TEMPORAL DISTRIBUTION OF *MORONE SAXATILIS* EGGS AND LARVAE AND *NEOMYSIS AMERICANA* IN THE SHUBENACADIE ESTUARY

by

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Submitted in partial fulfillment of the requirements
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The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “TEMPORAL DISTRIBUTION OF *MORONE SAXATILIS* EGGS AND LARVAE AND *NEOMYSIS AMERICANA* IN THE SHUBENACADIE ESTUARY” by Craig M. Reesor in partial fulfilment of the requirements for the degree of Master of Science.

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Dedication

You can have anything in life if you will sacrifice everything else for it.

- J.M. Barrie

to the trip to the Smithsonian and,
all the other brilliant ideas we never saw materialize, but most of all
I dedicate this thesis to my family, especially to my dear mother

Nihil illegitum carborundum!

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Abstract

In the Maritimes, only two striped bass spawning populations remain: the Miramichi River in New Brunswick and the Shubenacadie – Stewiacke system in Nova Scotia. The Shubenacadie – Stewiacke system is subjected to a well pronounced twice daily tidal bore which induces dramatic changes in water parameters and challenges pelagic life. This system will be subject to potential change through brine discharge, a by-product of the Alton Natural Gas Storage Project. .

Examining the temporal distribution of mysids, striped bass eggs and larvae at a fixed location around the Alton Project site will provide baseline information on population structure and insights into how egg and larvae distributions change with respect to tidal cycles, temperature and salinity.

Surface plankton net tows from the top 0.75m of the water column were used to collect mysids, striped bass eggs and larvae over 14 months over two years. Daily mean egg abundance surpassed 1000 eggs/m^3 once in 2008. A decrease of 1.9 °C in water temperature at the Alton Project site coincided with a cessation of eggs, and presumably, spawning. Spawning resumed when temperatures surpassed 15 °C. In contrast, the largest spawning event of the 2009 season occurred as water temperatures decreased (14 to 12.7 °C). The 2009 spawning season was longer (49 days) than 2008 (31 days) by 18 days, and in both years spawning peaked within the last week of May and first week of June. Two large spawning events, over 4000 daily mean eggs/m^3 apiece, were detected May 24 and June 2, 2009.

Mysids were present in high numbers throughout May to November, with some tows greater than 14,000 individuals/m^3 in June 2008 and August 2009. Over the length of the ebb tide, as salinity decreases, mysid abundance also decreased. Whereas, striped bass egg abundance was consistently lowest at high tide and increased progressively over about 300 minutes through the ebb tide. Both striped bass larvae and mysids displayed patchiness in their temporal distribution suggesting passive transport in the this system. In both 2008 and 2009, larvae were detected at the Alton Project site for 38 days. The colder temperatures and larger tidal range of 2009, coupled with large increase in rainfall during the larval season contributed to the over 30-fold lower abundance over that found in 2008.

When abundance was related in concert with temperature and salinity, mysids were ever present at high abundances except on three occasions. Mysid abundance decreased when salinity dropped beneath 5 ‰ during both years, and in 2008 when temperatures were lower than 15 °C. Salinity was impacted according to a seven-day lag after rainfall in both years, although the minimum volume of rainfall and associated impact on salinity have yet to be described.

Keywords: striped bass, mysid shrimp, tidal bore, temporal heterogeneity, Bay of Fundy, Shubenacadie River, nursery habitat, fish population,

List of Abbreviations and Symbols Used

TL	….	Total length
YOY	….	Fish in their first year of life; young of the year
°C	….	Temperature
‰, ppt	….	Parts per thousand; a measure of salinity
lux, lx	….	Unit of illumination equal to 1 lumen per square meter
m^2, km^2	….	Meters or kilometres squared
m^3, km^3	….	Cubic meter or kilometers
mm	….	Millimetres
cm	….	Centimeters
m	….	Meters
ug	….	Micro-grams
mg	….	Milligrams
g	….	Grams
L	….	Liter
s	….	Second

Acknowledgements

I've only just a minute,
Only sixty seconds in it.
Forced upon me, can't refuse it,
Didn't seek it, didn't choose it,
But it's up to me to use it.
I must suffer if I lose it,
Give an account if I abuse it,
Just a tiny little minute,
But eternity is in it.

Dr. Benjamin Mays

I wish to respectfully acknowledge the funding partner, Alton Natural Gas Storage LP., for kick-starting and partially providing the means of this journey…. more than $2.4 * 10^6$ unexpected, exciting and memorable minutes.

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To Conor, Mom and Grandad, I'm glad that you had faith in me that I would finish, even when I was pricing flights. The enduring support, love, constant encouragement and telling me to keep my stick on the ice meant the world to me. A special shout out to my mother who although providing unanimous and ubiquitous support, love and encouragement did provide one of the final incentives to finish.

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I never saw a wild thing
sorry for itself.
A small bird will drop frozen dead from a bough
without ever having felt sorry for itself.

D.H. Lawrence

Chapter 1. Introduction

Estuaries are one of the more sensitive types of ecotones in the world, creating an important niche for both terrestrial and aquatic organisms. Estuarine ecosystems are particularly vulnerable to anthropogenic stressors as they receive run-off from both urban and agricultural developments. The balance between economic growth and the preservation and recovery of our ecosystems is of pressing concern. Healthy estuaries serve as vital nursery grounds for numerous species of diadromous fish. High levels of nutrients and invertebrate prey, attributed to the hydrodynamic properties of estuaries, provide an ideal environment for early life history stages of many species of fish (Krebs 2009). Many of these early rearing habitats have suffered degradation due to a variety of factors such as pollution, hydroelectric dams or urbanization.

Striped bass, *Morone saxatilis* (Walbaum, 1792), use estuaries from Florida to New Brunswick as both spawning grounds and nursery habitat for their pelagic egg and larval stages (Bigelow and Schroeder 1953; Rulifson and Dadswell 1995). In the Maritimes, only two striped bass spawning populations remain: the Shubenacadie – Stewiacke system in Nova Scotia and the Miramichi River in New Brunswick. Historically, striped bass populations also existed in the Annapolis and Saint John Rivers, but now are believed to be extirpated (Douglas et al. 2003). Striped bass eggs and larvae in the Shubenacadie – Stewiacke system and key YOY prey items, such as invertebrate mysids known as opossum shrimp *Neomysis americana*, will be subject to brine discharged from the Alton Natural Gas Storage Project (Alton Project site), a proposed solution mining project (see Section 1.1.). Without pre-construction baseline population and ecological data for striped bass, Atlantic salmon (*Salmo salar*) and Atlantic sturgeon (*Acipenser oxyrhynchus oxyrhynchus*) – all species of concern and specifically mentioned in the initial environmental impact assessment (Jacques Whitford 2007) – natural inter-annual fluctuations of life-history characteristics of these species would go undocumented. Collecting species-specific data is important so any perceived impacts of the proposed brine discharge can be fully assessed. The necessary data to understand if population change is within natural cycling or if it is linked to increased brine discharge within the estuary would be crucial in determining management responses. Few studies have been conducted on the Shubenacadie – Stewiacke system with even fewer looking at the temporal distribution of striped bass eggs and larvae, and none identifying critical habitat for these life stages or identifying prey item abundance. Identifying critical habitat is important because striped bass eggs and larvae are harmed by environmental disturbances which will greatly impact recruitment. Gathering baseline data on species that occupy or potentially occupy the intake and discharge site area is a reasonable step to provide information for the Alton Project. This thesis represents the first steps in identifying critical temporal fish habitat for striped bass eggs and larvae in the Shubenacadie – Stewiacke system as well as identifying prey item abundance. Although outlined as ‘at-risk’ species in the 2007 environmental assessment, neither Atlantic salmon nor Atlantic sturgeon were caught during this study; therefore, neither was not considered further.

Therefore, examining the temporal distribution and abundance of striped bass eggs and larvae and mysids at a fixed location around the Alton Project site should provide baseline information on population structure and insights into how egg and larval distributions change with respect to stages of development, over tidal cycles, and seasonally. Mysids are considered under a similar approach. In addition, mechanisms for retention of these elements can be inferred. These baseline data will also be useful for fish stock management decisions.

1.1. Alton Project

In December 2007, the Nova Scotia Government approved the Alton Natural Gas Storage L.P. in Alton, Nova Scotia, with the requirement that "monitoring programs and plans be developed in consultation with the Department of Fisheries and Oceans (DFO)". In response, the Nova Scotia Agricultural College (NSAC) was contracted to survey the presence and relative abundances of invertebrates, fish eggs, larvae and juveniles at the proposed Alton Project site on the Shubenacadie River (Lat. 45 09.423 Long. 063 23.133; Figure 1) during May to November of 2008 and 2009.

The Alton Project will create natural gas storage caverns at Alton, about 12 km east from the study site on the Shubenacadie River. About 28 million cubic meters of natural gas storage space will be created through a process called "solution mining" that involves drawing water from the Shubenacadie estuary that will then be used to dissolve underground crystalline sodium chloride formations to create caverns. About 10,000 m^3 day^{-1} of estuarine water (natural variation 0 - 28 ‰) is proposed for extraction. It is expected that effluent brine will be returned to the river at a salinity of no more than 25 ‰. The returning brine, a maximum of 9,000 m^3 day^{-1}, will be diluted from 260 ‰ to 25 ‰ by 100,000 m^3 of river water diverted into a constructed channel during the flood tide (Martec 2007a). The resulting brine (mixture of estuarine water and sodium chloride) will be pumped from these caverns to man-made ponds adjacent to the Shubenacadie River, where it will be diluted with more estuarine water. This briny solution will then be pumped back into the river near the location of the intake pipe. Both the intake and discharge pipe will be located about 2 km below the confluence of the Shubenacadie and Stewiacke Rivers (Figure 1). Both pipes pose potential threats to aquatic life.

At the discharge pipe, the concern is from released brine that may significantly alter water chemistry locally and throughout the estuary. This discharge is a concern for eggs and early stage larvae that act as passive particles and have no or limited ability to maintain position in the water column.

Chemical analysis of salt cores taken from the proposed Alton Project site are primarily crystalline sodium chloride, although common oceanic elements were present in low levels such as strontium (180 µg/L), copper (0.3 µg/L), iron (17 µg/L), lead (0.2 µg/L), and manganese (2 µg/L); (Jacques Whitford 2007). Sodium chloride (NaCl), in high concentrations (≥ 5 g NaCl/L) is acutely toxic to larval striped bass (Grizzle and Cummins 1996). NaCl toxicity is distinct from that posed by seawater and can occur in early stage juvenile striped bass in soft freshwater (water hardness is a measure of dissolved minerals, usually calcium and magnesium <30 mg/L) when Na^+ concentration is high and hardness (mostly Ca^{2+}) concentration is low. Toxicity results from a loss of K^+ created by increased gill permeability (Grizzle and Cummins 1996). In the Shubenacadie estuary, the threat of NaCl toxicity appears to be low because hardness ranges from 30 to 150 mg/L depending on recent freshets and sampling time i.e. hardness is tidally dependent (Duston and Rowlands, unpubl. data). Therefore, the threat posed by salinity and hardness alteration will likely be minimized by the dilution of brine with estuarine water before release and by the relative hardness of the Shubenacadie – Stewiacke system (Lay 1979; Martec 2007a), but this hypothesis is untested *in situ*. Increased brine or alteration of brine chemistry in the estuary might affect olfaction or olfaction responses during the adult pre-spawn migration and consequently impact migration.

The intake pipe poses a physical threat to pelagic organisms with little or no swimming ability, such as striped bass eggs and larvae or mysids both from an initial intake perspective and because extracted water will be centrifuged just after extraction. A second area of concern with the intake pipe is the possible change in currents and hydrodynamics in and around the constructed channel, which may result in physical damage of striped bass eggs and larvae that have no or limited ability to avoid this area. The government-led assessment panel considered these threats when reviewing the project and deemed them acceptable risks. However, the panel also recognized the uniqueness of the striped bass population that is endemic to this river system and, given the poor state of knowledge of this population, requested monitoring of early life history stages before and after solution mining to identify relative abundances with respect to tide and season that may be vulnerable to intake activities and discharged brine. Therefore, determining the temporal distribution of invertebrates and early history stages of striped bass will provide information to engineers and operators for the design, construction, and operation of the brine pumping station.

1.2. Shubenacadie – Stewiacke Striped Bass

Extirpation of two of the three striped bass spawning rivers within the Bay of Fundy has prompted the recommendation of this species as ‘threatened’ by the Committee on the Status of Endangered Wildlife In Canada (COSEWIC 2004). The Bay of Fundy striped bass population is anadromous and considered an ‘evolutionarily significant unit’ being genetically discrete from both the Miramichi and U.S. populations, with under ten percent of the Shubenacadie - Stewiacke population being transient fish of U.S. origin (Wirgin et al. 1993a; Diaz et al. 1997). Furthermore, the endemic striped bass represent the only known self - sustaining population utilizing a tidal bore river as a spawning and nursery habitat (Rulifson and Dadswell 1995). Seasonal long-term habitat separation, exclusive prey species and differences in the fatty acid profiles of eggs suggest that two distinct life cycles exist within this system, although they are not necessarily reproductively isolated as they share a similar spawning area and nursery habitat. One subpopulation (based on colour morphology) overwinters at the head of the Shubenacadie River in Grand Lake, while the other subpopulation overwinters in the Bay of Fundy (Paramore 1998; Paramore and Rulifson 2001; Morris et al. 2003). Adult striped bass numbers in the Shubenacadie – Stewiacke watershed are high following strong recruitment of the 1999 year-class (Douglas et al. 2003). Current adult numbers are unknown, but are likely much greater than 2002 estimate of “no less than 15,000 adults” (Douglas et al. 2003). However, the current strength of numbers must not lead to complacency since striped bass populations throughout their geographic range typically exhibit long-term ‘boom-bust’ cycles, with one good year-class recruitment every 20 years or so (Bigelow and Schroeder 1953), not atypical of a top level predator and compounded by habitat disruption, pollution and other anthropogenic stressors (Krebs 2009).

With the bulk of east coast U.S. striped bass recruitment and production originating from the Chesapeake Bay and Hudson River estuary (Berggren and Lieberman 1978; Wirgin et al. 1993b), the majority of striped bass research has focused on U.S. populations. The information known about Canadian populations is relatively limited; especially given only two populations remain. The previous study examining the temporal distribution of striped bass eggs in the Shubenacadie, derived two hypotheses pertaining to spawning: (1) Striped bass on the Shubenacadie River require a threshold temperature of 18 °C to initiate spawning and, (2) Spawning occurs during the neap tide of the lunar cycle as to provide the smallest tidal range (Rulifson and Tull 1999).

The mega-tidal Shubenacadie estuary contrasts markedly with stratified estuaries such as Chesapeake Bay, suggesting Shubenacadie striped bass have evolved behavioural and/or physiological adaptations to allow their survival in this dynamic habitat. The adaptations tend to focus on providing 'cushioning' for the egg in the entropic watershed; among some the adaptations include a smaller oil globule, and a larger and heavier egg than those populations which inhabit less energetic and dynamic systems (Bergey et al. 2003). Although the degree of specialization is unknown, these adaptations allow eggs and larvae to survive the tidal bore that dominates the Shubenacadie estuary.

One aspect of this tidal bore environment is that salinity can change from 0 to 20 ‰ within one hour (Rulifson and Tull 1999). Survival of Shubenacadie striped bass eggs is only reduced when salinity is greater or equal to 30 ‰, and larval growth is also impeded at similar salinity (Cook et al. 2010). In addition, juvenile growth is largely independent of salinity (Duston et al. 2004). High salinity tolerance is beneficial during ebb and flow tides where pelagic eggs and larvae reside. Juveniles and young of the year have been found in Cobequid Bay (inner Bay of Fundy), suggesting this area may be a nursery habitat

(Bradford et al. 2001; Rulifson et al. 2008). In contrast, low concentrations of strontium found from otolith microchemistry provide evidence suggesting that the Shubenacadie population juvenile nursery grounds may be located upriver, perhaps within the estuary (Morris et al. 2003). If juveniles spend significant periods in the potential Cobequid Bay nursery habitat, then time spent near the discharge site may be reduced.

