000	White Lake FCS (Bay of Quinte strain)
2014	June	Swim-up fry	n/a	950,000	White Lake FCS (Bay of Quinte strain)
2015	May	Swim-up fry	n/a	1,017,625	White Lake FCS (Bay of Quinte strain)
2015	July	3-months	0.3	52,963	White Lake FCS (Bay of Quinte strain)
2016	May	Swim-up fry	n/a	168,000	White Lake FCS (Bay of Quinte strain)
2016	June	3-months	0.45	115,722	White Lake FCS (Bay of Quinte strain)

Table A.2. Electrofishing sampling summary for April 2016 walleye spawning assessment in Hamilton Harbour (Obtained from Hoyle et al., 2015).

TABLE 8.7.2. Electrofishing sampling summary for the April 2016 Walleye spawning assessment in Hamilton Harbour.

Location	Sampling period	Fish observed	Fish captured	Total sampling time
Eastern shore	Night 1	11	9	4027 seconds
	Night 2	26	23	4129 seconds
Western shore	Night 1	Not Sampled	Not Sampled	Not Sampled
	Night 2	9	7	3018 seconds
Southern shore	Night 1	1	1	1963 seconds
	Night 2	9	9	2034 seconds
Total	All Nights	56	49	15171

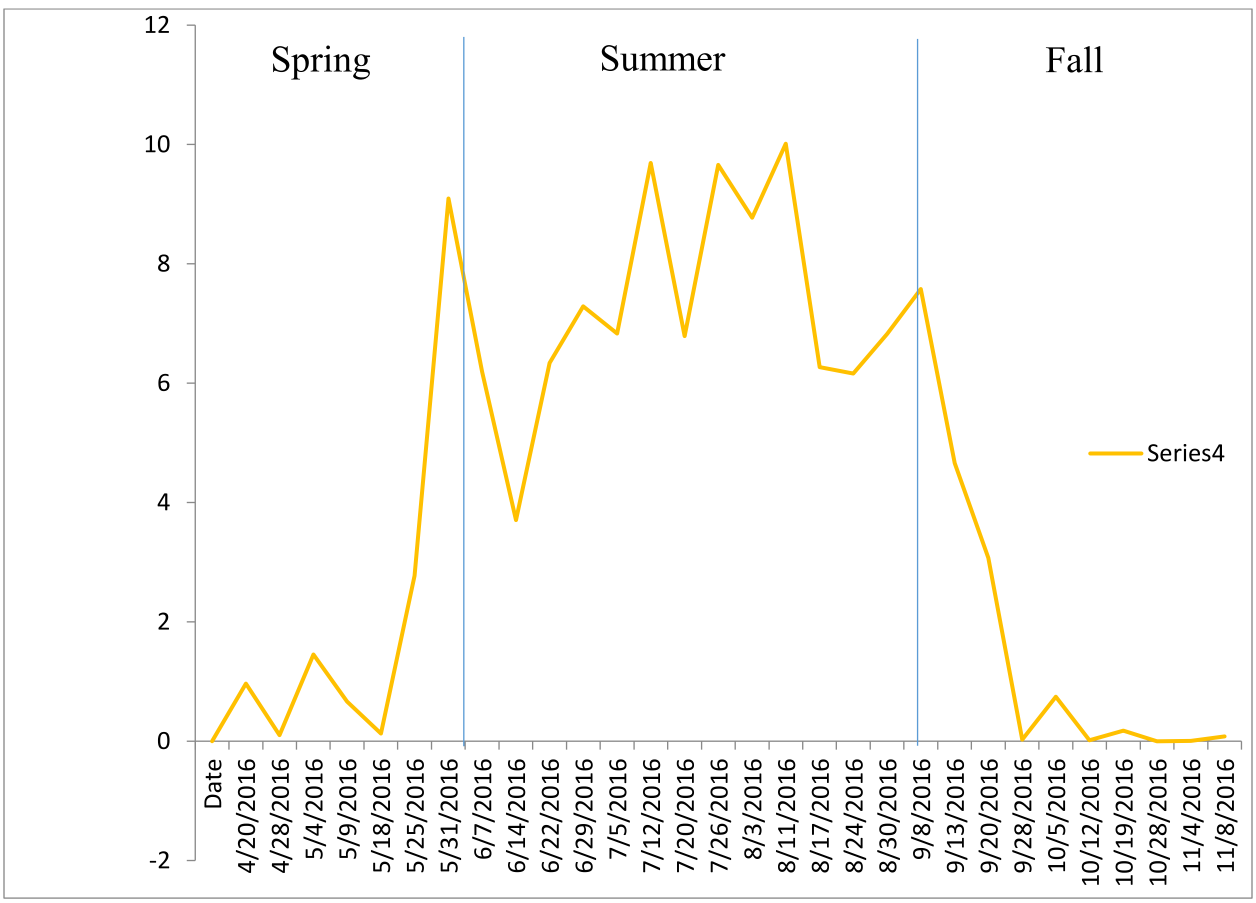

Figure A.1. Difference in surface and lake bottom temperature values for Hamilton Harbour between April and November, 2016. Vertical lines indicate the summer months within the stratification period.

