Near Dam Spatio-Temporal Distribution of Migrating Elver and Juvenile American Eel (*Anguilla rostrata*) in the Downstream Reach of the Mactaquac Generating Station, Wolastoq | Saint John River, New Brunswick

by

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Abstract

American eel (*Anguilla rostrata*) is a catadromous species native to the Wolastoq | Saint John River (WSJR), New Brunswick. In 1980, a complete absence of juvenile eels (elvers) was reported near the Mactaquac Generating Station (MQGS), possibly reflecting a velocity barrier. From 2015-2017, various surveying and trapping techniques were implemented within 20 km downstream of MQGS. It was determined that juvenile eels (of average length 116.5 mm ± 14.2 mm and median age 1 year) are present at MQGS throughout the summer months, with abundance peaking in mid- to late July. Spatial distribution at the MQGS was not random, with the northern bank seeing higher relative abundances, particularly close to the Accelerated Rearing Facility. Highest relative abundance occurred within the spillway structures. The majority of elver recaptures occurred within the spillway gate of their original capture, with low movement between the two separate spillways. An ideal future upstream passage structure would consider collection at both spillways and within all gates.

Dedication

To my Raya sunshine.

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I would first like to thank my supervisor, Dr. Tommi Linnansaari. His support and persistence throughout this project have been invaluable. I am deeply grateful for both this learning experience and his guidance as we've traversed the mysterious and elusive eels of the Wolastoq | Saint John River.

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List of Symbols, Nomenclature, or Abbreviations

ARF – Accelerated Rearing Facility

COSEWIC – Committee on the Status of Endangered Wildlife in Canada

CRI – Canadian Rivers Institute

DFO – Fisheries and Oceans Canada

DS – Diversion Sluiceway

MAES – Mactaquac Aquatic Ecosystem Study

MQGS – Mactaquac Generating Station

MLAP – Mactaquac Life Achievement Project

MS – Main Spillway

NBP – Énergie NB Power

rkm – River Kilometer

TL – Total length

UNB – University of New Brunswick

VIE – Visible Implant Elastomer

WSJR – Wolastoq | Saint John River

WT – Wet weight

Chapter 1: General Introduction

Brittany V. Dixon

1.1 Life history of Anguillid eels

The genus *Anguilla* consists of 19 species or subspecies of ray-finned fish known as freshwater eels (Inoue *et al.* 2010; Williamson *et al.* 2023). Freshwater eels are catadromous fish and spend a portion of their life in both marine and continental bodies of water. All eel species spawn at sea where they emerge from eggs adrift over the deep ocean and begin their landward journey. At this stage, the young larval eels (leptocephali) are transparent and laterally compressed (Kuroki *et al.* 2014). Leptocephali live in the ocean surface layer and are passively transported by oceanic currents, consuming only particulate organic material (also referred to as 'marine snow') such as zooplankton fecal pellets and discarded larvacean houses of protein and cellulose (Otake *et al.* 1993; Mochioka and Iwamizu 1996; Miller 2009). Once larval eels arrive at the continental shelf, they metamorphose into glass eels, transitioning from a pelagic-oceanic to a benthic-continental organism. While still transparent, the eel will begin to elongate and take on typical eel-like characteristics. Glass eels rely on tidal transport to begin their continental ascent; however, some eels may remain in salt water without ever entering brackish water, while others remain in brackish water without transitioning to a freshwater phase (Tsukamoto *et al.* 1998; Edeline *et al.* 2005) or make trips to and from brackish and freshwater locations (Lamson *et al.* 2006; Sweezey 2014).

The American eel (*Anguilla rostrata* (Lesueur 1817)) is widely distributed within the western North Atlantic Ocean. Its range extends from southwestern Greenland, along the rivers of eastern North and Central America, and as far south as Panama and the West

Indies (Schmidt 1922; Schmidt 1923; Scott and Scott 1988). American eels consist of one single, global breeding population (panmictic) which begins its complex life history by spawning in the Sargasso Sea (Côté *et al.* 2013; Pavey *et al.* 2015; Ulmo-Diaz *et al.* 2023), or Mid-Atlantic Ridge (Chang *et al.* 2020). Peak spawning is hypothesized to occur in March (Pratt *et al.* 2014). After hatching, leptocephali are transported a great distance by the Gulf Stream and other oceanic currents up along the eastern coast of North America, and they lack the homing ability to return to specific, genetically determined home rivers (Pavey *et al.* 2015). Upon reaching the continental shelf, leptocephali metamorphose into glass eels at a mean age of 200 days (Wang and Tzeng 2000). Glass eels move shoreward by means of both active swimming and current drift (McCleave and Kleckner 1982). Upon entering estuaries and freshwater rivers at a mean age of <1 year, the coastal eels develop into pigmented elver eels (Bertin 1956; Jessop 1998; Wang and Tzeng 2000).

In the Maritime Provinces of Canada, elvers have been known to enter coastal streams as early as March in the East River Chester, NS (Jessop 2020) and April along the Bay of Fundy (Brunswick Aquaculture 2016, pers. comm.), with initial observations within the Wolastoq | Saint John River (WSJR) in May and June (Jessop and Harvie 2003). During the elver life stage (commonly three to twelve months or more; See "*Defining an elver*" section below), some American eels are motivated to migrate upstream, guided by an instinctual attraction to oncoming flow (Haro and Krueger 1991). As a nocturnal fish, the eels will burrow into variable substrate during daylight hours (Tomie *et al.* 2013), while upstream travel occurs primarily during the active hours of the night, with activity peaks coinciding with light changes at dawn and dusk (Bohun and

Winn 1966). Throughout the day, elvers will protect themselves from harm and predation by resting within the variable substrate of the river bottom. The interaction of elvers with the river substrate assists in their upstream progress, as small eels will spend more time resting in the substrate than moving through the water column (Barbin and Krueger 1994).

As American eels settle into the habitat, they transition into the sexually immature life stage where they are known as yellow eels. At this stage, eels experience sexual differentiation and are often associated with yellowish pigment on their ventral surface. Density can play a large role in the sexual differentiation of eels at this stage, with higher densities promoting male production (Krueger and Oliveira 1999). An opportunistic predatory species, eels will feed on a variety of prey types, including aquatic insect larvae, crustaceans, worms and other invertebrates, and small fishes (Barak and Mason 1992). Yellow eels typically stay within their established home range where they feed at night and remain concealed within substrate throughout the day (Jellyman and Sykes 2003, Thibault *et al.* 2007, Braham *et al.* 2024). After a period ranging from three to twenty years for northern temperate anguillids (Aoyama and Miller 2003), the adult American eel undergoes a final metamorphosis to a silver eel – a transition that supports their migration back to the Sargasso Sea to spawn, and thus to complete their life cycle. The timing of outmigration is variable due to the wide geographic range and typically occurs earlier throughout the summer in populations further away from the Sargasso Sea (*e.g.*, in Ontario; Dumont *et al*. 1998; McGrath *et al.* 2003) and later during autumn along the Atlantic coast (Jessop 1987; Carr and Whoriskey 2008). Many questions remain surrounding the spawning and leptocephali life stages of anguillid eels, and thus,

significant research effort is ongoing to understand the behaviour and distribution of eels as they traverse the ocean (Béguer-Pon *et al*. 2015; Chang *et al.* 2020).

1.2 Defining an Elver

The definition of an 'elver' is not clear-cut. Conflicting definitions can be found in literature and depend on the opinion of eel researchers, fishers, or dam operators. It becomes important to understand the morphological and behavioural characteristics of an elver to distinguish between definitions used in literature and industry. Three parameters are commonly used when attempting to define an elver, and are outlined here:

Length-based definition: The fisheries management definition as laid out by the Canadian Science Advisory Secretariat and Maritime Provinces Fishery Regulations defines elvers as eels of less than 100 mm in total length (DFO 2010). At this length, elvers are uniformly pigmented with a distinct ventral margin (Haro and Krueger 1988). Elvers have also been described as 55-65 mm (Jessop and Harvie 2003), or alternatively, during the 2016 regional peer review for American eel, elvers were defined as measuring typically between 6-7 cm in total length and it was noted that clarification is often required when defining an elver by length (DFO 2017).

Age-based definition: A biological definition based on age is a common descriptor for elvers. Notably, an eel of less than one year in freshwater or river age is described as an elver (Jessop and Harvie 2003; DFO 2017).

Behaviour-based definition: Elvers have been defined based on their distinctive migratory behaviour, *i.e.*, as juvenile eels that show a clear motivational instinct to migrate upstream by following flow patterns and travelling through potentially difficult terrain (*e.g.*, Leblanc 1973).

For the purpose of this thesis, and to remain comparable to previous elver studies in the WSJR, elvers will be defined as schooling juvenile eels showing a distinct motivation to migrate upstream (positive rheotaxis) throughout the spring and summer of the year.

1.3 Status of the American eel

The American eel holds significant value across multiple sectors, contributing to fisheries industries, Indigenous culture, and the health of river ecosystems. The juvenile eel fishery, including glass eels and elvers, is a highly lucrative industry. Because anguillid eels have not been bred in captivity at commercial scale, fish-farmed eels are caught as wild juveniles and then raised to market size. This practice results in a strong demand for juvenile eel export from North America to Asian markets for rearing (Weeder and Uphoff 2009). The American eel is also a culturally important species to Indigenous peoples of Canada, as a current and historically important part of the Mi'kmaq and Maliseet diet (Jayawardane 2014) and with archaeological evidence showing that eel fishing has been practiced for over 4,000 years (MacGregor *et al.* 2008). Furthermore, as a predatory species, the American eel plays an important ecological role within river systems and remains an excellent indicator of river health (Smith and Saunders 1955).

The status of the anguillid eels is currently under close scrutiny as members of the genus continue to suffer decreases in worldwide populations. The consumption of anguillid eels has been discouraged in recent years as the sustainability of eel fishing has caused increased conservation concern. Due to a number of natural and anthropogenic threats throughout their geographical range, the American eel has seen a tremendous reduction in numbers since the 1980s. In 2012, the Committee on the Status of

Endangered Wildlife in Canada (COSEWIC) recommended listing the American eel as a threatened species (COSEWIC 2012). Abundance estimates from the Laurentian Great Lakes and the upper portion of the St. Lawrence River were reportedly experiencing a 90 % decline, which also led to listing American eel under Ontario's *Endangered Species Act* (ESA 2007). Indicators at the mouth of the St. Lawrence River, which represent production from the entire watershed, also declined but much less steeply (ICES 2023). Elsewhere, abundance trends were spatially variable, with declining trends outnumbering increasing trends (Cornic *et al*. 2021, ICES 2023).

As a species undertaking long-range migrations, American eels face a gauntlet of challenges to complete their life cycle. Global climate change and shifts in oceanographic conditions influence the Gulf Stream currents, thus potentially weakening larval drift towards the North American coast and reducing recruitment of eels to freshwater areas (Friedland *et al.* 2007). Human impact on river systems frequently results in poor water quality and overall habitat degradation *(*Machut *et al.* 2007). While commercial and recreational fisheries for eels were closed by 2005 in Ontario and restricted in Quebec, licenses continue to exist in eastern Canada (COSEWIC 2012), including a quota of 200 kg (~ approx. 1 million glass eels) in the WSJR in 2022 (Anchan 2022). Along with the threat of overfishing, the negative impact of hydroelectric dams has been listed as a major contributor to eel mortality since the mid-1980s *(*Haro *et al.* 2000; de Lafontaine *et al.* 2010). If no form of fish passage is provided, dams serve as barriers that obstruct the elvers' ability to migrate upstream to historically productive juvenile habitats; as much as 84 % of freshwater habitat may be currently unavailable for eels due to barriers for movement (Pratt *et al.* 2014). The negative impact of dams is worth investigating as a

clear threat to American eel survival. While researchers have made advancements for eel passage systems, many dams remain with limited or no safe passage (up or downstream) available to migrating eels (Verreault *et al.* 2004; Hitt *et al*. 2012).

1.4 Hydropower in the Wolastoq | Saint John River, and the Mactaquac Generating Station

Within the Maritime Provinces, numerous rivers are obstructed by hydroelectric dams, prematurely ending the upstream migration of elvers unless specific upstream passage structures are constructed. The WSJR is managed for hydropower production by a provincial owner-operator, the corporation Énergie NB Power (NBP). NBP operates a number of hydropower facilities in the WSJR system, including the Mactaquac Generating Station (MQGS), Beechwood Generating Station, Tobique-Narrows Generating Station, and Grand Falls Generating Station (Figure 1.1).

Historically, American eels were able to travel 351 river kilometers (rkm) upstream to Grand Falls (Figure 1.1). However, their migration was initially impeded by the construction of a series of dams, greatly diminishing the eel migratory potential and amount of suitable habitat (Kidd *et al.* 2011; Ellis *et al.* 2016). The Tobique-Narrows Generating Station (315 rkm) was erected in 1953, followed by the Beechwood Dam (285 rkm) in 1955. The Mactaquac Generating Station (150 rkm; Figure 1.1; Figure 1.2) became operational in 1968, with an expected service-life of 100 years.

The MQGS is the first facility in the system (farthest downstream) and therefore is the first physical obstruction that eels encounter when making their way up the river. The dam is located 18 rkm upstream from the City of Fredericton on the mainstem of the

WSJR (Figure 1.1). The facility is approximately 1,100 metres long with a hydraulic head of 36.6 metres under typical operating conditions. The dam functions as a hybrid station with a combination of "run of the river" and peak-load cycles, where power generation is derived from the river's natural flow, but also increases during times of daily demand (Ruggles and Watt 1975). It currently has the capacity to generate ~670 megawatts of power using six Kaplan turbines. The final two turbines became operational by 1980 (unit 5 installed fall 1979, unit 6 in spring 1980). The MQGS supplies approximately 12 % of the electric power production for New Brunswick (Linnansaari *et al.* 2015).

While construction of the MQGS included the implementation of a fish collection facility for the upstream migrating fish, the focus of the facility's fish-lift was primarily centered around Atlantic salmon (*Salmo salar*) and river herring (*Alosa* spp.) passage. Unfortunately, no consideration was made for American eel passage at that time and the fish-lift in its current state is not suitable for elvers due to their small size and swimming capabilities (Ruggles and Watt 1975; Jessop and Harvie 2003). Elvers have an advantageous ability to overcome obstacles by making their way up damp, vertical surfaces (Legault 1988). Various engineered species- and life-stage-specific structures exist to facilitate the upstream passage of American eel elvers (Solomon and Beach 2004, Haro 2013) and in many hydropower generating stations functional passage has been arranged for juvenile eels (Solomon and Beach 2004). Very importantly, siting the passage structure in a location where young migratory eels naturally aggregate is the key factor in arranging functional upstream passage for eels (Linnansaari *et al.* 2017).

1.5 Mactaquac Aquatic Ecosystem Study

Although American eel upstream passage was not given consideration when MQGS became operational in 1968, there is now an opportunity to re-visit various fish passage issues related to the station, including passage for American eel. The MQGS is expected to reach the end of its useful service life by 2030 due to an alkali-aggregate reaction impacting the viability of the structural concrete (Stantec 2016). NBP has been tasked with making an informed decision for the future of the hydroelectric station. In 2014, NBP began the process of evaluating the future options for the MQGS, known as the Mactaquac Project. Three future options for the MQGS were originally introduced for further evaluation in 2013, and a fourth option titled the Mactaquac Life Achievement Project (MLAP) was added in 2016 and is currently pursued by NBP (Stantec 2016). The MLAP scenario seeks to use various approaches to maintain, repair, and refurbish the existing structures and power generating infrastructure at MQGS with the goal to operate the dam to its intended 100-year lifespan.

NBP engaged the Canadian Rivers Institute (CRI) at the University of New Brunswick (UNB) to design an extensive, multidisciplinary, aquatic ecosystem study to support an informed, science-based decision, originally to determine a preferred option, but lately to support decision-making regarding the MLAP option. CRI initiated the Mactaquac Aquatic Ecosystem Study (MAES) in 2014 with three study themes examining the whole river ecosystem, environmental flows, and fish passage.

Within the fish passage theme of the MAES project, six fish species were initially selected for detailed study. The selected fish species required more detail with some aspect related to their life history in the WSJR that was necessary to make a science-

based decision regarding impacts of the initially proposed options on their populations. Along with Atlantic salmon, striped bass (*Morone saxatilis*), shortnose sturgeon (*Acipenser brevirostrum*), Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*), and muskellunge (*Esox masquinongy*), the American eel was selected due to its unfavorable conservation status, puzzling history, and limited research and knowledge at the MQGS. The elver life stage became the focal phase for this study, as it is the life stage that demonstrates the affinity to migrate upstream to colonize the upper reaches of the river and because unresolved questions regarding the elvers and the potential effects of hydropower generation at MQGS have been posed (Jessop and Harvie 2003).

1.6 History of juvenile American eels at the Mactaquac Generating Station

Literature concerning the presence and movement of American eel elvers in the WSJR is limited. In 1973, a qualitative study was conducted at the Mactaquac dam and researchers reported a high abundance of elvers swimming along the surface of the water. The mass of elvers was visually compared to "*wind ruffling the surface"*, and on the evening of July 16, 1973, a small group of fishermen were able to collect approximately 115 pounds of elvers (approx. 26,500 total elvers) over 7.5 hours (LeBlanc 1973). In a subsequent study by LeBlanc (1974), researchers also reported substantial numbers of elvers arriving at the dam throughout July 1974. An additional study was released in 2003 and detailed personal observations of elvers at the dam prior to 1980 "*forming ribbons along the outer walls of the fishway at the Mactaquac Dam"* (Jessop and Harvie 2003). However, in the same report, Jessop and Harvie (2003) noted that since 1980 no elvers had been observed entering the fish collection facility of the dam. As described previously, the final two Kaplan turbines were installed at the dam by 1980, and this

timing coincides with the apparent disappearance of elvers entering the area. Jessop and Harvie (2003) hypothesized that the resultant change in daily and hourly discharge patterns at the dam may have created a velocity barrier at an undefined point downstream, therefore repressing elver upstream migration. At the time, no further research was conducted to test these suggestions.

1.7 Thesis Outline

Synthesizing the information above, the objective of this thesis was to better understand the ecology of American eel elvers in the lower WSJR, and specifically, to determine how and why the hydropower generation at MQGS may affect the distribution of elvers downstream. The main question was: Are American eel elvers present at the MQGS, and if yes, where and when can they be found? If they are not at MQGS, what prevents their migration?

The thesis is structured such that Chapters 2 and 3 examine interlinked but separate research questions, and both research chapters are written in a stand-alone article format, while Chapter 4 will synthesize the information from both research chapters.

Chapter 2 addresses the following question: what is the distribution, both spatially and temporally, of American eel elvers as they make their migratory approach to the MQGS? Further, Chapter 2 addresses the question: Is there a velocity barrier to American eel elver migration in the WSJR? This question investigates the timing of elver migration, elver distribution in the area downstream of the dam, and the age of elvers sampled from 2015-17 using otolith analysis.

Building upon the findings in the Chapter 2, Chapter 3 focuses its attention on the high-density elver locations of the main spillway and diversion sluiceway of the MQGS. Using visible implant elastomer tagging, Chapter 3 specifically describes the general distribution, movement behaviour and catch-per-unit-effort of elvers found in the spillway structures of the MQGS and draws conclusions about recommended locations of a potential upstream passage structure.

Chapter 4 summarizes the overall conclusions of the thesis. By answering each of the chapter objectives, this chapter discusses and analyzes the results in detail and provides recommendations to fisheries management regarding feasibility of upstream passage of American eel elvers in the WSJR. Finally, Chapter 4 outlines necessary next steps that are required to adequately understand the possibility of enabling the American eel to traverse the MQGS.

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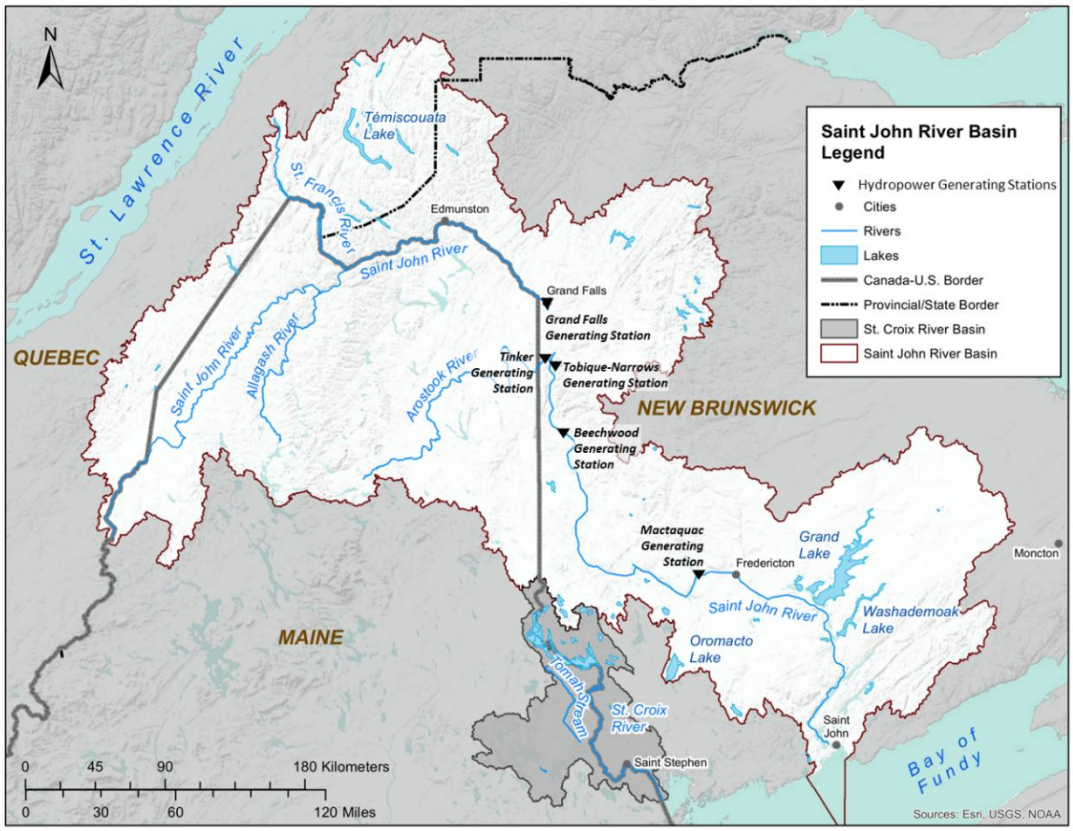

Figure 1.1 Wolastoq | Saint John River catchment showing locations of five main hydropower generating stations. The Mactaquac Generating Station is the lowermost dam, located 150 rkm upstream of the Bay of Fundy. Moving upstream, the Beechwood Generating Station is located at 285 rkm, the Tobique-Narrows Generating Station is located near the confluence of the Tobique River and WSJR at 315 rkm, the Tinker Generating Station is positioned on the Aroostook River (a tributary of the WSJR) near the mouth of the tributary at 318 rkm, and the Grand Falls Generating Station is located further upstream at 351 rkm. (Modified from the original map courtesy of International Joint Commission 2025).

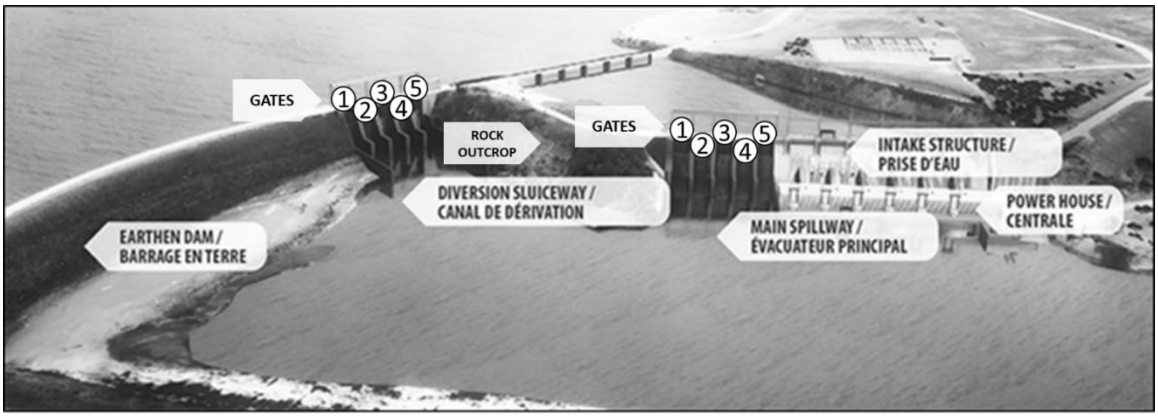

Figure 1.2 The Mactaquac Generating Station on the Wolastoq | Saint John River, NB, located 18 rkm upstream from the City of Fredericton. Main structures include the earthen dam, a diversion sluiceway, a natural rock outcrop, the main spillway, and the generating unit, consisting of intake structure and powerhouse. Both the diversion sluiceway (DS) and main spillway (MS) consist of five independently operated gated sections (henceforth DS1 through DS5, and MS1 through MS5) containing angled ogee weir surfaces. (Modified from the original diagram courtesy of NB Power 2014.)

Chapter 2: The spatio-temporal distribution and biological characteristics of elver and juvenile American eel (*Anguilla rostrata*) during their migratory approach to the Mactaquac Generating Station, Wolastoq | Saint John River, New Brunswick

Brittany V. Dixon, R. Allen Curry & Tommi Linnansaari

Abstract

As juvenile eels, known as elvers, the catadromous American eel (*Anguilla rostrata*) enters the coastal streams of Atlantic Canada from April-June each year and begins its upstream migration. American eels are experiencing significant population declines due to various factors, such as the construction of hydropower dams throughout their historic migratory range, including that of the Mactaquac Generating Station (MQGS) of the Wolastoq | Saint John River (WSJR). While elvers were observed prior to 1980 approaching the downstream vicinity of the MQGS, no elvers have been reported at the dam in the years following. Previous studies hypothesized the possibility of a velocity barrier in the downstream reach of the WSJR, leading to a migration bottleneck. Various passive and active trapping methods were deployed within 20 rkm downstream of the MQGS to evaluate the spatio-temporal distribution and biological characteristics of elvers. Elvers were discovered within 1 rkm of the dam, signifying that a barrier to migration does not exist. Elvers showed preference to certain locations in the vicinity of the MQGS, perhaps due to preferential velocity and attraction flows, with abundance peaking in mid- to late July. Observed elvers showed consistent upstream migratory behaviour and had an average length of 116.5 mm ± 14.2 mm and median age of 1 year (range 0-3 years) indicating that only a low abundance of elvers in their first year of freshwater entry (age 0) are present at MQGS. Overall, the presence of migratory elvers was consistently observed at MQGS, suggesting that an upstream passage system for elvers is possible at this location, but such structure should take elver distribution and behaviour into consideration to be effective.

2.1 Introduction

The American eel (*Anguilla rostrata* (LeSueur 1817)) is a catadromous fish that is widely distributed in the western Atlantic Ocean and its coastal and inflowing waters between Greenland and northern South America (ICES 2023). Within this vast range the American eel forms a single panmictic stock, which spawns in the oceanic waters of the Sargasso Sea (Béguer-Pon *et al*. 2015, Ulmo-Diaz *et al*. 2023), although a novel Mid-Atlantic Ridge hypothesis has been recently proposed to challenge this dogma (Chang *et al.* 2020). After hatching, larval eels (leptocephali) move by ocean currents and active swimming towards continental habitats and metamorphose into transparent glass eels on reaching the continental shelf at a mean age of 200 days (Wang and Tzeng 2000). As glass eels enter continental rearing habitats (sheltered coastal waters, estuaries, and freshwaters) via both active swimming and current drift at a mean age of 255 days, they develop into pigmented elvers (Bertin 1956; Jessop 1998; Wang and Tzeng 2000). Some elvers, but not all, migrate inland to fresh waters. This migration takes place in April-June in the Atlantic Provinces of Canada (Jessop 1998; Jessop and Harvie 2003). Juvenile eels may move upstream both as elvers and at the subsequent yellow eel stage, occupying both riverine and lacustrine habitats (Haro and Krueger 1991; Jessop 1998; Morrison and Secor 2003). After a prolonged growth stage (typically 5 to 25 years), yellow eels metamorphose into sexually maturing silver eels which exit continental waters and migrate back to the Sargasso Sea / Mid-Atlantic Ridge where they spawn and die (Bradford 2013; Béguer-Pon *et al.* 2015; Chang *et al.* 2020).

American eels face major conservation challenges (ICES 2023). In 2012, the Committee on the Status of Endangered Wildlife in Canada assessed the Canadian

component of the species as threatened (COSEWIC 2012), and subsequent reviews of abundance indicators have found declining series to outnumber increasing ones (Cornic *et al*. 2021). In the United States, a benchmark assessment (ASMFC 2023) concluded that the US component of the population is depleted, with current low populations relative to historic norms.

Dams are viewed as major threats to American eel conservation, along with fisheries, introduced parasites, and habitat degradation (Weiler 2011; de Lafontaine *et al.* 2010; Chaput *et al.* 2014). Most large dams have hydroelectric turbines which put downstream migrating eels at risk of lethal blade strikes (Righton *et al.* 2021). Large dams generally block all or nearly all upstream eel passage, although effective passage is offered at some sites by eel-optimized fishways or shipping canals. Blockage effects of small dams are more variable (Cairns *et al.* 2022). Dam blockages in the American eel range prevent eel access to very large quantities of upstream habitat (Pratt *et al.* 2014). However, conservation impacts of dam blockages are incompletely understood because they do not directly cause eel mortality, but could instead cause density-dependent reductions in growth rates or shifts in sex-ratios among eels that are prevented from ascending rivers (Machut *et al.* 2007; Costa *et al.* 2008).

The Wolastoq | Saint John River (WSJR) is the fourth largest river on the east coast of North America by drainage area (Jones *et al.* 2022). Eels historically occupied the WSJR river basin in the upstream reach of the MQGS (Francis 1980) and up to Grand Falls (351 river kilometers (rkm)) (Jessop and Harvie 2003, Pratt *et al.* 2014) and possibly higher (Cairns *et al.* 2014). However, four hydroelectric dams constructed on the

WSJR mainstem between 1931 and 1968 have essentially eliminated upstream migration (Kidd *et al.* 2011; Ellis *et al.* 2016).