Studying early life history is important to understand which factors might affect recruitment. Recruitment of individuals into a year class is paramount for the survival of fish species and is dependent on a wide variety of variables. Physical parameters of rivers provide insights into dispersion mechanisms and advection potential of eggs and larvae; in this case, from the Shubenacadie estuary into Cobequid Bay. The risk of advection increases if large freshets occur because they will remove eggs and larvae from estuary nursery grounds prematurely. Among U.S. Chesapeake Bay populations, factors affecting distribution include tidal height, freshwater discharge, salinity and temperature (North et al. 2005; North and Houde 2006; Martino and Houde 2010). High inter-annual variability in striped bass recruitment even with only these four factors further complicates modeling population dynamics in this system (Martino and Houde 2010). More data is required to model recruitment and population dynamics variability.

Both spatial and temporal nursery habitat is critical habitat that is considered essential to the survival of this species; however, it is yet to be described in enough detail to provide insight into how egg and early stage larvae remain within the habitat area especially given such an energetic river system. The primary goal of this study is to describe the temporal distribution of striped bass eggs and larvae within the Shubenacadie watershed relative to the Alton Project site using surface plankton tows from a small boat. When early life history stages of a predator and its prey share a temporal overlap, defining potential nursery habitat may be possible depending on the extent of the predator prey dynamic. Therefore, a secondary goal is to describe the quantitatively describe the temporal distribution of mysids.

1.3. Shubenacadie – Stewiacke Mysids

The pelagic mysid, *Neomysis americana*, commonly called opossum shrimp, is known to be an important prey item of YOY juvenile striped bass in other nursery grounds (Markle and Grant 1970; Nemerson and Able 2003; Schiariti et al. 2006) and abundant in plankton tows in the Shubenacadie (Duston unpubl. obs.). Opossum shrimp are common along the Atlantic coast of both North and South America, and are important food items of young fish. They were shown to be the principal prey item among striped bass >50mm TL in the Miramichi River estuary (Robichaud-LeBlanc et al. 1997). To date, there is no published study on mysid dynamics in the Shubenacadie estuary. Therefore, evidence of mysids as a prey item in other striped bass nursery habitats coupled with high abundances found in the Shubenacadie suggests that they should be studied as a potential prey item and secondary monitoring species. By examining the relationship mysid abundance with young of the year (YOY) and larvae temporal distributions of striped bass, salinity and temperature relationships can be inferred. As well, an understanding of key prey items and their temporal relationship to striped bass is beneficial.

1.4. Retention Strategies in Estuaries

In fisheries, recruitment can be defined as the ability of a species to retain individuals of a cohort to the following year. Individuals surviving successive years are recruited to successive year classes. Provided they survive past the egg and larval stage, their probability of recruitment to successive year classes increases significantly (Houde 1987). Recruitment is highly species and stage dependent. Ten-fold or greater fluctuations in year class recruitment can be based on relatively small changes in environmental conditions during early life stages (Houde 1987; Lasker 1987). Recruitment to the first year class is closely related to the ability of any given organism to be retained in a suitable nursery habitat such as one with both cover for predator avoidance and ample food supplies.

Most of the knowledge and theories on survival and growth of early life history stages of striped bass have been derived from systems with less energetics than the Shubenacadie; such as large, stratified estuaries like the Hudson River or Chesapeake Bay (Roman et al. 2001; Kimmerer et al. 2002; North et al. 2005). The mega-tidal Shubenacadie River estuary contrasts markedly with stratified estuaries, in that it displays characteristics of a fully mixed estuary, lending further evidence that striped bass may have evolved to be better suited for this dynamic environment.

In stratified estuaries, a major factor retaining eggs and larvae in the estuary nursery habitat is the estuarine turbidity maximum. This occurs when an estuary has enough depth to allow development of a two layer circulation system. During flood tide the bottom current generally flows upstream while the top layer's current flows seaward. The resultant shear zone between the two layers of the halocline induces flocculation of organics and dissolved solids in the fresh water. The mixing action generated through this interaction increases particulates in the water column, resulting in a zone of high turbidity and high abundance of potential prey near the salt front (Schubel 1968; Robichaud-LeBlanc et al. 1996; North et al. 2005). This region is known as the estuarine turbidity maximum. This turbid entrapment area allows for lower predator effectiveness and lower energetic cost of predator avoidance (Sirois and Dodson 2000) thus reducing the dual threats of starvation and predation (Houde 1987; Lasker 1987; North and Houde 2006). The distinct layers also allow for select tidal stream transport, where organisms can modify their vertical position to take advantage of the residue currents in order to modify their position within the estuary (Forward and Tankersley 2001). As the Shubenacadie tidal bore induces vertical mixing, predominant theories suggesting pelagic organisms act either as passive particles or select specific currents for adjustment of spatial position do not appear to apply. A third goal of this study is to broaden the understanding of mechanism(s) that eggs and larvae with limited swimming ability use to remain in this active estuary.

1.5. Thesis Objective

Approval of the environmental impact assessment from the Nova Scotia government for the Alton Underground Natural Gas Storage Facility Project was subject to a number of conditions. The survey data collected will contribute much needed information regarding baseline trends and allow future studies to expand upon those trends too develop models and broaden insights into striped bass biology. As a result of those two guiding thoughts and the goals of this study; the following action was identified for this study.

Quantify the temporal changes in abundance of early life history stages of striped bass and it's hypothesized primary prey the opossum shrimp with respect to tide, season, rainfall and associated changes in salinity and temperature.

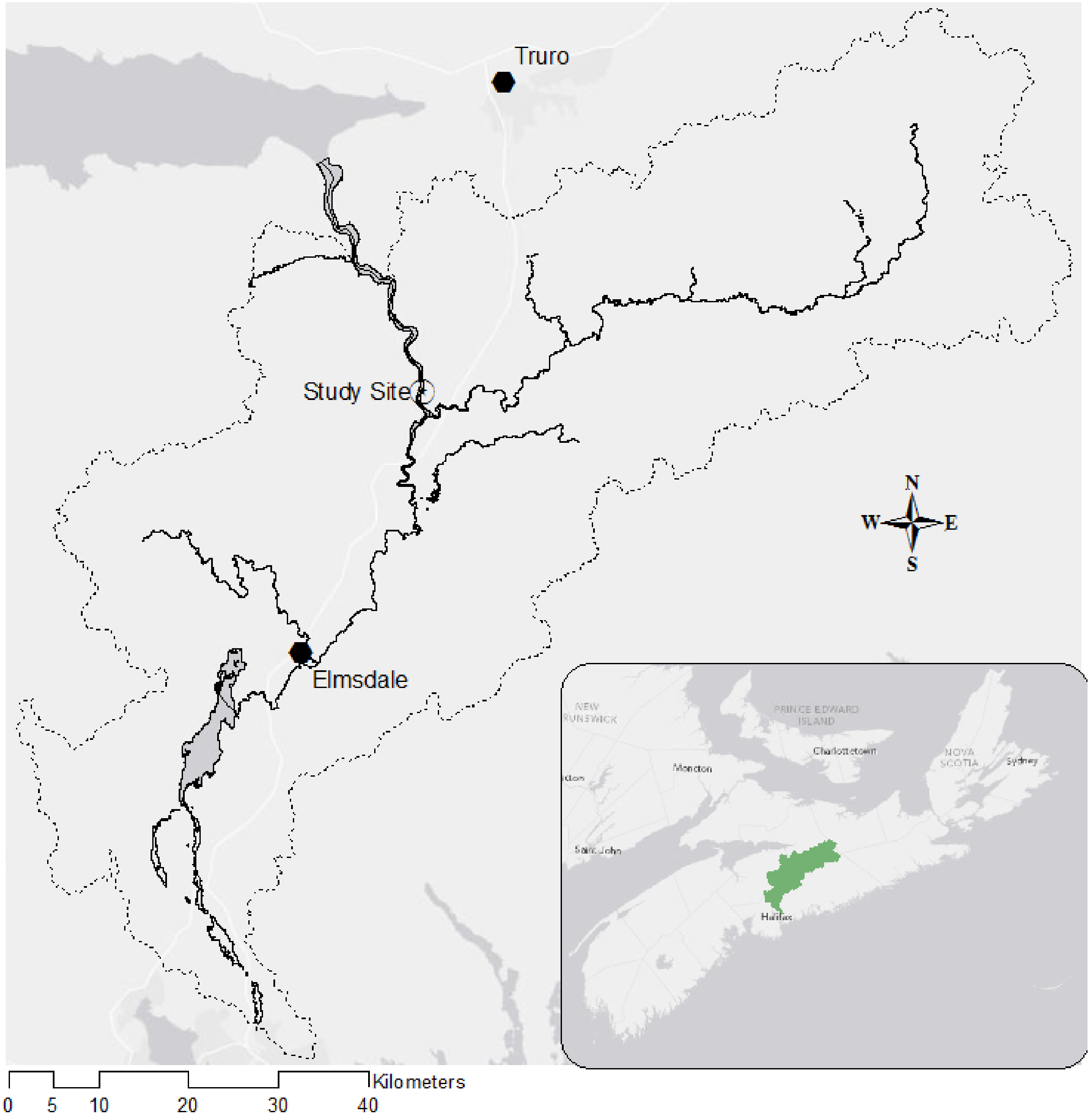


Figure 1. The Shubenacadie– Stewiacke system. The watershed (dotted line) is outlined with the study site shown. The location of the watershed is shown in relation to Nova Scotia, Canada (map insert). Data provided by the Province of Nova Scotia via the Dalhousie GISciences Centre.

Chapter 2. Materials and Methods

2.1. Site Description and Tides

The watershed that feeds the Shubenacadie and Stewiacke Rivers is the third largest secondary watershed in Nova Scotia approximately 2600 km^2; smaller than both the Salmon and Mira (~2900 km^2) and the Mersey (~3030 km^2) watersheds (Nova Scotia Museum of Natural History 1996). The Shubenacadie River and estuary includes 68 lakes in the Shubenacadie headwater region in addition to the Stewiacke River, a large tributary. Historically the Shubenacadie River headwater region, encompassing all areas upstream of Grand Lake, receives, on average, 1.37 m of rainfall per year. The remaining watershed, which encompasses all areas downstream from the outlet of Grand Lake and including the tributaries of the Stewiacke River, receives 1.14 m of annual precipitation per year (Lay 1979). This entire watershed drains into Cobequid Bay of central Nova Scotia, Canada (Figure 1; Lay 1979).

The confluence of the Shubenacadie and Stewiacke Rivers is 26 kilometers upstream from Cobequid Bay, and 46km downstream from Grand Lake (Figure 1). Based upon watershed area, the Shubenacadie River as it enters the Cobequid Bay is a sixth order Strahler river (Ward et al. 2008). Strahler stream orders can be used to define stream size based on a hierarchy of tributaries within the river network (Waugh 2002). The Strahler number is similar in magnitude to the Saint John River, New Brunswick which is a seventh order river as it enters the Bay of Fundy (R. France, NSAC, pers. comm.).

The proposed Alton Project site is a one kilometer section of the Shubenacadie River spanning the planned diversion channel site, 23 kilometers south of the mouth of the Shubenacadie River at Cobequid Bay (Lat. 45 09.2359 Long. 063 23.635; Figure 1). River width at the study site at high tide was 240 m, decreasing to 150 m at low tide with a large sand bar on the west bank, with a cross-sectional area ranging between 155 to 1602 m^2 (Figure 2; G. Stewart, NSAC, pers. comm.). The sand bar has occupied the same area since the 1980s (Matrix 2007). The estimated ebb and flood volumes of a large tide (4.1 m range) at the study site are over eight million and six million cubic meters per day, respectively, with the volume of a small tide (1.6 m range) approximately 50% of those values (Jacques Whitford 2007).

The Shubenacadie estuary is mega-tidal (> 10m large tidal range at mouth) with a well pronounced tidal bore occurring twice daily (Canadian Hydrographic Service 2008). At the study site, the tidal bore and following flood tide causes dramatic changes in depth (0.7 to 2.7 m) and salinity (0 to 20 ‰) with moderate changes (<5 °C) in temperature occurring in less than an hour (Figure 3). The strong, turbulent current from the bore ensures that the water column is thoroughly mixed with respect to temperature, salinity and suspended sediment, with no evidence of stratification either vertically or laterally (Parker 1984; Tull 1997; Martec 2007b). Typically the photic zone in the Shubenacadie is very limited (<0.20 m), with surface turbidity varying between <20 to >300 nephelometric turbidity units (NTU; Reesor unpubl.data). The high turbidity is caused from river turbulence and exacerbated through a tidal bore increasing suspended solids and re-suspending silt and clay in the water column. At the Alton Project site, a threshold depth of 2.2 m is reached before a salinity increase is measurable from the incoming marine water traveling upriver (Martec 2007b).

On average, flood tides in the Shubenacadie estuary last 1.25 hours at the Alton Project site, and are preceded by the tidal bore. High slack water at the site lasts for approximately 20 minutes followed by the ebb tide which last about 10 hours (Figure 4). Freshets and droughts as well as lunar phase have considerable impact on the Shubenacadie – Stewiacke system by increasing ebb time and reducing bore speed, or vice versa, by up to an hour (Martec 2007b). The tidal amplitude is greatly reduced over the length of the estuary. Tidal range at the estuary mouth is roughly ten meters, whereas as at the Alton Project site, tidal range is closer to three meters (Figure 4).

2.2. Measurement of Physical Parameters

Hand-held meters were used during sampling to measure water depth to 0.1 m (SKU: SM-5), and surface water salinity (‰) and temperature (°C; YSI model 85). Surface water samples from selected tows were collected in 2008 for analysis of surface turbidity levels (NTU; Hach 2100A). Underwater light intensity units up to 1.9 meters depth was determined using a spherical sensor (LiCor 193SA) attached to one inch PVC pipe with five centimetre increments marked. Depth versus salinity profiles were obtained by attaching the YSI 85 probe to a PVC pipe. Water temperature closer to the spawning grounds, 2 and 12 km upstream on the Stewiacke River, was recorded every 30 minutes between May to October (2008) and every to 60 minutes between April to November (2009) using a temperature logger (Vemco logger: minilogger 8k; Figure 5). Conductivity units, temperature and depth at the study site were logged at either 10 (2008) or 20 (2009) minute intervals from May to October by a logger (CTD-Diver, Schlumberger -- Van Essen Instruments; model 85256). Daily mean water temperature from the Alton Project site were calculated using the mean of 144 (2008) or 72 (2009) readings recorded every 10 (2008) or 20 (2009) minutes over a 24 hour period (Figure 5). Rainfall and air temperature data from the nearest weather monitoring station inside the watershed was taken from Halifax Stanfield International Airport (World Meteorological Organization ID 71395) and accessed through the Environment Canada website (Government of Canada and Meteorological Service of Canada 2010). Tidal range, unless explicitly stated, was obtained from the Canadian Hydrological Survey station at Burntcoat Head (#270) to better illustrate tidal forcings that impact the river, potential strength of advection and illustrate the counterpoint to rainfall and freshets.

2.3. Sampling Procedure

The sampling period consisted of 14 months over two years; 13 May to 6 November 2008 and 5 May to 28 October 2009. In total, 554 plankton net tow samples were collected. Samples were collected from the top 0.75 m of the water column using a standard conical plankton net (0.5 m mouth diameter, mesh 500 µM, length-to-width ratio 3:1) fitted with a factory calibrated flow-meter (R2030 General Oceanics, Florida) attached in the mouth of the net allowing estimates of water volume (m^3) filtered during each tow. The net was towed horizontally into the current, 2 to 3 m behind a flat-bottomed boat (3.5m long, 4hp outboard motor). Sampling was restricted to the surface region because of strong currents lower in the water column that cannot be overcome with a small boat and motor as well as an inability to submerge the net while maintaining a horizontal tow. If striped bass eggs act as passive particles and the water column is vertically homogeneous, the river can be characterized with a water sample from any depth (Findlay et al. 1991a,b).