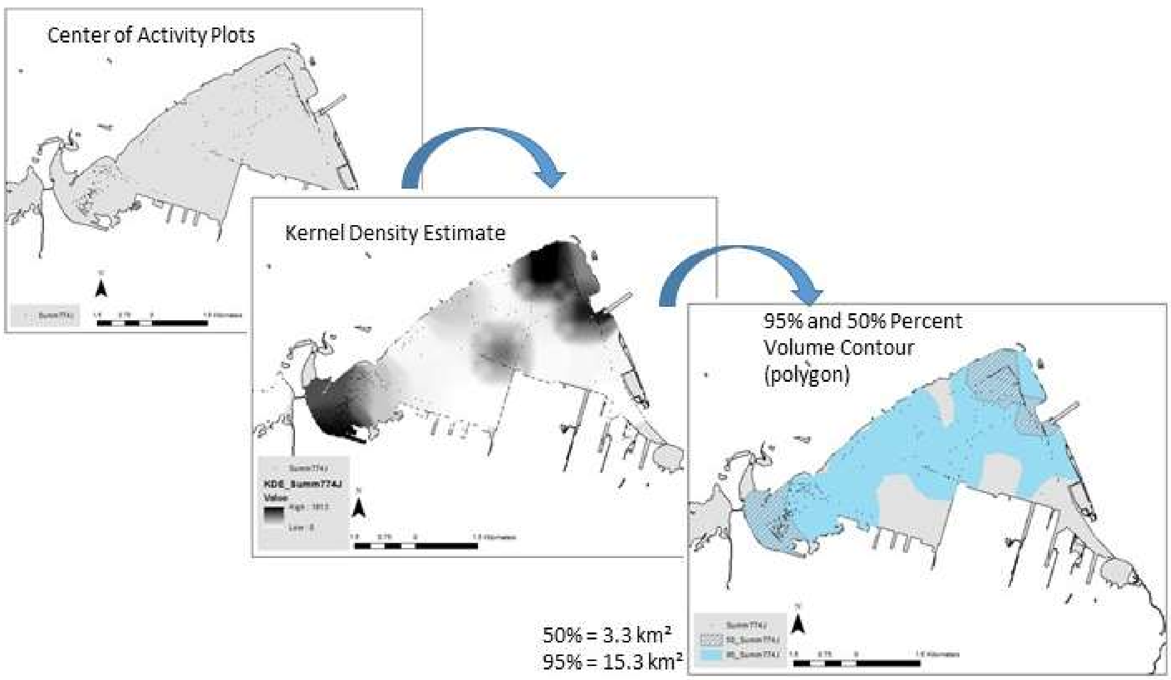

Figure A.2. Three step process to obtain the home and core use ranges, from Center of Activity locations, the Kernel Density Estimate tool in ArcMap (Esri, 2017), and 95 and 50 Percent Volume Contour polygons.