The Mactaquac Generating Station (MQGS) is the most downstream dam on the WSJR, and its completion in 1968 reduced habitat available to eels in the system by 46 % of undammed levels (Pratt *et al*. 2014). The MQGS incorporates a fish-lift system designed to pass Atlantic salmon (*Salmo salar*) and gaspereau (collectively Alewife *Alosa pseudoharengus* and blueback herring *A. aestivalis*) (Jessop and Harvie 2003; Chateauvert *et al.* 2018), but no provision for American eel passage was made. Eels continue to be widely recorded downstream of MQGS but are rarely encountered upstream from it (Pratt *et al.* 2014, Ellis *et al.* 2016, Eissenhauer *et al.* 2024).

With the formation of the Mactaquac Aquatic Ecosystem Study (MAES), there has been a new opportunity to evaluate the potential for American eel fish passage at the MQGS. Initiated in 2014, MAES Phase 1 incorporated three overarching themes that covered 29 study topics, including whole river ecosystems, environmental flows, and fish passage. As a species of declining population and increasing conservation concern, American eel was selected for the study, with the migratory life stage of the American eel elver of particular interest.

Future changes at MQGS may provide an opportunity to improve multi-species fish passage at the dam, but provision of effective American eel passage at MQGS requires an understanding of juvenile eel movements and behaviour near the facility. LeBlanc (1973) described masses of elvers swimming along the surface of the water at the base of the dam in summer 1973, likening them to "*wind ruffling the surface*", with substantial observations of elvers reported during the following year as well (LeBlanc

1974). In 1973-1979, elvers were regularly present and were described as "*forming ribbons along the outer walls of the fishway at the Mactaquac Dam*" (Jessop and Harvie 2003), although no quantitative estimates of elver abundance or size were provided. Starting in 1980, and continuing at least to 2002, elvers were no longer seen at the dam (Jessop and Harvie 2003). Jessop and Harvie (2003) noted that the cessation of observed elver visitation to the dam coincides with the installation and operational start of the final two (of total six) Kaplan turbine units at the dam, installed in October 1979 and February 1980, and a shift in dam operations to water discharge that was pulsed on daily and hourly cycles. The authors hypothesized that the execution of a daily peak-load generation cycle may have resulted in a velocity barrier inhibiting elver migration to the dam.

A negative relation between increased discharge at the MQGS and the absence of elvers was substantiated by Jessop (2003) who observed that increases to river discharge (*i.e.*, stream velocity) coincided with decreases in daily elver counts at the mouth of the East River, Chester, Nova Scotia, while accounting for temperature and tidal influences. As weak swimmers, elvers have difficulty traversing water velocities exceeding 25 cms^{-1} and show a preference for moving along riverbanks where water velocities are minimized (McCleave 1980; Barbin and Krueger 1994; Piper *et al.* 2012). Elvers attempt to overcome high water velocities by using quick bursts of swimming through the water layer just above the substrate and by taking frequent breaks at rest points a few metres apart (McCleave 1980). While the cause-effect relationship between elver absence and operation of MQGS has not been empirically demonstrated, the abrupt disappearance of American eel elvers coinciding with the start-up of the last two turbine units may be

suggestive of either 1) seasonal discharge patterns that may create a velocity barrier to upstream elver migration at some unknown location downstream of the MQGS, or 2) modification of the local velocity fields around the dam's fish collection facility such that elvers reach the MQGS, but are no longer present at the fish collection facility where they were regularly observed in 1973-1979.

Elver influx has been associated with an increase in water temperature and reduced discharge (Jessop 2003), but Jessop and Harvie (2003) warn about drawing conclusions about the correlation between timing of the absence of elvers at the dam in 1980 and the installation of the last two turbines given the lack of site-specific quantitative evidence. The installation of the MQGS hydroelectric facility may have had unintended and unanticipated environmental impacts (Jessop and Harvie 2003). Until now, research documenting elver behaviour in the WSJR has been solely qualitative and speculative, but the disappearance of elvers at the dam gives rise to important research questions.

The goal of this study was to test the hypothesis proposed by Jessop and Harvie (2003) that a velocity barrier in the lower WSJR is preventing elvers from reaching the MQGS. Stemming from this hypothesis, the first objective was to clarify the spatial distribution of elvers in the WSJR as they approach within 20 km of MQGS to 1) identify the upper limit of American eel elvers in the lower WSJR, which might signal a velocity barrier and 2) describe in detail the spatial distribution of elvers at this uppermost (barrier) location. A velocity barrier was defined as a section of river where water velocity is too high for elvers to swim against and progress upstream. The second objective was to develop a better understanding of the temporal distribution patterns of

elver migration (*i.e.*, start and end of migration; peak migration timing) and to describe the biological characteristics (*i.e.*, size and age of individuals) of the migratory contingent of young eels at their uppermost location in the river. These data (movements, behaviours, and migration timing) were collected to recommend any changes to the hydropower operator that may be necessary to facilitate American eel elver upstream migration and eventually, to offer recommendations for an upstream passage system design.

2.2 Methods

2.2.1 Study area

The Wolastoq | Saint John River (WSJR) has its headwaters in northern Maine and flows approximately 670 km southeast before draining into the lower Bay of Fundy at Saint John, New Brunswick (Figure 2.1). The WSJR has a total drainage area of > 55,000 km^2 within the provinces of New Brunswick and Quebec, and the state of Maine (Kidd *et al.* 2011). Along the WSJR, the substrate upstream of Fredericton is primarily cobble and sand with some boulders and bedrock, while the area downstream of the city is relatively sandy (Curry and Munkittrick 2005; Kidd *et al.* 2011). Throughout the main stem of the Fredericton region of the WSJR, the river's average width is 750 metres with a depth of 3 metres (Curry and Munkittrick 2005).

The WSJR is harnessed for hydropower by five major dam structures along its reach, with three along the main length of the river (Grand Falls, Beechwood, and Mactaquac Generating Stations), one near the mouth of the Aroostook tributary (Tinker Generating Station), and the final dam near the mouth of the Tobique River (Tobique-Narrows Generating Station) (Figure 2.1). The MQGS is the largest and lowermost dam,

located 150 rkm from the mouth of the river (Kidd *et al.* 2011; Figure 2.1; Figure 2.2). The dam's size and location make it a major obstacle for fish migration. In particular, American eel upstream migration has been seen to halt altogether as the elvers make their approach towards the MQGS (Jessop and Harvie 2003, Pratt *et al.* 2014, Ellis *et al.* 2016).

The flow fields in the area within the vicinity of the dam can range from areas of high velocity and turbulence to areas of still water and back eddies. The varying flows are due to the type of structures and their functions within the MQGS. The earthen dam holds the reservoir of water upstream of the dam being directed through the six turbines of the powerhouse for energy production (Figure 2.2). However, in high flow periods such as spring freshet, there is more water flowing through the river than can be effectively passed through the turbines. To allow water to bypass the turbines entirely, the MQGS has ten spillway gates (five located at the main spillway and five at the diversion sluiceway; Figure 2.2) that can be opened to allow water to rapidly escape from the reservoir. The powerhouse, with its six turbines and the affiliated fish-lift structure, also creates a variable flow pattern along the face of the powerhouse (where the turbines and fish-lift are located), as operators manipulate flows to generate power or to attract specific species of fish into the lift to be transported upstream of the dam (Chateauvert *et al.* 2018). These various structures and their functions come together to create a collision of opposing and complementary flow patterns that can alter the behaviour of fish as they approach the dam.

Downstream of the MQGS, the WSJR is a relatively low gradient (average 0.1 % from mouth (0 rkm) to City of Fredericton). While there are sections of higher gradient

slopes (peaks between 0.4 to 0.8 %; Figure 2.3), the overall gradient in this section of river is greatly reduced during high tide events. The low gradient, coupled with the large tidal range of the Bay of Fundy (ca. 6 – 8 m at Saint John), creates a tidal head that reaches approximately 130-140 rkm upstream (Kidd *et al.* 2011; Andrews *et al.* 2020), and 20 km downstream of the MQGS (Figure 2.4A). The saltwater intrusion reaches its upper limit to define the Saint John estuary at ~70 rkm upstream near the village of Gagetown (Carter and Dadswell 1983).

The final 20 rkm between the City of Fredericton and the MQGS also consists of a relatively low average gradient (average 0.12 % from Fredericton to MQGS; Figure 2.3), but with sections where the gradient reaches up to 0.4 %, and remains relatively consistent even during times of high tide (Figure 2.3; A. O'Sullivan 2021, University of New Brunswick Faculty of Forestry and Environmental Management, pers. comm.). Based on the river gradient and interaction with lower tidal influence, the output from hydrological models predicting flows potentially exceeding elver capabilities (Wegscheider 2020; Figure 2.5) found that these 20 rkm were deemed most probable as the site of a potential velocity barrier and was defined as the focused study reach (Figure 2.4A). Areas both upstream and downstream of a potential velocity barrier were specifically targeted for elver trapping efforts; areas downstream (Velocity Barrier Downstream; VBDS) and upstream (Velocity Barrier Upstream; VBUS) had designated elver trapping areas (Figure 2.4C; 2.5). The Nashwaak River (Figure 2.4D) is a tributary of the WSJR located on the north side of Fredericton in the 20 rkm study area and was included as a reference location, as the river gradient downstream of the confluence to the

mouth of WSJR is low and therefore, the likelihood of encountering a potential velocity barrier preventing upstream migration by elvers is also low.

Various traps (see below) were placed along the banks of the river in clusters to ensure that enough area was covered such that it became likely that an elver travelling towards the MQGS would eventually encounter a trap. In addition to the VBUS, VBDS, and reference reaches described above, traps were also placed in clusters within 1 rkm downstream of the MQGS (Figure 2.3B and C); see trap descriptions and placement details in Section 2.2.2.)

2.2.2 Capture techniques, locations, and monitoring of young eels

Surveying a river of the magnitude of WSJR posed logistical challenges for capturing migrating elvers. Previous studies have surveyed elvers in estuaries and smaller rivers and streams (*e.g.* Jessop 1998; Wang and Tzeng 1998; Jessop 2000) and therefore, the trapping methodologies and surveying techniques had to adapt to the unique study location of the WSJR and compliment different aspects of elver behaviour. A targeted sampling approach using traps was developed and employed during the suspected timing of elver upstream migration from June-August 2015-2016 (Tables 2.1 – 2.3). Different passive (N=4) and active (N=1) trapping techniques were used that complemented the swimming capabilities and substrate use of elvers based on previously developed trap designs (Figure 2.6).

The first passive trapping method was a habitat trap (Figure 2.6A), adapted from the design of Silberschneider *et al.* (2001). Each trap was constructed using unravelled sisal rope attached to a plant saucer (diameter 25 cm) with a concrete base as the anchor. The sisal rope imitated the appearance of a macrophyte tuft. Young eels are known to use

submerged vegetation for cover and prefer complex natural habitats for protection, particularly during daylight hours (Barbin and Krueger 1994; Glova 1999). The small size of the trap made it portable and useful over a large spatial scale. The traps required minimal monitoring as eels could enter and exit with ease, and they could be placed in complex habitats with variable flows. As the eels could leave at-will, the traps provided a relative catch per unit effort (CPUE). As was the case with all the passive traps used in this study, the traps were checked for elver presence in daylight (day survey) – a time when elvers were most likely to be seeking cover.

The second passive trap type was a tube trap (Figure 2.6B), constructed using black PVC pipe (diameter 5 cm; length 35 cm). A mesh-netting (mesh size 1.2 mm) was secured over one end. The tube was attached to a concrete base as an anchor. Juvenile eels prefer interstitial spaces for cover (Glova 1999), and the small tube enclosure provided the eels with a dark and concealed hiding spot. The tube trap mirrored the advantages provided by the habitat trap.

The third passive trap used in this study was a box trap (Figure 2.6C). Unravelled sisal rope was attached to the inside of a tote, and holes were cut in alternative sides of the tote (15 cm x 10 cm). One hole was covered in mesh-netting (mesh size 1.2 mm) while the other was covered in conical netting with a small hole at the tip of the funnel to allow for entrance into the tote. Because the opening is small and pointed directly inside the trap, eels that enter have difficulty finding the exit and remain trapped within the closed tote. The function of the opposite hole with the mesh was to allow the river water to make its way through the tote and attract elvers towards the upstream flow, and to retain flow of fresh, oxygenated water through the trap. Because eels are not able to

escape, this trap gives an estimate of CPUE. However, it is less portable and unlike the previous trap types, requires daily monitoring.

The active trapping technique involved use of an abundance net (Figure 2.6D). The method consisted of a net (1 m x 0.8 m) of fine mesh (mesh size 2 mm). The net was laid flat on the river bottom using chains around the exterior for added weight. Rope (length 1.5 m) was attached to the net at the corners and mid-sections. Over time, elvers would swim over the net, and after a designated period of time (5 mins), the rope was pulled upwards to trap eels within the net. Since use of this trap is cast by hand and timed, it is portable and gives an estimate of CPUE. It is most useful during night surveys when elvers are observed in their active state and it can be deployed along the banks of the river.

In 2016, two eel ramps were acquired near the end of the survey season (Figure 2.6E) as a fourth passive capture method used in this study. These pre-fabricated ramps (Lakeside Engineering Inc., USA) were designed to catch American eel elvers by taking advantage of their upstream migratory behaviour. A pump (174 L/min) attached to a long hose was used to bring water from the river to the ramp. Most of this water was used to create a primary attraction flow and was expelled at the base of the ramp, but a small portion was directed to the uppermost crest of the ramp (secondary attraction flow) to entice the eels to make their way up the ramp's inclined matted surface (122 cm long, 45 cm wide). The young eels were able to climb the river embankment towards the ramp guided by the oncoming primary attraction flow. Once they arrived at the base of the ramp, they followed the gentle trickle of secondary attraction flow until they arrived at the crest of the ramp and descended into the collection tote below.

To understand American eel elver distribution and timing of movements as they approached the MQGS, the various traps described above were deployed strategically throughout the WSJR (Figure 2.4); the placement strategy of the traps evolved both within season and between years as more information became available regarding elver and juvenile eel spatial distribution. Beginning in June 2015, habitat traps and tube traps were placed at 12 separate sites (Table 2.1; Figure 2.4C) in clusters of approximately four to five traps per site along both banks of the river within 20 km downstream of the MQGS. Of these 12 sites, six sites were located downstream of where a relative higher gradient was observed, thus representing a potential location for velocity barrier (Velocity Barrier Downstream; VBDS; Table 2.1; Figure 2.4C). In addition, six sites were located just upstream of the predicted velocity barrier (Velocity Barrier Upstream; VBUS; Table 2.1; Figure 2.4C), and it was assumed this design would allow a contrast between sites that are accessible to elvers (VBDS) and those that are inaccessible (VBUS). Two trap clusters were also placed along the Nashwaak River (NASH) near its confluence with the WSJR (Table 2.1; Figure 2.4D). In all reaches, the spatial clusters of traps covered enough area along the possible migratory pathways to ensure elvers would have ample opportunities to enter a trap. The number of day survey checks for traps in these river reaches (VBDS, VBUS, and NASH) was primarily 10-11 events and occurred between June and August 2015 (Table 2.1).

As the 2015 sampling season progressed, visual observations of elvers influenced the relocation of select traps, and the focus shifted to recording the near-dam vicinity distribution (from the MQGS and up to 1 rkm downstream) to better understand elver behaviour and flow preference as they approached the MQGS structure (Figure 2.4B;

Table 2.2). A combination of habitat traps, tube traps, and box traps were deployed to determine distribution and CPUE at nine sites within that area (Table 2.2; Figure 2.4B); N = 3 traps were clustered at each site (with exception of N = 2 at the Site 3 (Accelerated Rearing Facility (ARF); Table 2.2). From mid-July until August 2015, a total of 14 day survey events were undertaken where traps were checked within the near-dam vicinity (Table 2.2).

In 2016, the methodology transitioned to night surveys using the abundance net as an alternative to habitat traps used in 2015 (habitat traps were still used for providing additional elvers that were used in the length analysis, but not for CPUE). The abundance net was deployed at seven sites along the banks of the near-dam area to better discern CPUE between different areas (Table 2.3; Figure 2.4B); the net was deployed N = 2 times at each site during each trapping occasion. Active night surveys using the abundance net were conducted every few days throughout the sampling season from late June to late August 2016 (Table 2.3). A total of 10-11 active survey nights were sampled in 2016. Once the eel ramps were acquired late in the field season, one ramp was deployed on the north bank at a location 150 m downstream of the ARF (Table 2.3) and was operated from August 24 to November 17, 2016. Elvers were surveyed during 15 separate trap-check events.

By 2017, elvers were discovered in the MQGS spillways and, as a result, the study objectives shifted from spatial analysis (See Chapter 3). The capture of upstream-migrating elvers was focused at the MQGS diversion sluiceway and main spillway (Figure 2.2) using dip netting between June to August 2017; for these elvers, only the size information is reported herein for a more complete description of all collected size

data throughout the thesis data collection period; 2017 CPUE data is reported in Chapter 3. In addition, eel ramps (Figure 2.4B) continued to be operated from June 16 to July 13, 2017, and the captures from these 2017 events (five checks at the downstream ramp; seven checks at the ARF ramp; Table 2.3) is reported herein.

The mean water velocity (ms^{-1}; Marsh-McBirney Flo-Mate Model 2000, 60 % depth), temperature (handheld general-purpose liquid-in-glass thermometer), and substrate composition (Modified Wentworth Scale, Gautreau *et al.* 2015) were estimated at each site and is reported where applicable.

2.2.3 Measurement and ageing of elvers and young eels

All American eels were assessed for total length (TL) and wet weight (WT). Upon capture, eels were anesthetized using a clove oil bath (active ingredient eugenol, 40 mg/L; mixed with ethanol as a carrier in 1:10 ratio). After elvers were anaesthetized (*i.e.*, unresponsive to touch, ceased typical undulating movement), total length (1 mm) and wet weight (Ohaus Scout Pro; 0.01 g) were measured. Pigmentation was noted as per Haro and Krueger (1988), however, as it became evident there was effectively no variability in pigmentation stage (elvers had pigmentation stage 7), further notetaking on this aspect was discontinued after summer 2015. After recovery from the anaesthesia (*i.e.,* showed normal swimming activity), the eels were released at the point of their capture. A random selection of elvers were euthanized each summer (using an overdose of clove oil solution) for ageing analysis. In total, 30 elvers were retained between 2015-2017 and ranged in size between 43 mm – 152 mm. The elvers used for ageing analysis were collected within 1 rkm of MQGS, from June 2015 (N=2), May-August 2016 (N=9), and June-August 2017 (N=8). However, after discussion with commercial elver fishermen in

the Bay of Fundy regarding the size range of elvers upon entry to the WSJR, and the apparent lack of elvers in similar size at MQGS, additional elvers (N=11) were obtained from a Bay of Fundy estuary near the mouth of the WSJR in 2016 for the ageing analysis.

To determine the age of the eels retrieved during this study, the annual growth rings were counted on sagittal otoliths (Stevenson and Campana 1992; Poole and Reynolds 1996). The method employed in this study was adapted from the removal, embedding, and polishing method described in Secor *et al.* (1992). The sagittal otolith was used as it is the largest of the three otolith structures in teleost fishes, making it easier to handle, manipulate, and observe the clearest resolution of the microstructural features (Secor *et al.* 1992). The sagittal otoliths were extracted by making a longitudinal cut through the head from the dorsal surface of the eel, in laboratory. From this view, the otic capsules to the left and right of the head revealed the sagittal otoliths which were removed carefully with forceps and stored for ageing analysis (Hu and Todd 1981). Once the otoliths of all eels had been removed, the otoliths were embedded in hardened thermoplastic glue (Crystal Bond). Before handling the otolith, a small amount (*i.e.*, slightly larger in size than the otolith that was to be embedded within) of hard Crystal Bond glue was placed on a glass slide and warmed to the point that the glue softened (65-100˚C). Next, the otolith was carefully transferred to the slide and pressed into the glue along the medial surface, and the glue was then left to cool and harden. The final step before aging involved the grinding and polishing of the otolith to allow reading of annual rings. In this study, the otoliths were polished through the sagittal plane (Appendix 1), which allowed the otolith to lie in the flattened position as it was embedded into the Crystal Bond. Due to the extremely small size of the juvenile eel otoliths (and

particularly the core which is typically less than 20µm in diameter), the polishing proceeded in small incremental steps, with frequent checks on progress through a compound microscope and transitioning from a fine sandpaper (400 grit) to a polishing cloth (2000 grit) until the core became visible.

After the polishing was complete, and the core of the otolith was clearly visible, photographs of the otoliths were taken using a compound microscope under 100x magnification. Annulus rings were identified that coincided with juvenile eel movement from oceanic to continental phase (Poole *et al.* 2004; ICES 2009). The first dark band outside the nucleus forms during the eel's first winter in the estuary and has been defined as the origin point in age determination (age zero ring, or "freshwater check"), where subsequent rings represent the winter annuli and were counted to represent the freshwater age of each eel (Poole *et al.* 2004, ICES 2009; Walsh *et al.* 2016).

All elver handling protocols were carried out under UNB Animal User Protocol AUP17039.

2.2.4 Statistical analysis

To examine whether there were differences in American eel elver relative abundance between the trapping locations at the vicinity of the MQGS, the most consistent method providing CPUE data across sampled sites were used. As only the habitat traps (Figure 2.6A) and abundance net (Figure 2.6D) produced sufficient data for statistical analyses of spatial patterns, CPUE data for both habitat traps and the abundance net were assessed in 2015 and 2016. The replicates (two or three / sampled site; Table 2.2 and 2.3) from each sampling location at each sampling date were averaged to give a representative CPUE value for each site/time event. These CPUE data across

annually sampled sites were assembled into a full matrix of all sampling events (14 events in 2015; 11 events in 2016) as replicates, and related-samples Friedman's two-way analysis of variance by ranks was conducted to detect any differences in average relative abundance between the sampled locations. The non-parametric test was selected due to a large number of zeros in data matrix and resulting non-normality and heteroscedasticity. In a few instances where a site was not sampled during all events, the missing value was replaced by the site's CPUE average to achieve a balanced design (N = 4 of 126 values in 2015; N = 2 of 77 values in 2016). Post-hoc pairwise comparisons were Bonferroni corrected. Differences in temporal patterns in relative abundance between sites were not formally statistically analysed due to the nature of the data; visual inspection and description of general patterns are reported. Similarly, formal inter-annual comparisons were not conducted due to incomparability of CPUE data stemming from different sampling methods and timing of sampling between years.

Between-year differences (2015-17) in the average length of elvers collected at the MQGS were compared using one-way ANOVA with underlying tests regarding normality (Shapiro-Wilk test) and homogeneity of variances (Levene test); Shapiro-Wilk test indicated small deviation in normality; due to the large sample size, ANOVA was carried out nevertheless. Multiple pairwise comparisons were conducted using Tukey HSD test. Statistical analyses were conducted in SPSS 26.0.

2.3 Results

In 2015, the habitat, tube, and box traps located in the predicted area of a potential velocity barrier for elvers (VBDS river reach 20 rkm downstream of the MQGS, from 130-150 rkm upstream of the Bay of Fundy; Figure 2.4C) did not prove successful in

capturing elvers. Overall, 13 individual eels were captured within the six trapping locations in the VBDS reach (Table 2.1), but they ranged in TL from 15.0 to 33.2 cm (avg. 24.1 cm) and were effectively yellow eels. Similarly, only one eel was captured in the Nashwaak River reference area (Table 2.1) and was determined to be non-elver by its size (TL = 19.8 cm). The reach predicted to be upstream of a potential velocity barrier (VBUS) produced a total of 12 eels (Table 2.1). The majority of the VBUS captures were yellow eels (ranging TL = 14.1 to 23.0 cm), and there were five eels ranging from TL = 10.3 to 11.9 cm and < 2 g in weight and were suspected to be elvers.

As the primary objective for the VBDS and VBUS areas downstream of MQGS was to evaluate the presence and location of a velocity barrier, but a few potential elvers were in fact encountered upstream of the predicted velocity barrier location (the VBUS reach; Table 2.1), trapping efforts were then attempted directly at locations in the vicinity of the MQGS starting mid-July 2015. Upon discovery of elvers in the MQGS area within 1 rkm of the dam, it was determined that a velocity barrier does not exist, and all further trapping effort was directed immediately to the MQGS reach. It was further observed that only a single eel was captured in the tube traps and zero in the box traps during trapping efforts in the VBDS/VBUS/NASH reaches, and therefore, all near-dam trapping efforts focused solely on using habitat traps for the rest of field season in 2015. Information provided below reports results solely from the near MQGS area (Figure 2.4B) using habitat traps (Figure 2.6A).

After trapping operation started in the vicinity of the MQGS (from the MQGS and up to 1 rkm downstream) in mid-July 2015, elvers were captured at several locations near the MQGS using habitat traps (Table 2.2; Figure 2.7A). Given that at least some elvers

were captured at most sites in the MQGS reach (Table 2.2), this suggested that there is no apparent velocity barrier impeding the elvers' ability to approach the dam. The CPUE data indicated that significant differences existed between the nine different trapping locations used in 2015 in the vicinity of the MQGS (Friedman's 2-way ANOVA; $F_8 = 45.31$; $p < 0.001$; Figure 2.7A; Table 2.2). Areas of heightened elver activity were recorded along the north bank of MQGS (Sites 1 – 4; Figure 2.4B; Table 2.2.), with eels showing obvious attraction towards the Accelerated Rearing Facility (ARF; Site 3, Figure 2.4B) location in particular (Figure 2.7A; Table 2.2). A much lower abundance (*i.e.*, a near absence) of elvers was observed on the trapping site situated by the earthen dam, and all four sites on the south bank of MQGS area (Table 2.2; Figure 2.7A). Site 3 was identified in Bonferroni-adjusted pairwise statistical comparisons (following Friedman's 2-way ANOVA) being statistically different from all sites located on the south bank of the river (Sites 8-11; $p < 0.02$ in all cases).

While 2015 data did not include the initial arrival of elvers at MQGS (due to late starting date), it showed a declining temporal distribution of elvers through the later part of the summer. Elver abundance peaked in mid-July followed by a swift decline such that CPUE was very low across all sites through August (Figure 2.7A).

By 2016, it was determined that active trapping using the abundance net during night surveys was most effective among capture techniques tried at achieving a CPUE estimate of elver abundance. Sampling in 2016 focused on $n = 2$ abundance net "sets" deployed at each of seven monitored sites for each sampling date. Like the previous year, there were significant differences in elver abundance between the monitored sites (Friedman's 2-way ANOVA; $F_6 = 39.91$; $p < 0.001$; Figure 2.7B; Table 2.3) and the

relatively higher elver abundance was observed on the monitored sites on the north bank as opposed to the site by the earthen dam or the sites on the south bank. Similarly to the previous summer, the highest total capture was observed at the ARF site (Site 3) but other sites on the north bank indicated high abundance as well (Table 2.3). In fact, when the CPUE data of individual sampling dates was examined, other sites on the north bank had a higher CPUE on occasion than the ARF site (Figure 2.7B), and of the north bank sites, only Site 4 was observed to have a statistically lower CPUE than Site 3 (Tukey 3.56, $p = 0.008$), with no other Bonferroni corrected statistical differences. The CPUE at the site located by the earthen dam (Site 7) was statistically lower from all sites on north bank ($p <= 0.039$) except Site 4 ($p = 1.0$), and additionally, Site 9 on south bank had a statistically lower CPUE than site 3 ($p = 0.002$).

The timing of elver presence in 2016 followed a similar large-scale trend as observed in 2015. The monitoring started earlier in 2016, and elvers were readily captured on the first survey date in mid-June (Figure 2.7B). The peak CPUE was observed in July, similar to 2015. Although some sites visited in 2015 (Site 8, 10, and 11) were replaced by new monitoring sites (Site 5 and 6) due to limited accessibility, the new sites also had elvers present with peaks in late June through July (Figure 2.7B). The abundance of elvers was much lower through the month of August at all sites where monitoring was conducted using the abundance net (Figure 2.7B), consistent with the trend observed in 2015.

The abundance of elvers from the eel ramp deployed in mid-August 2016 showed that this method of elver capture was not only feasible, but that moderate elver abundance was observed through mid-August to mid-September, and thus that some elvers remain in

the MQGS area even after habitat traps (2015) or abundance net (2016) indicated a very low abundance (Figure 2.8A). In 2017, two American eel ramps operated and subsequently caught elvers within the area near MQGS from June 16 to July 13 (Figure 2.8B). Eel abundance showed a steady increase over time peaking in mid-July, primarily at the downstream location which was located 150 m downstream of the ARF (Figure 2.4B). Unfortunately ramp operations became unreliable for accurate assessments after mid-July due to logistical constraints and operational difficulties.

Small variability in average total length of elvers captured at MQGS was observed between the years (Figure 2.9). The average (± SD) elver TL was 113.3 mm ± 15.2 mm (2015; N=327; range 71 mm – 202 mm), 110.8 mm ± 14.3 mm (2016; N=182; range 82 mm – 175 mm), and 117.2 mm ± 13.9 mm (2017; N=2640; 80 mm – 175 mm). These average lengths were statistically significantly different (ANOVA; $F_{2,3146} = 26.7$; $p < 0.001$), and Tukey HSD test revealed that average size was significantly larger in 2017 in comparison to both 2015 and 2016 ($p < 0.001$), but no differences were observed between 2015 and 2016 average size ($p = 0.124$). Otolith analysis suggested that the elvers encountered at MQGS ranged from 0 to 3 years (Figure 2.10). Additionally, it was determined that as elver age increases, there is a positive relationship with an increase in total length (Figure 2.10). The age 0 elvers encountered at MQGS were larger (TL = 75 mm – 95 mm) than the age 0 elvers sampled at the Bay of Fundy estuary (TL = 43 mm – 77 mm) (Figure 2.10). Based on the relationship between the lengths and ages of elvers found at MQGS (Figure 2.9; Figure 2.10), it was determined that a low percentage of measured elvers were age 0 (4.5 – 7.0 %). Most elvers encountered at MQGS fell within the length range of 1 year old (54.7 – 57.2 %), while others are predicted to be two years

old (33.4 – 35.2 %) and a smaller cohort are within the range of three years old (20.5 – 22.4 %).