As the season progressed, sampling frequency decreased because temporal changes in egg and larval abundance over tidal cycles and days became less variable. Initially sampling occurred a minimum of three times per week during striped bass spawning and the subsequent larval season (mid- May to mid- July). Subsequently, sampling was reduced to a minimum of twice weekly until September, at which time sampling was further reduced to a minimum of once weekly until late October (2009) or until the river became ice laden in November (2008).

Sample collection occurred during daylight hours in both 2008 and 2009, but on 24 May 2009 sampling continued until 2300 h and a 28 hr continuous sampling period was undertaken on 3-4 June 2009 providing sampling over three complete ebb tides. Most sampling commenced at high slack water and were repeated every 30 to 60 minutes for up to ten hours during the ebb tide. Some sampling commenced during the final two hours of the ebb tide to gather data late into ebb tides, terminated before the tidal bore and flood tide for safety reasons, and resumed during the following ebb tide. High slack water served as a reference point allowing comparisons among days. The high frequency of sampling was necessary due to rapid salinity changes and concomitant changes in ichthyoplankton abundance. Reducing sample variability is not feasible in such a dynamic system as it is suggested by (Cheek 1961 *in* Setzler et al., 1980). High slack water was defined as the period between 2.0 to 2.5 hours after the tabulated high tide time at Saint John, N.B. (Canadian Hydrographic Service station #65). Saint John is the location historically used as a basis for fisherman in the Bay of Fundy to calculate tide times. Sampling frequency on any given day was limited by man-power availability and the logistics of working in the field for extended periods.

Plankton net tow duration was typically either 90 seconds or three minutes, depending on striped bass egg abundance and the amount of river detritus. The start and end position of each tow was recorded using either a hand held GPS (Garmin model 60CSX) in 2008 or marker posts along the river bank in 2009. Occasional high water currents early on the ebb tide made it impossible to hold station, and during freshets the boat was usually forced several hundred meters downstream during a tow. Still, sampling occurred in the main channel 5 to 20 m from a marker post located at N45 09.477 W063 23.117 on the eastern bank of the river. When striped bass were spawning and personnel were available, additional samples were collected upstream closer to the spawning grounds on the Stewiacke River (Figure 1), about 500 m upstream at the confluence with the Shubenacadie River (N= 15 samples in 2008 and N= 53 samples in 2009) during the same ebb tide to compare relative abundance with the Alton Project site. When samples were taken upstream from the confluence, the plankton nets were held from the back of a moored boat for up to 15 minutes, similar to previous methodology conducted for ichthyology surveys on this river (Tull 1997; Rulifson and Tull 1999; Douglas et al. 2003).

2.4. Sample Preservation, Sorting and Enumeration

Buffered 10 % formalin and ambient river water (ratio about 30:70) were used to fix all tow samples. Rose Bengal dye (5 %) was added to the formalin from late July 2008 onwards. The dye stained fish and invertebrates pink making it easier to sort them from detritus (Mason and Yevich 1967). The volume of formalin used varied depending on the detritus load in the sample. Once fixed, samples were transported to the NSAC for enumeration and identification and stored in two-litre plastic containers until processing. Even with Rose Bengal dye, enumeration and sorting was difficult and time consuming because of prodigious amounts of detritus.

Each sample was emptied into a shallow plastic tray where juvenile fish and larger pieces of detritus were removed. Juvenile fish were identified by species and measured (fork length to 0.1 cm, body weight to 0.1 g). The remaining material was poured into a four-litre beaker and filled to the two-litre mark with seawater. Then, to re-suspend and homogenize the material, a small silica aquarium air diffuser was placed at the base of the beaker and air bubbled through vigorously. Triplicate sub-samples were taken with a small beaker on a handle fashioned from a wire rod. Due to the time and personnel constraints of counting detritus-heavy samples, the volume of sub-samples varied (120, 60 or 15 mL).

Sub-samples were counted in a 15 cm diameter circular dissection plate, and meso- and macroplankton (ichthyoplankton) were isolated with the aid of a dissecting microscope (Model: Olympus America), forceps, and dissecting needles. Striped bass eggs were counted and stage of development was coarsely assessed. The developmental stage was assessed more rigorously and consistently in 2009 than 2008. Eggs were categorized into one of two stages visible under the dissecting scope; STAGE 1 –where no development was visible, STAGE 2 – some blastula development was visible up to pre-hatch. Striped bass larvae were separated from detritus and invertebrates using a pulse of saltwater on which they floated to the surface, then counted and a random sub-sample ($n \leq 30$) taken for measurement of total body length

(0.1 mm) and body weight (0.01 g). Other fish species were preserved in formalin (10 %) for subsequent identification and measurement of total length and weight. Storage due to formalin caused no significant shrinkage in body length among 18 NSAC hatchery reared larvae with measurements taken 1, 4, 12 and 33 days post formalin storage.

The invertebrate survey was restricted to *Neomysis americana* mysids and no nauplii stages were counted. The invertebrate survey was restricted to enumerating mysids because of manpower and time restraints and to satisfy the outlined goals of this study. Similarly carapace length, identifying sexes and attempting to gauge health of the mysid was not done due to the above constraints.

Descriptive analysis was used to examine and describe the presence and abundance of mysids, and striped bass eggs and larvae. Abundance was standardized per cubic meter of water. Estimates of daily mean abundance were calculated by dividing the sum of ichthyoplankton or mysids collected during each day (up to 12 tows) by the sum of water volume filtered during that day. Egg and larval striped bass and mysid abundances were pooled at increments of one degree centigrade or one ppt salinity. The mean abundance was taken for each pooled value and standard error. Values from individual tows were overlaid to provide context. To facilitate graphing of within tide abuundance, 'high' egg abundance data of >1000 eggs/m^3 from both 2008 and 2009 were kept separate from 'low' egg abundance, <300 eggs/m^3. Lagged rainfall was calculated through autocorrelation of mean rainfall of the prior seven days against daily salinity at the Alton Project site. Lagged rainfall was used instead of the current day rainfall to account for ground surface discharge and runoff times from the watershed and as a means of skirting the complicated issue of calculating the hydrological antecedent moisture index and surface cover for the Shubenacadie – Stewiacke watershed. Spearman ranked correlations (ρ) were used to test for significance of lagged rainfall interaction on salinity.

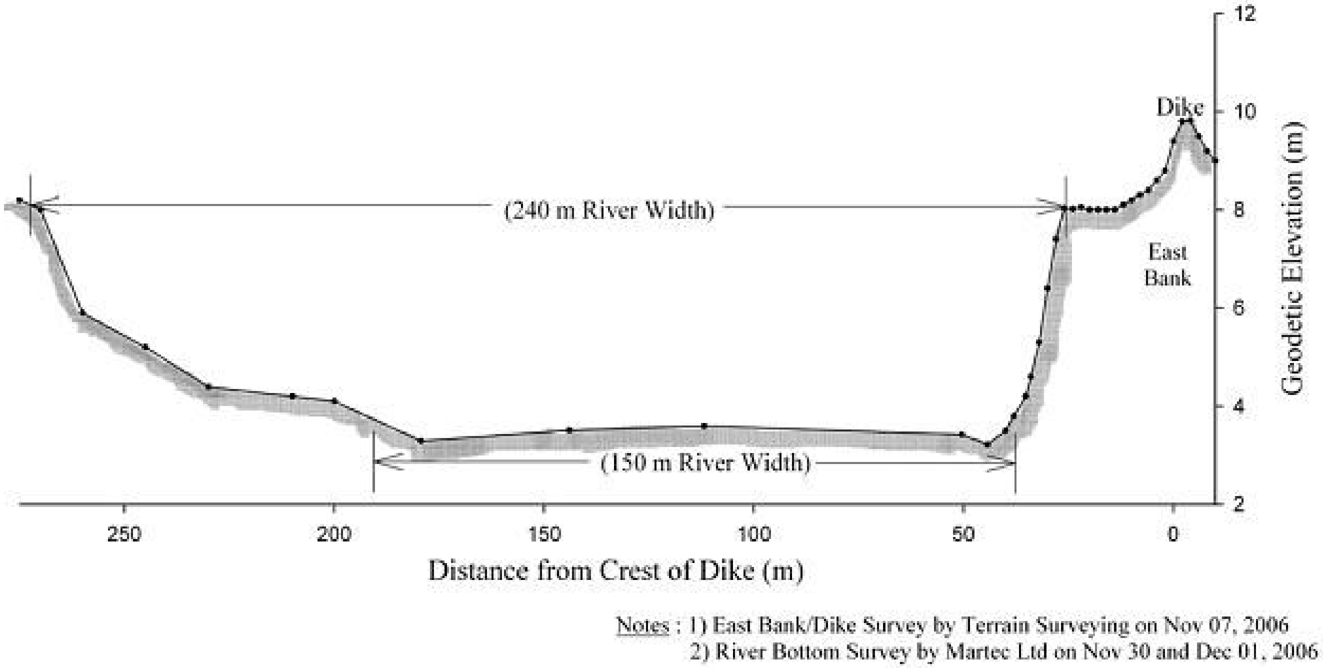


Figure 2. River cross-section at the Alton Project site in fall 2006. Geodetic Elevation (m) = Water Elevation (m) + 3.8. The location is skewed towards low water depths; the most frequent water elevation during fall 2006 was 0.4 m (4.2 m Geodetic). (Taken from Martec 2007b).

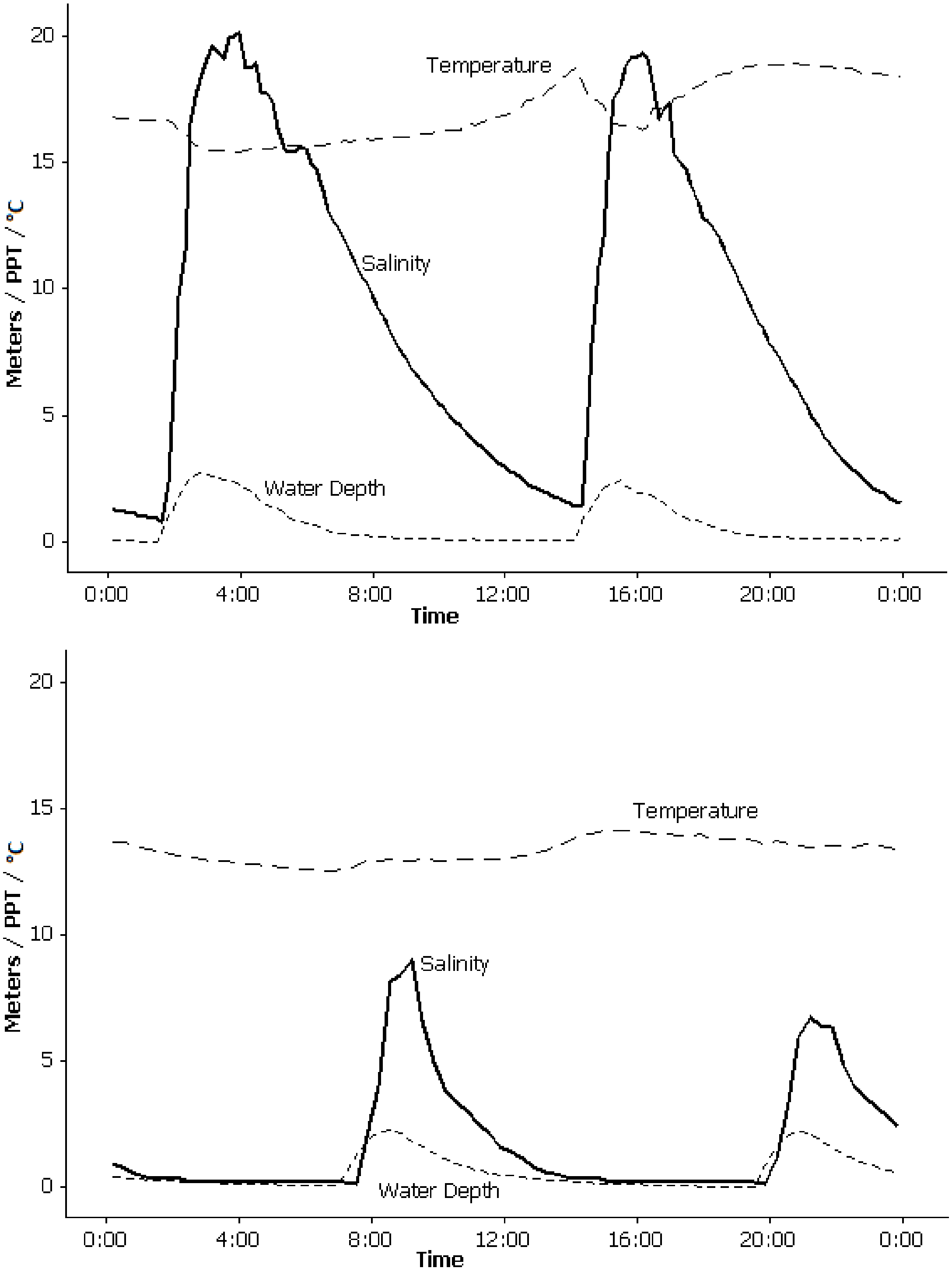


Figure 3. Examples of effects from the tidal bore and flood tide on surface water temperature, salinity and water depth. June 19th, 2008 (upper panel) and May 17th, 2009 (lower panel). Data logger was attached to a cinderblock ~0.5 m from bottom at the study site.

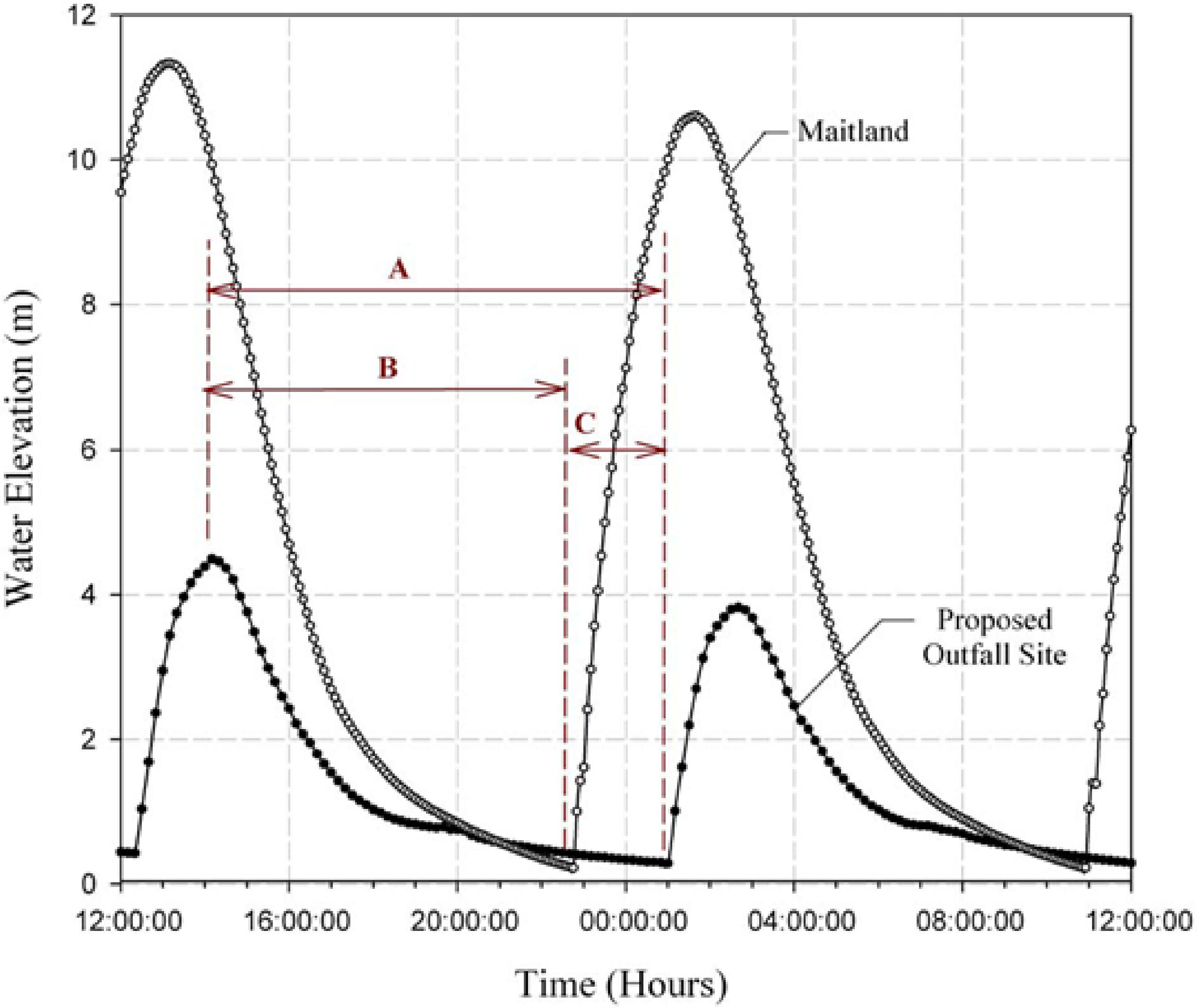


Figure 4. Water elevation profiles measured at Maitland and proposed outfall site during during a large tide in fall 2006. A = average time of ebb tide at the discharge site (10 h 56 m); B = average time between high tide at outfall site and next tidal reversal at Maitland (8 h 19 m); C= and the average time for bore to move up river from Maitland to discharge site (2 h 37 m). (Taken from Martec 2007b).