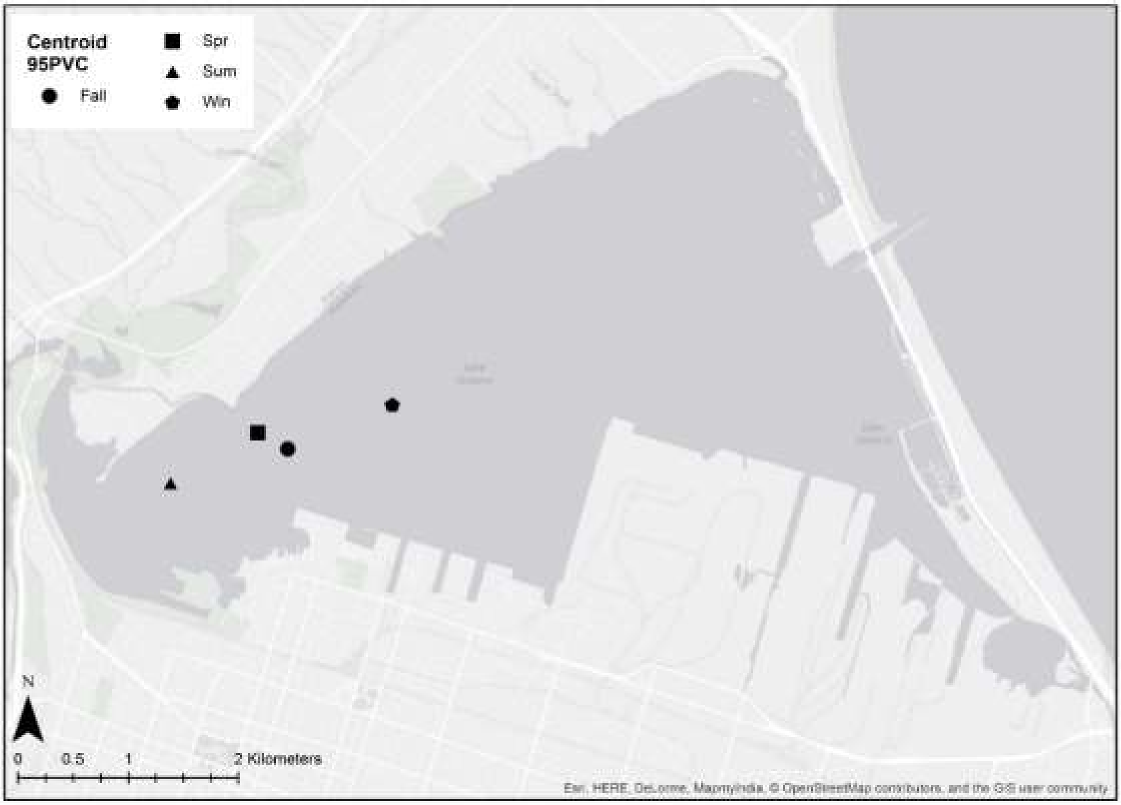

Figure A.3. Centroid positions obtained from the overlaid individual 95 Percent Volume Contour polygons of the (refer to Figure 3.21).

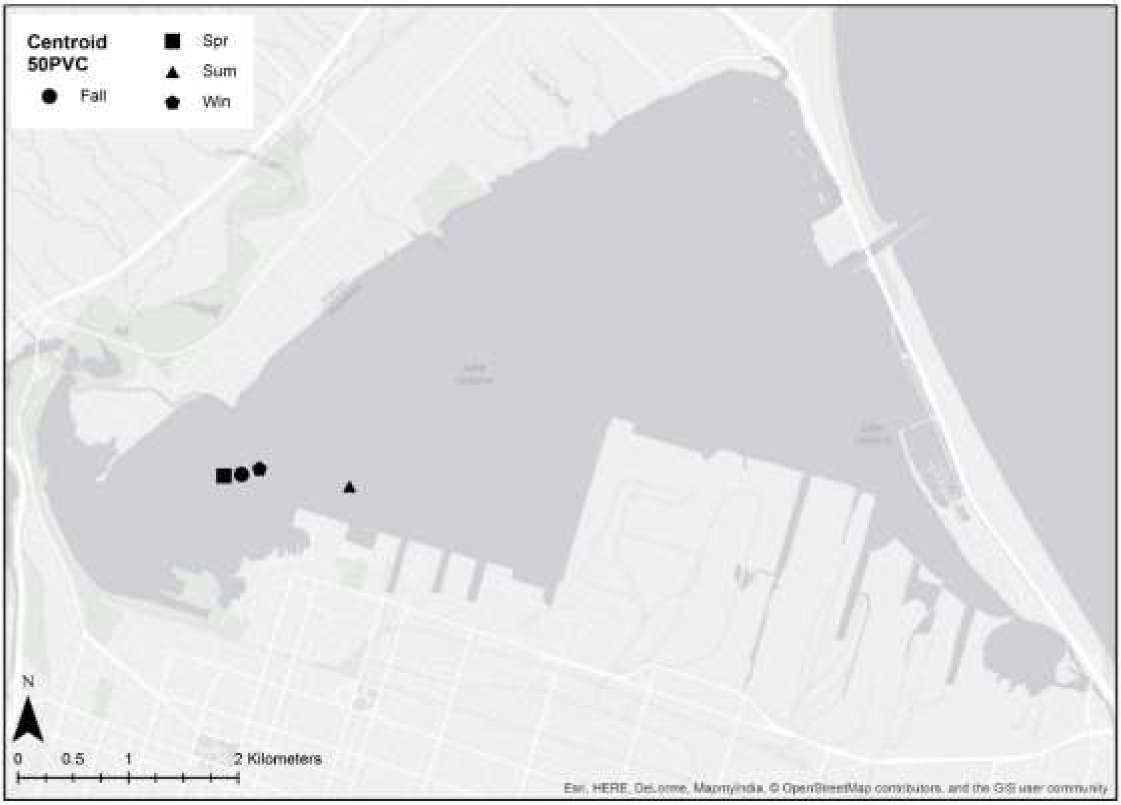

Figure A.4. Centroid positions obtained from the overlaid individual 50 Percent Volume Contour polygons of the (refer to Figure 3.21).