2.4 Discussion

Based on the hypothesis proposed by Jessop and Harvie (2003), this study aimed to determine the spatial and temporal distribution of American eel elvers in relation to a potential velocity barrier in the lower WSJR. It was determined that no such velocity barrier exists within the downstream approach to the MQGS; instead, an upstream migrating contingent of American eels, herein termed elvers, with an average length annually varying between ~111 – 117 mm and aged 0 – 3 years are readily present at MQGS. Furthermore, it was discovered that while elvers are present at the MQGS, they are not randomly distributed within the dam's vicinity but are found in higher relative abundance adjacent to small trickling inflows on the river's north bank and their temporal migration patterns show a clear timeline of peak abundance at the dam from mid-June to the end of July.

American eel elvers were observed attempting to migrate upstream at the MQGS in both of the studied years, contrary to previous reports citing the absence of elver activity at the dam (Jessop and Harvie 2003). Jessop and Harvie (2003) speculated that the installation of the additional two turbine units in late 1979 and early 1980 may have had inadvertent impacts on the upstream migration of elvers. However, the data obtained in this study suggest that, in the contemporary period, the operation of the hydroelectric facility does not create a velocity barrier to migrating elvers, as defined in this study (*i.e.*, juvenile eels demonstrating strong rheophilic affinity and migratory behaviour). Thus, it is unclear what may have explained the absence of elvers in 1980, however, Jessop and

Harvie (2003) hypothesized that perhaps declining larval production in the Sargasso Sea or unfavorable oceanic conditions could have had an adverse effect on the number of elvers and their distribution through the WSJR. Alternative explanation may relate to interpretation and terminology of an "elver" *vs*. juvenile American eel between Jessop and Harvie (2003) and this study, and this aspect – related to the size of American eels observed at MQGS – will be further discussed below.

Elver presence within the near-dam vicinity was not randomly distributed and there were significantly more elvers on the north bank of the river on approach to the dam and near the Artificial Rearing Facility (ARF) outflow than found at comparable locations along the south bank during either sampled year. A possible explanation can be traced to the flow from the spillway and turbines as it crosses the width of the river and hits the south bank. As the south bank receives the majority of the water's flow, and thus force, the north bank remains relatively slow-flowing and elvers may encounter less resistance. The slower flow in these areas is beneficial as the small eels avoid swimming through free stream velocities (McCleave 1980). Alternatively, elvers may have difficulty moving between and residing within the high flow habitats of the south bank. Validating the hypothesis that the higher abundance of elvers on the north bank is due to the favorable flow fields is a subject for a future study using appropriate computational fluid dynamic model where flow fields and relative abundance of elvers can be directly compared.

The ARF outflow along the north bank created a significant point of attraction. The ARF outflow consists of a trickling stream of water exiting from an Atlantic salmon rearing facility. When in operation, this facility collects warm water expelled from the six

generating units of the MQGS and passes it through the incubation building to accelerate growth and production of juvenile Atlantic salmon parr (*Salmo salar*) (Farmer *et al.* 1990). The outflow from the ARF releases a constant stream of water into the river, and elvers were observed moving up the rocks of the shore towards the source of this flow, accumulating at the outflow in numbers greater than other locations in the MQGS vicinity. When operational, the water within the facility is notedly warmer than river water (Farmer *et al.* 1990). However, from June to January, operations at the ARF cease and the water from the outflow reverts to standard river water (no warming involved) (G. Perley 2015, Fisheries and Oceans Canada, pers. comm.). Therefore, unsurprisingly, our temperature readings at the elver traps below the ARF outflow found similar readings to other sites within the dam's vicinity (Table 2.2; Table 2.3). Nonetheless, elvers were consistently located moving from the river up the ARF outflow stream as would be predicted from other studies observing movements up damp, vertical surfaces (Legault 1988; Tesch 2003). Their behaviour near the outflow supports the recommendation that an appropriate upstream passage system with small flows for attraction in otherwise calm areas at the dam may allow elvers to move upstream of MQGS.

While elvers were abundant within the vicinity of the dam throughout the late summer months of both 2015 and 2016, elvers were rarely found further downstream (20 rkm from dam) in 2015, making any analysis of eels from this area ineffective (and thus effort was discontinued after 2015). One potential explanation for this observation may be that the elvers have rapidly arrived in this downstream area of the river using selective tidal stream transport (McCleave and Kleckner 1982) and are still in a period of active upstream migration (Jessop and Harvie 2003) and, therefore, not settling into the

downstream traps for extended periods of time. Once at the dam, the eels are unable to move further upstream and consequently accumulate in greater numbers and must settle into the habitat making them susceptible to our trapping techniques, which is consistent with juvenile eel behaviour at the base of large dams (Smith and Saunders 1955).

Additionally, the elvers migrate through very large areas within the downstream section of the WSJR and more traps may have been needed to adequately sample the available habitat. Further study would be required to evaluate how the young eels redistribute to the downstream reaches after they cease trying to ascend the MQGS, and whether a larger effort using different traps (*e.g.*, an elver fyke net) would be successful for interception during their upstream migration in the lower sections. In 2016, elvers continued to be captured in an eel ramp located ~230 m downstream of the MQGS even after relative abundance at the sites close to MQGS declined to near 0. This suggests a period of downstream redistribution and settling later in the summer may be occurring, a hypothesis for future studies.

Unfortunately, time and logistical constraints prevented effective use of eel ramps in late summer / autumn of 2017, preventing additional study of abundance patterns further away from MQGS. While a potentially promising future method, challenges to elver ramp operations are presented in a hydro-regulated river due to hydropeaking operations. Setting an eel ramp at the river's edge can result in the ramp and its water intakes fluctuating from exposed to inundated in a peaking cycle. Throughout July and August 2017, operational constraints also led to persistent power issues affecting the ramp pumps, ultimately resulting in an early end to our 2017 ramp surveys. Coordination

with hydro-operator and eel ramp operations will be paramount for this method to be successful.

Elver arrival at MQGS increased from late June until late July / early August, peaking in mid-to late July. These results suggest a seasonal pattern of migration. This is another important result for future elver capture and translocation facility designs; a permanent upstream passage system for American eel elvers may not be required and a passage system deployed only during the relatively short peak migration season would be effective for passing elvers upstream of MQGS. Therefore, an efficient passage system may not be a considerable time burden, and a transportable structure could be removed during the non-migratory period to avoid months of considerable flow (spring freshet, and autumn rainstorms) and velocity (to avoid damage and additional cost).

The average length of surveyed American eels from 2015-2017 at MQGS was larger (with a pooled average length for 2015-17 at TL = 116.5 mm ± 14.2 mm) than the defined length of an elver as per the Canadian Science Advisory Secretariat and Maritime Provinces Fishery Regulations, *i.e.*, <100 mm (DFO 2010). This result implies that the eels caught at the MQGS do not meet this earlier length-based definition as elvers and may be young yellow eels instead. However, according to the behaviour-based definition (juvenile eel with positive rheotaxis and clear upstream migration motivation; see General Introduction, Section 1.2), the observed eels were considered to meet the criteria for an elver. The LeBlanc (1973) elver survey noted that, while elvers were found by the thousands throughout July, no “glass-elver” stage eels were captured, reported, or sighted in the MQGS area, and that all captures represented pigmented eels. However, the author’s classification of a “glass-elver” was not clear and neither length nor age

distributions have been previously provided for the MQGS area in any study and thus cannot be compared with the current work. The limited historical documentation of juvenile eel / elver size or age observed at MQGS renders it is impossible to assess if the life stage (*i.e.*, glass, elver, or yellow eels) of migrating eels has changed through time, although anecdotal information obtained from a previous Fisheries and Oceans Canada biologist maintains that young eels < 70mm would have been previously abundant at the MQGS (B. Jessop 2015, Fisheries and Oceans Canada Maritime Region, retired, pers. comm.). As there is no clarity regarding the size of the elvers at MQGS before 1980, the discrepancy regarding elver presence between the current study and absence in Jessop and Harvie (2003) could also be simply a difference in definition. In their report on elver observations in 1980, Jessop and Harvie (2003) defined migrating elvers as juvenile eels recently arrived from the sea and having a length of 55-65 mm and indeed, this size class was not observed in the current study either. Contrastingly, in 1992, 1,900 juvenile eels of 74-133 mm were collected 0.5 km downstream of the MQGS but were not considered "elvers" at the time (unpublished data referenced in Jessop and Harvie 2003). These larger juvenile eels of 1992 show similar length characteristics as the elvers captured in this study. Whether or not smaller juvenile eels reached the MQGS pre-1980 and continue to be absent to the current day cannot be determined but is possible. Because different definitions of elvers exist, this study nevertheless concludes that in 2015-2017, juvenile eels whose behaviour at the dam is consistent with the strong upstream migratory movements of elvers are present at the MQGS and match the description of young yellow eels that have also been observed undertaking migratory behaviour elsewhere (Haro and Krueger 1991). As the age 0 elvers sampled from the lowermost

sections (estuary) in the WSJR and small tributaries of the Bay of Fundy were 43-72 mm, it is recommended that further research is required to determine if elvers migrating upriver are spending an additional year within the WSJR system before ascending to the MQGS. If so, this suggests that elvers meeting the size-based criterion (< 100 mm) are overwintering at an unknown location downstream.

The results of this study also highlighted differences in American eel elver lengths between years (2015-2017). There were no significant differences between elver lengths from 2015 and 2016, but elvers in 2017 were significantly larger. While collection methods differed between all years as the most suitable trapping methodology evolved through this study, the capture locations and numbers along the banks of the downstream vicinity of the MQGS were more similar between 2015 and 2016 as opposed to the 2017 survey that differed with a focus on data collection from the diversion sluiceway and main spillway gates of the MQGS. Therefore, the difference in length distributions between 2015 and 2017 and between 2016 and 2017 could be a result of the methods and capture locations, and consistent annual surveys would be required to properly draw conclusions on elver length over time.

To clarify the life phase of eels present at the dam, otoliths were examined to determine the relationship between elver length and age. As expected, a positive relationship between the two variables was observed. Elver age-length from 2015-2017 was suggestive that the average elver at the MQGS was aged at 1 year within the freshwater system of the WSJR. However, they ranged from freshwater age 0 to 3 among the young eels that exhibit high upstream migration motivation. Elvers acquired from a Bay of Fundy estuary were indeed freshwater age 0, which is expected as they would

have only recently entered the freshwater system. That some elvers encountered at MQGS were freshwater age 0 was a curious finding, albeit their size was larger than age 0 elvers collected in the estuary. The age and length observations suggest that age 0 elvers can make it from Bay of Fundy to the dam in a time span of a two to three months and grow from 45 – 80 mm size to approx. 80 – 95 mm, but most elvers take several years to migrate the 150 rkm to the MQGS and may remain in this area for multiple years without the opportunity to advance beyond the dam although retaining their motivation to colonize the upstream area. Further analysis would require elver aging at multiple sites along the WSJR to determine the progression of age over a large distance migration.

Upstream passage for American eels in the WSJR may be important for regional eel survival, aiding in its global population sustainability and recovery, supporting sustainable elver fisheries, Indigenous reconciliation, and overall hydropower dam management in an environmentally benign fashion. A variety of eel ramp ladders have been developed for upstream passage at barriers (Solomon and Beach 2004) and by documenting the spatial distribution of eels at the MQGS in this study, there is potential to design a passage structure at a location of increased elver abundance, or a location where an abundance index for WSJR American eel presence could be established. This study provides baseline information on American eel elver movement, abundance, and distribution in the near-dam area to help inform discussions regarding future management and passage of American eels at the MQGS.

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Table 2.1 Juvenile American eel trapping sites by reach (VBUS: Velocity Barrier Upstream, VBDS: Velocity Barrier Downstream, and NASH: Nashwaak River reference location; Figure 2.4) in summer 2015 using habitat traps, including timing and frequency of trapping, average velocity at each site, and the total number of eels (of any size) captured at each site. Note that the Site number corresponds to the location indicated in Figure 2.4C (VBUS, VBDS) and 2.4D (NASH). Distance (Dist) shows location of sites relative to Mactaquac Generating Station measured as river km on mid-channel; positive number shows mid-channel distance upstream from corner of the powerhouse; negative numbers indicate distance downstream).

Reach	Site	Site Lat	Site Long	Dist (km)	Start Date	End Date	Avg. Velocity (m/s)	Avg. Temp. (°C)	Substrate	Total trap checks (# of traps)	Total Eels Captured
VBUS	12	45.96270	-66.83909	-2.4	28 July	20 August	0.050	21.8	Cobble	9 (5)	3
VBUS	13	45.95983	-66.84143	-2.3	15 June	20 August	-0.001	15.5	Sand; Pebble	16 (4)	6
VBUS	14	45.98933	-66.78538	-4.5	04 June	20 July	0.009	17.9	Sand	10 (5)	0
VBUS	15	45.98730	-66.78536	-4.5	04 June	20 July	0.024	17.9	Small pebble	10 (5)	2
VBUS	16	45.97392	-66.78776	-4.5	02 June	15 July	0.208	18.1	Sand	10 (5)	0
VBUS	17	45.97082	-66.78825	-4.5	02 June	15 July	0.207	17.8	Sand; Gravel	10 (5)	1
VBDS	18	45.97753	-66.74113	-7.9	04 June	20 July	0.232	17.9	Sand	11 (2)	5
VBDS	19	45.97464	-66.74299	-7.9	04 June	20 July	0.222	17.9	Sand	11 (2)	1
VBDS	20	45.97372	-66.74587	-7.6	04 June	20 July	0.065	17.9	Sand	11 (4)	0
VBDS	21	45.97192	-66.75353	-7.1	04 June	20 July	0.048	17.6	Sand	11 (4)	1
VBDS	22	45.96896	-66.74713	-7.6	02 June	15 July	0.091	18.0	Sand	11 (4)	4
VBDS	23	45.96751	-66.74961	-7.5	02 June	15 July	-0.040	17.3	Sand	11 (4)	2
NASH	24	45.95752	-66.61008	> -15 km	09 June	16 July	0.050	17.2	Sand	7 (4)	1
NASH	25	45.97326	-66.58955	> -15 km	05 June	20 July	0.214	18.1	Small pebble	10 (3)	0

Table 2.2 Total number of American eels, of any size, captured within the vicinity of the Mactaquac Generating Station (within 1 km of the dam) in 2015 using habitat traps, including timing and frequency of trapping, average velocity, average temperature, and substrate at each site. Distance (Dist) shows location of sites relative to Mactaquac Generating Station measured as river km on mid-channel; positive number shows mid-channel distance upstream from corner of the powerhouse; negative numbers indicate distance downstream).

Site #	Site Name	Site Lat	Site Long	Dist (km)	Start Date	End Date	Avg. Velocity (m/s)	Avg. Temp. (°C)	Substrate	Total trap checks (# of traps)	Total Eels Captured
1	North Bank Downstream	45.95998	-66.86057	-0.63	16-Jul	20-Aug	0.123	21.4	Pebble; Small cobble	13 (3)	9
2	North Bank Downstream of ARF	45.95753	-66.86246	-0.32	16-Jul	20-Aug	-0.039	21.4	Small cobble	14 (3)	16
3	Accelerated Rearing Facility (ARF)	45.95700	-66.86308	-0.22	16-Jul	20-Aug	-0.071	21.3	Sand; Small cobble	14 (2)	144*
4	North Bank Upstream	45.95592	-66.86390	-0.10	16-Jul	20-Aug	-0.031	21.6	Sand; Cobble	14 (3)	24
5	Fish Collection Bank	45.95561	-66.86553	-0.01	**No checks in 2015**						
6	Powerhouse Corner	45.95556	-66.86560	0.00	**No checks in 2015**						
7	Earthen Dam	45.95113	-66.86897	0.52	16-Jul	20-Aug	0.012	21.5	Sand; Small cobble; Cobble	14 (3)	3
8	South Bank Upstream	45.95105	-66.86658	0.38	16-Jul	20-Aug	-0.037	21.8	Sand; Cobble	14 (3)	1
9	South Bank Mid-Upstream	45.95188	-66.86532	0.25	16-Jul	20-Aug	0.059	21.2	Sand; Gravel; Small to large cobble; Bedrock	14 (3)	2
10	South Bank Mid-Downstream	45.95420	-66.86188	-0.10	16-Jul	20-Aug	0.123	21.1	Small to large cobble; Bedrock	11 (3)	0
11	South Bank Downstream	45.95522	-66.86065	-0.22	16-Jul	20-Aug	0.054	21.3	Sand; Small to large cobble	14 (3)	3

* Additional 58 eels were captured in exploratory surveys from July 10-15 at the ARF location.

Table 2.3 Total number of American eels, of any size, captured within the vicinity of the Mactaquac Generating Station (within 1 km of the dam) in 2016 (and 2017, indicated with *, for eel ramp site R1 and R2) using the abundance net, including timing and frequency of trapping, average velocity, average temperature, and substrate at each site. Distance (Dist) shows location of sites relative to Mactaquac Generating Station measured as river km on mid-channel; positive number shows mid-channel distance upstream from corner of the powerhouse; negative numbers indicate distance downstream).

Site #	Site Name	Site Lat	Site Long	Dist (km)	Start Date	End Date	Avg. Velocity (m/s)	Avg. Temp. (°C)	Substrate	Total trap checks (# of traps)	Total Eels Captured
1	North Bank Downstream	45.95998	-66.86057	-0.63	27-Jun	25-Aug	0.001	20.0	Pebble; Small cobble	10 (2)	24
2	North Bank Downstream of ARF	45.95753	-66.86246	-0.32	**No checks in 2016**						
3	Accelerated Rearing Facility (ARF)	45.95700	-66.86308	-0.22	20-Jun	25-Aug	-0.007	20.0	Sand; Small cobble	11 (2)	83
4	North Bank Upstream	45.95592	-66.86390	-0.10	20-Jun	25-Aug	-0.037	19.6	Sand; Cobble	11 (2)	15
5	Fish Collection Bank	45.95561	-66.86553	-0.01	20-Jun	25-Aug	-0.020	20.1	Sand; Cobble	10 (2)	41
6	Powerhouse Corner	45.95556	-66.86560	0.00	20-Jun	25-Aug	-0.012	20.0	Sand; Cobble	11 (2)	52
7	Earthen Dam	45.95113	-66.86897	0.52	20-Jun	25-Aug	-0.001	19.4	Sand; Small cobble; Cobble	11 (2)	0
8	South Bank Upstream	45.95105	-66.86658	0.38	**No checks in 2016**						
9	South Bank Mid-Upstream	45.95188	-66.86532	0.25	20-Jun	25-Aug	-0.018	18.9	Small to large cobble; Bedrock	11 (2)	4
10	South Bank Mid-Downstream	45.95420	-66.86188	-0.10	**No checks in 2016**						
11	South Bank Downstream	45.95522	-66.86065	-0.22	**No checks in 2016**						
R1	Elver Ramp Downstream	45.95807	-66.86197	-0.40	24-Aug	17-Nov	n/a	n/a	Small cobble	15 (1)	88
					27-June*	13-July*	n/a	n/a		5(1)	539
R2	Elver Ramp at ARF	45.95700	-66.86308	-0.22	16-June*	13-July*	n/a	n/a	Sand; Small cobble	7(1)	104

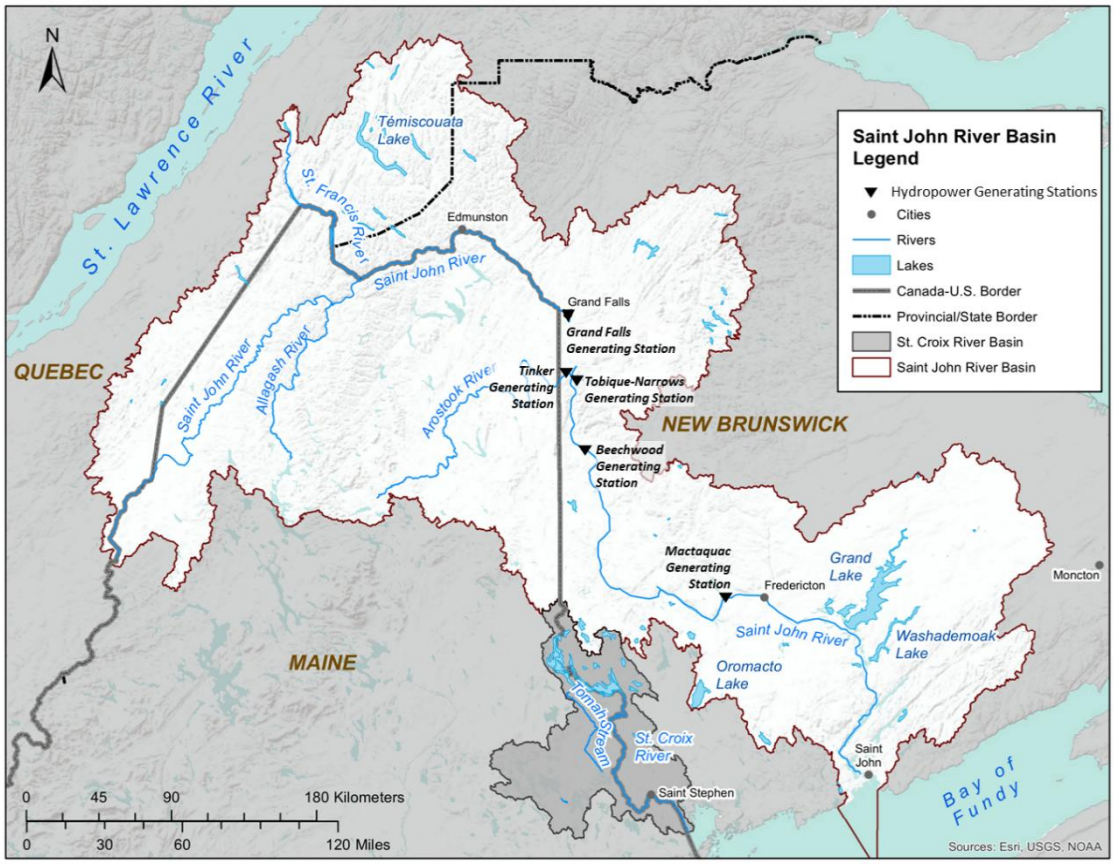

Figure 2.1 Wolastoq | Saint John River catchment showing locations of five main hydropower generating stations. The Mactaquac Generating Station is the lowermost dam, located 150 rkm upstream of the Bay of Fundy. Moving upstream, the Beechwood Generating Station is located at 285 rkm, the Tobique-Narrows Generating Station is located near the confluence of the Tobique River and WSJR at 315 rkm, the Tinker Generating Station is positioned on the Aroostook River (a tributary of the WSJR) near the mouth of the tributary at 318 rkm, and the Grand Falls Generating Station is located further upstream at 351 rkm. (Modified from the original map courtesy of International Joint Commission 2025).

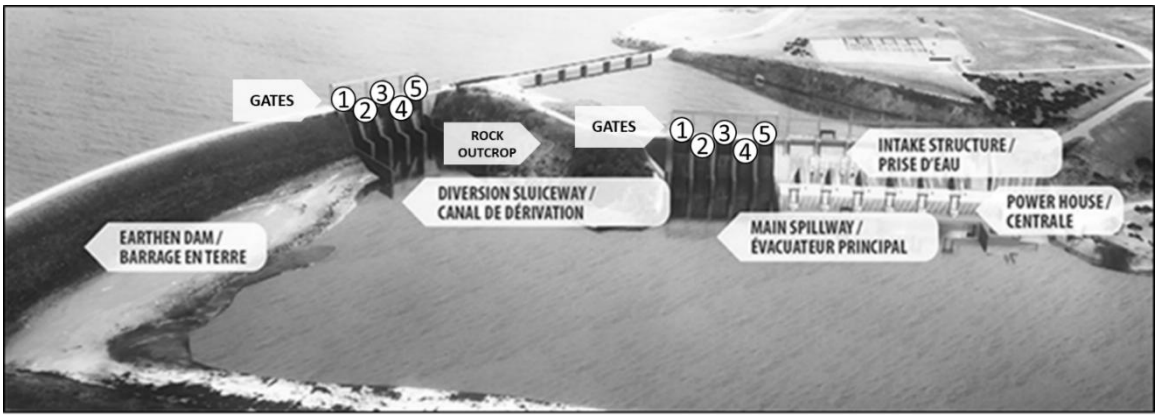

Figure 2.2 The Mactaquac Generating Station on the Wolastoq | Saint John River, NB, located 18 rkm upstream from the City of Fredericton. Main structures include the earthen dam, a diversion sluiceway, a natural rock outcrop, the main spillway, and the generating unit, consisting of intake structure and powerhouse. Both the diversion sluiceway (DS) and main spillway (MS) consist of five independently operated gated sections (henceforth DS1 through DS5, and MS1 through MS5) containing angled ogee weir surfaces. (Modified from the original diagram courtesy of NB Power 2014).

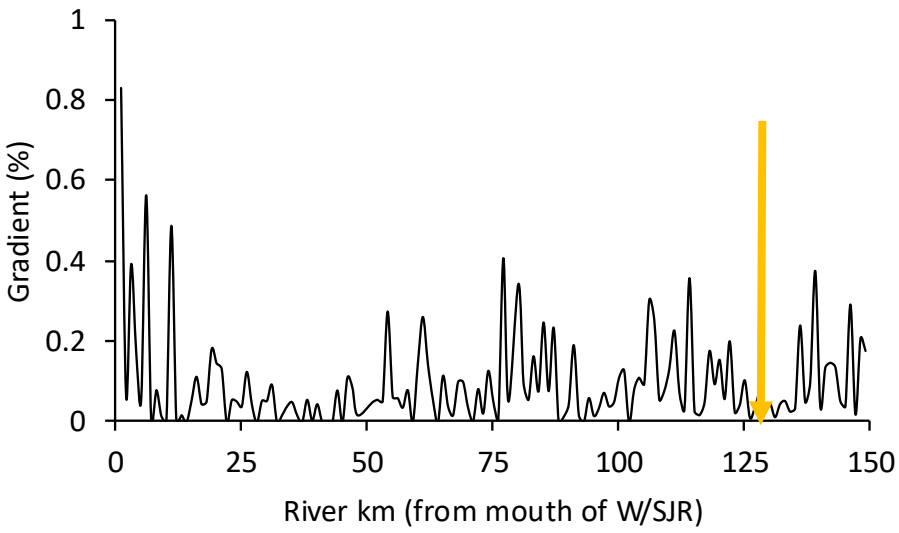

Figure 2.3 The water surface gradient of the Wolastoq | Saint John River, NB from the mouth of the river (0 rkm) to the Mactaquac Generating Station (150 rkm). The arrow at 130 rkm represents the approximate location the tidal head (Kidd *et al.* 2011; Andrews *et al.* 2020) and encompasses our study area (20 rkm reach of the WSJR downstream of MQGS) (Figure courtesy of A O'Sullivan, UNB, Faculty of Forestry and Environmental Management).

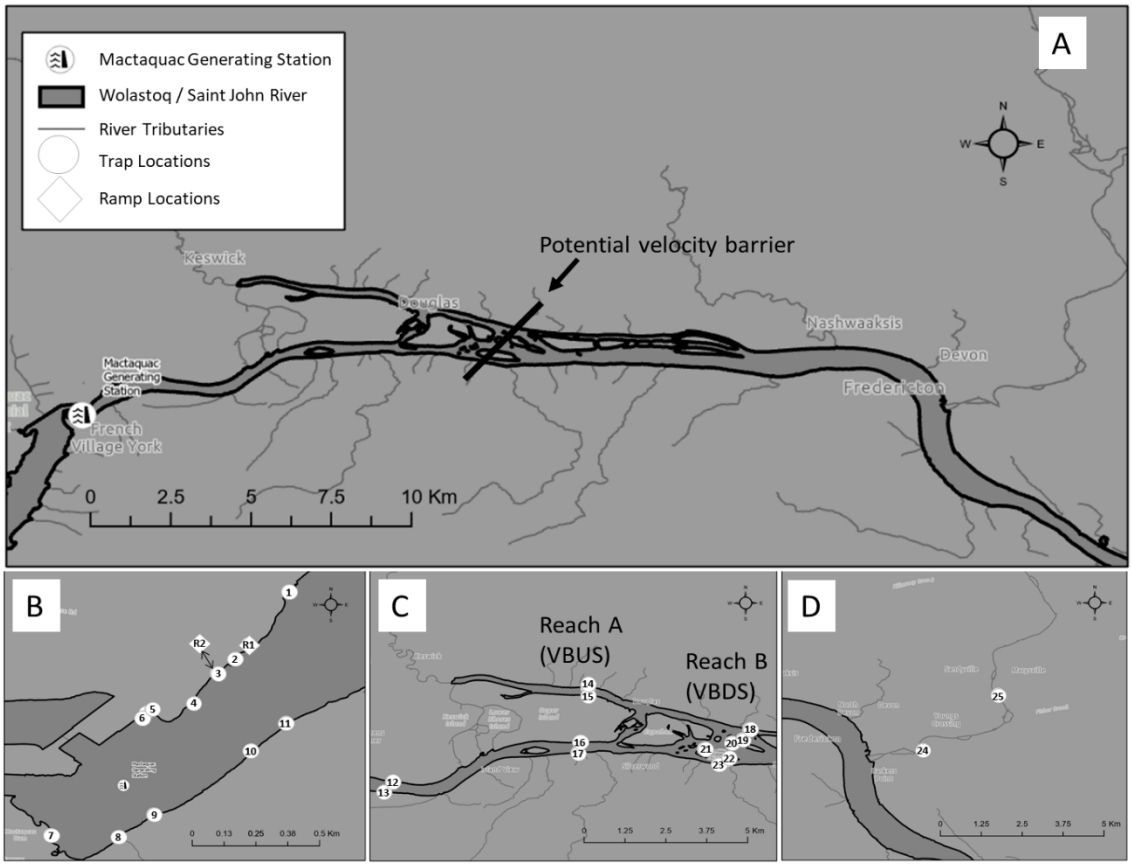

Figure 2.4 Panel A: Map of study area within the Wolastoq | Saint John River, Fredericton, NB to the Mactaquac Generating Station (MQGS). Panel B: Trap cluster locations of habitat trap, tube traps, box traps, and abundance net for American eel elvers within 1 rkm downstream of the MQGS (*i.e.*, "vicinity") for 2015-2017 field seasons (exact trap locations vary by year). The locations of the two ramps deployed within the 2016-2017 field season are included as R1 and R2. Panel C: Trap cluster locations of habitat traps and tube traps deployed in 2015 for American eel elvers upstream and downstream of potential velocity barrier at 140 rkm (Velocity Barrier Upstream: VBUS, Velocity Barrier Downstream: VBDS). Reach A includes clusters of traps in locations upstream of potential velocity barrier, while Reach B includes traps downstream of

barrier. Panel D: Trap cluster locations of habitat traps deployed in 2015 for American eel elvers within the Nashwaak River (a reference location).