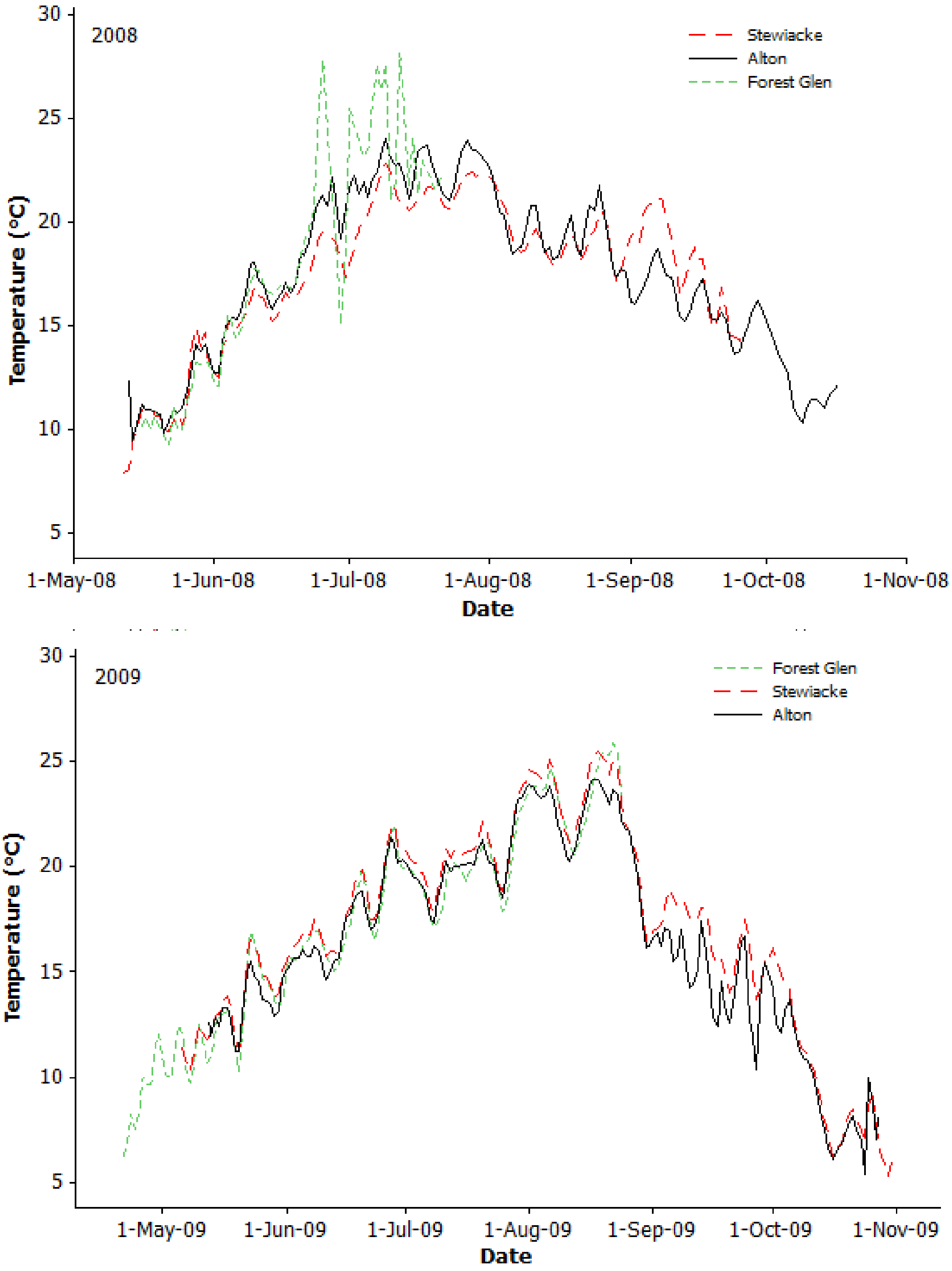


Figure 5. Temperature profiles from data loggers from 2 (Stewiacke) and 12 (Forest Glenn) km upstream on the Stewiacke River, as well as the Alton Project site during the 2008 and 2009 sampling season.

Chapter 3. Striped Bass

3.1. Striped Bass Distribution and Population Status

Striped bass, Family *Moronidae* is characterized by a spiny, double, dorsal fin, dark green pigmentation dorsally, a faintly silver side with seven or eight horizontal bands, and a white belly (Bigelow and Schroeder 1953). It is a voracious, non-selective, opportunistic predator (O'Connor 2010). Adults prey on a variety of fish and large invertebrates while the young consume zooplankton, shrimp, and crustaceans (Bigelow and Schroeder 1953; Markle and Grant 1970; Overton et al. 2009). It is a highly eurythermal species experiencing temperatures ranging from < 2 °C during winter to an upper lethal of 31 °C, with a historical geographic range extending from the St. Lawrence estuary along the Atlantic coast of the United States to the Gulf of Mexico. Within this broad geographic range, differences in life history patterns exist. South of Cape Hatteras, North Carolina, striped bass are considered riverine, contrasting with the anadromous nature of populations north of Cape Hatteras (Bigelow and Schroeder 1953; Setzler et al. 1980; Fay et al. 1983).

Historically, five rivers in Eastern Canada supported spawning populations: the St. Lawrence, Miramichi, Saint John, Annapolis and Shubenacadie Rivers (Rulifson and Dadswell 1995). Within the Bay of Fundy, the Annapolis and Saint John Rivers still support a recreational fishery, consisting mainly of migrants from U.S. populations, but have not shown evidence of successful reproduction since the 1970s. Installation of hydroelectric dams, and the resultant change in tidal currents, water quality and chemistry on both rivers are speculated as reasons why the Annapolis and Saint John populations have declined (Bradford et al. 2001; Douglas et al. 2006). The lack of spawning success in the Bay of Fundy contributed to the termination of the striped bass commercial fishery in Nova Scotia by 1970, leaving a small bycatch and angling fishery, although fishing derbies occurred in Grand Lake into the mid-1980s (Jessop 1991).

Toward the end of the 19th and beginning of the 20th centuries Grand Lake produced occasionally up to 0.8 tonnes of striped bass (Jessop 1991). For early life stages in the Shubenacadie, it is important to understand what factors affect recruitment and survival of this population to implement best management practices, to improve population health, and to avoid or mitigate risks of a population collapse.

3.2. Life History

3.2.1. Striped Bass Life Cycle

Recruitment for striped bass is marked by high inter-annual variability. Ten age classes were reported present in the Shubenacadie during the 1990s, up from six in the 1970s (Jessop and Vithayasai 1979; Rulifson and Dadswell 1995; Paramore 1998). Funding from the Alton Project provided an opportunity to study the Shubenacadie population, where a large juvenile recruitment in 1999 and good recruitment over the past decade have now produced adults contributing large numbers of eggs and larvae (Douglas et al. 2003).

Males reach sexual maturity at around age three and females mature at age four to six (Bigelow and Schroeder 1953). In the Shubenacadie, males are larger than females at age classes one and two but females surpass males in fork length beyond age three (Paramore 1998). Throughout, the 1990s, males in the Shubenacadie population have been roughly twice as numerous as females (Rulifson and Dadswell 1995; Paramore 1998), the reverse of the 1:1.8 found in the 1970s (Jessop and Vithayasai 1979).

Spawning occurs in spring, between March to early June, depending on latitude and water temperature, and results in clear eggs which are externally fertilized (Rulifson and Tull 1999). Females are iteroparous. Fecundity, based on age, in the Shubenacadie range between 58,000 and 1.3 million eggs per female (Paramore 1998), whereas fecundity by weight is 100 000 eggs per kilogram of female body weight. Over a three year study, striped bass egg viability of two southern U.S. rivers was 70 % similar to the Shubenacadie, where egg fertilization rates were estimated at 77% for the 1994 season (Bulak et al. 1993; Tull 1997).

Water temperature has a strong influence on the onset of spawning, although its role is still unclear. Perhaps an absolute temperature threshold needs to be reached to trigger spawning, or perhaps the accumulated water temperature throughout the season is important, or the rate of change in river temperature (Bulak 1994; Secor and Houde 1995; Jahn 2010). Additional data to understand this relationship will be collected in this study.

Spawning of the Shubenacadie - Stewiacke population occurs at the head of the tide where low salinity prevails (<0.5 ‰) on the Stewiacke River (Rulifson and Tull 1999). The total egg production for the Shubenacadie population in 1994 was estimated at 106 ± 10.6 million (Rulifson and Tull 1999). Water hardened striped bass eggs are about 3.5 mm diameter and are slightly negatively buoyant but remain suspended in the water column by the turbulent water of the tidal estuary (Mangor-Jensen et al. 1993; Rulifson and Tull 1999; Bergey et al. 2003). Egg development is rapid, hatching as quickly as 48 hours post-fertilization at 17 to 18 °C; however, water temperature on the Shubenacadie during spawning conditions is often lower, requiring more time for the eggs to hatch. During this period, the eggs are passive particles for a minimum of four or more tidal cycles, and yet a proportion of these eggs remain in the system regardless of the net outflow of the Shubenacadie estuary.

Environmental cues for spawning in the Shubenacadie are limited, but even less information exist on the temporal distribution of larvae within the system. An exploratory study on the Shubenacadie examining the temporal distribution of striped bass eggs and larvae caught only 61 larvae during the 1994 season (Rulifson and Tull, 1999). A subsequent stock assessment had very low numbers collected during beach seining (Douglas et al. 2003).

Larval first feeding occurs around six days post-hatch or at a body length of 5 to 7 mm (Bigelow and Schroeder 1953). During the first week post-hatch, the critical swimming speed of larvae increases over three fold from 0.54 to 2.64 cm/s (Peterson and Harmon 2001). Prey items change in their level of importance to YOY striped bass depending on larval size and flow levels. They also coincide with recruitment levels (Martino 2008). Copepods, such as *Eurytemora affinis*, dominate as prey items for striped bass within the first three weeks then mysids begin to enter the diet (Heubach et al. 1963; Robichaud-LeBlanc et al. 1997). Striped bass become piscivorous with age, and begin this behaviour between 70 and 100 mm total length (Markle and Grant 1970; Nemerson and Able 2003).

Once spawning is complete, adults disperse into Cobequid Bay and the outer Bay of Fundy to feed for the summer and are followed by YOY and juveniles during September and October (Rulifson et al. 2008). Young of the year dominate striped bass beach seine catches in the Cobequid bay during the early fall (Bradford et al. 2001; Rulifson et al. 2008). In comparison, striped bass YOY remain in the Hudson River estuary throughout the season (O'Connor 2010). Feeding of Miramichi striped bass YOY slows and eventually ceases when water temperatures drop below 10 °C (Robichaud-LeBlanc et al. 1997); it is unknown if a similar feeding threshold exists for the Shubenacadie population.

Long, harsh winters are the hypothesized caused for northern populations of striped bass to exhibit a faster growth rate than those at southern latitudes during the growing season (Conover et al. 1997). Young of the year from the Miramichi population exhibited mean daily gains of 0.72 mm/day throughout the summer season (Robichaud-LeBlanc et al. 1998), twice the rate of fish from Albemarle Sound, North Carolina population which exhibited daily gains of 0.35 mm/day (Conover 1990) . Differences in growth between the Shubenacadie and Miramichi populations were not significantly different (Douglas 2001). A portion of adults from the Shubenacadie striped bass population migrate back up the Shubenacadie to overwinter in Grand Lake (Douglas et al. 2006). In contrast, intermediate salinities are required by the

Hudson River population during overwintering (Hurst and Conover 2002). Another portion of the Shubenacadie population migrate down the eastern seaboard to U.S. rivers (Rulifson et al. 2008). Winter upstream migration is believed to be cued by low temperatures (6.5 to 8.0 °C). Although this is not universal among northern populations, dormancy and inactivity similar to hibernation have been described in populations during the winter months (Merriman 1941; Bradford et al. 1997). The Miramichi is perhaps the only population where lethal marine conditions in the Gulf of St. Lawrence require overwintering in freshwater (Douglas et al. 2003).

3.2.2. Nursery vs. Critical Habitat

Nursery habitat is a geographical area with importance for breeding, high foraging potential and typically low predation risks for developing offspring, which may or may not require migration to reach (Krebs 2009). Striped bass, like many aquatic species, reproduce in lotic systems where the nursery grounds are dynamic and move spatially, encompassing a wide geographic range. This is furthered enhanced by the tidal element of the Shubenacadie, where the watershed discharge and tidal range are counterpoint to one another. Explicit bounds of the nursery habitat for the Shubenacadie – Stewiacke watershed have yet to be identified.

It is also important to differentiate critical habitat from nursery habitat as they are not necessarily equivalent. Critical habitat is defined as an area vital for the successful reproduction of the species (Government of Canada 2008). Considered a biological or physical feature essential to the conservation of a species, which may require special consideration or protection, critical habitat may or may not be within the current geographic range of that species (U.S. Fish & Wildlife Service 2009). Once defined for the Shubenacadie and Stewiacke rivers, it may be possible to identify similar critical habitats on both the Annapolis and Saint John rivers. Through surveying and describing temporal changes in egg abundance, the nursery and critical habitats can be observed. Critical habitat of striped bass in the Shubenacadie watershed remains unidentified.

3.3. Striped Bass Prey

The critical period hypothesis states that during the time larvae transition from endogenous to exogenous food sources, the correct prey must be present with enough abundance or larvae will perish (Hjort 1926). To survive, the temporal or spatial distribution of the fish larvae has to match that of their prey. First feeding among striped bass larvae commences from five to ten days post hatch, depending on salinity and temperature (Peterson et al. 1996). Reduced light as well as increased turbulence reduced larval growth rate in Chesapeake Bay; however, the addition of turbidity in combination with turbulence mitigated some of the negative effects encountered during foraging (Chesney 1989). Striped bass larvae traversing to slow moving systems may result in a greater feeding success due to higher prey concentrations (Chick and Van Den Avyle 1999). In contrast, higher river flow resulted in a greater percent of larvae feeding as well as stronger year classes in Chesapeake estuaries (Martino and Houde 2010). In both cases, the greater larval survival and feeding depended on prey density levels aligning spatially and temporally with the larvae. Among Miramichi striped bass, the transfer between endogenous to exogenous food sources, roughly eight days after hatching, correlated with peak abundance in prey such as copepod nauplii (Robichaud-LeBlanc et al. 1997). In small non-piscivorous striped bass, copepods and mysids have been identified as important food items in the Miramichi and some U.S. estuaries (Heubach et al. 1963; Robichaud-LeBlanc et al. 1997; North and Houde 2006). By contrast, no prey items in the Shubenacadie have been identified or described previously for larval and YOY striped bass.