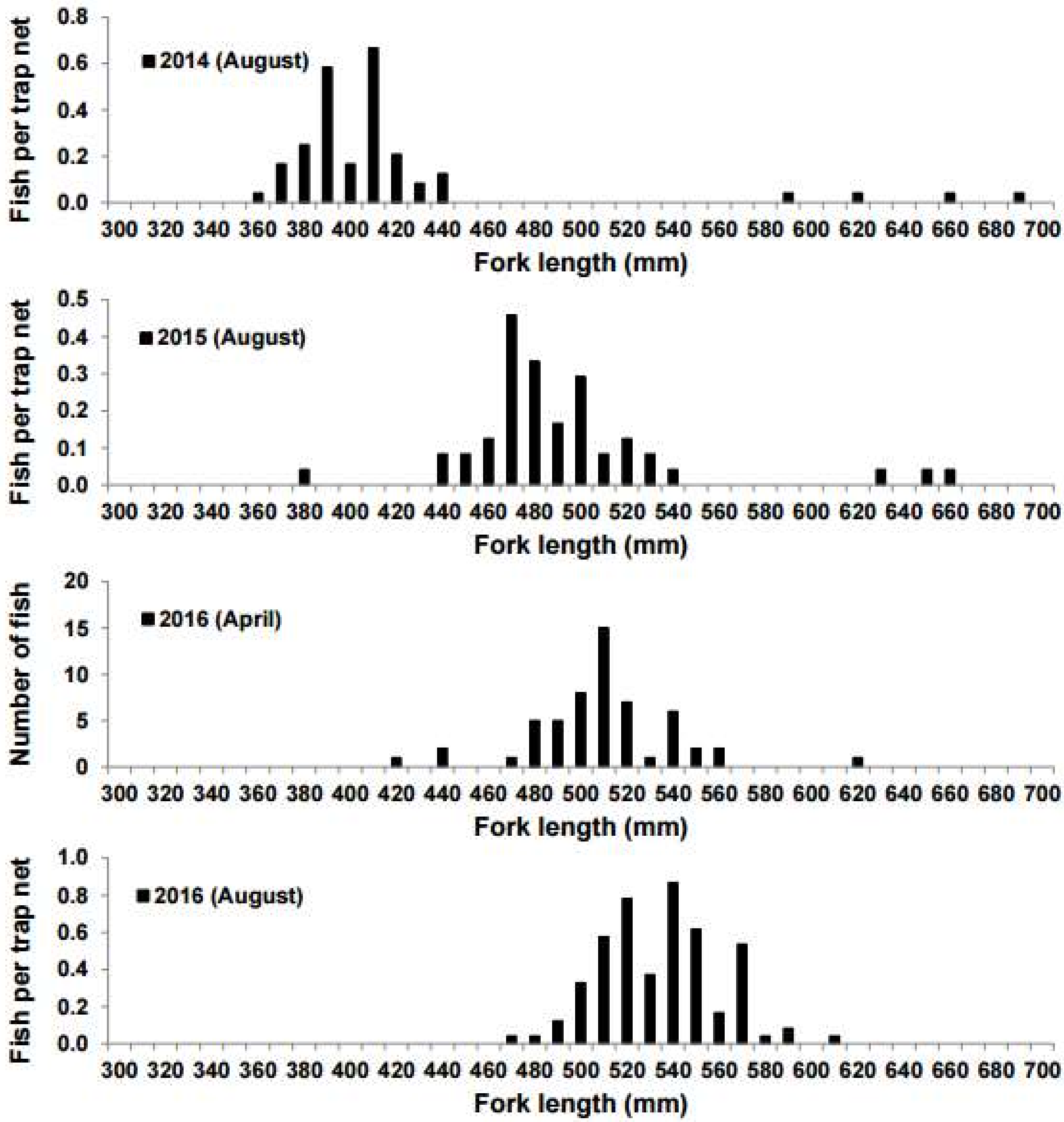

Figure A.5. Size distribution of walleye caught during Near Shore Community Index Netting surveys by Ontario Ministry of Natural Resources and Forestry. Surveys conducted in Hamilton Harbour in August of 2014, 2015, and 2016, and during the walleye spawning assessment in April 2016. Note that April 2016 plot shows total number of fish, not fish per net. (Obtained from Hoyle *et al*., 2017)