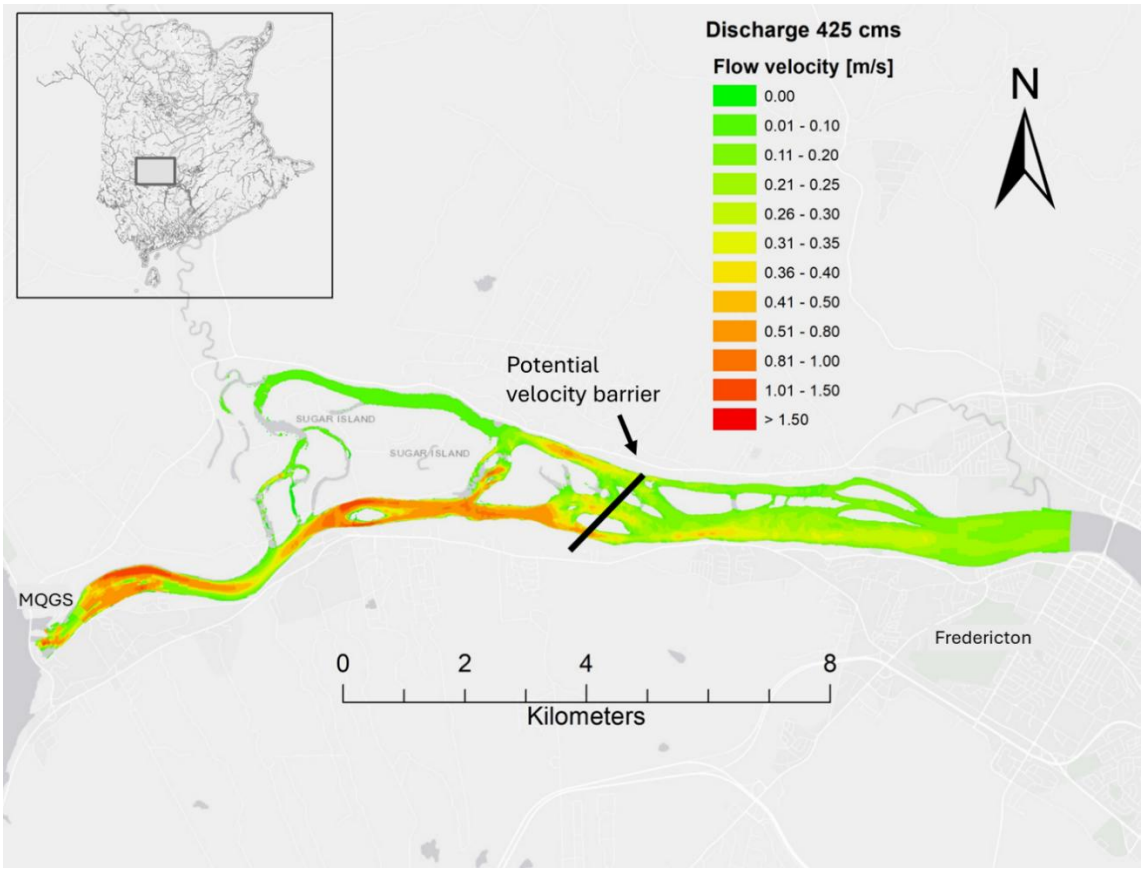

Figure 2.5 The distribution of modeled depth-averaged velocity downstream of the Mactaquac Generating Station; simulation presented for typical summer low flow discharge Q = 425 m^3/s. The flow velocity (m/s) threshold reported as a velocity barrier by Jessop and Harvie (2003) is at 25 cms^{-1}. Potential velocity barrier location is indicated by an arrow, and study reaches on both sides are highlighted (Velocity Barrier Upstream VBUS; Velocity Barrier Downstream VBDS; Figure's hydrodynamic modeling output courtesy of B Wegscheider, UNB, Department of Biology).

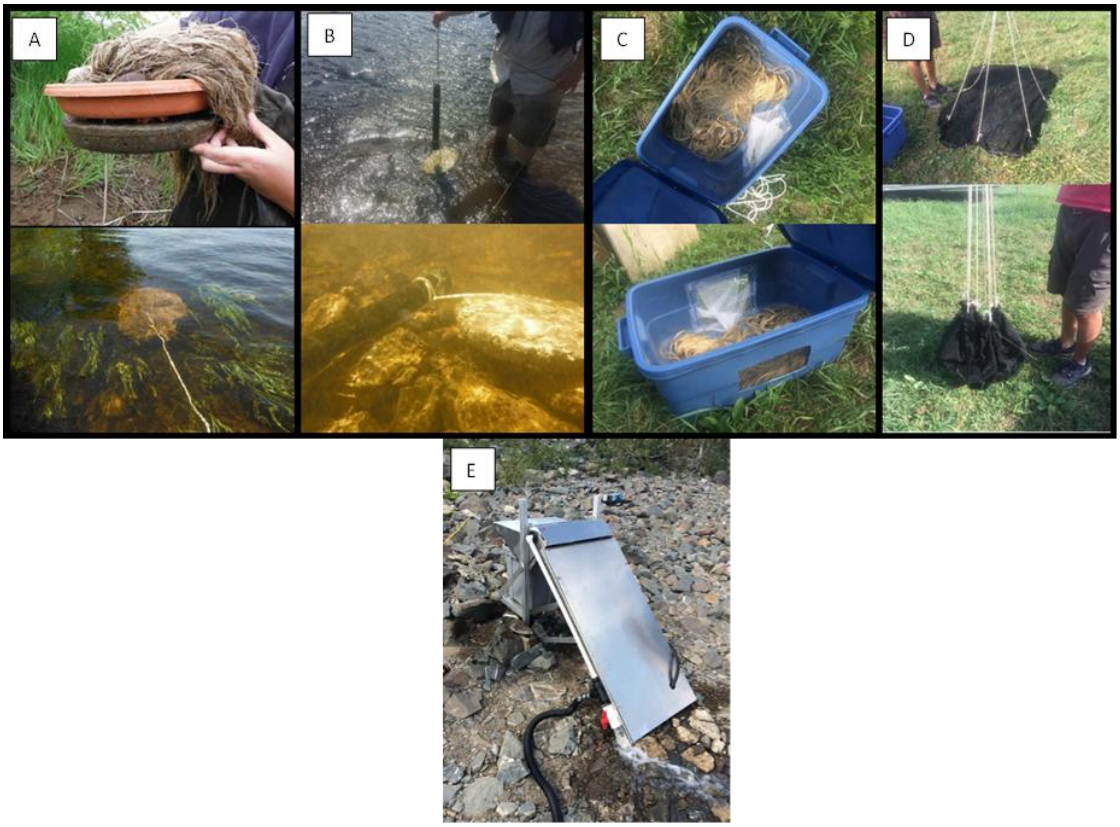

Figure 2.6 Gear used to capture elvers and juvenile American eels in the Wolastoq | Saint John River. A) Habitat trap, B) tube trap, C) box trap, D) abundance net, and E) eel attraction flow ramp.

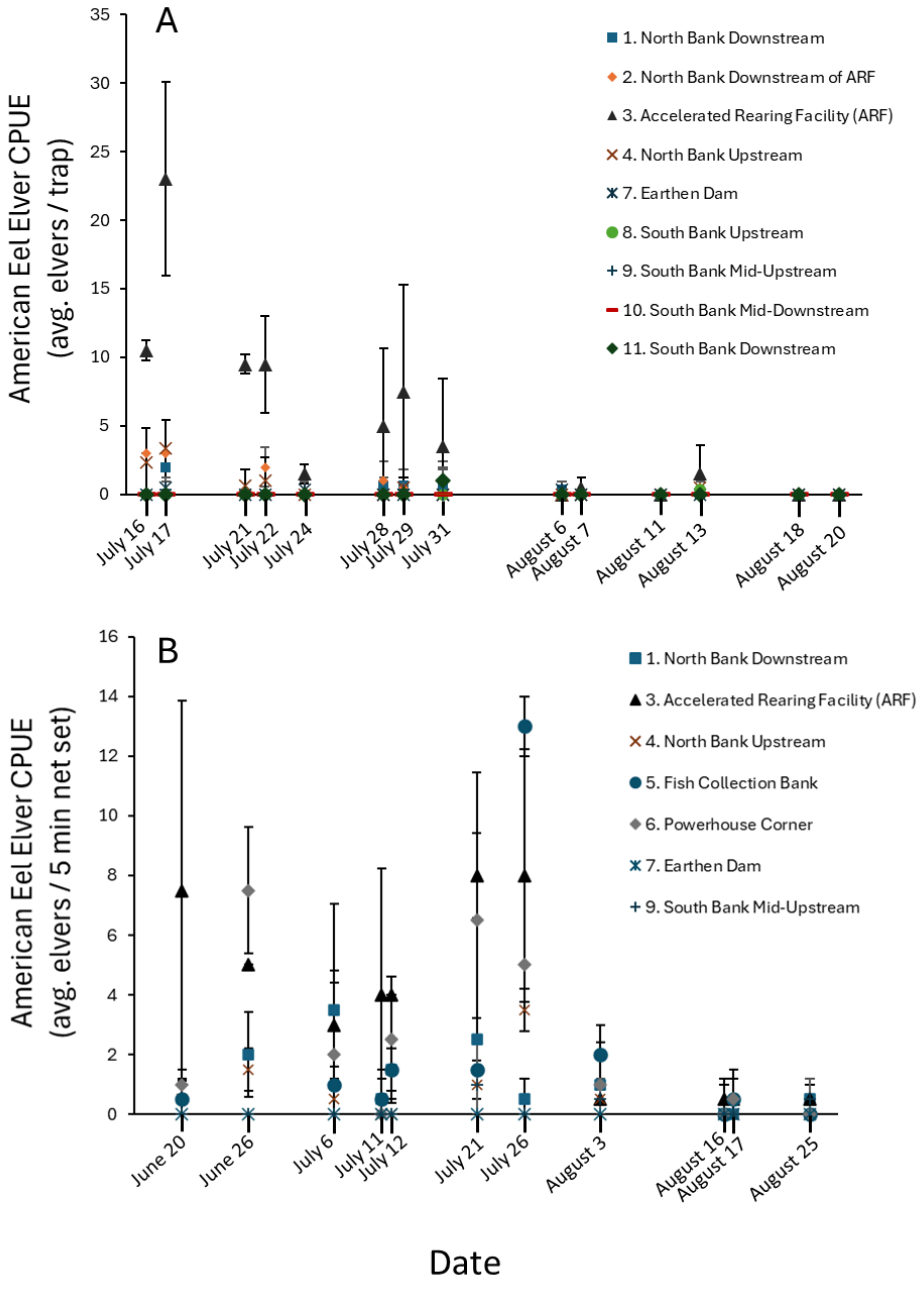

Figure 2.7 Average American eel elver catch per unit effort (CPUE) at locations within ~1 rkm of MQGS using A) habitat trap survey during summer 2015, and B) abundance net survey during summer 2016. Refer to Figure 2.4B for map of locations as described in legend with corresponding numbers to sites. Error bars represent standard deviation of the average catch. Note the temporal difference between panels A and B on x-axis.

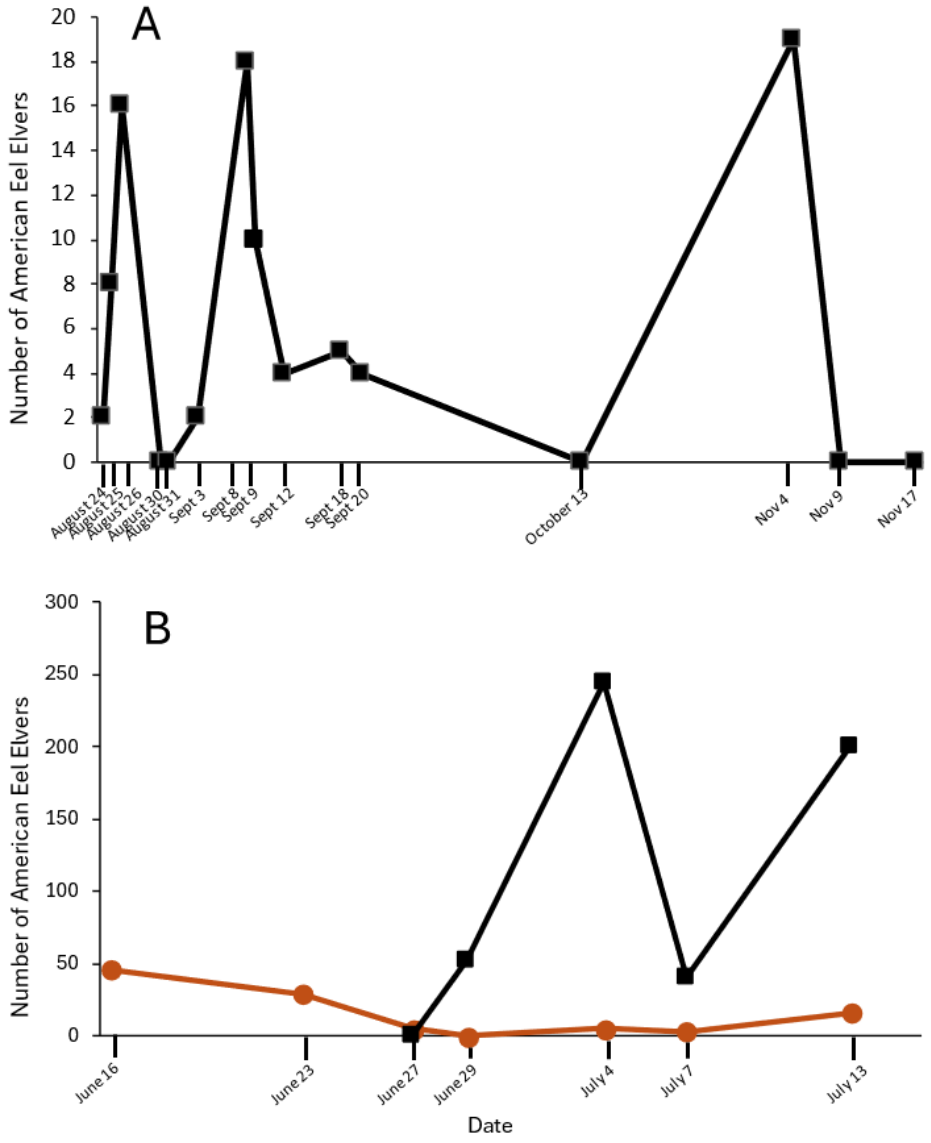

Figure 2.8 Number of American eel elvers caught by eel ramps in A) 2016 (one ramp at site R1; Figure 2.4b), and B) 2017 (two ramps, sites R1 and R2; Figure 2.4b) at the Mactaquac Generating Station. Black boxes represent ramps at site R1. Brown circles represent ramp at site R2. Note the temporal difference between panels A and B on x-axis.

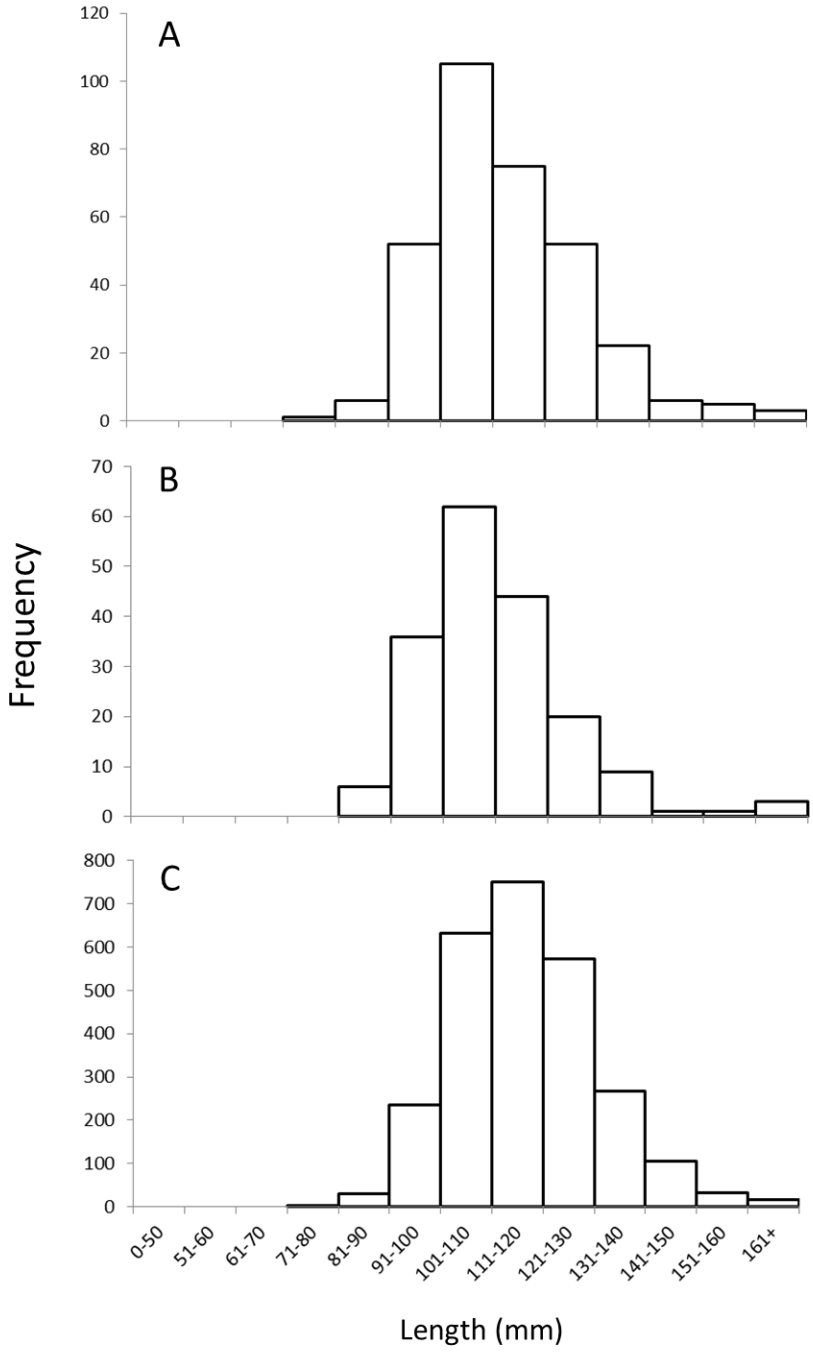

Figure 2.9 Length-frequency plots of 2015-17 American eel elvers captured at the Mactaquac Generating Station in the Wolastoq |Saint John River in A) 2015 (habitat traps); B) 2016 (habitat traps and abundance net); C) 2017 (dip nets at spillways). Note the different scale of the y-axis per panel.

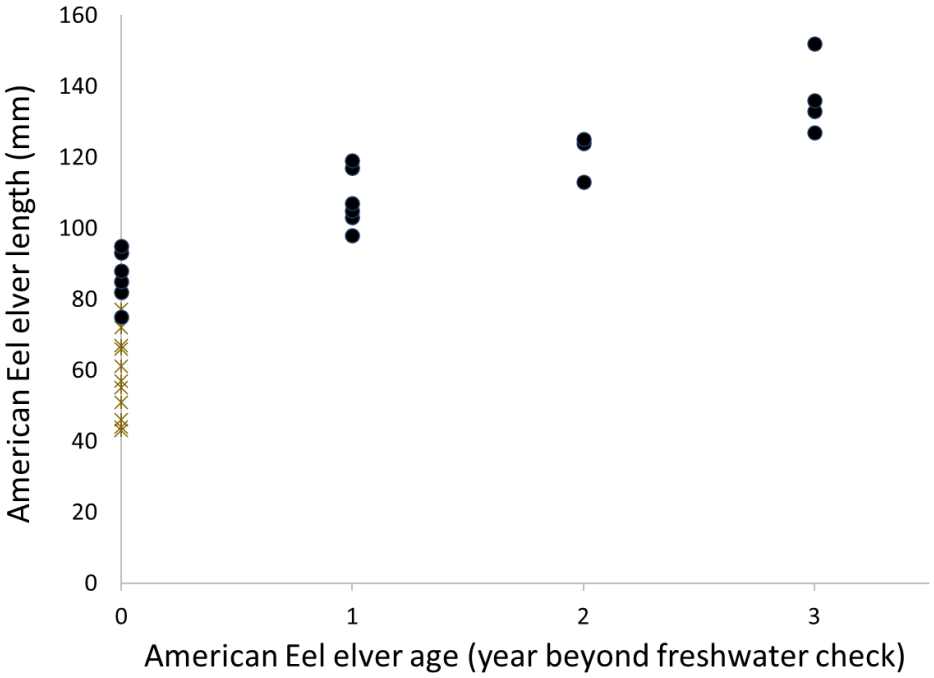

Figure 2.10 Relationship between age and total length (mm) of American eel elvers (n=30) captured at a Bay of Fundy estuary near the mouth of the Wolastoq | Saint John River (stars) and the downstream vicinity of the Mactaquac Generating Station (within 1 rkm; black circles).

Chapter 3: Capture rates and movements of American eel (*Anguilla rostrata*) elvers within and between the spillway structures of the Mactaquac Generating Station, Wolastoq | Saint John River

Brittany V. Dixon, R. Allen Curry & Tommi Linnansaari

Abstract

Upstream migrating American eel elvers (migrating juvenile eels) were studied at the Mactaquac Generating Station (MQGS) of the Wolastoq | Saint John River (WSJR) to inform fisheries management regarding their potential upstream passage options. Visible Implant Elastomer (VIE) tagging of elvers was used to assess whether individuals move between the two MQGS spillway structures (diversion sluiceway and main spillway), as well as between the gates within a single structure, and to monitor these movements over time. Migrating elvers were encountered at all gates of both spillways. The peak occurrence determined by hand-netting at spillway walls was in mid-July (CPUE: 33 elvers/min) and had effectively stopped by late September (CPUE: <1 elvers/min). Overall, the number of elvers approaching the dam and using the spilling or leaking water flows of the walls appeared very large, especially in the late June/July timeframe, but no attempts to quantify the total migrating population were conducted. VIE-tagging revealed that the vast majority of upstream migrating elvers may only be present for a short duration at the spillways as recapture rates of VIE-tagged elvers was very low (5.5 % of tagged elvers) throughout the entire field season, whereas recapture rates peaked (60.4 % of all recaptures) during the night directly after a tagging event. Elvers were mostly re-encountered within the same gate and spillway structure where they were originally tagged (54.2 % of all recaptures). However, there was some evidence of dispersal of VIE-tagged elvers into different gates within the same spillway structure (41 % of all recaptures) but only very low evidence of movement between the two spillway structures (4.9 % of all recaptures). Therefore, it is recommended that if upstream passage structure is contemplated at the Mactaquac Generating Station, it is advisable to consider a

mechanism at both the diversion sluiceway and main spillway, and ideally, it is best to construct a mechanism that can be maneuvered and cycled between different gates within each spillway to accomplish the most effective capture/passage of migrating elvers at the dam. Other aspects, like parasite presence and likelihood of eventual downstream passage should be considered before decisions regarding provisioning of upstream passage of elvers should be made.

3.1 Introduction

The construction and presence of dams and hydropower stations along natural waterways have long been noted as a substantial obstacle to the upstream movement of migratory fishes (Ovidio and Philippart 2002; Schilt 2007). For many fishes, the impacts of hydropower structures on vital habitat characteristics and species behaviour are extensive and diverse, and include the restriction or delay of migration, degradation of habitat, increase in predation, and fluctuations in water quality; all factors potentially contributing to population decline or physiological stress (*e.g.*, Schilt 2007 and numerous references therein).

The American eel (*Anguilla rostrata*) is an example of a fish species severely affected by dams and hydropower installations. In general, populations of American eel have seen a dramatic reduction in numbers since the 1980s with a 100% likelihood of a decline and 69.2 to 99.6% likelihood of a decline of at least 50% (DFO 2025a). This downward trend was particularly apparent in Canadian populations of American eels in the 1980's and 90's, but various contemporary indices point towards relatively stable yellow eel trends since the 2000's (DFO 2025a). Population estimates from the Great Lakes and St. Lawrence River have noted a 90 % decline and noticeable declines have been recorded throughout the Maritimes, resulting in the species being classified as threatened in 2012 by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2012; Bradford 2013). However, in December 2025, the Government of Canada decided to not list the American eel under the Species at Risk Act (DFO 2025b). In Atlantic Canada, inefficient or lacking fish passage at hydropower dams have reportedly led to the decline and loss of many species, including the American eel

(COSEWIC 2012) and DFO has committed to focusing on reducing impediments to fish passage by strengthening compliance with Fisheries Act (DFO 2025b).

Before evaluating whether fish passage issues may be present at a site of a hydropower dam, the study species must first be able to naturally make its way to the foot of the dam. For the American eel of the Wolastoq | Saint John River (WSJR), New Brunswick, Canada, previous research by Jessop and Harvey (2003) suggested that American eel elvers may be unable to reach the base of the Mactaquac Generating Station (MQGS), where elvers had been historically observed in impressive numbers (LeBlanc 1973; LeBlanc 1974). Since 1980, an absence of elvers was reported near the fish collection gallery of the MQGS (*i.e.,* the location of previous abundant sightings), suggesting a possible link between the timing of elver disappearance and the installation of the final two turbines at the dam (Jessop and Harvie 2003). Recently, however, Dixon *et al.* (Chapter 2) discovered that the hypothesis regarding a turbine-induced velocity barrier was inaccurate, at least for a certain upstream-migrating contingent of young eels, as they were discovered in locations around the base of the MQGS. Dixon *et al.* (Chapter 2) further established these as elvers ranging in size from 71 mm to 202 mm total length and freshwater age 0 to 3, arriving in peak numbers at the MQGS between June and mid-July with a clear propensity for upstream migration due to their attraction to move towards incoming flows. Given that elvers are indeed at the MQGS and thus available to move beyond the dam, it is prudent to examine finer scale spatial distribution of elvers at the dam for the purpose of potentially designing an upstream passage system for elvers.

Consideration and implementation of engineered or natural-like passage structures can ameliorate the negative effects of dams in rivers (Linnansaari *et al*. 2015).

Provisioning functional fish passage is often challenging. Meta-analyses examining fish passage efficiency world-wide have indicated generally low success in engineered fish passage structures in both up- and downstream direction (e.g., Bunt *et al*. 2012; Noonan *et al*. 2012; Bunt *et al.* 2016). Various upstream fish passage systems have been constructed around the world to rectify the migratory barriers put in place by dams of all sizes (*e.g.*, Linnansaari *et al*. 2015). The diversity of the systems that exist often call to question the efficiency and usefulness of one particular fish passage solution over another (Larinier 1998). In multi-species situations, passage structures must also be specifically engineered to provide efficient passage for each applicable species in question or allow for separate structures to provide species-specific solutions. Additionally, most systems are designed based on salmonid species and therefore don't accommodate the behaviour or swimming abilities of most other species in rivers (Brown *et al.* 2013).

It is generally understood that providing safe downstream passage for out-migrating adult eels is extremely difficult (Eyler *et al*. 2016; Mensinger *et al*. 2021; Pratt *et al*. 2021), but upstream passage systems for elvers and juvenile eels pose a different set of challenges. Upstream-migrating American eels are small and poor swimmers in fast water which complicates the engineering of passage systems that must consider various important parameters as outlined in Anwar (2018), including length, durability, substrate, slope, and attraction flow. A common upstream passage solution for migrating juvenile American eels consists of a positively sloped ramp lined with wetted substrate (Solomon and Beach 2004) and an attraction flow positioned at the entrance of the ramp (Piper *et al.* 2012). Upstream passage solutions have been developed to evaluate the efficacy of

varying substrata, often comparing substrata materials and ramp placement in relation to obstacle location (Anwar 2018; Watz *et al*. 2019).

The current fish lift system at MQGS was mainly developed for passing adult Atlantic Salmon (*Salmo salar*) and river herrings (*i.e.*, gaspereau, collectively Alewife *Alosa pseudoharengus* and blueback herring *A. aestivalis*; Chateauvert *et al.* 2018). Like many fishways around the world, it is ineffective for small, weaker-swimming species like juvenile eels that markedly differ in movement and behaviour from other adult migratory fishes (Larinier 1998; Noonan *et al.* 2012). Anguilliform morphotypes, such as American eel, are unable to leap at a distance or swim at a speed that is comparable to subcarangiform morphotypes (Clough *et al*. 2004; Kerr *et al.* 2015). This typically means that American eel elvers may have some difficulty ascending most traditional fish passage systems (McCleave 1980). Alternatively, American eel elvers (< 10 cm) and other anguilliform morphotypes are adapted to bypass obstacles by climbing damp, vertical surfaces consisting of substrate and material irregularities (Legault 1988; Tesch 2003; Lamson *et al.* 2006). The fish lift system of the MQGS was not designed for the passage American eel elvers approaching the dam, although they have been observed both approaching and entering the structures leading to MQGS fish lift (R. Bradford 2015, DFO Maritime Region, pers. comm.). Elvers have never been counted due to their ability to pass easily through the openings of the facility's fish lift "hopper" (Ingram and Ensor 1990), and, for operational reasons, smaller drainage holes cannot be used in the lift (Larinier 1998). If provisioning of upstream passage for American eel elvers will be a desirable objective for fisheries management in the future, a separate engineered structure will be required to supplement the current fish lift operations at MQGS.