From May through November, another important food item for feeding bass larvae and juveniles is the mysid opossum shrimp, *Neomysis americana*. Mysids become a staple prey item three weeks after exogenous feeding begins; and is the dominant prey item between > 50 mm and < 115 mm total length (Heubach et al. 1963; Markle and Grant 1970; Robichaud-LeBlanc et al. 1997). It is also unclear how *N. americana* remains in the vertically homogenous Shubenacadie estuary. Other members of the genus are known to ascend during the flood and descend during the ebb tides for transport around estuaries (Kimmerer et al. 1998). Attempts to quantify a minimum prey density requirement for early feeding striped bass are not conclusive although the threshold may be as low as 50 prey items per liter. Growth and survival are positively related to prey density (Chesney 1989; Tsai 1991). This study will not use gut contents to study prey items, but will examine temporal distributions of striped bass larvae and mysids for potential overlap within similar habitat areas.

3.4. Results

3.4.1. Striped Bass Spawning: 2008 and 2009

In 2008, eggs were collected between May 25 and June 24 during which the estuary warmed from 10 to 24 ^{o}C (Figure 6, upper panel). Daily average egg abundance over this 31-day period exceeded 10 eggs/m^3 on seven sampling days, of which five were due to new spawning activity. The other two peaks were caused by eggs of at least 24 h post-fertilization. The daily average egg abundance peaked >100 eggs/m^3 in 2008 on three dates: June 1, 5 and 11 (Figure 6; upper panel). In 2008, eggs were first detected late in the ebb tide on May 25 (salinity <0.1 ‰, water temperature 10 ^{o}C) at an abundance of <1 egg/m^3. The first large spawning event occurred May 30 following a rapid increase in water temperature from 10 to 14 ^{o}C (Figure 6, upper panel). On June 1, the second spawning was detected; egg abundance was very high, exceeding 1000 eggs/m^3 (Figure 6, upper panel). This spawning event was associated with a large freshet of rain (46 mm) occurring on the previous day, and a 2 ^{o}C drop in temperature. The third large spawning event was detected June 5; 80 % of the eggs were newly fertilized and mean daily egg abundance was 45.5 /m^3. The last eggs of the year were detected on June 24 late in the ebb tide (1.1 to 1.5 ‰, 24.2 ^{o}C) with a low abundance of 2 eggs/m^3.

The 2009 spawning season was longer than 2008 by 18 days (49 days). In 2009 spawning was initiated about a week earlier (Figure 6) although in both years spawning peaked within the last week of May and first week of June; eggs were detected at the study site from May 18 to July 5. In 2009, eggs were first detected May 18, late in the ebb tide (0.6 to 0.1 ‰, 13.4 ^{o}C) at an abundance of less than 25 eggs/m^3(2 to 22 eggs/m^3). Two large peaks (>4000 eggs/m^3) were detected during the ebb tide of May 24 and June 2 (Figure 6; lower panel). Water temperatures exceeded 15 ^{o}C in early May 2009 for a short period, but spawning did not occur until May 18 (Figure 6, lower panel). The first large spawning event was detected May 24 following several days of increasing temperature and was associated with a new moon. Mean daily egg abundance on May 24 was the highest recorded during the two year study, 1803 eggs/m^3. Over the next three days, May 25 to 27, egg abundance decreased progressively. Most of these eggs were from the May 24 spawn, since less than 20% of these eggs were newly fertilized. Egg abundance at on May 31 and June 1 was relatively low, 3 to 10 eggs/m^3. By contrast, the following day (June 2) a second large spawning event was detected, where daily abundance was 1480 eggs/m^3 and over 90% of the eggs collected were newly fertilized (Figure 6, lower panel). Over the following month sampling was conducted nine times, with egg abundance low throughout. By June 4, the remainder of the large June 2 spawning had passed and egg abundance did not surpass 100 eggs/m^3 again. There was a minor spawn on June 17, where egg abundance reached an average daily abundance of 86 eggs/m^3. The last eggs in 2009 were detected on July 5, peculiarly at high slack water (14.4 ‰, 19.8 ^{o}C) at an abundance of less than one egg per cubic meter.

3.4.2. Striped Bass Eggs: Tidal and Lunar Trends

Large spawns were loosely connected to new moons in both years, although spawning occurred at all points in the lunar cycle. The new moon on June 3 2008 resulted in a tidal range of >4 m at the study site, a few days after the very large spawning on June 1. The smaller spawning on June 11 was during the falling tidal range (2.5m) and closer to the full moon (Figure 6). The first large spawn in 2009 started May 24 and coincided with the May 24 new moon. A second large spawn occurred on June 1, with a smaller spawn on June the 15, on the very beginning of increasing tidal range of the June 22nd new moon (Figure 6).

Within a tidal cycle, egg abundance was consistently lowest at high tide and then increased progressively throughout the ebb tide in association with a decrease in salinity. Whether a large or small spawn, egg abundance increased during the ebb tide up to about 300 minutes (5 hours) and then sometimes declined.

On June 1 2008, the only large detected spawning event of that year, egg abundance exceeded 1500 eggs/m^3 three hours into the ebb tides, peaking at 3252 eggs/m^3 and remained > 1500 eggs/m^3 for nearly two hours (Figure 7, upper panel). By comparison in 2009 two very large spawning events were detected--May 24 and June 2-- when egg abundance exceeded 4000 eggs/m^3 (Figure 7, bottom panel); May 24 (4193 eggs/m^3; 2.2 ‰, 15.8 ^{o}C) and June 2 (4620 eggs/m^3; 1.8 ‰, 18.1 ^{o}C). The day after these two spawning events, eggs, now 24 h post-fertilization, exceeded 1000 eggs/m^3 late in the ebb tide at > 6.5 hours (Figure 7, bottom panel).

Striped bass eggs were detected over a wide range of temperatures. The 2008 season yielded eggs over a thermal range of six degrees (12.3 to 18.2 °C) and included two peaks; one centered at 16 °C, which showing a sharp increase in egg abundance, and a much smaller peak at 24°C. The width of both peaks was only a degree or two before decline in egg abundance occurred and were characterized by rapid changes in abundance (Figure 9, upper panel). In contrast, the 2009 egg collection occurred over nearly double the thermal range (10.5 to 21.5 °C) of the 2008 eggs. There was only one peak in abundance and it was still centered over 16 °C, but unlike 2008 the width of the peak was larger than one or two degrees, roughly 13 to 19 °C (Figure 9, lower panel). A rapid change in egg abundance beyond 13 to 19 °C was similar to 2008. With regard to salinity, striped bass egg abundance displayed a patchy distribution with only slightly lower abundances at higher salinities during the 2008 season (Figure 10). Eggs collected during the 2009 spawning showed a greater inverse relationship to salinity as well as a patchy distribution (Figure 10). Throughout a tidal cycle, egg collection was strongly inversely proportional to salinity (see Figure 7 and 8).

Figure 6. Summary of striped bass egg abundance (bars; total daily mean eggs per m^3) at the Alton Project site on the Shubenacadie River in relation to mean daily water temperature (dotted line) about 4 km downstream on the Stewiacke River from the main spawning grounds for both 2008 (upper panel) and 2009 (lower panel). F= full moon, N= new moon. Open diamonds indicate days when sampling was conducted but eggs were not detected, whereas open triangles indicate days when no sampling occurred.

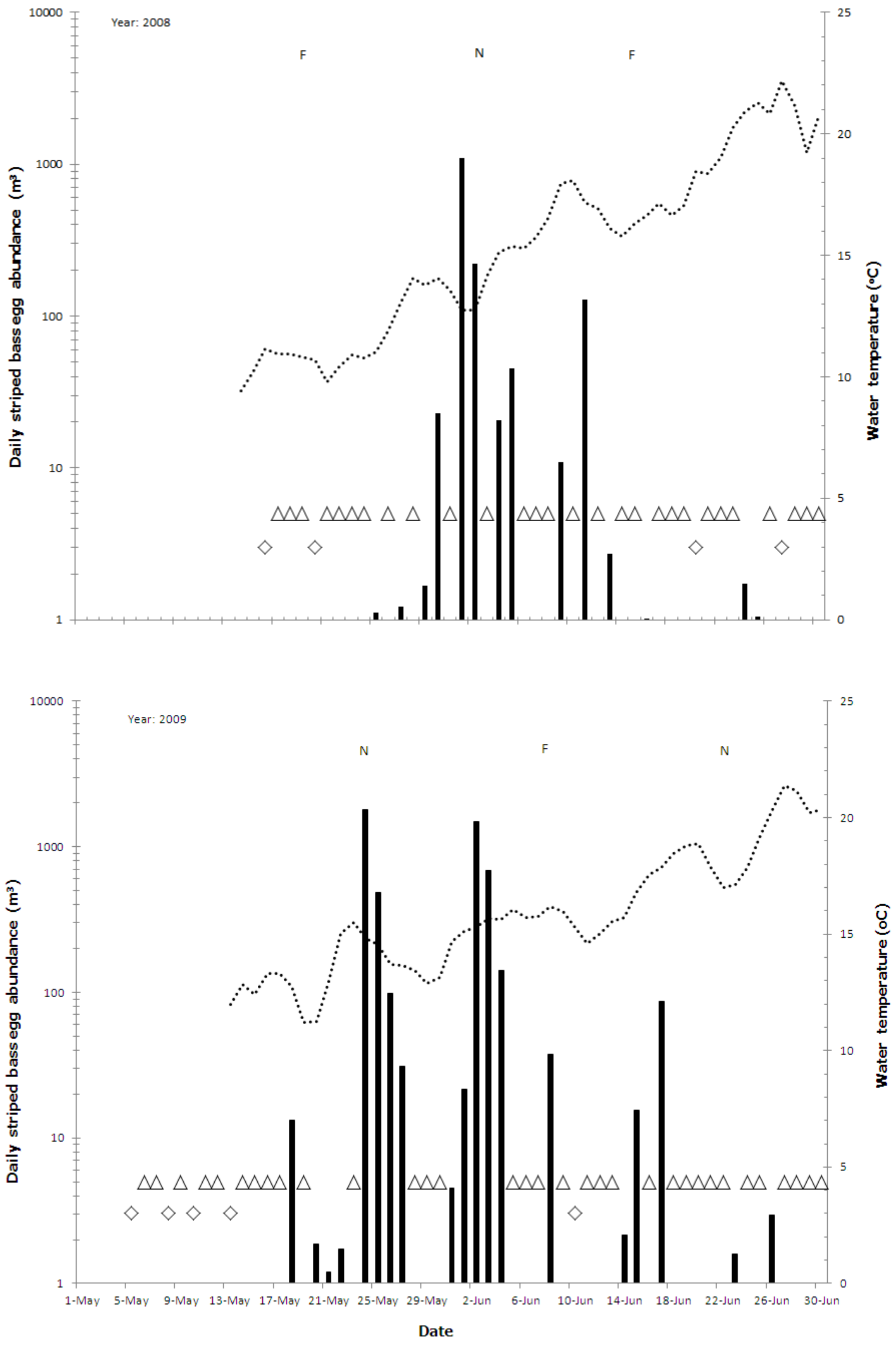
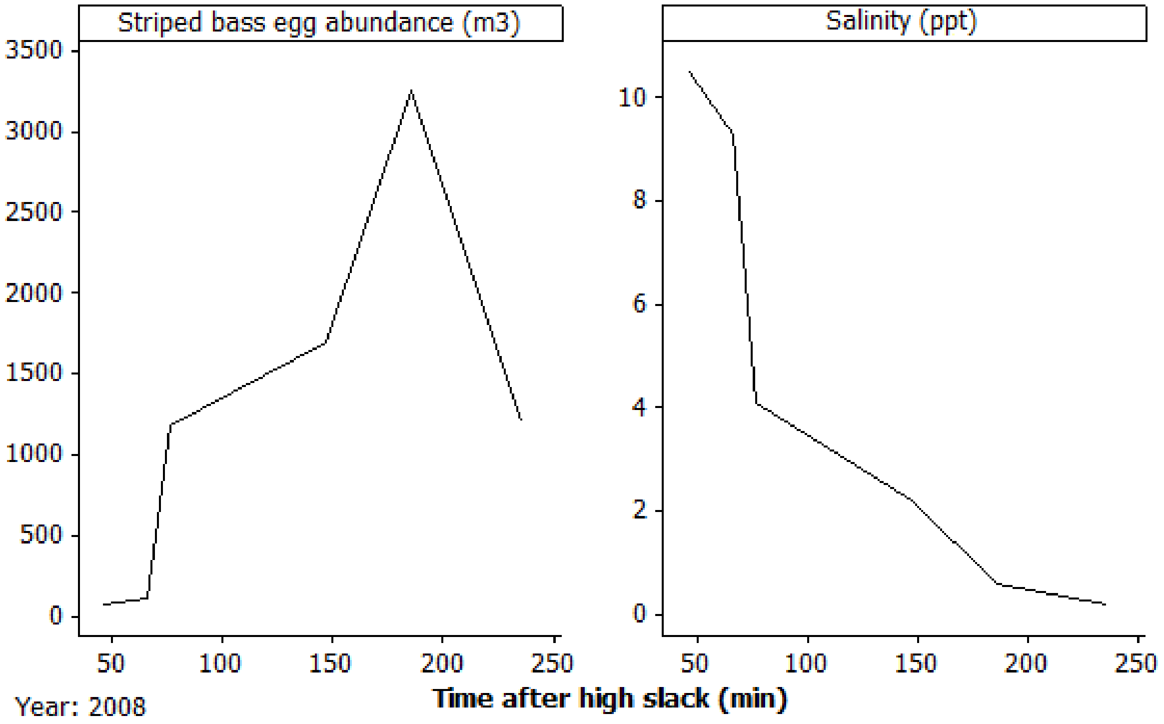
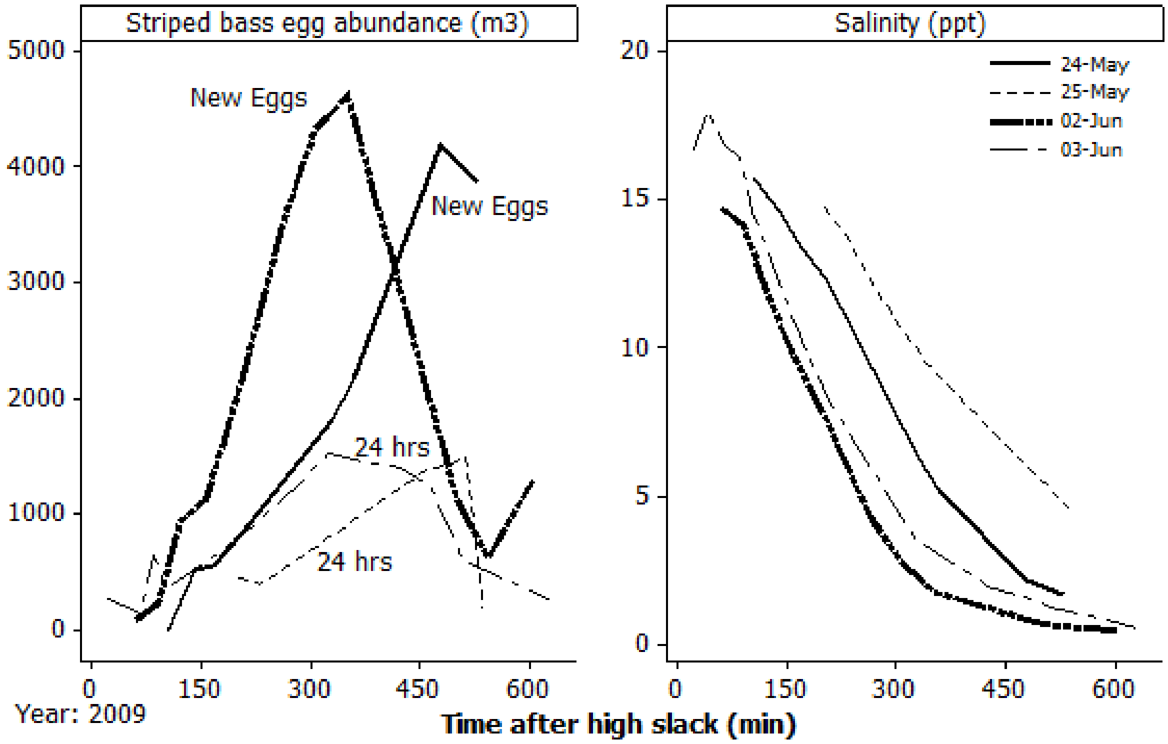

Year: 2008
F
N
F
10000
1000
100
10
1
Daily striped bass egg abundance (m³)
25
20
15
10
5
0
Water temperature (°C)
Year: 2009
N
F
N
10000
1000
100
10
1
Daily striped bass egg abundance (m³)
25
20
15
10
5
0
Water temperature (oC)
1-May
5-May
9-May
13-May
17-May
21-May
25-May
29-May
2-Jun
6-Jun
10-Jun
14-Jun
18-Jun
22-Jun
26-Jun
30-Jun
Date

Figure 7. 'Large' spawning event of striped bass (>1000 eggs/m^3). Egg abundance (eggs/m^3) with respect to minutes after high slack water (min) and surface salinity (‰). Upper panel: June 1, 2008. Lower panel: May 24, 25, June 2, 3, 2009. The lower panel illustrates the difference in abundance between recently spawned eggs (thicker lines) and abundances composed primarily of 24 h post-fertilization eggs. Note: scales are different between panels.