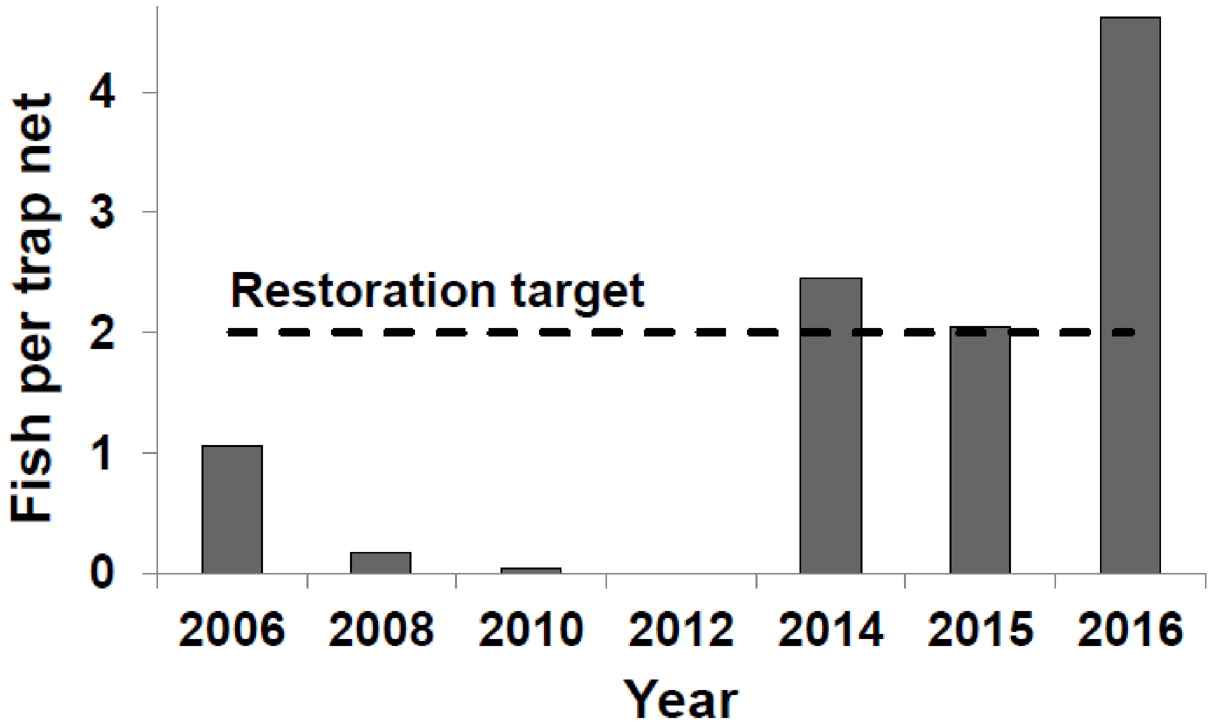

Figure A.6. Walleye catch (number of fish per trap net lift) for years indicated. (Obtained from Hoyle *et al.,* 2017)