While a plethora of upstream passage options exist for American eel, it is important to look at many factors when determining what system might work for any particular situation. Aside from the suitability of engineering aspects of the passage structure *per se*, previous research has demonstrated that many additional aspects define functional upstream passage (*e.g.*, Linnansaari *et al*. 2017). Such determinants include, but are not limited to, assessing the ideal location where the migratory elvers are naturally abundant so that a potential passage structure can be found by the ascending fish. Another important factor to determine is to assess whether certain locations in the vicinity of the dam (from the MQGS and up to 1 rkm downstream) encounter the whole or only a fraction of population downstream of the obstruction, as this will determine if functional passage can be accomplished by one structure, or whether multiple structures are needed to manage the whole population. It is also useful to consider elver behaviour in that juvenile eels are known to follow cues during their migratory journey upstream, including following a positive rheotaxis and swimming near the banks or edges of channels (Piper *et al.* 2012). By travelling through shallow water, elvers are able to avoid high water velocities and orient themselves in the waterway (Barbin and Krueger 1994).

The spillway structures of the MQGS have their own unique set of conditions, brought about by the variable incidental trickle flow of water passing underneath the various spillway gates even when they are closed. This variability leads to differences in attraction flows and substrate types from gate to gate, and potentially different encounter rates and movement patterns between and within the two MQGS spillways. Understanding whether certain spillway gates attract disproportionate numbers of elvers will facilitate recommendations for optimal upstream passage placement, ultimately

ensuring that American eel can once again achieve their full migratory potential along the WSJR.

After discovering the presence of migratory American eel elvers amongst the spillway structures at the MQGS (as described in Dixon *et al.* Chapter 2), it became necessary to evaluate general movement patterns, fine-scale movements, and behaviour of the American eel elvers within the vicinity of the MQGS to support science-based decision making of the preferred location for a potential future upstream passage structure for elvers. Specifically, the three objectives of this study were to understand whether American eel elvers 1) move between the two main water control structures of the MQGS (the main spillway and diversion sluiceway); 2) move between the different gates within each water control structure; and 3) are relatively more abundant in one water control structure over another, or within certain gates within each structure.

3.2 Methods

3.2.1 Study area

Flowing through the state of Maine and the provinces of Quebec and New Brunswick, the WSJR travels ~670 km downstream to the lower Bay of Fundy in Saint John, New Brunswick (Figure 3.1). With a total drainage area of > 55,000 km^2, the WSJR has been used to generate hydropower for decades with the installation of five major hydropower dam structures along its main stem and major tributaries (Kidd *et al.* 2011). The largest and lowermost of these structures is the MQGS, first operational in 1968 and located 150 rkm upstream from the Bay of Fundy (Kidd *et al.* 2011; Figure 3.1; Figure 3.2). The presence of American eel elvers (defined as juvenile eels showing a distinct motivation to migrate upstream, *i.e.* positive rheotaxis, throughout the spring and

summer of the year) in the general vicinity of the MQGS was described in Dixon *et al.* (Chapter 2).

The MQGS is composed of five main constructed or natural elements: the earthen dam, the diversion sluiceway, the main spillway, the intake structure/powerhouse, and the natural rock outcrop that separates the sluiceway and spillway (Figure 3.2A). The diversion sluiceway and main spillway of the MQGS serve as the main release channels for excess water not passing through the turbines for power generation (Figure 3.2A). Collectively, these structures are referred to as 'spillways'. Both spillways consist of five gates equipped with hydraulically operated 'stop-log gates' that remain closed for the majority of the year (hereafter "gate" meaning the physical stop-log gate that can be opened for spilling water, and its "bay" encased from both sides by concrete wall). Each gate is 36.8 m tall and 13.7 m wide (total for each spillway structure is 83.2 m wide) and is an ogee weir design with a bottom release of water (Figure 3.2B). However, due to an aggressive alkali-aggregate reaction, the concrete in these structures has deteriorated and cracks now exist along the concrete walls of the ogee weir structure. An imperfect seal between the stop-log gate and the concrete have resulted in flows of varying intensity and volume. This water, in turn, has given rise to surges of algal growth along the ogee weir walls, in varying degrees of coverage. The diverse combinations of trickling flow and algae growth may result in different mediums for elvers to climb upon (ogee weir entry approximately at 45° angle at a typical tailwater level, with climbing angle changing along the surface; Figure 3.2B), leading potentially to different preferences of occupancy between various spillway gates.

As a part of the American eel elver presence investigations at MQGS (see Dixon *et al.* Chapter 2), access was granted to the MQGS spillways by boat late into the 2016 field season. The presence of numerous elvers was discovered at both spillway structures as the elvers attempted to traverse the ogee weir surface (schematically represented in Figure 3.2B), leading to the implementation of coordinated surveys from June – September 2017 to track the arrival, peak time, departure, and movements of elvers within and between the two spillway structures.

3.2.2 Visible Implant Elastomer tag-recapture survey

From June – September 2017, elver movement between and within the spillways was investigated using Visible Implant Elastomer (VIE) tags (Northwest Marine Technology, WA, USA). VIE has been used in mark-recapture studies involving eels and other fishes with positive outcomes related to percent tag retention and survival (Skinner *et al.* 2006; Eissenhauer *et al.* 2024). Elvers were captured at night by moving along the ogee weir surfaces of each spillway by boat. Elvers climbing the spillway surface were tapped gently to startle them upon which they fell into an outstretched 10 x 15 cm aquarium dip net. Time spent capturing elvers was recorded during surveys conducted between July 11 – September 29, 2017, to generate a catch-per-unit-effort (CPUE).

Captured elvers were anesthetized (clove oil 80 ppm, ethanol as carrier in 1:10 ratio). After sufficient sedation was reached (*i.e.*, elver unresponsive to touch), a VIE-tag was injected just beneath the dorsal integument of the elver using a small needle and applicator; thus, each tag is an implanted fluorescent elastomer under the dorsal skin. The marking scheme utilized a mass-marking such that specific combinations of color-coded tags were used for each spillway gate on each tagging occasion (but elvers within

gate/occasion could not be individually identified). Five different tag colors were used in various combinations, noting whether a color was situated closer to the anterior, midbody, or posterior regions of the eel. Tagged elvers were allowed to recover and released to their point of capture after exhibiting normal swimming behaviour. The percent of tag loss and the effect on survival of tagged elvers was assumed to be insignificant for the objectives of this study based on the findings in other studies that have systematically studied VIE-tag retention in eels and other small-sized freshwater fishes (Imbert *et al*. 2007; Jungwirth *et al*. 2019) and specifically examining the effect on elvers at MQGS (Eissenhauer *et al.* 2024).

From June 22 – September 29, 2017, VIE-tagging and recapture surveys were conducted on a regular basis (~ 1-3 times per week). Within that timeframe, a total of 13 capture-and-tag events ('T-surveys'; Table 3.1) were conducted between June 22 – August 21, 2017, during which time elvers were captured, VIE-tagged, and released. Each elver that was captured was carefully inspected for the presence of VIE-tags from previous sampling rounds, and previously tagged elvers were counted. Due to the generally very large number of elvers, it was not possible to collect and tag every observed elver during each sampling event and thus total number of tagged elvers represents only a proportion of all elvers observed in each tagging survey night. It is also noteworthy that due to the time constraints, the tagging did not necessarily occur in each of the spillway structures, nor within each of the gates within the spillway during each of the tagging events (Table 3.1).

Additionally, by mid-July it was determined that the tagging process was limiting time available to find recaptures, and subsequent surveys were conducted on alternate

nights where no eels were tagged, and all effort was dedicated to observing recaptures of the eels tagged during mainly the previous (but also any earlier) night. The recapture-check 'R-surveys' (where no tagging occurred) occurred eight times between July 19 – September 29, 2017 (Table 3.1).

On four occasions (August 2-3; August 9-10; August 15-17; August 21-22, 2017), elvers were captured and tagged at a select gate within the diversion sluiceway during a night survey event (a T-survey), released that night, and then elvers were captured and checked for tags the following night (an R-survey) at all ten spillway gates *(i.e.*, both spillway structures; Table 3.1). By tagging during the first night and then capturing elvers during the second event, this pairing of events permitted us to focus our tag-recapture efforts and granted the opportunity to check for elver movement on a finer temporal scale.

3.2.3. Statistical Analysis

To determine if the average American eel elver CPUE was statistically different between the two spillway structures (main spillway and diversion sluiceway), a paired t-test was used to evaluate the seven dates in August and September when both structures were equally sampled (Table 3.1; Dates with "R" survey between Aug 3 – Sep 29, 2017). The normality of the differences between the pairs was tested using Shapiro-Wilk test, and the differences were normally distributed.

To further understand elver distribution between gates within each spillway, the difference in average American eel elver CPUE was calculated using a 1-way ANOVA test by looking at the two spillway structures separately and evaluating the differences between each gate of the same structure. Data was only included from dates when CPUE

was collected and when all gates within a spillway structure were surveyed to ensure a balanced design to not bias results (Table 3.2; seven dates for diversion sluiceway and nine dates for main spillway between July 11 – Sept 29, 2017). For ANOVA results that concluded that a significant difference was present between the gates, a post-hoc comparison (Tukey-test) was carried out to further understand where the differences between gates resided. The normality of data was tested using Shapiro-Wilk test and the data were normally distributed for all cases. The homogeneity of variances was tested using Levene's test; if heteroscedasticity was detected and F-statistic suggested a significant difference, Welch's and Brown-Forsythe tests were additionally conducted to test for the robustness of the equality of the means; these tests do not assume equal variances.

Statistical analyses were conducted in SPSS 29.0.

3.3 Results

Throughout the 2017 field season, 6018 elvers were captured during the VIE-tagging surveys. Migrating elvers were readily captured during the first survey on June 22 and continued to be captured to the last survey on September 29, and were found in both spillway structures and within all gates (Table 3.2; Figure 3.3; 3.4). In 2017, the average length of the captured elvers was 117.2 ± 13.9 mm (N=2640; 80 mm – 175 mm). During the nighttime surveys into the MQGS spillway structures, we frequently observed thousands of elvers concentrated within the gates and attempting to ascend the ogee weir walls. They were visible both in the water and actively climbing the concrete surfaces. However, on nights when our surveys extended into dawn, we noted a sudden and striking disappearance of elvers as soon as daylight broke.

Of the captured elvers, 2783 (46.2 % of total) were captured during the 13 capture-tag 'T-surveys' from June 22 – August 21, 2017 (Figure 3.3). Of these captures, 2642 (94.9 %) were tagged (1622 or 61.4 % at the diversion sluiceway; 1020 or 38.6 % at the main spillway; Table 3.2) with 16 recaptures during subsequent T-surveys (Figure 3.3). During the eight recapture-check 'R-surveys' from July 19 – September 29, 2017 (where no eels were tagged, and effort was directed to detection of previously tagged elvers), 3235 (53.8 % of total) elvers were captured and 128 of them were recaptures (had been previously tagged) (Figure 3.4; Table 3.2). The four tag-recapture events that occurred over back-to-back nights (August 2-3; August 9-10; August 15-17; August 21-22, 2017; Table 3.2) saw relative higher rates of recaptures (7.3 % to 13.1 % of the new tags applied the previous night); overall, these four events accounted for 127 recaptures (88.2 % of total) of which 80 elvers were tagged one (or two in the case of Aug 17) night(s) before and an additional 47 recaptures had been tagged during any of the previous surveys (Table 3.2; Table 3.3). Of all tagged elvers, a total of 144 (5.5% of tagged) were recaptured during the field season (Figure 3.5; Table 3.2).

Of the elvers that were tagged and recaptured, only seven (0.3 % of tagged; 4.9 % of recaptures) were identified as transiting between the two spillways (Figure 3.5; Table 3.4). All seven of the recaptured elvers were tagged in the main spillway and eventually recaptured in the diversion sluiceway; no movements were observed in the opposite direction (Table 3.4). These seven recaptured elvers were tagged in either June or July, but six of these elvers were not recaptured until August (Table 3.3). Overall, time between initial tagging and recapture ranged from 7 to 54 days (median: 22 days) for the tagged individuals undertaking between-spillway movement (Table 3.3).

A greater proportion of the elvers that were tagged at a spillway location showed movement within that same structure, with 59 elvers (2.2 % of tagged elvers; 41.0 % of recaptures) moving between gates within a spillway (Figure 3.5; Table 3.4). Of the 59 recaptured elvers, seven between-gate movement events were recorded within the main spillway, while the remaining 52 between-gate movement events were observed within the diversion sluiceway (Table 3.3; 3.4), largely reflecting paired T- and R-surveys on subsequent days where the tagging occurred only at the diversion sluiceway. Between-gate movements within the diversion sluiceway did not show consistent patterns, and recaptures from other gates were observed in all gates, however, it was notable that gate DS2 had only one tagged elver from the other gates, while multiple recaptures were observed in the other four diversion sluiceway gates (Table 3.4). At the main spillway, between-gate movements were observed at gates MS2, MS3, and MS4, while no recaptures were observed in gates MS1 or MS5 (Table 3.4). For between-gate movement within a spillway structure, the range of dates between tagging and recapture fluctuated from 1 to 37 days (median: 11 days) at the main spillway, and for the diversion sluiceway the dates ranged from 1 to 70 days (median: 7 days) (Table 3.3).

The majority of recaptures occurred at their initial tagging gate, with 78 (3.0 % of tagged eels; 54.2 % of recaptures) elvers showing no movement (Figure 3.5; Table 3.4). All 78 of the elvers that were recaptured at their initial tagging gate were encountered in the diversion sluiceway; no within-gate re-encounters were observed at the main spillway (Table 3.4). For elvers that were recaptured at the same gate as their initial tagging event, the range of dates between tagging and recapture varied between 1 and 51 days (median:

7.5 days). Cases of long-time detections were rare, with 72 of the 78 elvers (92.3 %) being recaptured within 8 days of the initial tagging event (Table 3.3).

As most recaptures were of elvers tagged within the same gates as their initial tagging event, indicating that no movement had occurred, mean CPUE was compared between spillways and between gates within a spillway to understand any potential differences in CPUE and elver location preference. CPUEs were highest (> 30 elvers / min) in the early part of the season at both spillways and approached 0 by the end of September (Figure 3.6). Overall, mean CPUE was significantly higher in the diversion sluiceway (5.6 ± 1.3 elvers/min) than in the main spillway (2.9 ± 0.6 elvers/min) over the seven dates in August when both structures were equally sampled (t-paired$_6$ = 2.515; p = 0.046).

Between-gate CPUE differences were not significant in the main spillway (ANOVA; $F_{4,40}$ = 0.36; p = 0.83; Table 3.2), but were significant in the diversion sluiceway (ANOVA; $F_{4,30}$ = 3.27; p = 0.02). A post-hoc comparison indicated that the significant ANOVA was a result of the difference in CPUE between the diversion sluiceway gates DS5 (highest avg. CPUE 8.7 ± 2.4 elvers/min) and DS2 (lowest avg. CPUE 0.9 ± 0.3 elvers/min; Tukey; $q_{30,5}$ = 4.65; p = 0.02), while all other differences between gates were non-significant. However, in preparation for the ANOVA, Levene's test indicated heteroscedasticity in the data ($L_{4,30}$=3.52; p = 0.02). It is apparent from the data that the heteroscedasticity was indeed the result of the fact that the CPUE is lower and thus essentially non-varying at gate DS2. Tests allowing heteroscedasticity were used in support of ANOVA to ensure correct interpretation of data. Both Welch test ($W_{4,13.1}$=8.5; p<0.001) and Brown-Forsythe test (B-$F_{4,17.4}$=3.3; p = 0.04) indicated a

statistical mean difference in CPUE between different gates at diversion sluiceway, and that gate DS2 appears to have the lowest relative abundance of elvers (Figure 3.6A).

3.4 Discussion

Throughout the 2017 field season, the mark-recapture survey gave insight into the movement of American eel elvers within the vicinity of the MQGS, showing that elvers rarely moved between the two spillways (main spillway and diversion sluiceway). A greater percentage of recaptures occurred amongst elvers moving between the different gates within a spillway structure and the majority of recaptured elvers did not move from the water control gate where they were initially tagged. Most recaptures occurred during the subsequent night immediately following a tagging event (approx. 24 hours after tagging) and cases of long-time detection were infrequent; tagged individuals do not appear to remain in the recapture area for a long period of time with swift declines in recaptures as time went on. The peak of elver abundance appeared to occur in July with a decline into August and the remainder of the season and this trend corroborates the observations and results from previous years (Dixon *et al.* Chapter 2). In terms of relative abundance, it was observed that the average CPUE was higher at the diversion sluiceway than the main spillway. CPUE appeared significantly lower in one of the gates (DS2) at the diversion sluiceway.

Overall, the presence of thousands of elvers at both the main spillway and diversion sluiceway structures at MQGS is a positive discovery and reflects the similar observations made by LeBlanc (1973) within the spillways of the dam. Elvers occurred at both spillway structures and thus suggest an upstream passage structure could be built at either location. If one structure would have to be chosen over another for an upstream

bypass, the CPUE data indicated that a higher relative abundance was encountered at the diversion sluiceway. In addition, the direction of elver movement between the two spillway structures was only observed from main spillway to diversion sluiceway, despite the fact that the number of tagged elvers was higher at the diversion sluiceway. However, one must exercise caution to not over-extend the findings of this study, as the statistical comparison of the CPUE data did not include the earliest sampling times (due to lack of sampling both structures during same nights early in the season, *i.e.*, unbalanced design) when the CPUE was the highest at both structures. It is also important to note that the data for this study were only collected during one sampling year, and relative abundance may fluctuate inter-annually. While the infrequent and unidirectional movement from main spillway to diversion sluiceway suggests a better upstream passage structure siting at the latter location, one must consider that if *functional* upstream elver passage – that is, provisioning passage that is most effective at capturing a larger quantity of elvers with minimal delay (Linnansaari *et al.* 2017) – is the objective, then separate upstream passage structures may be required at both spillway structures.

Where within these spillways should the specific location for an upstream passage structure be? Overall, the most commonly recorded recapture observation was an elver remaining in the same gate during subsequent checks. If the objective is to achieve transportation of a high percentage of elvers arriving at the MQGS to a location upstream of the dam in a timely manner, having the flexibility to deploy passage systems in multiple gates (or the ability to move systems between gates) may be the most effective method to ensure elver capture, as our results showed elvers were more likely to remain at their initial tagging site and elvers were encountered in all spillway gates of both

structures. While recaptures of elvers within their original tagging gate were only observed at the diversion sluiceway, this cannot be interpreted as this result is most likely a direct outcome of the fact that all tagging for back-to-back tag-recapture events took place at the diversion sluiceway. While tag *inspections* took place equally between the two structures during the four events when a tagging night was immediately followed by tag recapture the following night, the low general rate of tag recaptures and low movement rate between gates and spillway structures therefore solely reflects the tagging occurring only at the diversion sluiceway and does not suggest that similar tag encounter patterns would not be present at the main spillway.

Some elvers moved from gate to gate as the summer season progressed. This implies that some elvers undertake broad movements from night to night and are not necessarily confined to a single gate. Therefore, if transportation of a lower percentage of the elvers upstream of the dam is an acceptable goal in order to establish a population within the area, there is evidence to suggest that a single point of capture with sufficient attraction flow may have adequate opportunity to capture elvers present in the area throughout the summer. If this is the management strategy for upstream passage, it then becomes advisable to focus the passage system efforts to a location where elvers are found in the greatest abundance. It is noted that gate-to-gate movements were much more commonly observed at the diversion sluiceway in comparison to the main spillway; however, and as above, this is likely an artefact of the tagging for the back-to-back events only taking place at the diversion sluiceway and reflects the study design.

The CPUE data did not suggest any differences between the gates in the main spillway, however, at the diversion sluiceway, gate DS2 had generally lower CPUE than

the other gates (and significantly lower than DS5), making it the less favourable option. Evaluating the conditions and motivating factors for gate selection and movement amongst gates continues to be integral information for passage system placement and construction.

Understanding the CPUE and timing differences between spillways and gates is vital in the strategic placement of a potential upstream passage system. Future management decisions regarding passage of American eels at the MQGS should take into consideration the baseline information of American eel spatial and temporal distribution during their migratory approach to the MQGS. If upstream passage is a fisheries management goal, then the logistics of the elver passage system is dependent not only on the results of this study, but in having clearly defined management objectives from fisheries management.

At the MQGS, data on variable trickle flows on the spillway's ogee weir surface and their substrates (such as different levels of filamentous algae coverage) have shown that having an understanding of the desired conditions for American eel elvers is integral in determining how attracted they are to a particular location (Dixon, unpublished data), therefore further guiding where an elver passage system should be installed. For example, preliminary inspection of trickle-flow and filamentous algae that has grown on the climbing surface points to a finding that if the ogee weir surface is completely dry and has no algae growth, elvers may avoid climbing on those spillway gates (Dixon, unpublished data). Elvers appear to cease attempts to climb the spillways during the day, and their activities during this time are unknown; however, the data suggests that they do not readily move between spillways. That behaviour, coupled with the observation that

tagged elvers rapidly disappear from future check points, suggests that elvers may not remain within their initial tagging area in perpetuity, but rather are drawn to specific spillway ogee weir conditions, attempt to climb said spillways, and eventually abandon the attempt to ascend the structure. This may indicate the necessity of nightly operations beginning early in the migration season to ensure functional upstream passage. Determining the ultimate location of a passage system must involve understanding the logistics of the obstacle in question (Larinier 1998) and take elver behaviour into consideration as it relates to MQGS conditions, and this is encouraged in future studies.

The results of this study are helpful in the context of any planning for optimizing upstream passage potential for American eel elvers, if that is a desired outcome for fisheries management in the future. Many studies examining upstream passage of migratory fishes have shown that adequate thought must be given not only to the construction of a passage system but also in the consideration of the placement of the passage system (Larinier 2002; Williams *et al.* 2012), including for migratory elvers approaching an upstream obstruction (Watz *et al.* 2017). A variety of eel ramp ladders have been developed for upstream passage at barriers (Solomon and Beach 2004; Haro 2013) and by documenting the spatial distribution of elvers at the MQGS, there is now potential to design a structure at a location of increased elver abundance.

Other factors that should be considered by fisheries management when making a decision for upstream passage include an evaluation of the current situation as it pertains to the parasitic nematode, *Anguillicoloides crassus*. *A. crassus* resides in the swim bladders of American eels and can spread easily when introduced to a body of water where eels are found (Scott Luna 2023). When glass eels first arrive in continental

waters, they are free of the *A. crassus* parasite. However, recent findings by Scott Luna (2023) have shown that when elvers arrive at the MQGS, they are already parasitized by *A. crassus*. If fisheries management hopes to keep the area upstream of the MQGS parasite-free, then a direct passage system would not be ideal and extra care must be taken before moving elvers upstream. It has been shown that American eel elvers can cleanse themselves of the parasite over time, and an intermediate period between collection and release may possibly help to rid them of *A. crassus* and ensure the spread of the parasite does not move beyond the MQGS, a technique that warrants further examination at MQGS.

Finally, upstream passage for American eels in the WSJR may be an important step towards regional eel survival, global population recovery, supporting sustainable elver fisheries, protecting Indigenous culture, and overall dam management. Having access to habitat upstream of the MQGS reveals 100's of rkm of available mainstem and tributary habitat to American eel. However, before implementing an upstream passage system at MQGS, it is recommended that fisheries management conducts a review and full consideration of the possibility and necessity of downstream passage options for mature silver American eels. As a catadromous species, this life stage will require a safe route for egress, and currently only turbine passage would be available to downstream migrating silver eels which likely would cause low survival. Future studies should also evaluate an index for the abundance or total population estimate of American eel elvers downstream of the MQGS.

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Table 3.1 American eel elvers captured and tagged (T-surveys) and recaptured with no further tagging (R-surveys) during survey events between June 22 – September 29, 2017. DS1 – DS5 represent the gates of the diversion sluiceway, and MS1 – MS5 the main spillway gates. The gray area indicates that no tagging/recapture effort took place in that gate during that date.

		Date																			
	Gate	22-Jun	27-Jun	29-Jun	04-Jul	06-Jul	11-Jul	13-Jul	19-Jul	26-Jul	27-Jul	02-Aug	03-Aug	09-Aug	10-Aug	15-Aug	16-Aug	17-Aug	21-Aug	22-Aug	14-Sep	29-Sep
Diversion Sluiceway	DS1		T	T		T							R		R	T	R	R		R	R	R
	DS2		T	T		T							R		R		R	R		R	R	R
	DS3		T	T		T	T	T				T	R	T	R		R	R		R	R	R
	DS4		T	T		T							R		R		R	R		R	R	R
	DS5		T	T		T							R		R		R	R	T	R	R	R
Main Spillway	MS1	T		T	T				R	T	T		R		R		R	R		R	R	R
	MS2	T		T	T					T	T		R		R		R	R		R	R	R
	MS3	T		T	T		T	T	R	T	T		R		R		R	R		R	R	R
	MS4	T		T	T					T	T		R		R		R	R		R	R	R
	MS5	T		T	T					T	T		R		R		R	R		R	R	R

Table 3.2 American eel elvers tagged (T-survey; T), captured for examining previously tagged elvers (R-survey; R, with captured numbers indicated with C to separate from tagging numbers during T-surveys), and recaptures of tagged elvers (R_C) during survey events between June 22 – September 29, 2017. In total, 6018 elvers were captured within various spillway gates of the Mactaquac Generating Station. Diversion sluiceway gates are represented as DS1-DS5; main spillway gates as MS1-MS5. Superscript letter indicates an index for Table 3.3 where details of each capture are explained. Average CPUE data calculated only using data from dates when all gates within each spillway structure was collected. The gates that have statistically different average CPUEs within the same spillway are indicated with an asterisk. R-survey dates involved in the four tag-recapture events that occurred over back-to-back nights are indicated with an asterisk.

| | | Date | | |

Table 3.3 Detailed description of American eel elver recapture events (Event Index in reference to superscripts in Table 3.2) at the two spillway structures of the Mactaquac Generating Station in 2017. The colour of each event row represents recapture location relatively to original tagging location based on the legend below. Note, that a recapture event referred to in Table 3.2 could include recaptured elvers originally tagged in various dates and/or locations, and thus an event index may occur in multiple lines in this table.

Event index from Table 3.2	Original tagging location	Location of recapture	Original tagging date	Recapture date	Days since tagging	Total number of recaptured elvers
A	MS3	MS2	29-Jun	04-Jul	5	1
B	MS3	DS3	22-Jun	11-Jul	19	1
C	MS4	MS3	29-Jun	13-Jul	14	1
D	MS4	MS3	26-Jul	27-Jul	1	2
E	MS5	DS3	26-Jul	02-Aug	7	1
F	MS3	DS2	11-Jul	03-Aug	23	1
F	DS3	DS2	02-Aug	03-Aug	1	1
G	DS3	DS3	02-Aug	03-Aug	1	34
H	DS3	DS4	02-Aug	03-Aug	1	1
I	DS3	DS5	02-Aug	03-Aug	1	2
J	MS3	MS1	13-Jul	03-Aug	21	1
K	MS2	MS3	26-Jul	03-Aug	8	1
L	DS3	DS3	02-Aug	09-Aug	7	5
M	DS3	DS1	02-Aug	10-Aug	8	3
M	DS3	DS1	09-Aug	10-Aug	1	2
N	DS3	DS3	02-Aug	10-Aug	8	2
N	DS3	DS3	09-Aug	10-Aug	1	4
O	DS4	DS3	02-Aug	10-Aug	8	2
O	DS4	DS3	09-Aug	10-Aug	1	3
P	DS5	DS3	02-Aug	10-Aug	8	2
Q	MS2	MS1	04-Jul	10-Aug	37	1
R	MS2	DS1	22-Jun	15-Aug	54	1
S	DS3	DS1	09-Aug	16-Aug	7	13
S	MS3	DS1	04-Jul	16-Aug	43	1
S	DS5	DS1	27-Jun	16-Aug	50	1
T	DS3	DS3	09-Aug	16-Aug	7	1
T	DS1	DS3	15-Aug	16-Aug	1	3
U	DS4	DS4	06-Jul	16-Aug	41	1
U	DS3	DS4	09-Aug	16-Aug	7	1
V	DS2	DS5	15-Aug	16-Aug	1	1
W	DS1	DS1	15-Aug	17-Aug	2	10
W	DS1	DS1	27-Jun	17-Aug	51	1
W	MS1	DS1	26-Jul	17-Aug	22	1
X	DS1	DS3	15-Aug	17-Aug	2	2
X	DS3	DS3	02-Aug	17-Aug	15	1
Y	DS5	DS5	27-Jun	17-Aug	51	1
Y	MS3	DS5	26-Jul	17-Aug	22	1
Y	DS3	DS5	09-Aug	17-Aug	8	1
Z	DS1	DS5	15-Aug	21-Aug	6	2
Z	DS3	DS5	09-Aug	21-Aug	12	1
Z	DS3	DS5	02-Aug	21-Aug	19	1
AA	DS1	DS1	15-Aug	22-Aug	7	3
AB	DS3	DS3	02-Aug	22-Aug	20	1
AB	DS3	DS3	09-Aug	22-Aug	13	1
AB	DS1	DS3	15-Aug	22-Aug	7	1
AC	DS5	DS4	21-Aug	22-Aug	1	4
AD	DS5	DS5	21-Aug	22-Aug	1	13
AD	DS1	DS5	15-Aug	22-Aug	7	4
AE	DS4	DS3	06-Jul	14-Sep	70	1

Movement	Recaptures
Different Spillway	7
Different Gate	59
Same Gate	78
	144

Table 3.4 Recaptured (N=144) VIE-tagged American eel elvers from the two spillway structures (Diversion Sluiceway, DS; Main Spillway MS) of the Mactaquac Generating Station. Both spillway structures have five separate gates (DS1 through DS5 and MS1 through MS5). Between spillway movements (N=7) of recaptured elvers are indicated in white; recaptures that occurred within spillway but away from the original tagging gate are indicated in light gray (N=59), and recaptures that occurred within the original tagging gate (N=78) are in dark gray.