Striped bass egg abundance (m3)
3500
3000
2500
2000
1500
1000
500
0
50
100
150
200
250
Salinity (ppt)
10
8
6
4
2
0
50
100
150
200
250
Year: 2008
Time after high slack (min)


Striped bass egg abundance (m3)
5000
4000
3000
2000
1000
0
New Eggs
New Eggs
24 hrs
24 hrs
0
150
300
450
600
Salinity (ppt)
20
15
10
5
0
24-May
25-May
02-Jun
03-Jun
0
150
300
450
600
Year: 2009
Time after high slack (min)

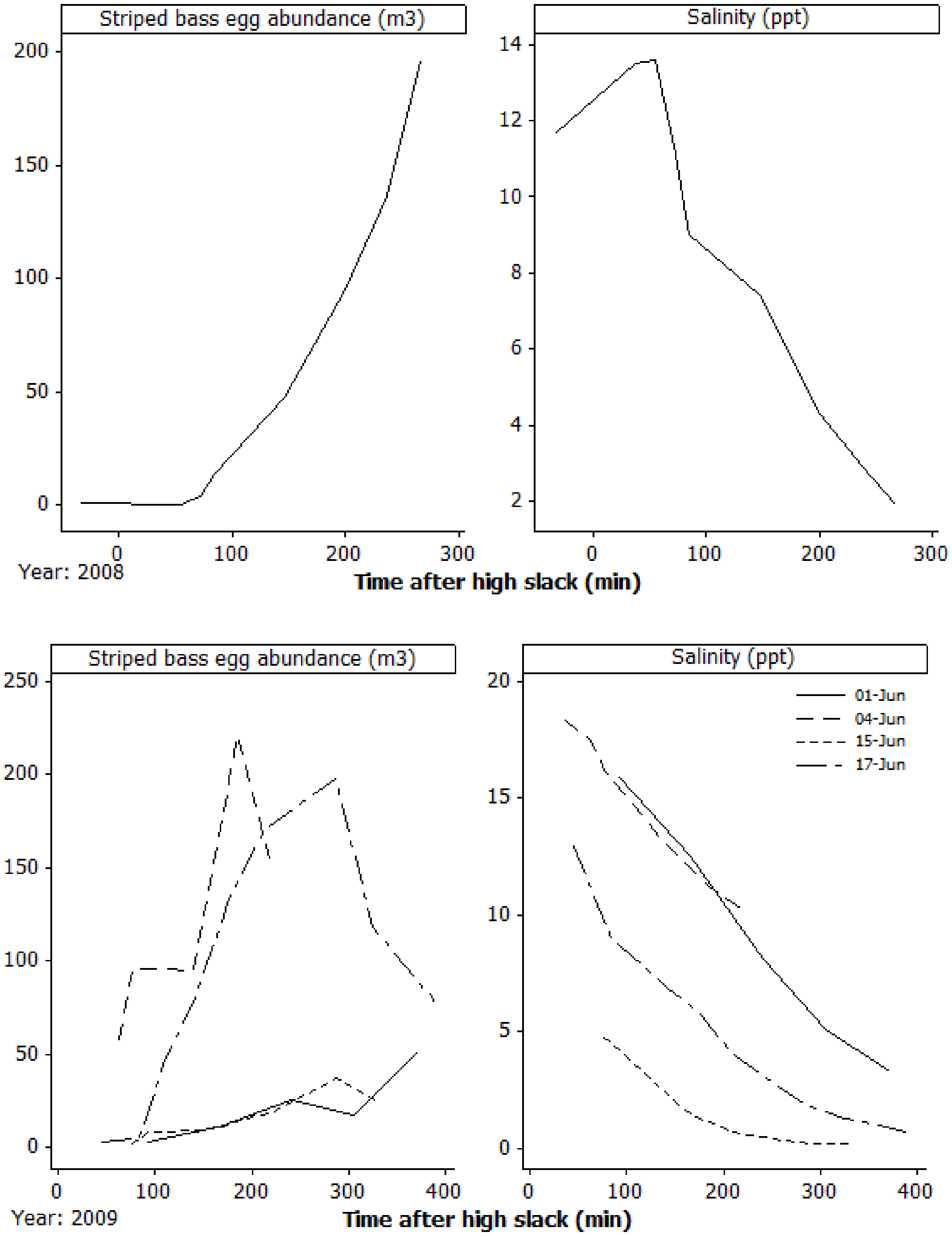


Figure 8. 'Small' spawning event of striped bass (<300 eggs/m^3). Egg abundance (eggs/m^3) with respect to minutes after high slack water (min) and salinity (‰). Upper panel: 2008, June 5. Lower panel: 2009, June 1, 4, 15 and 17. Note: scales differ between panels.

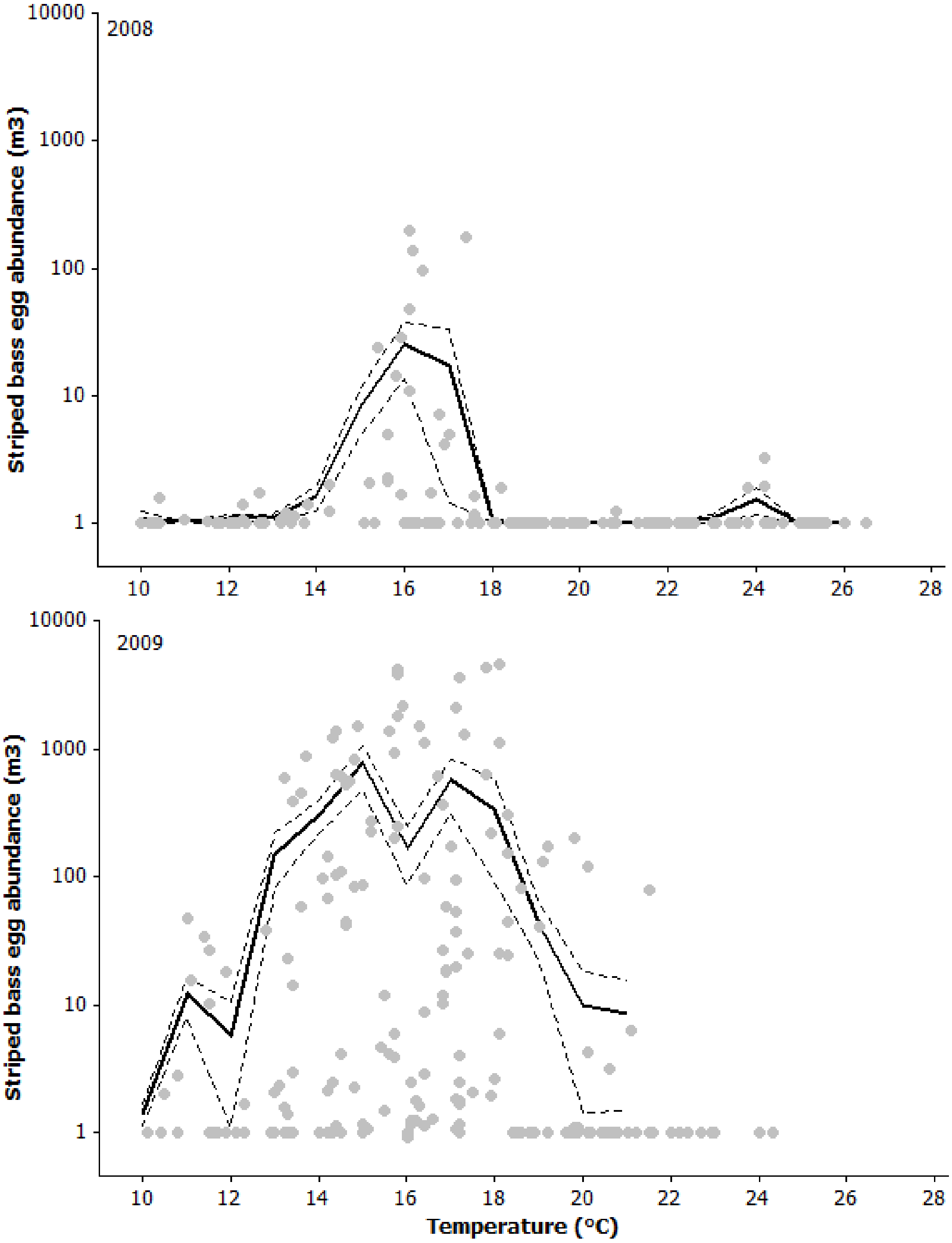


Figure 9. Thermal distribution of striped bass eggs detected at the Alton Project site during the 2008 (upper) and 2009 (lower) spawning season. Each dot represents an individual tow. Solid line represents the mean abundance (±SE) for the season as pooled at each temperature point. Note the log scale.

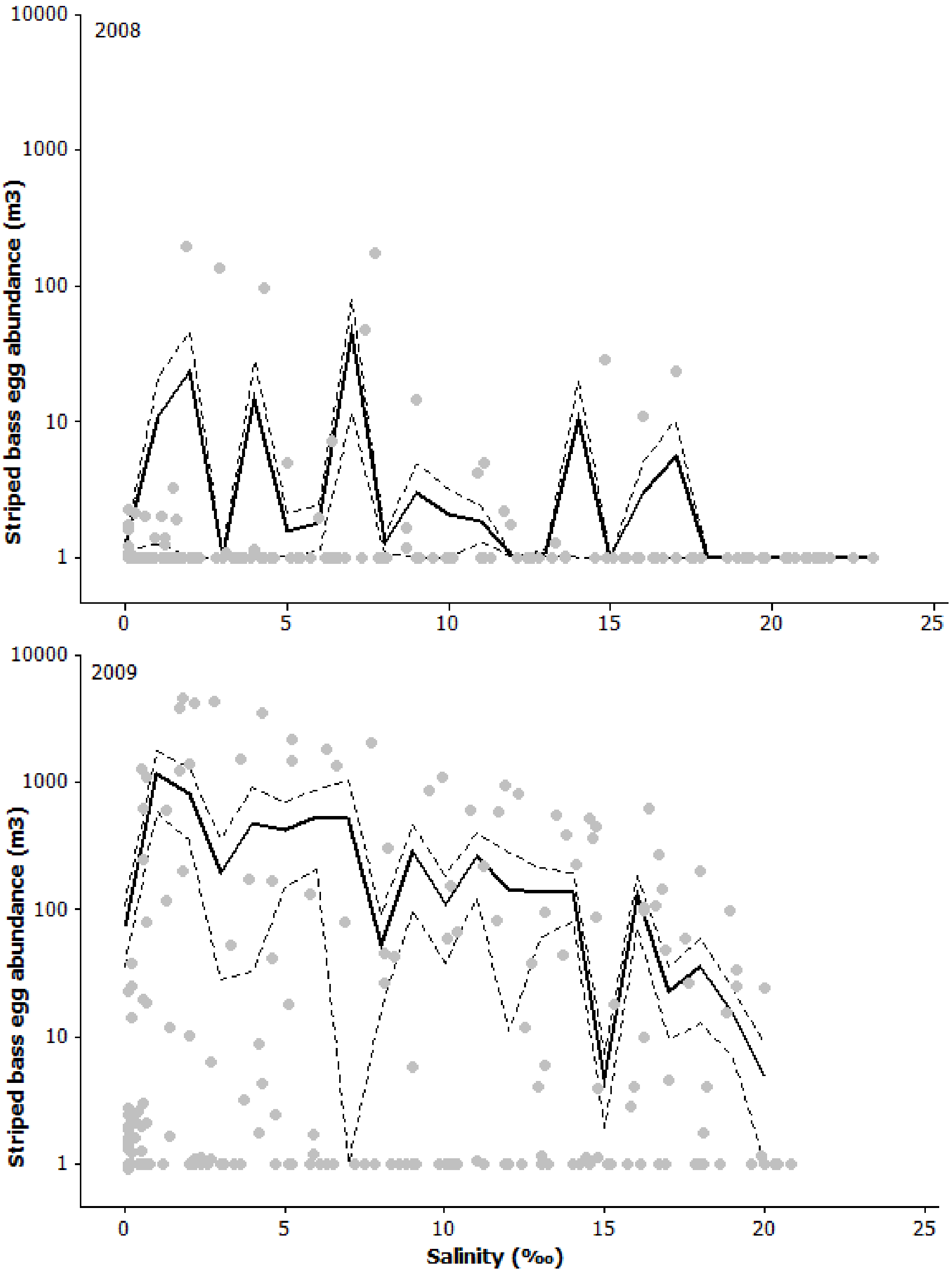


Figure 10. Salinity distribution of striped bass eggs at the Alton Project site channel during the 2008 (upper) and 2009 (lower) spawning seasons. Each dot represents an individual tow (coordinate); the solid line represents the mean abundance (±SE) for the season as pooled at each salinity point. Note the log scale.

3.4.3. Larvae

In both 2008 and 2009, larvae were detected at the Alton Project site over 38 days although timing was different. In 2008, larvae were detected from June 11 to July 18 whereas in 2009 they were found ten days earlier from June 1 to July 8 (Figure 11). The abundance of larval striped bass was relatively low compared to eggs in both years, and larval abundance was far greater in 2008 compared to 2009. There were no discernible pattern between larval abundance and lunar phase in either season.

Daily mean abundance in 2008 exceeded 10 larvae/m^3 on five occasions, peaking at 118 larvae/m^3 on June 24 (Figure 11). The first striped bass larvae were seen when the mean tidal range (Canadian Hydrographic Service station # 270) was 11 m and slowly increasing; water temperature was 20 °C and the average rainfall from the last week (<0.4 mm) was negligible. The largest one day abundance of larvae occurred with a similar tidal range and water temperatures (11.6 m and 22.4 °C) although there was much more rainfall in the week prior (4 mm; Figure 11). The drop in larval abundance after the peak occurs as lagged rainfall increased substantially (0.7 compared with 5.2 mm). As lagged rainfall was decreasing, an increase of three meters in the mean tidal range occurred and larval abundance remained low ($\leq$ 6 larvae/m^3) for the remainder of the season (Figure 11).