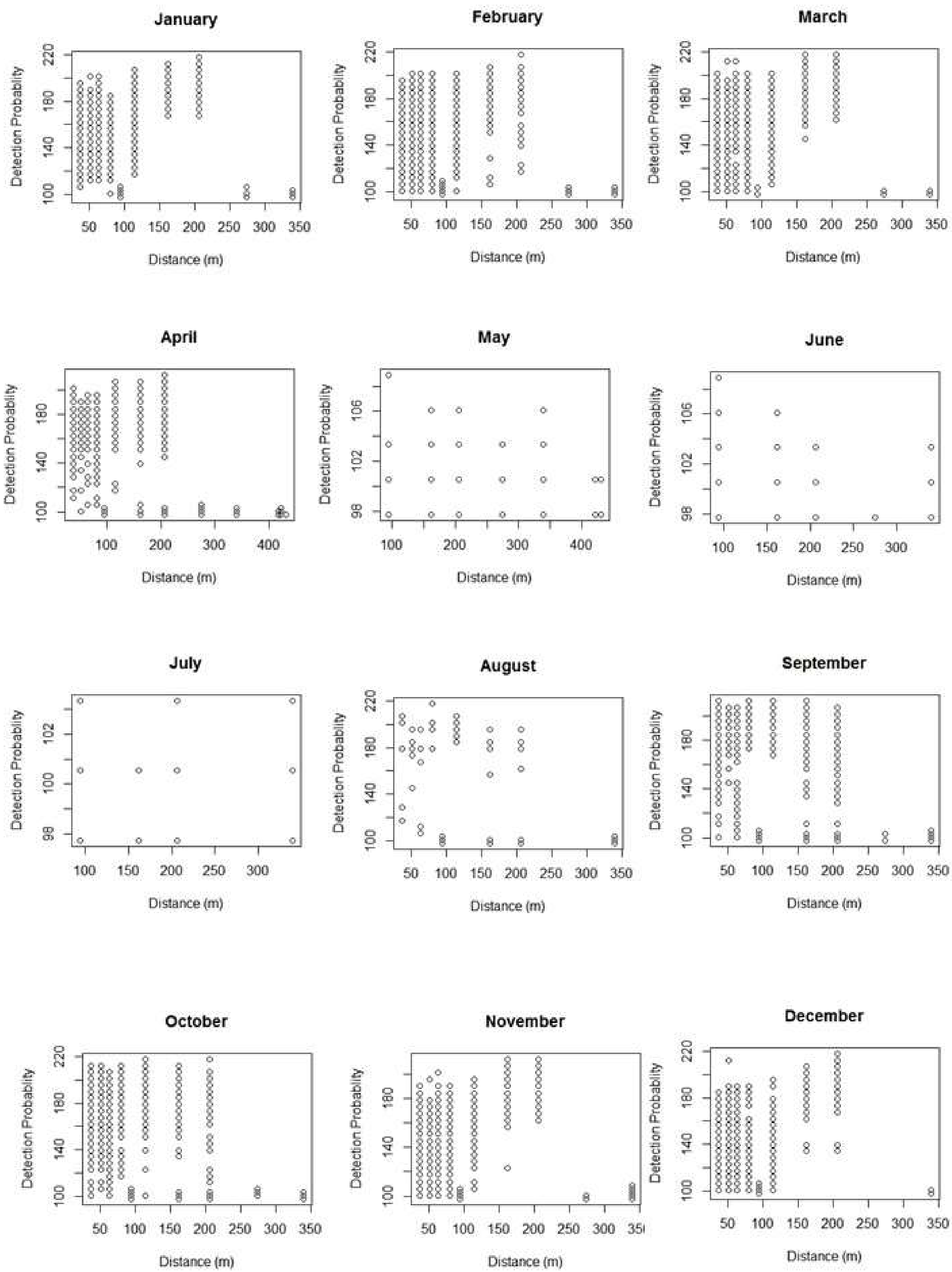

Figure A.7. Monthly detection probability plots using sentinel transmitters within Hamilton Harbour.

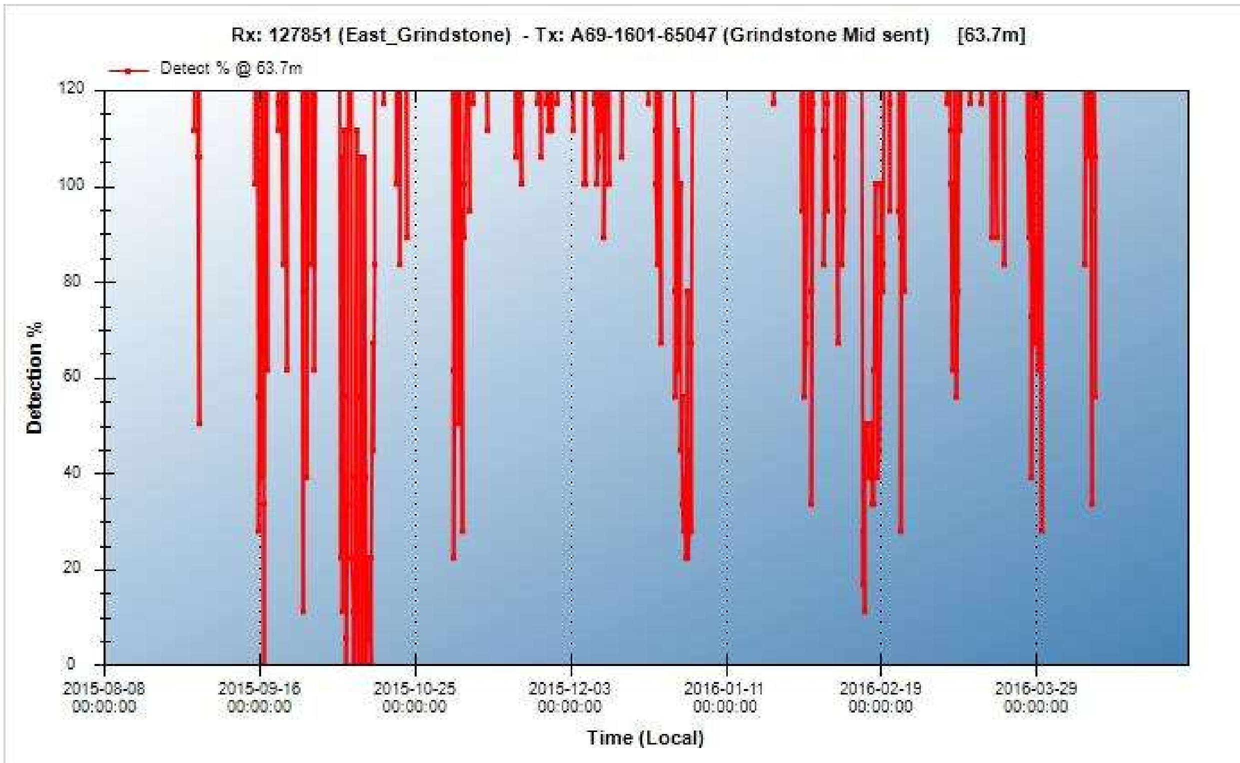

Figure A.8. Detection probability using sentinel transmitter ID47 from 63.7 m distance at the mouth of Cootes Paradise and Grindstone Marsh area at the west of Hamilton Harbour. Turbidity is known to negatively affect acoustic performance, drops in probability could be during events of high rain and surface run off.