Tag Encounter Location \ Tagging Location	DS1	DS2	DS3	DS4	DS5	MS1	MS2	MS3	MS4	MS5
DS1	14	0	18	0	1	1	1	1	0	0
DS2	0	0	1	0	0	0	0	1	0	0
DS3	6	0	49	6	2	0	0	1	0	1
DS4	0	0	2	1	4	0	0	0	0	0
DS5	6	1	5	0	14	0	0	1	0	0
MS1	0	0	0	0	0	0	1	1	0	0
MS2	0	0	0	0	0	0	0	1	0	0
MS3	0	0	0	0	0	0	1	0	3	0
MS4	0	0	0	0	0	0	0	0	0	0
MS5	0	0	0	0	0	0	0	0	0	0

Movement	Recaptures
Different Spillway	
DS to MS	0
MS to DS	7
Different Gate	
within MS	7
within DS	52
Same Gate	
within MS	0
within DS	78
	144

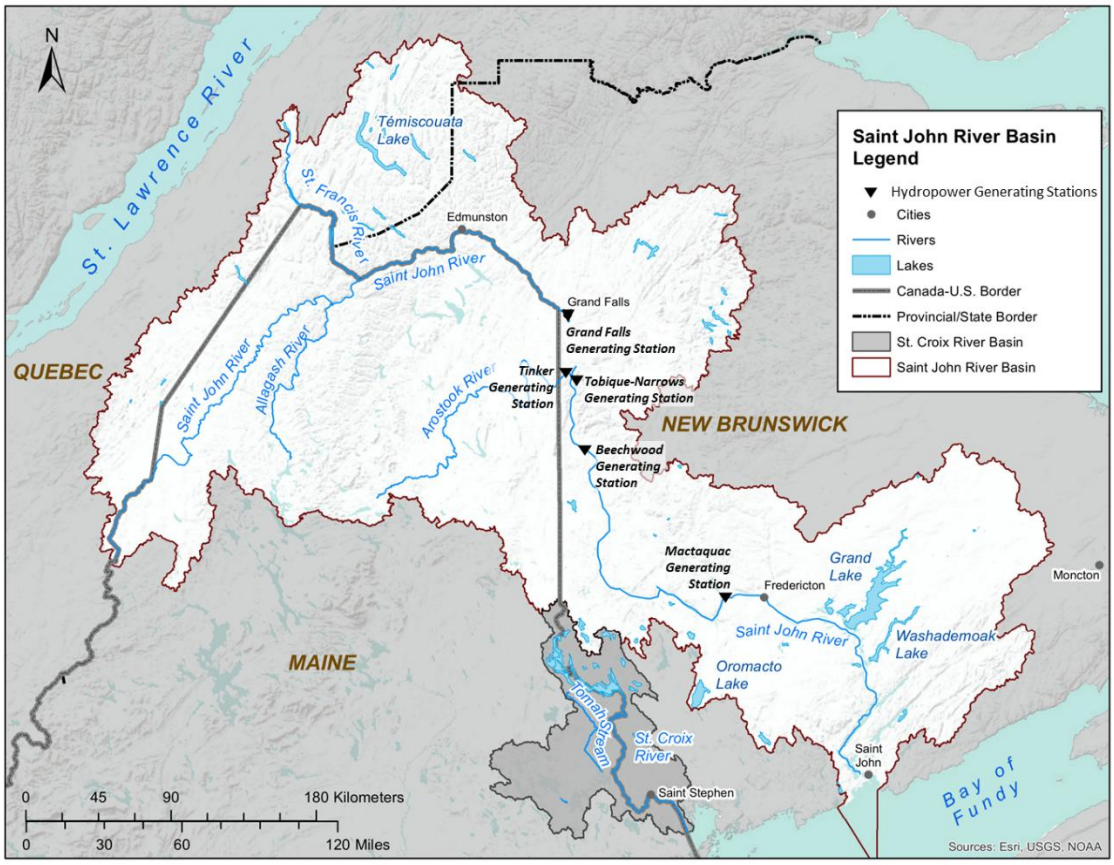
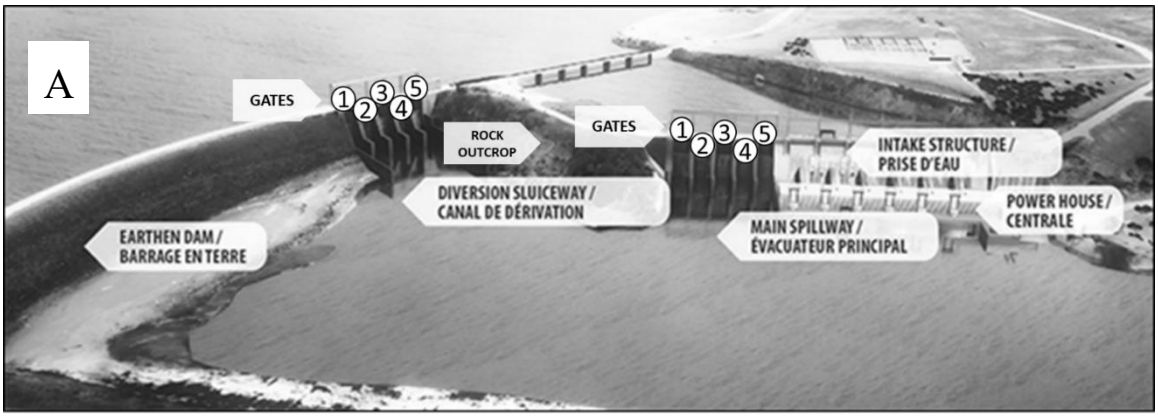


Figure 3.1 Wolastoq | Saint John River catchment showing locations of five main hydropower generating stations. The Mactaquac Generating Station is the lowermost dam, located 150 rkm upstream of the Bay of Fundy. Moving upstream, the Beechwood Generating Station is located at 285 rkm, the Tobique-Narrows Generating Station is located near the confluence of the Tobique River and WSJR at 315 rkm, the Tinker Generating Station is positioned on the Aroostook River (a tributary of the WSJR) near the mouth of the tributary at 318 rkm, and the Grand Falls Generating Station is located further upstream at 351 rkm. (Modified from the original map courtesy of International Joint Commission 2025).



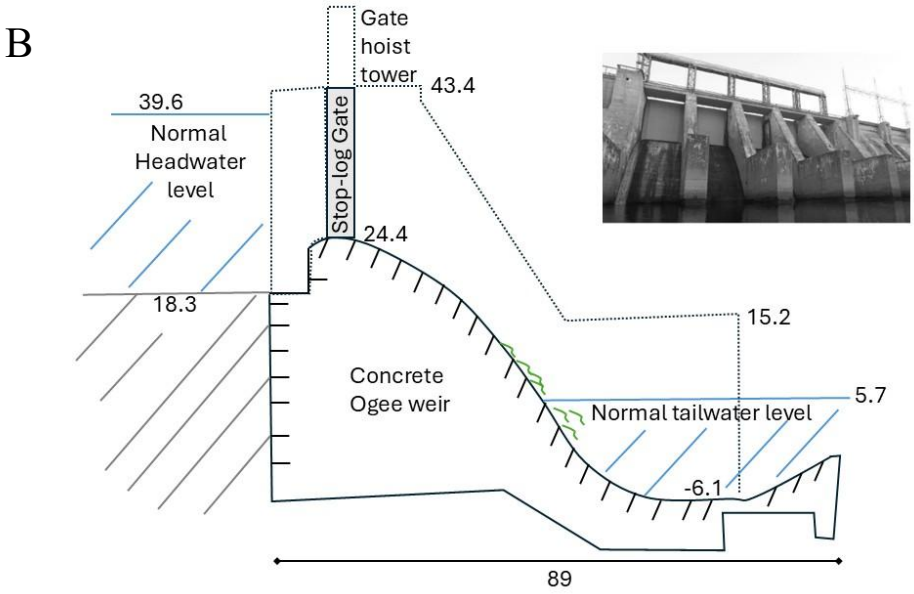


Figure 3.2 A) The Mactaquac Generating Station on the Wolastoq | Saint John River, NB, located 18 rkm upstream from the City of Fredericton. Main structures include the earthen dam, a diversion sluiceway, a natural rock outcrop, the main spillway, and the generating unit, consisting of intake structure and powerhouse. Both the diversion sluiceway (DS) and main spillway (MS) consist of five independently operated gated sections (henceforth DS1 through DS5, and MS1 through MS5) containing angled ogee weir surfaces. (Modified from the original diagram courtesy of NB Power 2014.) B) A graphic approximation of a side-view of the ogee weir construction used at the

Mactaquac Generating Station spillway structures. Measurement of critical locations are provided in meters and are relative to average sea level (ASL). Stippled lines represent concrete structures dividing the spillway gates shown on the photo insert. Typical American eel elver locations within spillways are highlighted in green (not to scale), while other physical features are drawn approximately to scale.

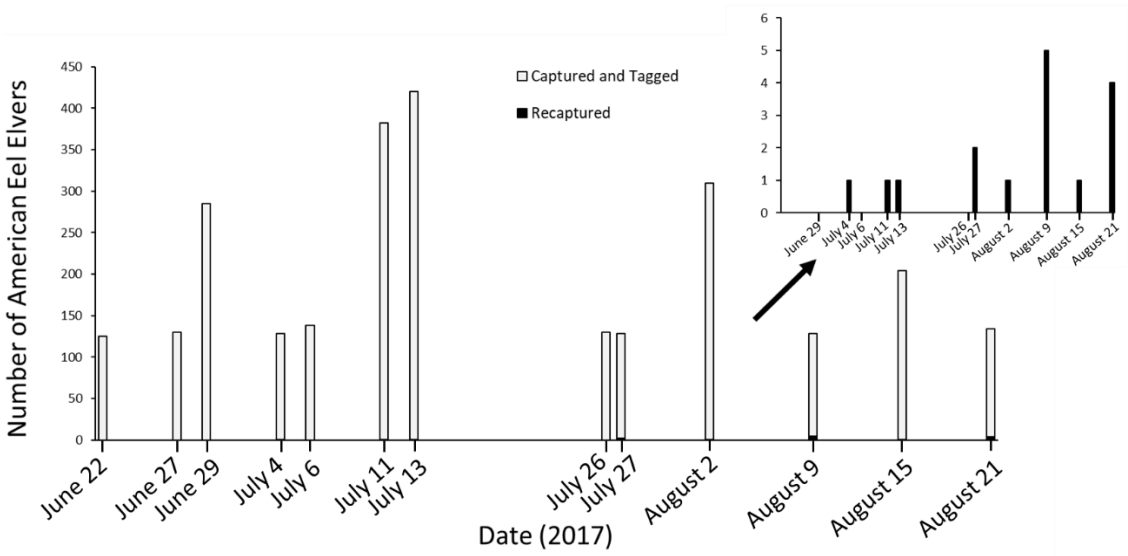


Figure 3.3 American eel elvers captured, tagged, and recaptured from MQGS spillway structures during capture-tag 'T-surveys' from June 22 – August 21, 2017. Recaptured elvers refer to any incident when an elver was caught after the initial tagging event. Graph insert highlights the recaptures on a reduced y-scale.

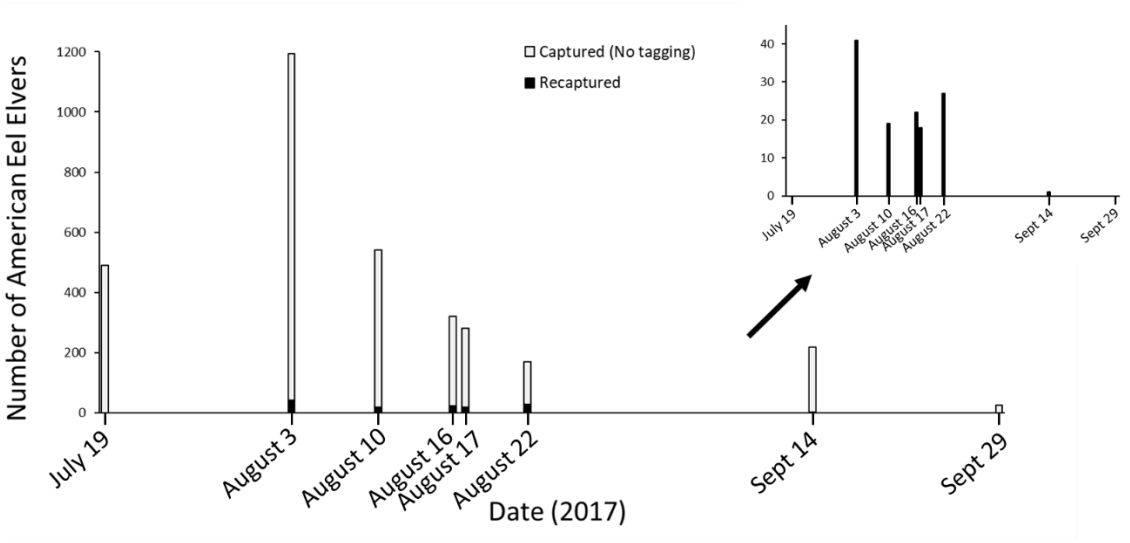


Figure 3.4 American eel elvers captured and recaptured from MQGS spillway structures during recapture-check 'R-surveys' from July 19 – September 29, 2017. No tagging occurred during these surveys. Recaptured elvers refer to any incident when an elver was caught after the initial tagging event. Graph insert highlights the recaptures on a reduced y-scale.

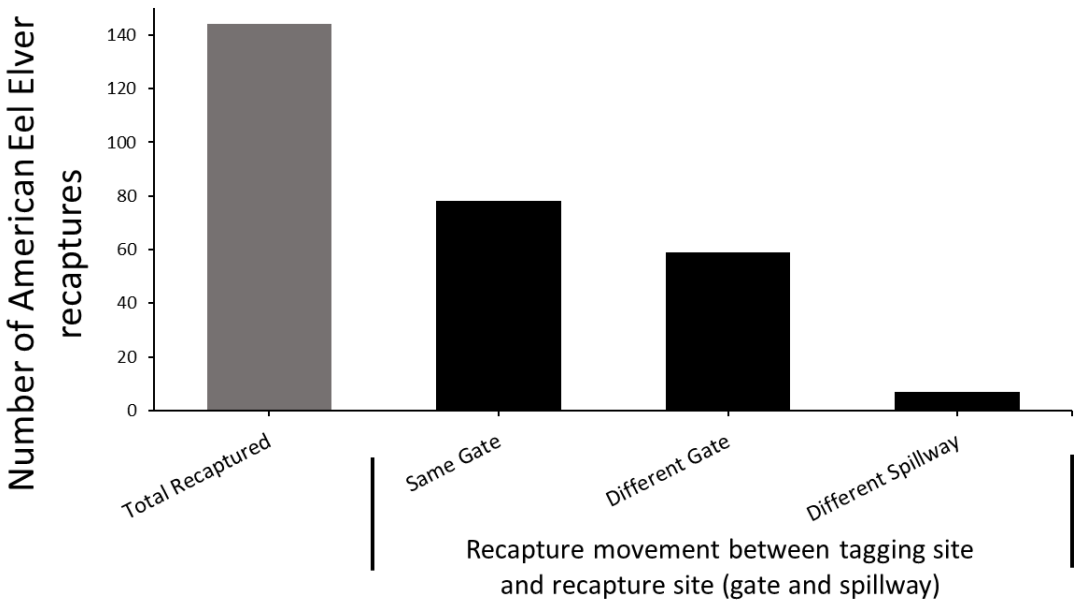


Figure 3.5 Number of total recaptures (N=144) of VIE-tagged American eel elvers in 2017 at the two spillways (main spillway and diversion sluiceway) of the Mactaquac Generating Station (gray bar). The black bars denote the split of the total recaptures into within spillway recaptures (including same (N=78) and different (N=59) gates within a given spillway) and between spillway (N=7) recaptures.

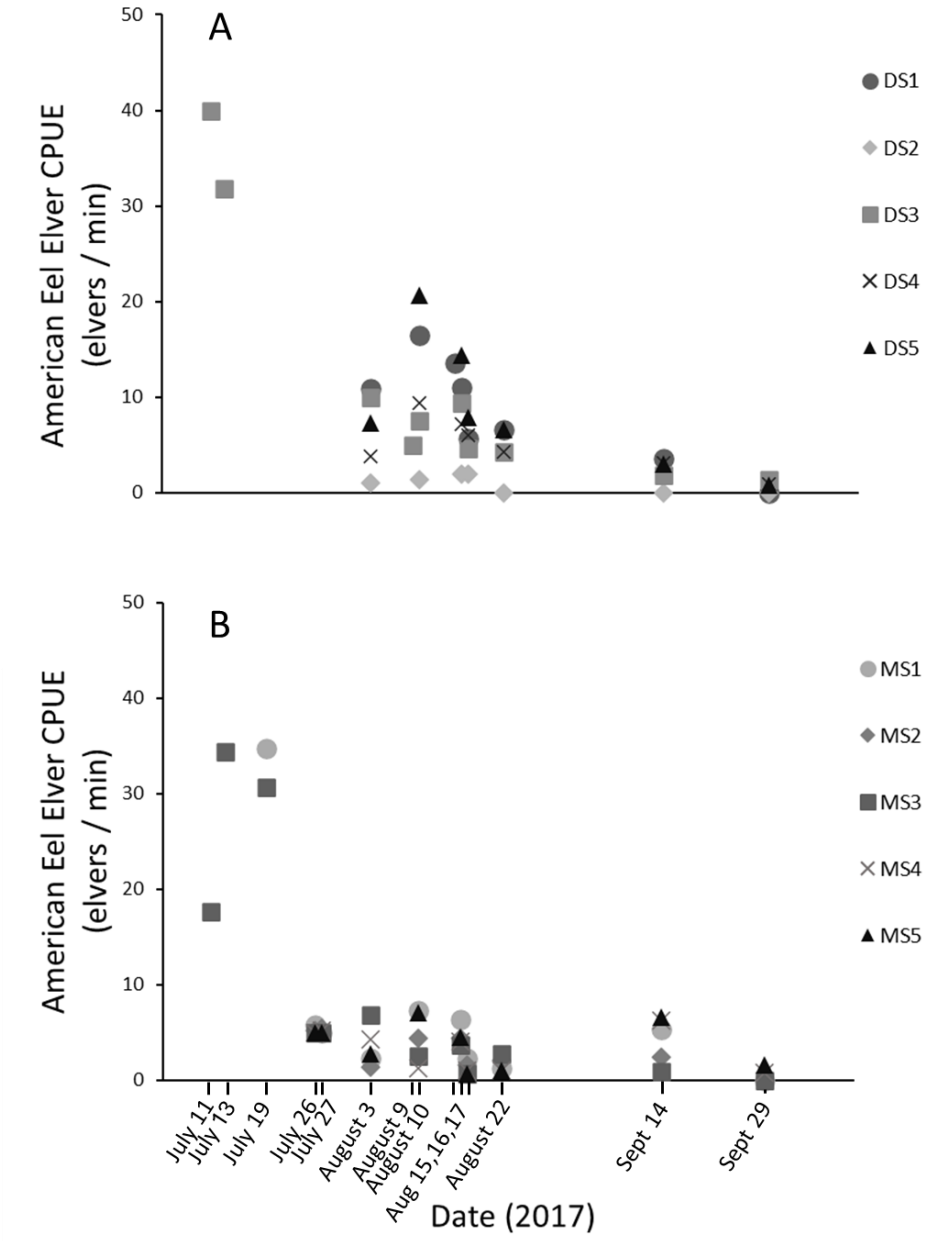


Figure 3.6 The catch-per-unit-effort (CPUE; elvers/min) of American eel elvers surveyed at the diversion sluiceway (Panel A) and main spillway (Panel B) structures of the Mactaquac Generating Station from July 11 – September 29, 2017. Survey dates were included only if effort was recorded as time spent capturing elvers.

Chapter 4: General Discussion

Brittany V. Dixon

This thesis set out to determine if American eel elvers are present at the downstream reach of the Mactaquac Generating Station (MQGS) by evaluating their spatio-temporal distribution and understanding elver behaviour and ecology during their migratory journey within the lower Wolastoq | Saint John River (WSJR). First, I wanted to determine elver distribution, both spatially and temporally, as they approach the MQGS to address the question of whether there may exist a migration bottleneck due to a velocity barrier within the WSJR. To make this determination, the distribution of elvers downstream of the MQGS, the timing of elver migration, and the size and age of elvers were explored. Secondly, I wanted to determine elver distribution, movement, and behaviour within and between the spillway structures of the MQGS by focusing surveying efforts on the main spillway and diversion sluiceway of the MQGS, where I observed large numbers of elvers when answering my first research objective. Furthermore, I set out to analyze the collective results of this study to make informed and research-based recommendations to fisheries management regarding options for efficient and effective upstream passage of elvers at the MQGS, should that become a desirable management objective in the future.

I found that American eel elvers were present within one river kilometer (rkm) of the MQGS, therefore, an apparent velocity barrier within the study area of 20 rkm downstream of the dam did not exist, as was once hypothesized (Jessop and Harvie 2003). Additionally, I found that elvers were not randomly distributed within the dam's vicinity, but were observed with greater abundance within the powerhouse side of the

river (north bank) and Accelerated Rearing Facility (ARF) traps (2015-2016) and within the diversion sluiceway (2017). Individually tagged elvers only appeared to remain in this area for a relatively short period of time and when tagged individuals were re-encountered, most were found within the same gate and spillway structure where they were originally discovered. I also found that elvers make their migratory approach to the dam throughout the months of June to September, with peak abundance occurring in July. The average length of the elvers surveyed at the MQGS was 116.5 mm ± 14.2 mm (2015-2017), with freshwater ages ranging from 0-3 years. I will elaborate on each of these main findings further below.

4.1 Elver presence at MQGS: spatial distribution, timing, size, and age

Due to the presence of American eel elvers within the vicinity (from the MQGS and up to 1 rkm downstream) downstream of the MQGS, it was determined that a velocity barrier to elver migration does not exist within the lower WSJR. Contrary to speculations made by Jessop and Harvie (2003), the installation of the final two turbine units in 1979-80 and the overall increase in operational capacity at the hydroelectric generating station does not appear to have caused a negative migratory impact downstream of the dam. In fact, while elvers were abundant at the MQGS, they were rarely captured in any traps further downstream (2-8 rkm), giving further evidence to the lack of a velocity barrier, because as elvers arrive in this area, they are still motivated to actively migrate upstream until such a point where a barrier (in this case, the MQGS itself) impedes further migration.

There is, however, a possible caveat in the assessment of no apparent velocity barrier being present in the lower WSJR. The historic reports of elver migrations in the

lower WSJR (*e.g.*, LeBlanc 1973; LeBlanc 1974; Jessop and Harvie 2003) do not report the size of the elvers and simply state that the elvers previously encountered at MQGS were "pigmented" and not transparent (*i.e.*, not glass eels). It is, therefore, not known whether historically there was a large contingent of elvers at MQGS that were in their first-year of freshwater life (age-0), *i.e.*, individuals generally in the 55-65 mm range, and if so, whether the Jessop and Harvey (2003) report refers to a sudden disappearance of this particular contingent from the MQGS, or whether the reference is to all upstream migrating young eels (defined as elvers in my thesis). In this context, it is important to state that if the Jessop and Harvie (2003) referred to a sudden disappearance of (possibly) formerly abundant 55-65 mm range elvers (in their first freshwater year), then my findings concur with their report as the elvers observed at MQGS in my studies were generally larger (see section below), and the age-0 elvers were infrequently encountered. Therefore, there remains a possibility that the age-0 elvers that I did not observe at MQGS in large numbers could be prevented by the flow-hypothesis somewhere further downstream in the WSJR, beyond the area under investigation in my thesis. This dilemma cannot, unfortunately, be resolved at this current time as it is not explicitly known what the size of the elvers was that the previous reports alluded to. To reconcile relative abundance of all previous and current elver studies at MQGS and its surrounding areas, Table 4.1 shows coarse-scale synthesis of the current understanding.

The American eel elvers present at the MQGS were not randomly distributed within this space (1 rkm). From 2015-2016, elvers were significantly more abundant along the north bank of the downstream vicinity of the dam, with particular attraction to the ARF. The lower velocity of the river's flow, coupled with the continuous attraction

flow of the ARF along this stretch, may be an explanation for the greater abundance of elvers. The high velocity of the south bank may make moving and residing within this area difficult for the weak-swimming elvers, again resulting in a preference for the north bank.

When research focus shifted to the spillway structures in 2017, thousands of elvers were observed attempting to traverse the 36.8 m high (and 13.7 m wide) ogee weir surface of each gate, similar to observations by LeBlanc (1973). There was a higher relative abundance (CPUE) of elvers distributed within the diversion sluiceway compared to the main spillway. When elvers were recaptured, they mostly appeared to remain within the same gate, although they did not remain in the spillway gates for an extended period of time, as observations of tagged eels rapidly declined as the field season progressed. The DS2 gate of the diversion sluiceway had generally lower numbers of elvers than the other gates (and significantly lower numbers than DS5). The reasons for the apparent lower abundance of elvers at the DS2 gate are currently not fully understood. During the course of my thesis work, I did, however, collect preliminary data on the two aspects of the spillway ogee weir surface conditions that may appear related to how attractive each spillway gate is for elvers attempting to ascend the structure. These two aspects were 1) the amount of flow trickling under the spillway stoplogs and therefore, down the ogee weir surface, and 2) the amount of filamentous algae growth on the surface (Figure 4.1). These flow/algae combinations appeared to create different "strata" (*e.g.*, "no flow, no algae"; "low flow, medium algae" etc.), and furthermore, my preliminary attempts to quantify the elver preference towards these combinations of flow/algae using standard quadrat counts (Figure 4.2) suggest that elvers may have

preferences / avoidances to strata with varying flow/algae combinations. While these data were eventually not fully analyzed in the context of this thesis, the apparent lack of algae growth on gate DS2 in comparison to other diversion sluiceway gates (Figure 4.3) may suggest a correlative relationship between algae and elver presence. The hypothesis of flow/algae strata affecting elver abundance is also supported by the notion that in the main spillway, where elver CPUE was less than in the diversion sluiceway, strata with no flow/no algae were commonly encountered, and these unfavorable physical conditions might explain the lower abundance of elvers; elvers would generally have greater success climbing a damp, steeply sloped surface. Fully examining the merits of flow/algae strata determining the relative abundance of elvers will be an important future endeavor because both flow and algae conditions encountered on the ogee weir surface vary during the season and especially between years (Figure 4.3; 4.4), and if the relative abundance of elvers responds to certain combination of these variables, then optimal upstream passage location (or elver collection location) may also change accordingly. Similar preferences of elvers regarding their climbing surfaces have been observed elsewhere. Anwar (2018) found that substrate type and slope can have a significant effect on an elver's ability to climb surfaces, with elvers climbing further and faster along rougher substrates. In these conditions, elvers are able to undulate their bodies to match the formation of the surface as they pushed off protruding substrate, instead of relying solely on surface tension (Jellyman 1977). Rougher substrates also disrupt and spread out the flow of water over larger areas, which can be beneficial to elvers as they search for lower velocity channels (Vowles *et al.* 2017).

With regards to the timing of higher elver abundance at the MQGS, during the 2015-2016 surveys, elver arrival at the MQGS increased from late June until early August, with a peak abundance occurring in mid-to-late July. A similar trend was noted in the 2017 spillway surveys, as the peak of elver abundance within the main spillway and diversion sluiceway appeared to occur in July and then quickly declined moving into August.

The length of the elvers captured in 2015 and 2016 saw no significant difference between years, however, elvers from both 2015 and 2016 were significantly smaller in size to those captured in 2017. Overall, the length distributions showed a similar pattern for all three years with upstream migrating elvers consisting of a range of sizes across multiple cohorts (see age information below).

The difference in length distributions between the initial two years and 2017 may be in part explained by the different trapping techniques and study areas that were implemented from year to year as my methods and objectives evolved. There were more similarities in methodology and greater overlaps in site locations between 2015 and 2016 than that of 2017, as the focus shifted from the downstream banks of the MQGS to the inner walls of the spillway structures. The average total length of elvers over the three years ranged from 113.3 mm ± 15.2 mm (2015, near-dam only), 110.8 mm ± 14.3 mm (2016), and 117.2 mm ± 13.9 mm (2017). Overall, these measurements differ from the size-based definition of elvers provided by the Canadian Science Advisory Secretariat (2010) and Maritime Provinces Fishery Regulations (Legislative Services Branch 2025) that define elvers as < 100 mm, and vary greatly from the length between 55-65 mm that Jessop and Harvie (2003) considered as their definition of elver. Therefore, the elvers

observed approaching the MQGS in 2015-2017 are of a larger size-class than the definitions used in other studies (but "unknown" for the LeBlanc 1973 study; *i.e.*, the only other study actually directly documenting elvers at MQGS). Irrespective of this size difference, my position of defining these upstream migratory eels as elvers remains unchanged: albeit larger in size (*vs*. elver definition in some other studies) they nevertheless exhibited elver-like behaviour with strong positive rheotaxis and motivation to migrate up the WSJR. Therefore, "elver" in the context of the WSJR appear to be an extension to the stricter size-based definition traditionally used in other studies.

The age of the elvers within the WSJR was determined using a sample of elvers from an estuary of the Bay of Fundy and from within the downstream vicinity of the MQGS. There was a positive relationship between elver age and total length. Unsurprisingly, all of the elvers collected from the estuary were freshwater age 0, having most likely only just arrived from the ocean. However, elvers sampled near the MQGS ranged from freshwater age 0 to 3. Using the aging information and applying it to the observed length distribution at MQGS, the data indicates that only very few elvers arrive at the dam within their first year of freshwater migration (age 0), and the majority either make their first appearance at the MQGS as age 1 or age 2 elvers, and yet others may have remained in this area for multiple years without the opportunity to travel further. The elvers sampled at MQGS are significant in that they all showed upstream migratory behaviour, regardless of age or length. This indicates that whether the elvers are spending multiple years traversing the large expanse between the mouth of the WSJR and the MQGS or are remaining at the base of the dam for numerous years, they are still

behaving as migratory elvers instead of settling into the habitat as would be expected of older yellow eels.