In contrast to 2008, the daily mean larval abundance in 2009 was less than 4 larvae/m^3, over 30-fold lower than 2008 (Figure 11). Striped bass larvae in 2009 were observed initially when the tidal range was similar to that observed in 2008 (11.3 m); however, water temperature was much colder (14.6 °C) and lagged rainfall was greater than 2008 (<0.4 compared with 1.2 mm). Peak larval abundance was 3.4 larvae/m^3 and occurred on June 8, with a mean tidal range of 11.1 m and a water temperature of 18.4 °C. Following the peak in abundance, lagged rainfall varied substantially from 5.4 to 0 to 8.9 mm over the next six days (Figure 11). Lagged rainfall remained above 5 mm for the next two weeks, dropping to < 0.1 on June 27. Larval abundance never reached $\geq$ 0.5 larvae/m^3 for the remainder of the season (Figure 11).

Although sporadic, abundance of striped bass larvae often tended to increase through the ebb tide (Figure 12). In 2008 the highest abundance of larvae was recorded on June 24 where 238 larvae/m^3 were caught in a single tow late in the ebb tide (1.1 ‰ and 24.7 ^{o}C). Also recorded late in the ebb tide was the highest abundance of larvae during the 2009 field season on June 8 (4.3 larvae/m^3, 3.0 ‰ and 18.9 ^{o}C).

The 2008 season saw no larvae caught when temperature was below 16 °C, rather, all larvae were found within temperatures of 16 to 26 °C (Figure 13; upper panel), a slightly greater range than the larvae occupied during 2009 (14 to 21 °C). There were six instances of larvae being found at < 16 °C in 2009, although all were at an extreme low abundance (0.04 to 2.5 larvae/m^3) and all were found at > 14 °C (Figure 13; bottom panel).

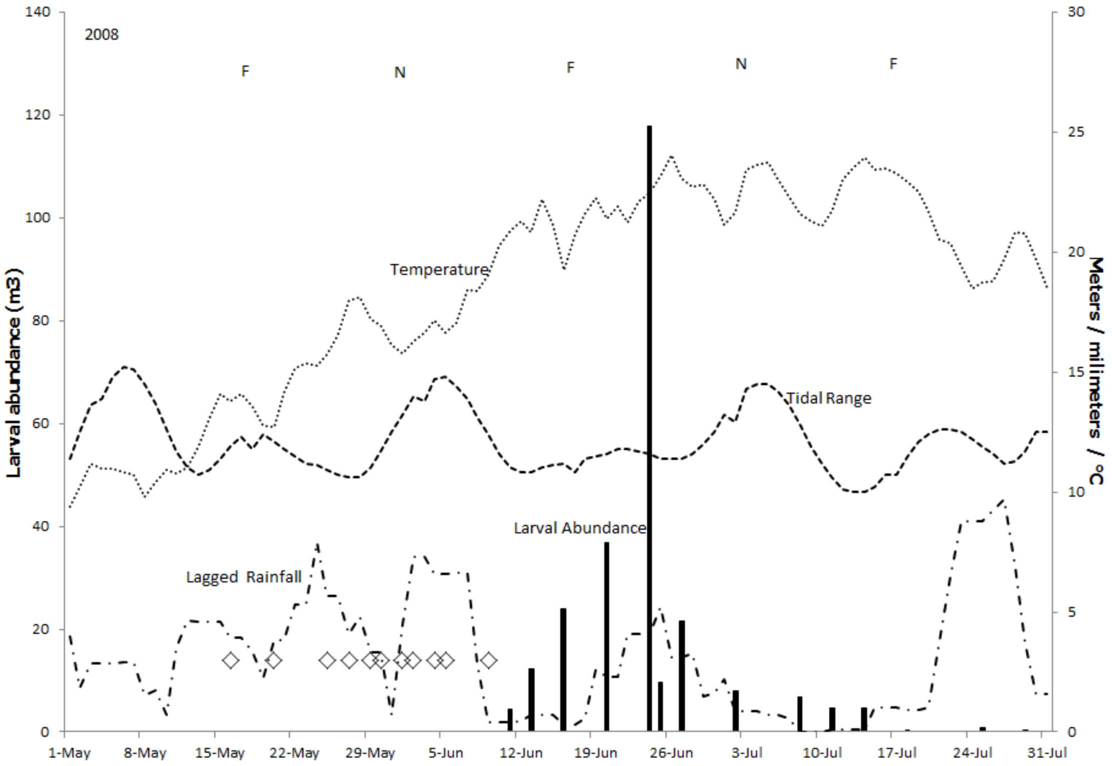
During both years, larvae were found at a wide range of salinities (Figure 14). In both years, larvae were observed at < 1 ‰ to 23 ‰ (2008: 0.2 to 20; 2009: 0.4 to 23 ‰). Abundance in 2008 seemed to have a slight negative relationship with salinity; most of the larvae were collected at lower salinities, although the ontogenetic changes in salinity tolerance and increased swimming ability might skew representation. Striped bass larvae in 2009 displayed an odd gap in catches wherein virtually no larvae were collected when salinities were between 6 and 14 ‰; although with such low numbers collected it was difficult to draw conclusions; even with the greater abundance of 2008 larval distribution was very patchy (Figure 14).

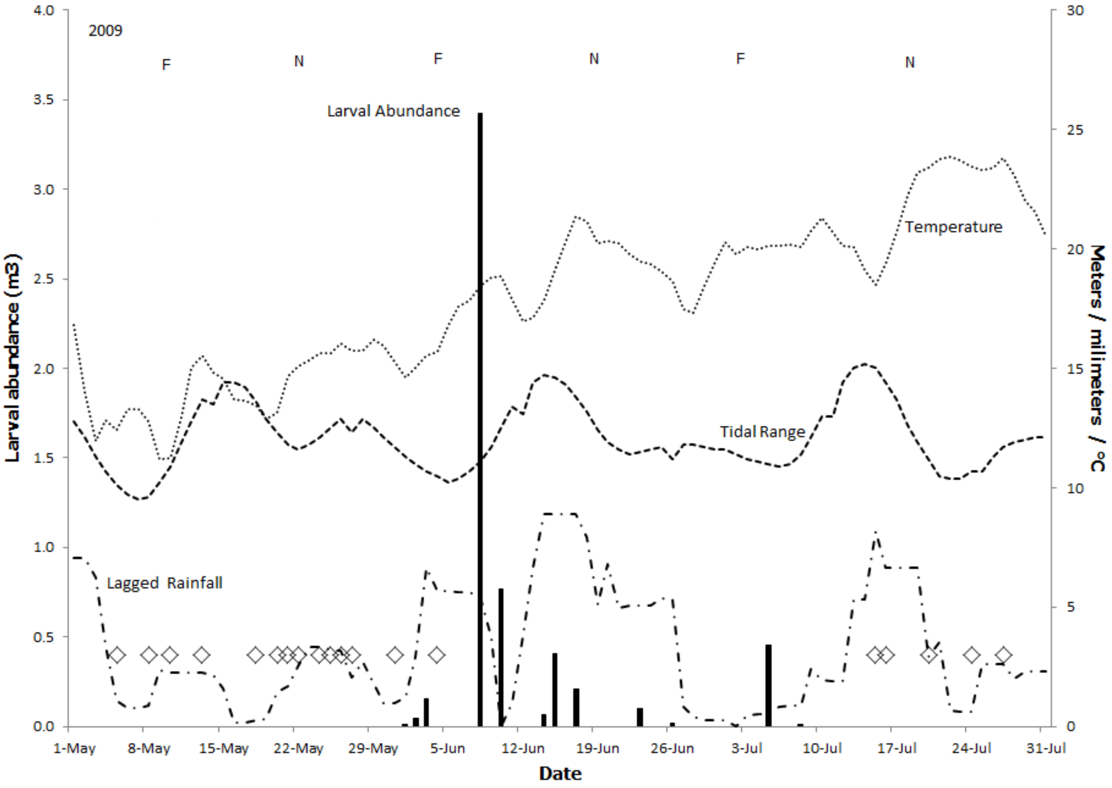
Rainfall had a large impact on the Shubenacadie system and was capable of affecting salinity and temperature. Daily precipitation at the Halifax International Airport reached as high as 80 mm in both years. Precipitation was greater in May 2008 (129.7 mm) than in 2009 (88.6 mm), but this trend reversed in June where 2008 had a dryer June (69.1 mm) than 2009 (149.3 mm) (Figure 15). Rainfall for July in both years was similar (79.5 mm in 2008 and 71.0 mm in 2009). During 2008, impact of tides (ρ 0.593; α=0.001; N=81) and the lagged rainfall (ρ -0.275; α=0.05; N=81) significantly influenced salinity. In contrast during 2009, the tidal impact on salinity was not significant (ρ 0.031; N=81) although lagged rainfall was significant at the 0.01 level (ρ -0.329).

Data from eleven days during the 2008 season was plotted to examine the larval length -weight relationship (N= 1000). Mean number of larvae per date was 79 (5% trimmed mean; range: 1 to 285) (Figure 16). Few larvae were caught during the 2009 season preventing analysis. The fitted regression line described nearly all of the variability in growth (R^2 = 96.1 %) (Eq. 1). Mean larval lengths (N = 1000) during July and August 2008 were plotted to examine growth. Mean lengths increased with season progression, standard deviation increased as well. During that timeframe, mean larval total length increased from 9.8 mm to 46.1 mm (Figure 17).

$$\text{Weight (g)} = 0.2987 - 0.03715\ \text{Length (mm)} + 0.001273\ \text{Length (mm)}{*}{*}2 \qquad (1)$$

Figure 11. Daily larval abundance in both 2008 and 2009 and associated water temperature, mean daily tidal range and the mean lagged seven day rainfall from May 1st to July 31st. Open diamonds indicate days when sampling was conducted but no larvae detected. Note: scales on Y-axis are different. F=full moon, N=new moon.


2008
F
N
F
N
F
Temperature
Tidal Range
Larval Abundance
Lagged Rainfall
Larval abundance (m3)
Meters / milimeters / °C
140
120
100
80
60
40
20
0
30
25
20
15
10
5
0
1-May
8-May
15-May
22-May
29-May
5-Jun
12-Jun
19-Jun
26-Jun
3-Jul
10-Jul
17-Jul
24-Jul
31-Jul


2009
F
N
F
N
F
N
Larval Abundance
Temperature
Tidal Range
Lagged Rainfall
Larval abundance (m3)
Meters / milimeters / °C
Date
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
30
25
20
15
10
5
0
1-May
8-May
15-May
22-May
29-May
5-Jun
12-Jun
19-Jun
26-Jun
3-Jul
10-Jul
17-Jul
24-Jul
31-Jul

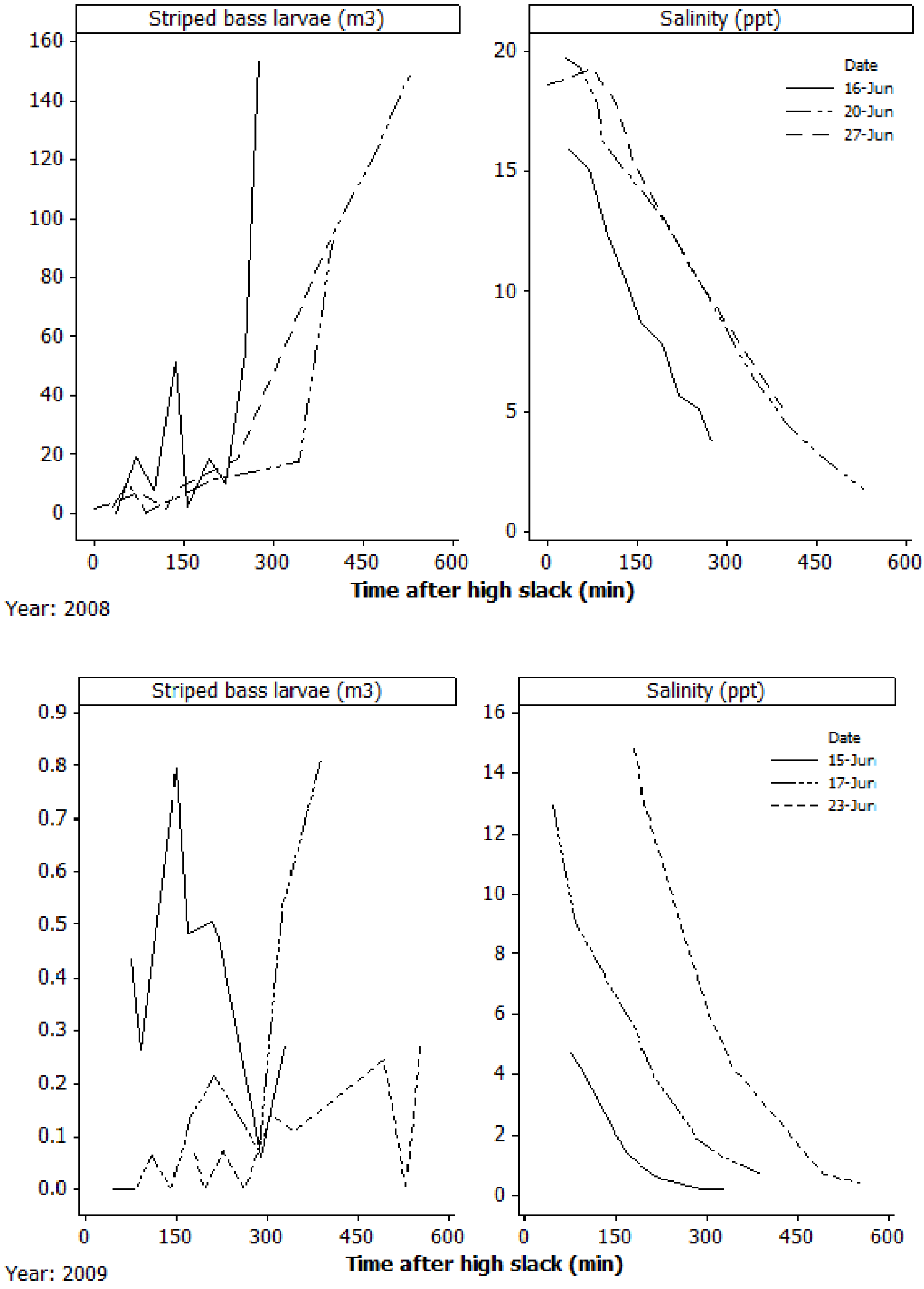
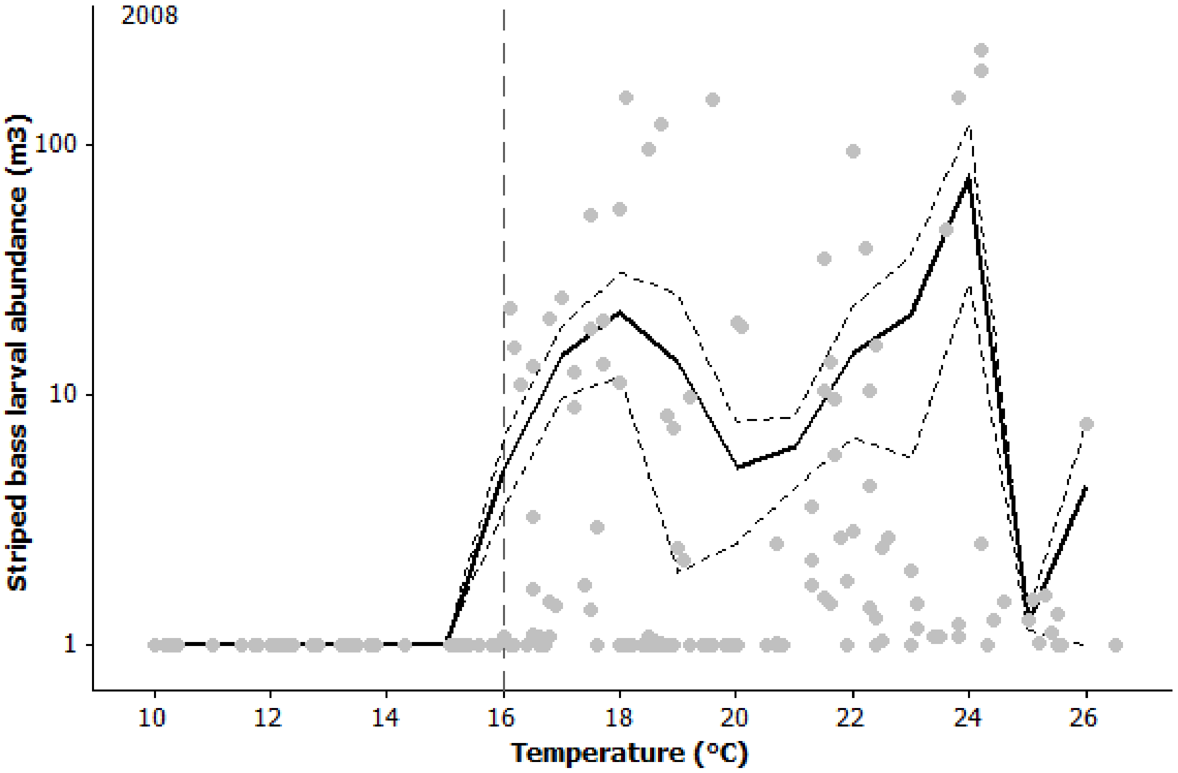
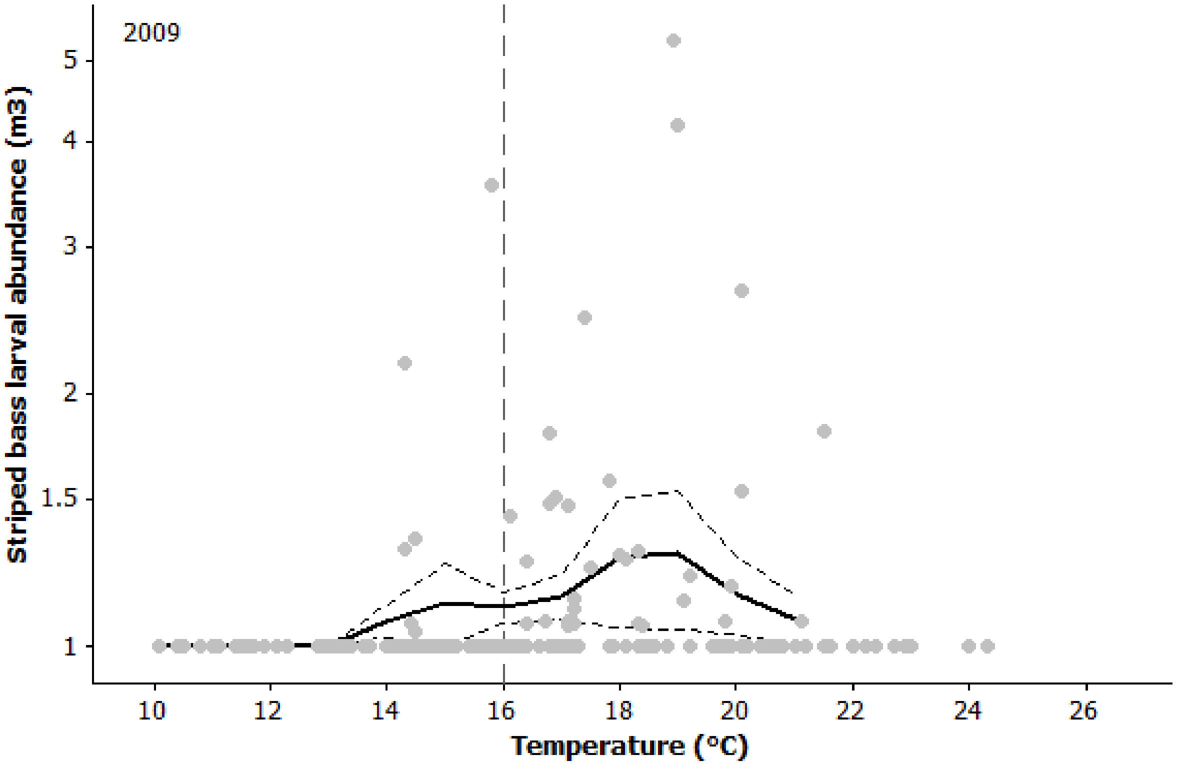