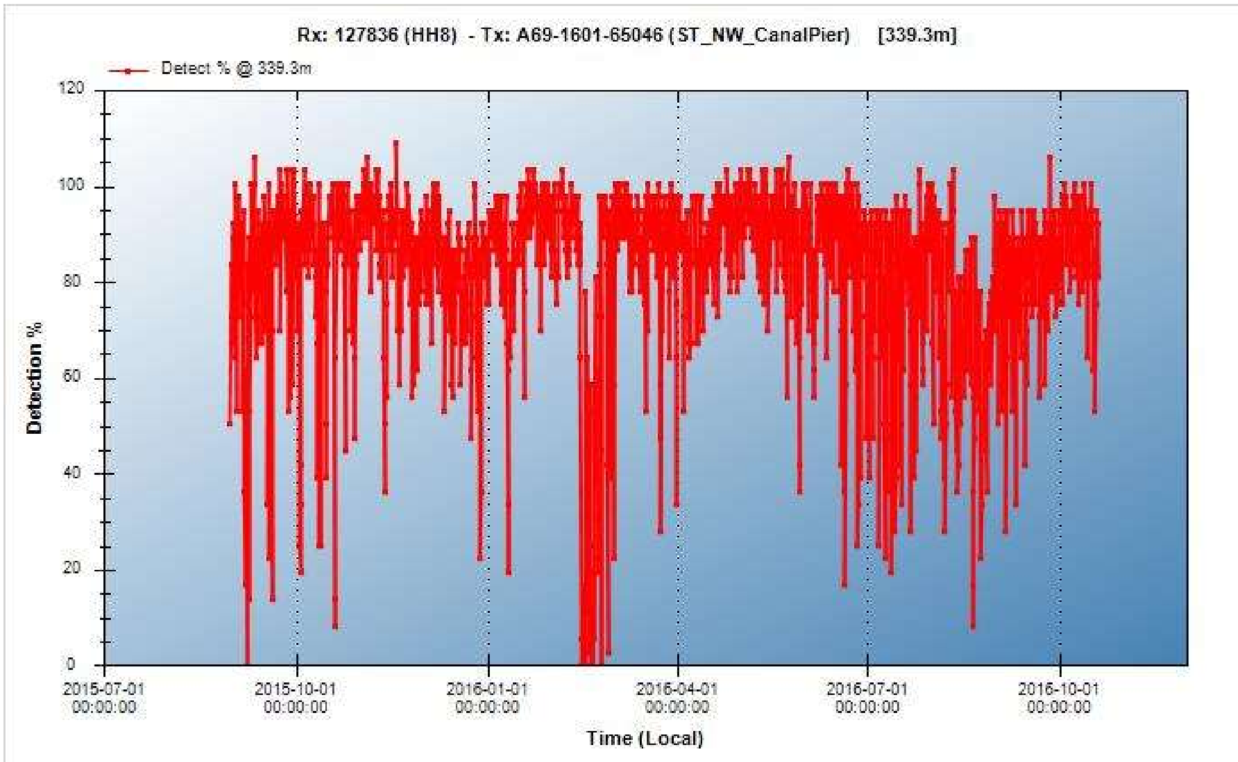

Figure A.9. Detection probability using sentinel transmitter ID46 from 339.3 m distance at the mouth of canal at the east of Hamilton Harbour.