4.2 Fine-scale movements of elvers at MQGS

The 2017 field season detailed the fine-scale movement of elvers between and within the two spillway structures of the MQGS. First, some elvers were recaptured after travelling between the main spillway and diversion sluiceway (a distance of approx. 480 m; center from one spillway to another; measured on water as opposed to "as the crow flies") and it was determined that this movement was quite uncommon (4.9 % of all recaptures). Elvers moving between spillway structures only ever travelled from the main spillway to the diversion sluiceway, even though more elvers were tagged at the diversion sluiceway. This information, coupled with the higher CPUE elver abundance at the diversion sluiceway would make this the optimal location for an upstream passage system, should fisheries management want to focus efforts in one spillway over the other.

When surveying for elver recaptures between the gates of a single spillway structure (either the main spillway or diversion sluiceway), some movement was recorded (41 % of all recaptures). However, elvers were more likely to remain in the gate where they were initially tagged, as this was the most common recapture observation (54.2 % of all recaptures). To optimize opportunities to capture elvers, an upstream passage system may be most effective if it has the ability to target multiple gates or move between gates. However, because some elvers were observed moving between gates, there is evidence to suggest a single point of capture could suffice, depending again on the objectives of fisheries management. Establishing a passage system in a single gate compared to

multiple gates may yield fewer captures for upstream transportation, but the reduced cost and effort may offset the lack of efficiency.

Overall, the recapture rate of elvers was quite low (5.5 % of tagged elvers) and most tagged elvers did not appear to remain in surveyed areas of the spillway structures for extended periods of time. Long-recurrence time observations were uncommon, with most recaptures occurring during the night immediately following a tagging event. Regular nightly operation of a passage system would therefore be necessary to ensure elvers were captured during their short window of migratory activity within the spillway structures.

4.3 Wider implications of study findings

Beyond providing local, specific recommendations to regional fisheries and dam management related to American eel elver distribution, biology, behavior, and passage options, the results of this study can be expanded to a larger scale to better understand the wider implications of my findings. The discovery that elvers within the downstream vicinity of the MQGS are not randomly distributed highlights the importance of applying careful consideration when selecting the location of upstream passage systems and the necessity of extensive research as an initial step of the planning process.

The WSJR is a unique sampling site in that research on elvers is typically conducted within smaller streams that are easier to sample. Therefore, the development of various trapping techniques and the extensive ‘trial and error’ involved in testing and deploying each one provided useful insight into their feasibility and effectiveness on a river of this magnitude. Some traps proved effective in capturing elvers (habitat traps, abundance net, attraction flow ramp) while others had to be discontinued after numerous

unsuccessful attempts (tube traps, box traps). Despite the efficacy of the successful trapping methods, for a river system this large it may be beneficial to consider alternative methods for large-scale elver collection (*e.g.*, an elver fyke net). This information is useful should future studies hope to capture and track elvers throughout large bodies of water.

The elvers of the MQGS are notable in that they appear to span several age classes (0-3 years within freshwater) while still retaining migratory behaviour. This finding is important because it raises questions about the consequences for elvers that remain trapped behind impassable barriers over multiple years. If elvers maintain positive rheotaxis across years, the potential of their upstream range under unrestricted conditions could be considerable. In contrast, when confined downstream of a barrier, elevated densities may lead to undesirable consequences, including reduced growth rates and a higher proportion of males within their population (Krueger and Oliveira 1999; Verreault *et al*. 2009).

4.4 Study limitations

It is important to acknowledge the limitations of my study when addressing conclusions. The WSJR is an expansive river system, with an overall length of > 670 rkm. The distance between the Bay of Fundy and the MQGS alone stretches over 150 rkm. For the purposes of this study, surveys were focused on the specific study area within 20 rkm downstream of the MQGS, strategically chosen to investigate the potential existence of a velocity barrier based on known river gradients and hydrological model outputs. With this narrower study area, the methodology was not designed to determine

the full extent of elver distribution in the lower WSJR, nor to assess the progression of age throughout this migratory range.

This study marks the first research into this eel life stage within the WSJR since the 1970s (LeBlanc 1973; LeBlanc 1974). As a result, the study involved extensive foundational work to determine which methods would be most effective for capturing and tracking elvers. Several techniques were tested, and new methods were developed and attempted during the process, with varying degrees of success. However, further work is needed to determine the most efficient approach for capturing large numbers of elvers in the MQGS area.

Once elvers were discovered within the spillway structures, it became clear that the number of elvers in the area was quite substantial. However, the VIE tagging efforts were not scaled sufficiently to achieve the desired number of recaptures to make any conclusions about population size in this area. To improve future research, a significantly larger VIE tagging program is recommended, potentially involving the tagging of thousands of elvers to ensure more extensive data collection and better insights into their movements. Data was collected in a later study in which the estimated abundance ranged from 100's of thousands to almost 1 million (Eissenhauer *et al.* 2024).

Finally, it is worth recognizing that as elvers would approach the ogee weir surface to ascend the spillway structure after dusk, there would naturally be a period of time where their numbers would continue to increase. Ideally, for this reason, CPUE measurements should be standardized by time after dusk, but due to logistical challenges and limited capacity, this was impossible to accomplish as surveys were conducted gate by gate throughout the night.

4.5 Future research

Future research should focus on several key areas to further our understanding of elver distribution and abundance within the WSJR. First, the extent of the upstream migration of freshwater age 0 elvers should be investigated to better understand their age progression and distribution patterns as they move from the Bay of Fundy upstream to the MQGS. This would ultimately shed more light into understanding whether or not age 0 elver upstream migration may be prevented, for example, by a velocity barrier as hypothesized by Jessop and Harvey (2003). It is also recommended that future studies within this stretch of the WSJR evaluate an index for the overall abundance or total population estimate of American eel elvers. Understanding the higher abundance of elvers on the north bank of the downstream vicinity of the MQGS would also require further assessment into hydrological flow fields. Additionally, further research is needed to assess the abundance of elvers at the MQGS, including the size of this population and whether it fluctuates between years. As there is evidence that elvers can remain within the downstream reach of the MQGS and retain their migratory motivation, it would then be integral to determine what happens to these elvers that are unable to overcome this barrier each year. Future studies would benefit from determining where the elvers go each year (observations declined swiftly in August), and what are the ecological consequences of their accumulation downstream of the dam and, more specifically, if this artificial concentration has an effect on the growth and sex-ratio of eels in this area, potentially influencing long-term population dynamics (Davey and Jellyman 2005; Verreault *et al*. 2009; Côté *et al.* 2015).

Future studies aimed at establishing an upstream passage system for elvers at the MQGS should focus on the physical conditions of the spillway structures in relation to the abundance and distribution of elvers attempting to pass over the gates. In this study, attempts were made to quantify whether elver density changes as they ascend the various ogee weir surfaces by using a standardize quadrat (Figure 4.2), but these data on climbing behaviour and density as a function of height above water are a subject for future analysis and study. Understanding how factors like gate condition (flow rate and algae coverage) influence the distribution of elvers will help determine the most suitable locations for the passage system, as well as the environmental conditions that best support their movement over an obstacle.

By continuing to analyze elver distribution and behaviour at the MQGS, we can ensure that an upstream passage system is implemented at an optimal time and location where elvers are abundant and actively migrating, thereby optimizing its effectiveness. Fisheries management would also be advised to investigate options for downstream passage for mature silver American eels before making any decisions on upstream passage at the MQGS to avoid the potential scenario of creating an ecological trap (*e.g.*, Ohms *et al.* 2022). Currently, only turbine passage is available for downstream migrating silver American eels at the MQGS, therefore a comprehensive review of downstream options would be advisable for future studies.

4.6 Conclusion

From previous research and observations, the elvers historically present at the MQGS were defined as either 55-65 mm in length (Jessop and Harvie 2003), between 6-7 cm (DFO 2017), or less than 100 mm (DFO 2010), while the only other previous study

on the WSJR to actually sample elvers did not report their sizes in any location (other than remarking the elvers at MQGS were not glass elvers, *i.e.*, meaning by their definition > 52mm), including the MQGS (LeBlanc 1973). However, the elvers captured throughout my thesis work were markedly longer than any of these historical definitions. Unfortunately, there are no data on direct measurements of the elver sizes that were historically encountered at MQGS (*i.e.*, LeBlanc 1973), and the other general elver studies in the Bay of Fundy region included captures that occurred shortly after coastal entry (*e.g.* Jessop 1998), and therefore, generally document smaller sizes for the upstream migratory eel contingent. Examination of upstream migrations that are conducted > 100 km inland are rare, and as such, it is difficult to establish direct comparison to whether the size range appears to have shifted, or even whether migration of elvers in this larger size category are anomalous or "normal". For MQGS, the data suggests that the freshwater age of the juvenile eels observed migrating upstream to the MQGS ranged from 0-3 years, and if the strong affinity for upstream migration is a behavioural determinant for defining "elver", then the definition for WSJR must be extended beyond those described in previous studies. While some elvers were able to make the journey to MQGS within their first year in freshwater, the lack of direct measurements of the elver sizes in historic assessments makes it difficult to compare the current and past observations and therefore, make firm conclusions regarding a shift from pre-turbine conditions, particularly in relation to turbines five and six. Therefore, it remains unknown if elvers in their first year of entry to the WSJR are being hindered by velocity barriers or other environmental factors that could impede their migration. However, an upstream

migratory contingent of American eels is currently arriving at MQGS and their upstream passage management is therefore a topic that will require attention.

Individual elvers are not randomly distributed at the MQGS; rather, they are concentrated in areas with incoming attraction flows, such as the main spillway and diversion sluiceway. To a smaller extent, elvers were also concentrated at other locations with attraction flows and where river velocity did not obstruct movement, such as the ARF of the downstream north bank. Elvers were present at the MQGS throughout June to August, with peak abundance occurring in July.

While elvers were found in both spillway structures, movement between the two structures may be limited. If efficient upstream passage is a goal for fisheries management, a passage structure may be required at both spillway locations. Since the movement between gates within a structure proved somewhat limited, an upstream passage system may need to span multiple locations to facilitate passage for elvers. This maneuverability would allow for more flexibility, addressing the various spatial locations at the MQGS where elvers are both abundant and motivated to migrate upstream. Deploying a non-permanent passage system during peak migration would improve efficiency, avoid unnecessary effort, and reduce costs for fisheries management.

Before any decisions are made regarding an upstream passage system, there are additional aspects that require consideration, including the negative impact of the parasitic nematode *Anguillicoloides crassus* on the swim bladder of American eels and the options for downstream passage for mature silver American eels. The findings of this thesis should not be applied without the context of a larger ecological assessment where all concerns, including parasite presence and downstream migration, are considered.

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Table 5.1. Summary of relative abundance of American eel elvers at and downstream of the Mactaquac Generating Station (MQGS) across available studies. Table was prepared by David Cairns (2025).

	At MQGS		Downstream of MQGS					References
	Sluiceways and adjacent water	Fish collection area						
	Km downstream of MQGS							
	0	0	0.1	0.5	1	1 - 10	10 - 25	
1973	●	●	X	X	X	X	X	Jessop & Harvie 2003, LeBlanc 1973
1974	●	●	X	X	X	X	X	Jessop & Harvie 2003, LeBlanc 1974
1975	X	●	X	X	X	X	X	Jessop & Harvie 2003
1976	X	●	X	X	X	X	X	Jessop & Harvie 2003
1977	X	●	X	X	X	X	X	Jessop & Harvie 2003
1978	X	●	X	X	X	X	X	Jessop & Harvie 2003
1979	X	●	X	X	X	X	X	Jessop & Harvie 2003
1980	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1981	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1982	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1983	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1984	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1985	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1986	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1987	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1988	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1989	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1990	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1991	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1992	X	◦	X	●	X	X	X	Jessop & Harvie 2003
1993	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1994	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1995	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1996	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1997	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1998	X	◦	X	X	X	X	X	Jessop & Harvie 2003
1999	X	◦	X	X	X	X	X	Jessop & Harvie 2003
2000	X	◦	X	X	X	X	X	Jessop & Harvie 2003
2001	X	◦	X	X	X	X	X	Jessop & Harvie 2003
2002	X	◦	X	X	X	X	X	Jessop & Harvie 2003
2003	X	X	X	X	X	X	X	
2004	X	X	X	X	X	X	X	
2005	X	X	X	X	X	X	X	
2006	X	X	X	X	X	X	X	
2007	X	X	X	X	X	X	X	
2008	X	X	X	X	X	X	X	
2009	X	X	X	X	X	X	X	
2010	X	X	X	X	X	X	X	
2011	X	X	X	X	X	X	X	
2012	X	X	X	X	X	X	X	
2013	X	X	X	X	X	X	X	
2014	X	X	X	X	X	X	X	
2015	X	X	●	•	X	•	◦	Dixon chapter 2
2016	X	X	●	•	X	X	X	Dixon chapter 2
2017	●	X	●	X	X	X	X	Dixon chapters 2&3
2018	X	X	X	X	X	X	X	
2019	X	X	X	X	X	X	X	
2020	X	X	X	X	X	X	X	
2021	●	X	X	X	X	X	X	Eissenhauer et al. 2025
2022	●	X	X	●	X	◦	◦	Eissenhauer et al. 2025
2023	●	X	X	●	X	◦	◦	Eissenhauer et al. 2025

Legend	No data	X
	Eel abundance:	
	None	◦
	Low	•
	Medium	●
	High	●



Figure 4.1 Images of the ogee weir spillway gates of the Mactaquac Generating Station that illustrate the combination of the amount of flow and filamentous algae growth on the surface. Panel A: Diversion sluiceway, gate 4 (August 4, 2016). Panel B: Main spillway, gate 5 (July 12, 2017). Panel C: Main spillway, gate 3 (July 19, 2017). Panel D: Main spillway, gate 5 (August 21, 2017).

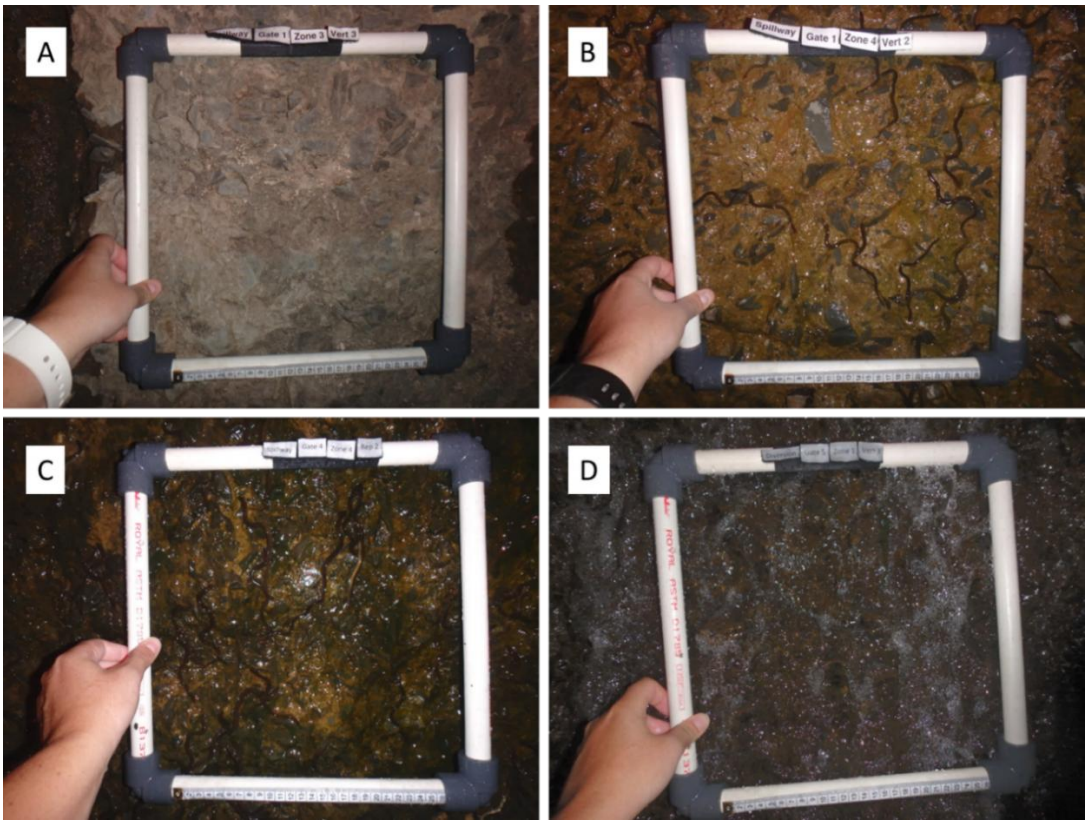

Figure 4.2 Examples of systematic quadrat (30 cm by 30 cm) counts conducted on different flow/algae stratum on various ogee weir spillway gate surfaces of the Mactaquac Generating Station. Panel A: Dry, no algae (August 1, 2017). Panel B: Wet, no algae (July 12, 2017). Panel C: Low flow, low algae (July 25, 2016). Panel D: Fast flow, low algae (August 4, 2016).

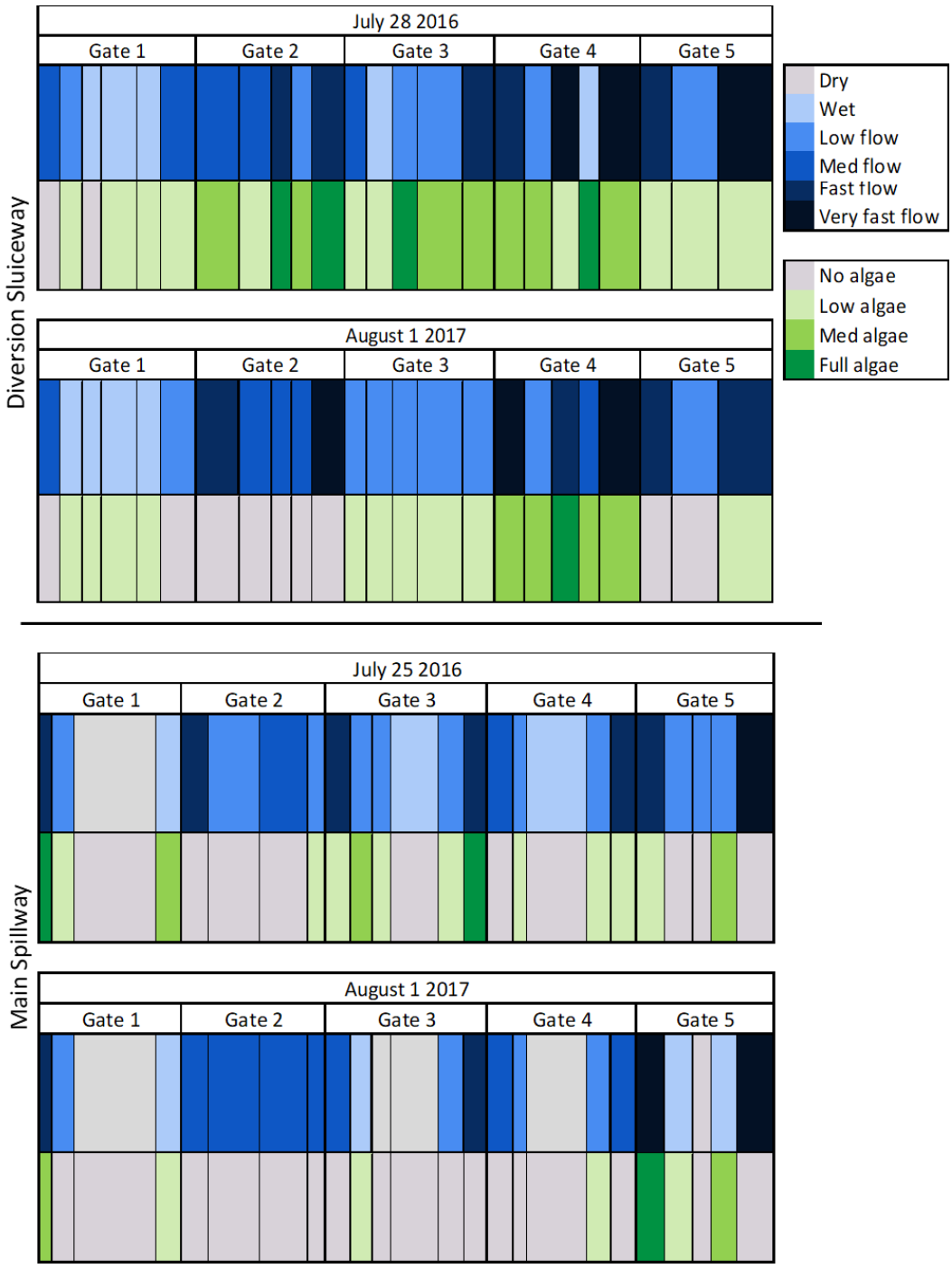

Figure 4.3 Illustration of the ogee weir surfaces of the spillway gates of the diversion sluiceway and main spillway of the Mactaquac Generating Station to represent the varying flow/algae combinations throughout the gated structures from surveys late-July to early-August 2016 and 2017.

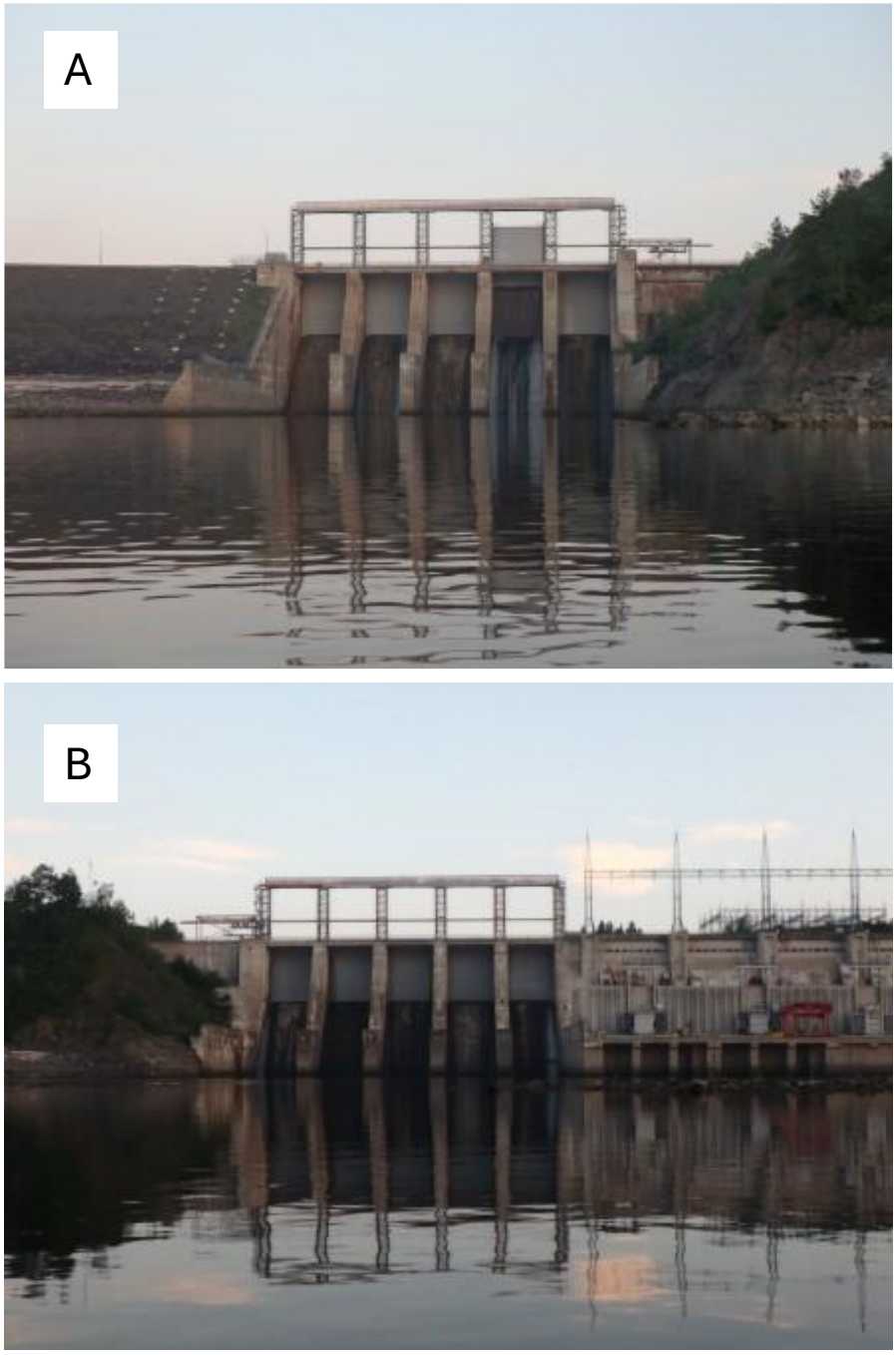

Figure 4.4 The ogee weir surfaces of the Mactaquac Generating Station spillway gates. Panel A: Diversion sluiceway. Panel B: Main spillway. July 19, 2017.

Appendix 1

Photographs of N=30 American Eel (*Anguilla rostrata*) otoliths collected from the Mactaquac Generating Station, Wolastoq | Saint John River and the Bay of Fundy estuary (Brunswick Aquaculture), in June-July 2015, May-August 2016, and June-August 2017.

Otoliths were prepared using a slightly modified version of the embedding and polishing method outlined in Secor *et al.* 1992. Photographs of otoliths were taken using a compound microscope under 100x magnification. Freshwater checks and winter annuli were evaluated to determine age of eel.

Secor D.H., Dean J.M., Laban E.H. 1992. Otolith Removal and Preparation for Microstructural Examination. In: Stevenson D.K., Campana S.E., editors. *Otolith Microstructure Examination and Analysis*. 19–57 p Canadian Special Publication of Fisheries and Aquatic Sciences.

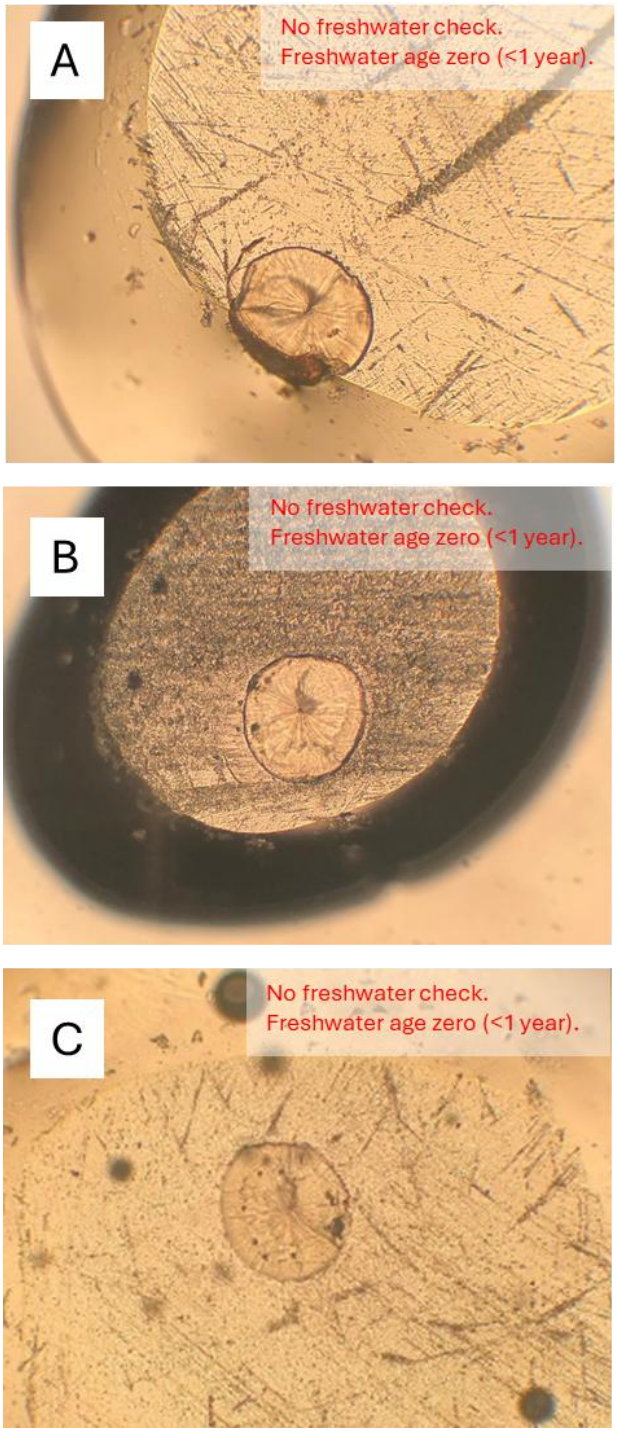

Figure A1.1 Otoliths removed from American eels (size class: 4.0-4.9 cm) captured in a Bay of Fundy estuary on May 16, 2016. A) Eel length: 4.3 cm. B) Eel length: 4.4 cm. C) Eel length: 4.6 cm.