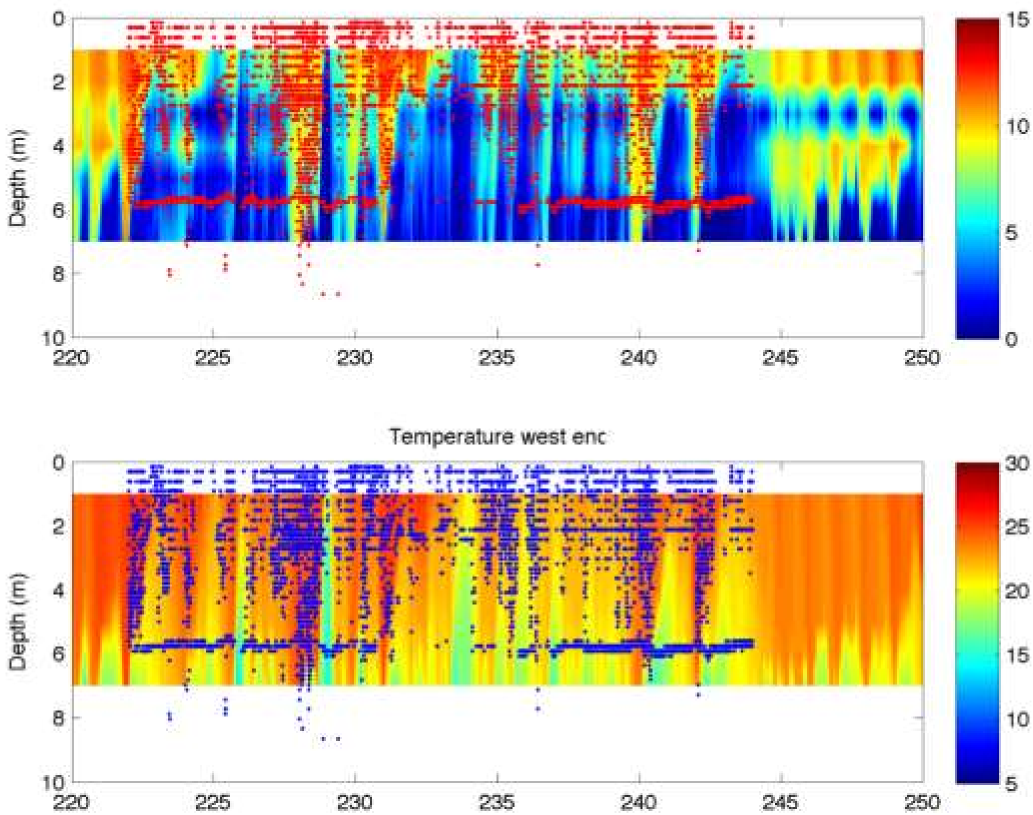

Figure A.10. Dissolved oxygen and temperature profile for days 220-250 of the year at the western end of Hamilton Harbour. Individual points are fish depth detections (multi-species), demonstrating their change in depth with the cyclic upwelling events.

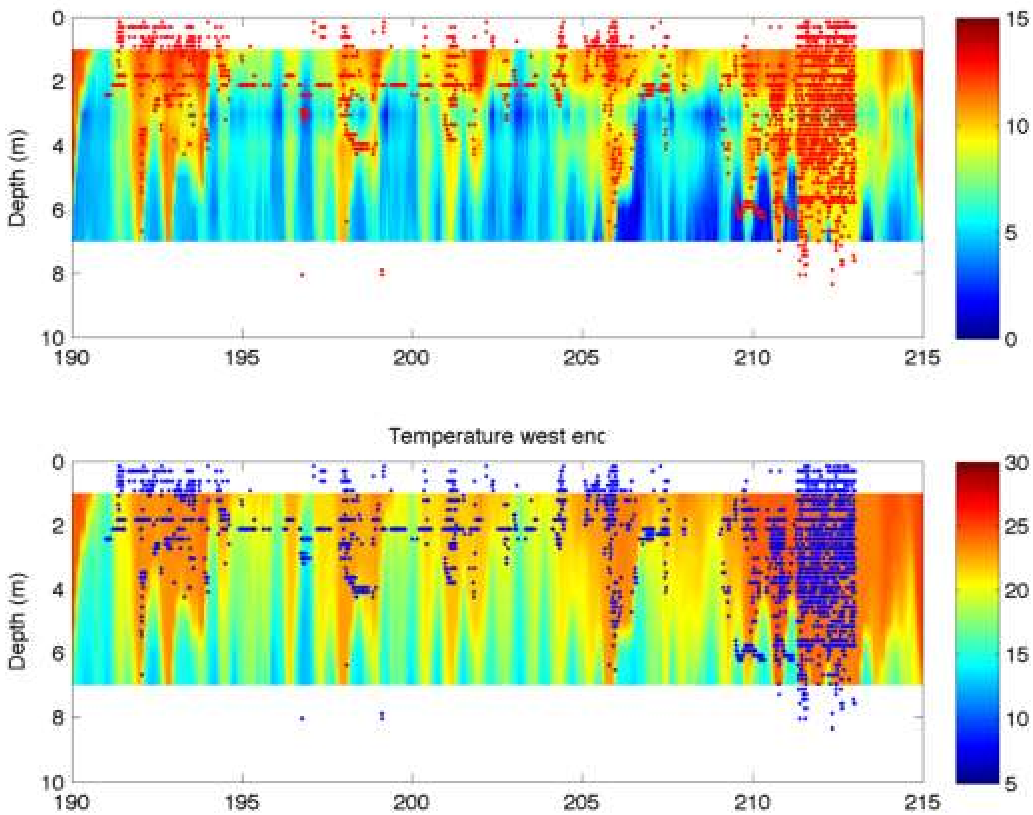

Figure A.11. Dissolved oxygen and temperature profile for days 190-215 of the year at the western end of Hamilton Harbour. Individual points are fish depth detections (multi-species), demonstrating their change in depth with the cyclic upwelling events. Turnover occurred around day 212.