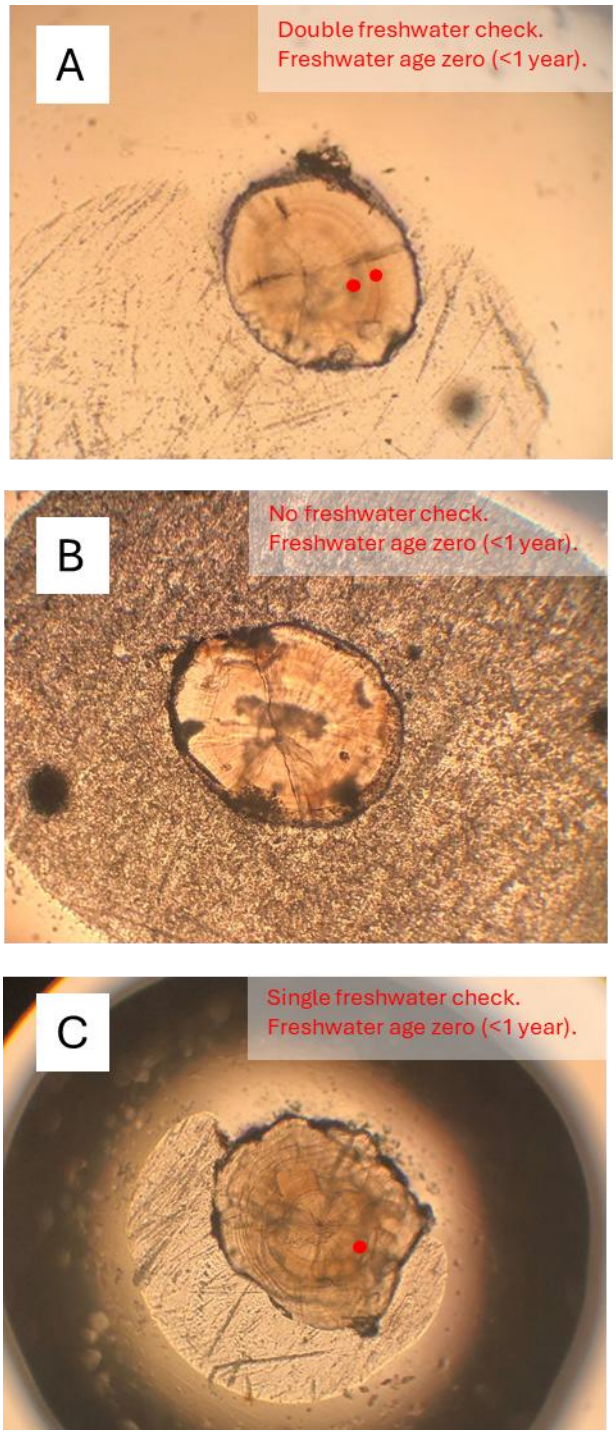

Figure A1.2 Otoliths removed from American eels (size class: 5.0-5.9 cm) captured in a Bay of Fundy estuary on May 16, 2016. Red dot indicates the presence of a freshwater check. A) Eel length: 5.1 cm. B) Eel length: 5.5 cm. C) Eel length: 5.7 cm.

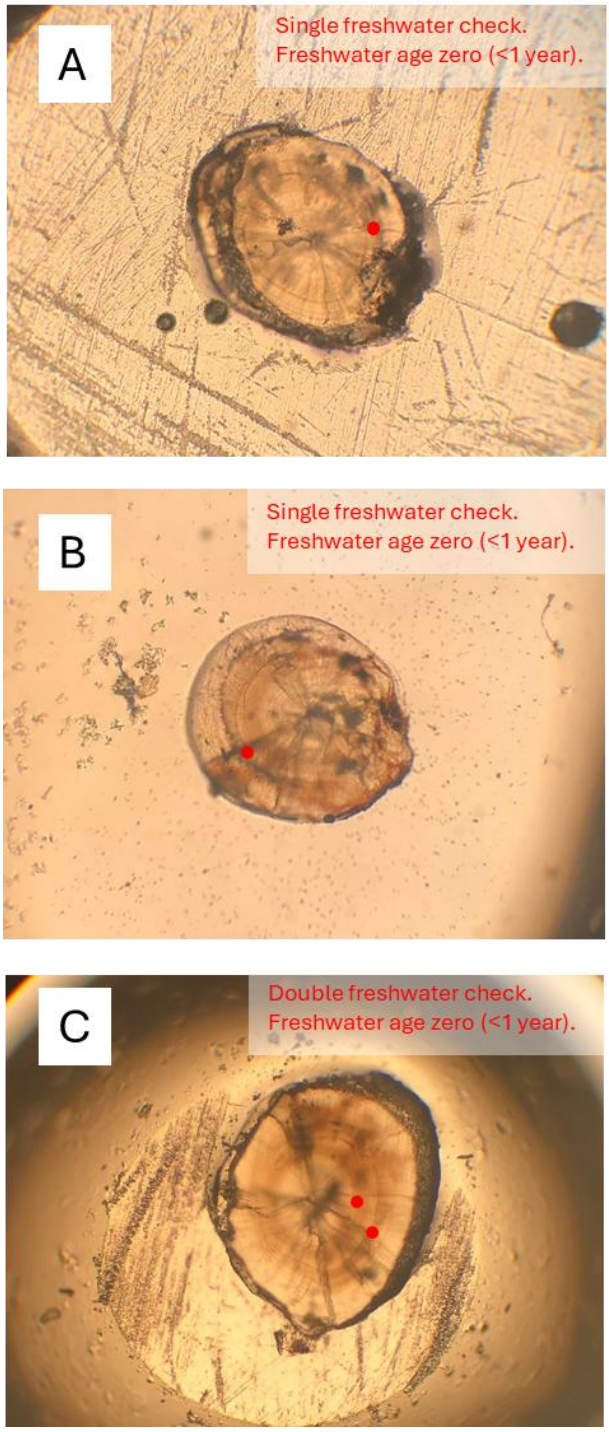

Figure A1.3 Otoliths removed from American eels (size class: 6.0-6.9 cm) captured in a Bay of Fundy estuary on May 16, 2016. Red dot indicates the presence of a freshwater check. A) Eel length: 6.1 cm. B) Eel length: 6.6 cm. C) Eel length: 6.7 cm.

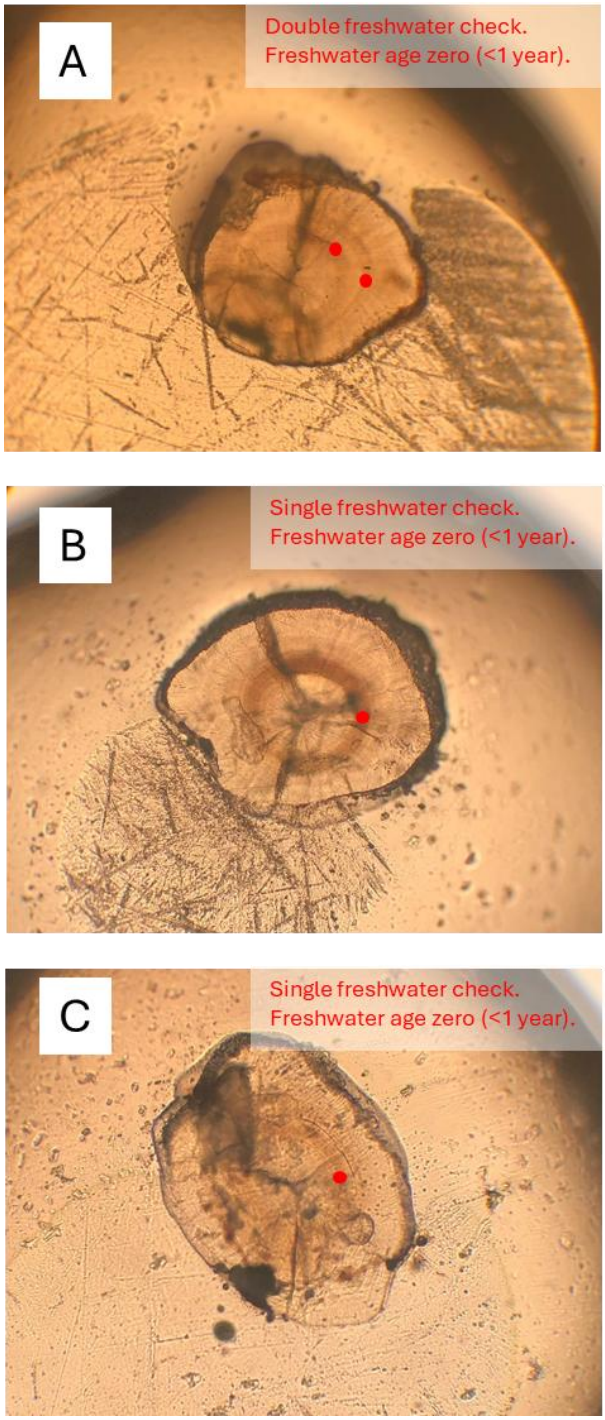

Figure A1.4 Otoliths removed from American eels (size class: 7.0-7.9 cm). Red dot indicates the presence of a freshwater check. A) Eel (length: 7.2 cm) captured in Bay of Fundy estuary on May 16, 2016. B) Eel (length: 7.5 cm) captured near MQGS on June 27, 2016. C) Eel (length: 7.7 cm) captured in Bay of Fundy estuary on May 16, 2016.

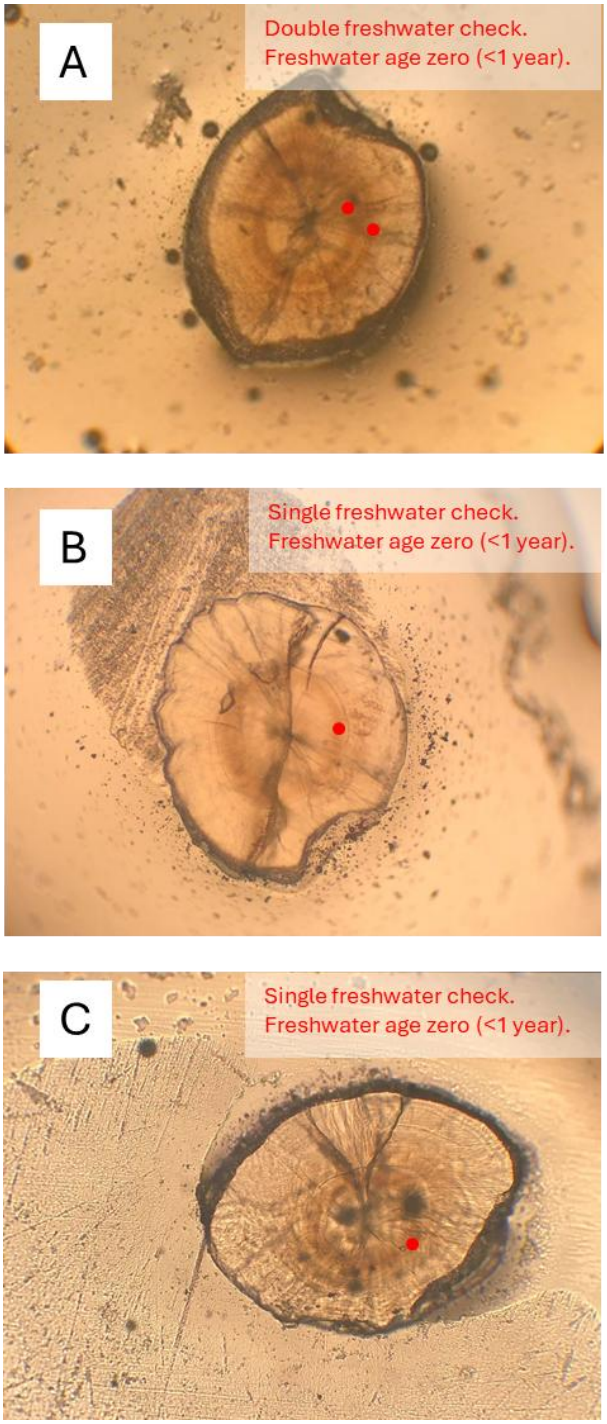

Figure A1.5 Otoliths removed from American eels (size class: 8.0-8.9 cm) captured near the MQGS. Red dot indicates the presence of a freshwater check. A) Eel (length: 8.2 cm) captured on June 28, 2015. B) Eel (length: 8.5 cm) captured on July 10, 2015. C) Eel (length: 8.8 cm) captured on July 27, 2016.

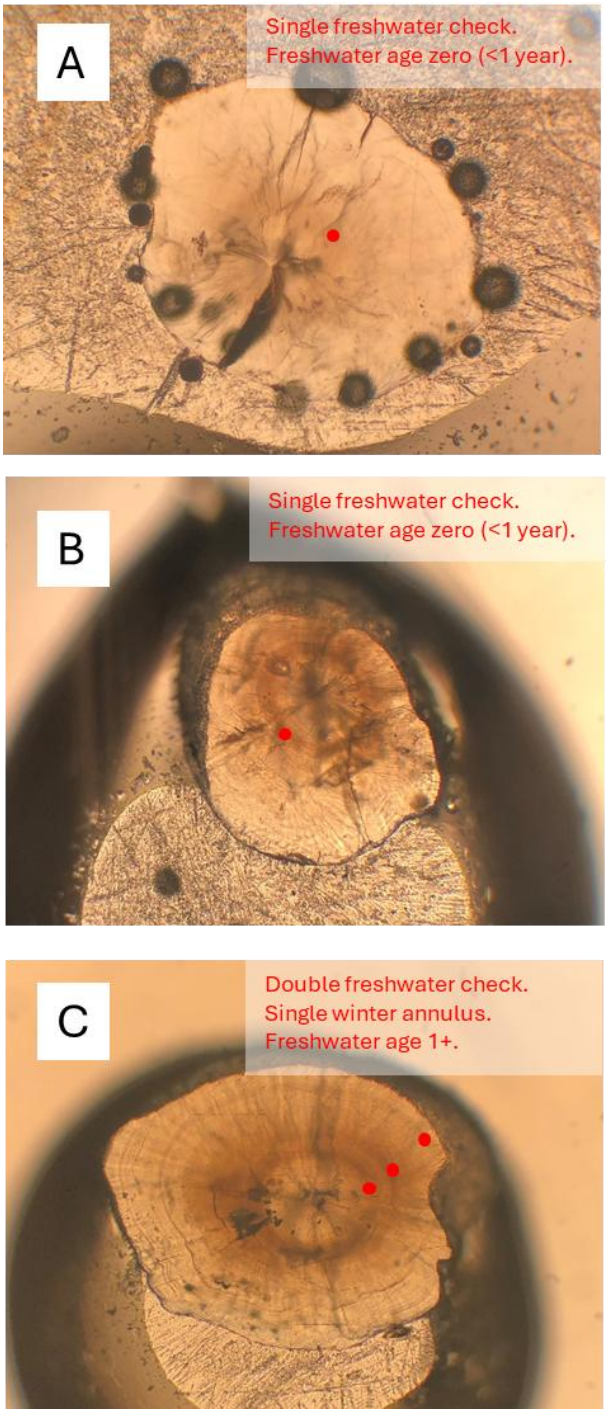

Figure A1.6 Otoliths removed from American eels (size class: 9.0-9.9 cm) captured near the MQGS. Red dot indicates the presence of a freshwater check/winter annulus. A) Eel (length: 9.3 cm) captured on July 11, 2016. B) Eel (length: 9.5 cm) captured on July 27, 2016. C) Eel (length: 9.8 cm) captured on June 13, 2017.

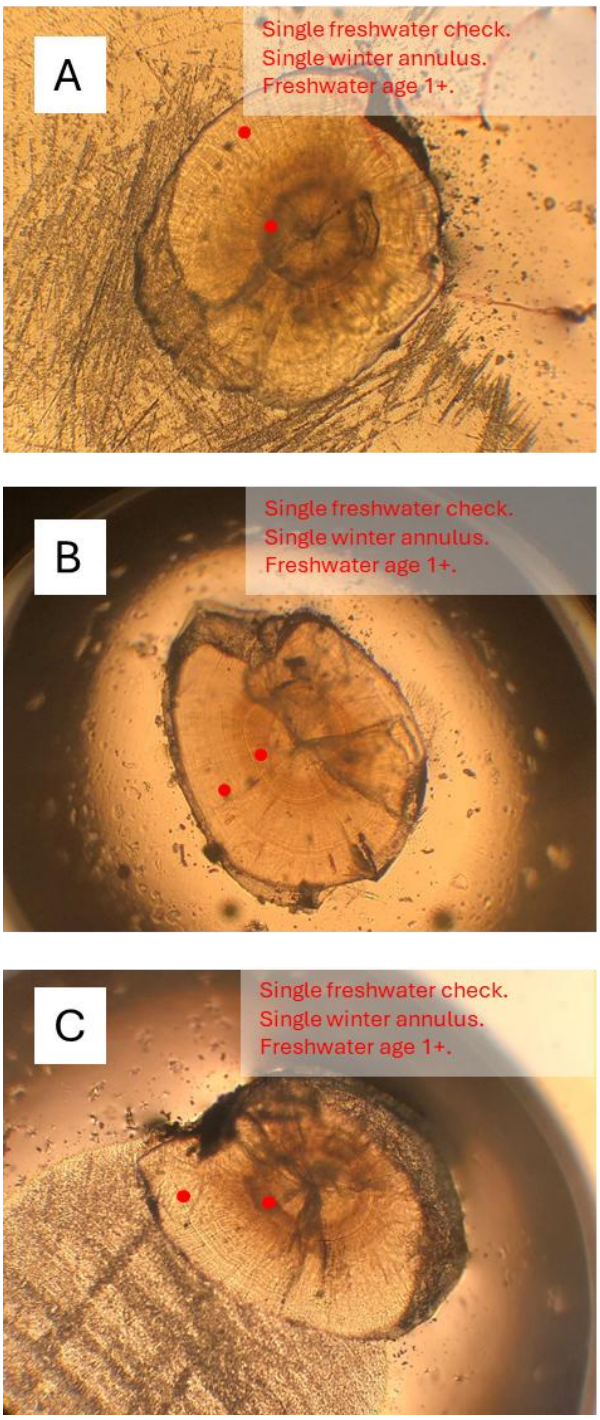

Figure A1.7 Otoliths removed from American eels (size class: 10.0-10.9 cm) captured near the MQGS. Red dot indicates the presence of a freshwater check/winter annulus. A) Eel (length: 10.3 cm) captured on August 18, 2016. B) Eel (length: 10.5 cm) captured on July 27, 2016. C) Eel (length: 10.7 cm) captured on August 9, 2017.

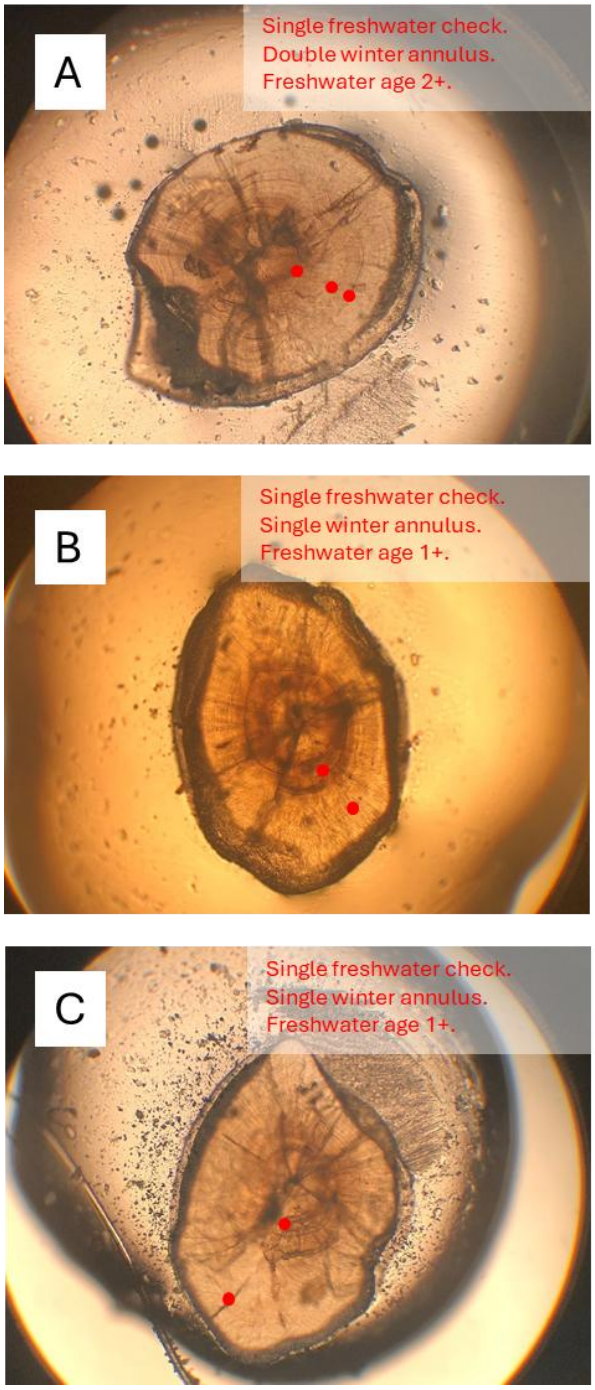

Figure A1.8 Otoliths removed from American eels (size class: 11.0-11.9 cm) captured near the MQGS. Red dot indicates the presence of a freshwater check/winter annulus. A) Eel (length: 11.3 cm) captured on August 9, 2017. B) Eel (length: 11.7 cm) captured on August 9, 2017. C) Eel (length: 11.9 cm) captured on July 27, 2016.

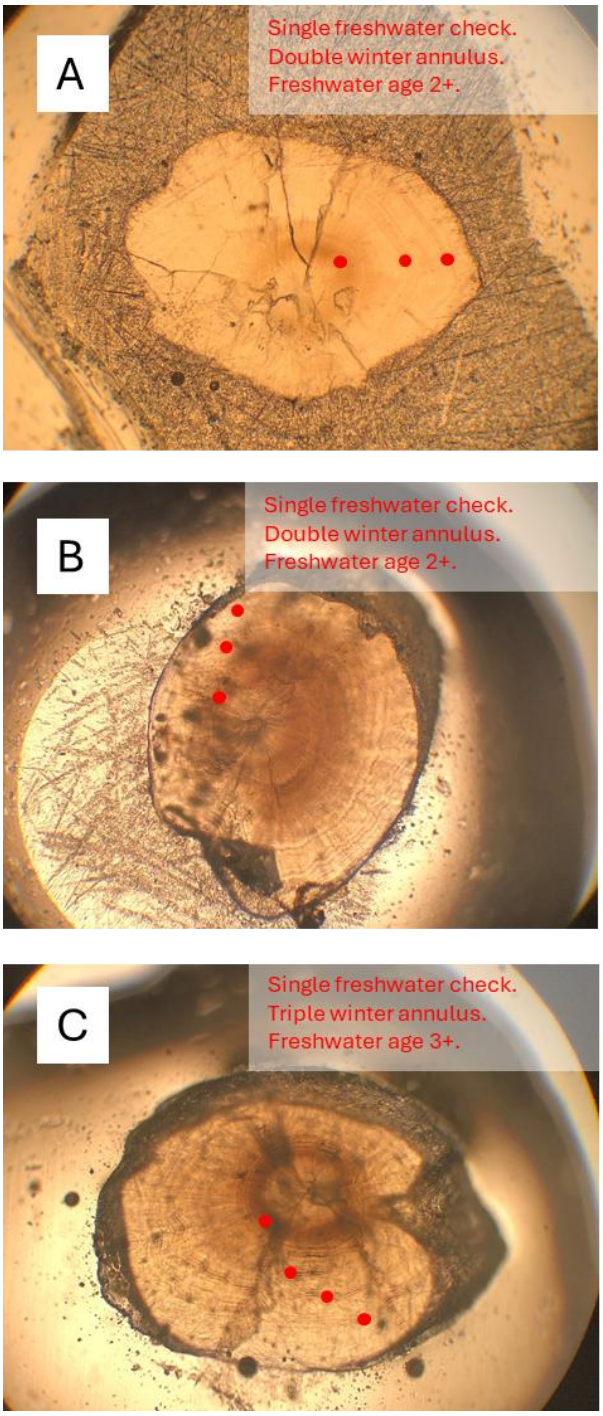

Figure A1.9 Otoliths removed from American eels (size class: 12.0-12.9 cm) captured near the MQGS. Red dot indicates the presence of a freshwater check/winter annulus. A) Eel (length: 12.4 cm) captured on August 9, 2017. B) Eel (length: 12.5 cm) captured on August 9, 2017. C) Eel (length: 12.7 cm) captured on July 27, 2016.

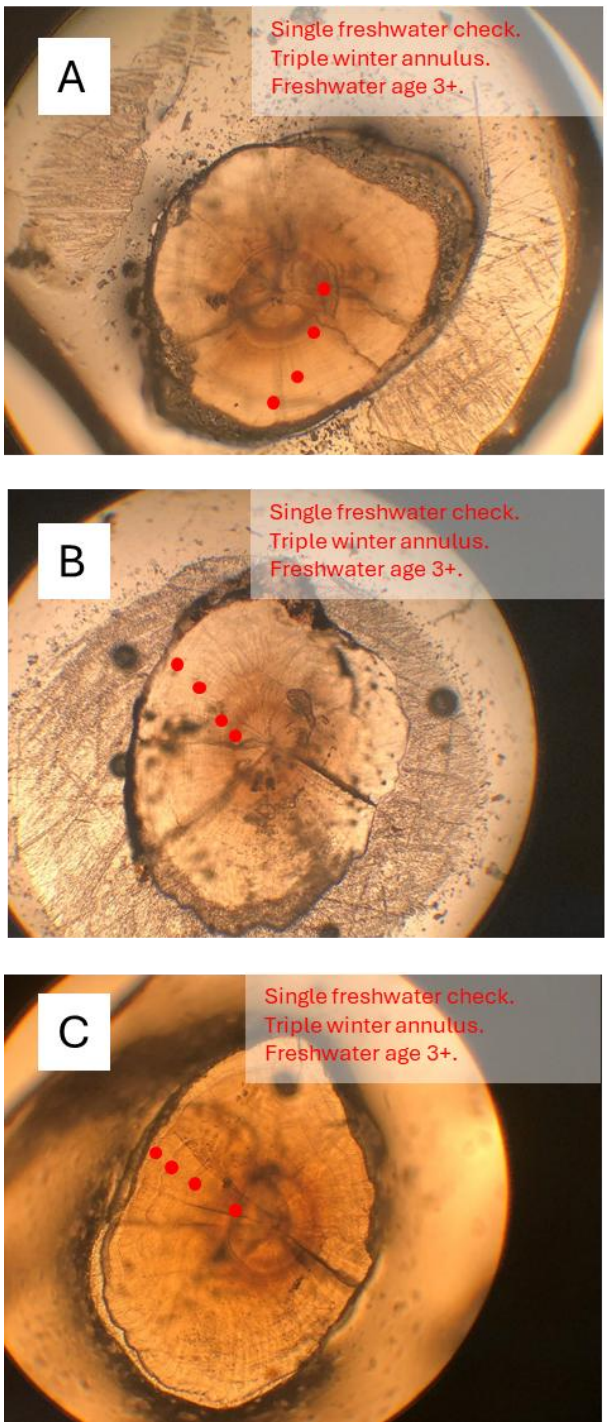

Figure A1.10 Otoliths removed from American eels (size class: 13.0-15.9 cm) captured near the MQGS. Red dot indicates the presence of a freshwater check/winter annulus. A) Eel (length: 13.3 cm) captured on August 9, 2017. B) Eel (length: 13.6 cm) captured on August 9, 2017. C) Eel (length: 15.2 cm) captured on June 14, 2016.

Curriculum Vitae

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Universities Attended: University of New Brunswick, Bachelor of Science, 2013

Publications:

Dixon B., Linnansaari T., Dolson-Edge R., Samways K. 2018. Assessment of potential for upstream passage for juvenile eel (*Anguilla rostrata*) at the Mactaquac Generating Station. Mactaquac Aquatic Ecosystem Study Report Series 2018–065. Canadian Rivers Institute, University of New Brunswick. 30 p.

Conference Presentations:

Dixon B., Linnansaari T., Curry A., Samways K. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and juvenile eels in the downstream reach of the Mactaquac Generating Station. 1st North American Eel Science Symposium. Electric Power Research Institute. December 12-13, 2017. Cornwall, Ontario, Canada.

Dixon B., Linnansaari T., Curry A. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and juvenile eels in the downstream reach of the Mactaquac Generating Station. 54th Annual Meeting of the Atlantic Society of Fish & Wildlife Biologists. October 25-26, 2017. Moncton, New Brunswick, Canada.

Dixon B., Linnansaari T., Curry A. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and juvenile eels in the downstream reach of the Mactaquac Generating Station. 43rd Annual Meeting of the Atlantic International Chapter of the American Fisheries Society. September 17-19, 2017. White Point, Nova Scotia, Canada.

Dixon B., Linnansaari T., Curry A. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and juvenile eels in the downstream reach of the Mactaquac Generating Station. Fredericton Fish and Game Association Meeting. September 12, 2017. Fredericton, New Brunswick, Canada.

Dixon B., Linnansaari T., Curry A. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and juvenile eels in the downstream reach of the Mactaquac Generating Station. The 1st UK International Eel Science Symposium. 'Science Into Management.' June 13-15, 2017. The Zoological Society of London, England.

Dixon B. 2017. Small, but Mighty: American Eels Fighting to Survive. 3 Minute Thesis Competition. University of New Brunswick. April 7, 2017. Fredericton, New Brunswick, Canada.

Dixon B., Linnansaari T., Curry A. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and juvenile eels in the downstream reach of the Mactaquac Generating Station. UNB Graduate Research Conference. March 18, 2017. Fredericton, New Brunswick, Canada.

Dixon B., Linnansaari T., Curry A. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and juvenile eels in the downstream reach of the Mactaquac Generating Station. Science Atlantic: Environment. March 3-5, 2017. Fredericton, New Brunswick, Canada.

Dixon B., Linnansaari T., Curry A. 2017. Near dam, spatio-temporal distribution of migrating American eel elvers and young yellow eel in the downstream reach of the Mactaquac Generating Station. Canadian Conference for Fisheries Research. January 5-7, 2017. Montreal, Quebec, Canada.

Dixon B. 2016. Mactaquac Aquatic Ecosystem Study (MAES) Near Dam, Spatio-temporal Distribution of Migrating Eel Elvers. NB Power Presentation. March 24, 2016. Fredericton, New Brunswick, Canada.

Dixon B., Linnansaari T., Curry A. 2015. Near Dam, Spatio-temporal Distribution of Migrating American Eel Elvers. Atlantic International Chapter (AIC) 41st Annual Meeting. September 20-22, 2015. Cap-Pélé, New Brunswick, Canada.