Figure 12. Larval abundance (larvae/m^3) with respect to minutes after high slack water (min) and salinity (‰). Upper panel: June 16, 20, 27 2008. Lower panel: June 15, 17, 23 2009. Note: scales are different between panels.

Figure 13. Thermal distribution of striped bass larvae at the Alton Project site during the 2008 and 2009 field season, upper and lower panels respectively. Mean abundance (solid line) with standard error shown. Each dot represents an individual tow; whereas the solid line represents the mean abundance (±SE) for the season as pooled at each temperature point. Vertical hashed line represents the lower temperature threshold for YOY growth in the Shubenacadie population (Duston et al. 2004; Cook et al. 2010). Note the log scale.


2008
Striped bass larval abundance (m3)
100
10
1
10
12
14
16
18
20
22
24
26
Temperature (°C)


2009
Striped bass larval abundance (m3)
5
4
3
2
1.5
1
10
12
14
16
18
20
22
24
26
Temperature (°C)

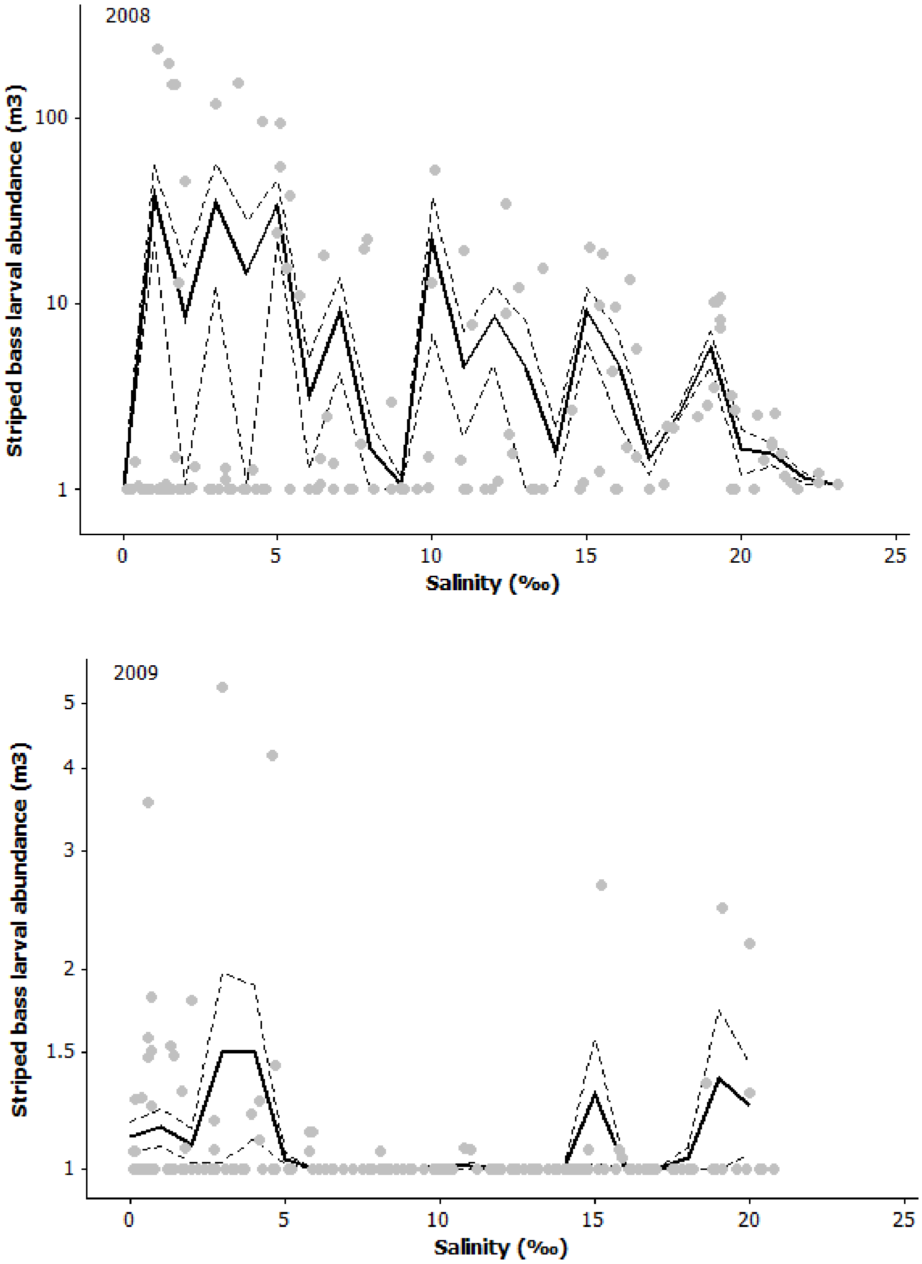
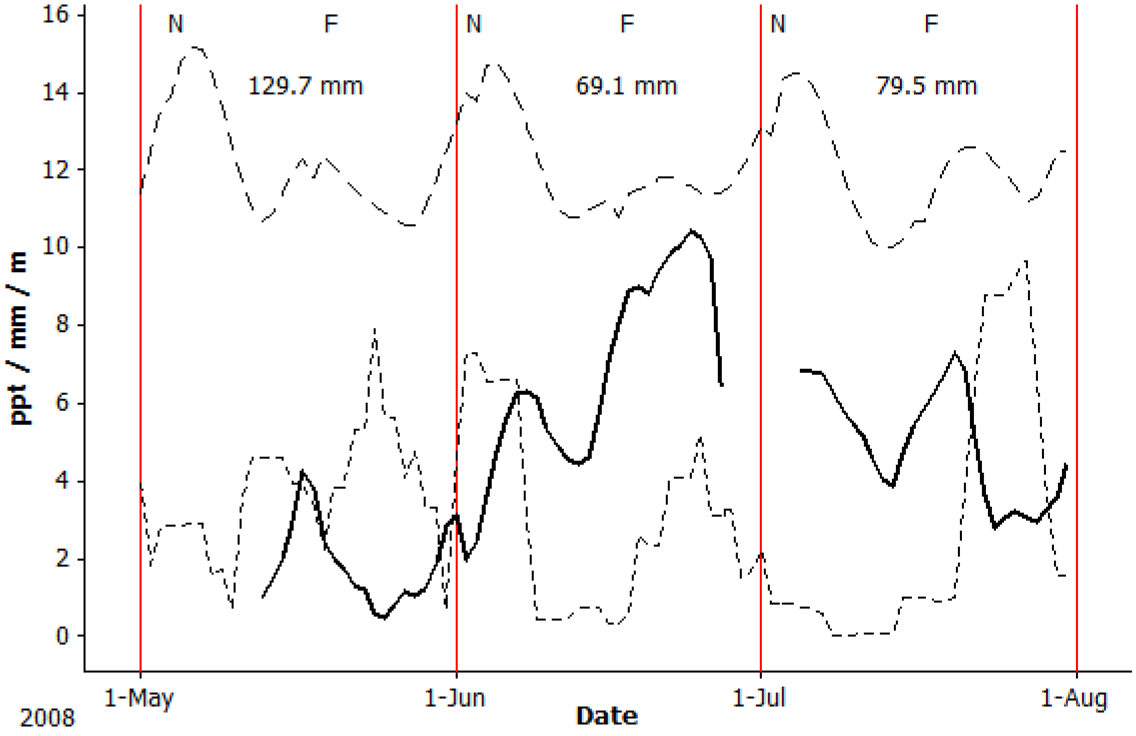
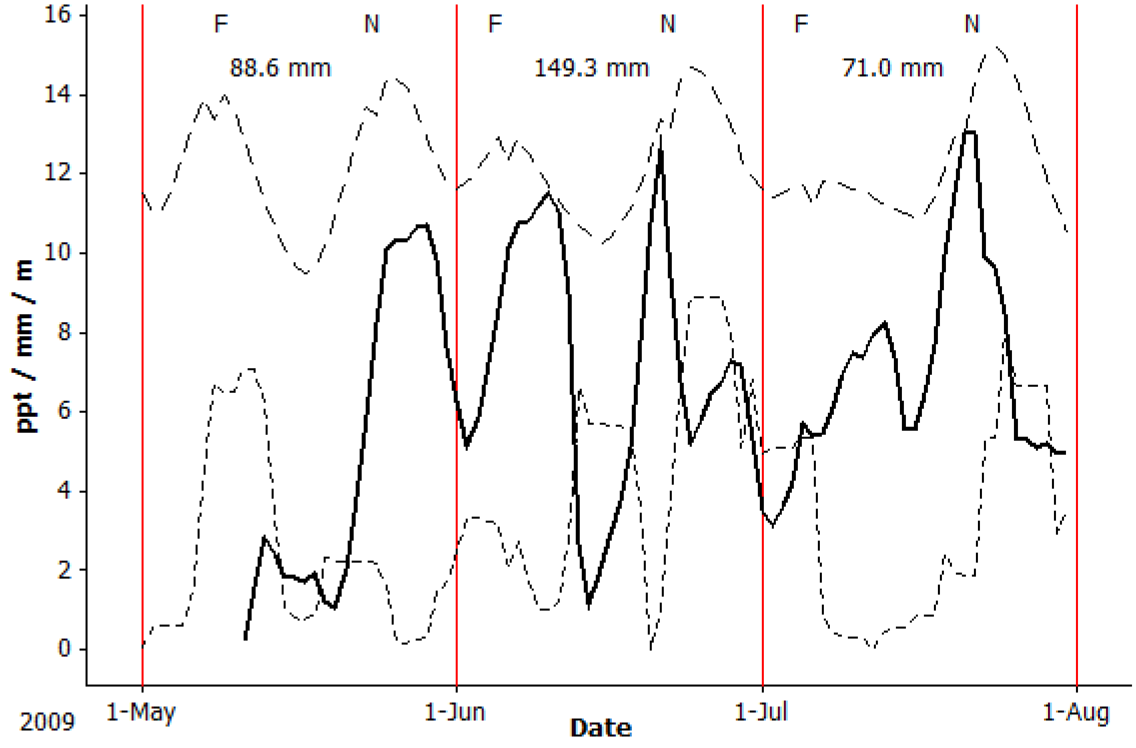


Figure 14. Salinity distribution of striped bass larvae at the Alton Project site during the 2008 and 2009 field seasons, upper and lower panels respectively. Mean abundance (solid line) with standard error shown. Each dot represents an individual tow; whereas the solid line represents the mean abundance (±SE) for the season as pooled at each salinity point. Note the log scale.

Figure 15. The mean daily salinity at the study site (solid line) is shown against values for rainfall lagged by seven days (short dashed line). Tidal range (long dashed line) is provided for perspective. Vertical lines separate each month and values within each are the monthly sum of rainfall. F=full moon, N=new moon. The data logger malfunctioned from June 28 to July 4, 2008.


N
F
N
F
N
F
129.7 mm
69.1 mm
79.5 mm
ppt / mm / m
16
14
12
10
8
6
4
2
0
1-May
1-Jun
1-Jul
1-Aug
Date
2008


F
N
F
N
F
N
88.6 mm
149.3 mm
71.0 mm
ppt / mm / m
16
14
12
10
8
6
4
2
0
1-May
1-Jun
1-Jul
1-Aug
Date
2009

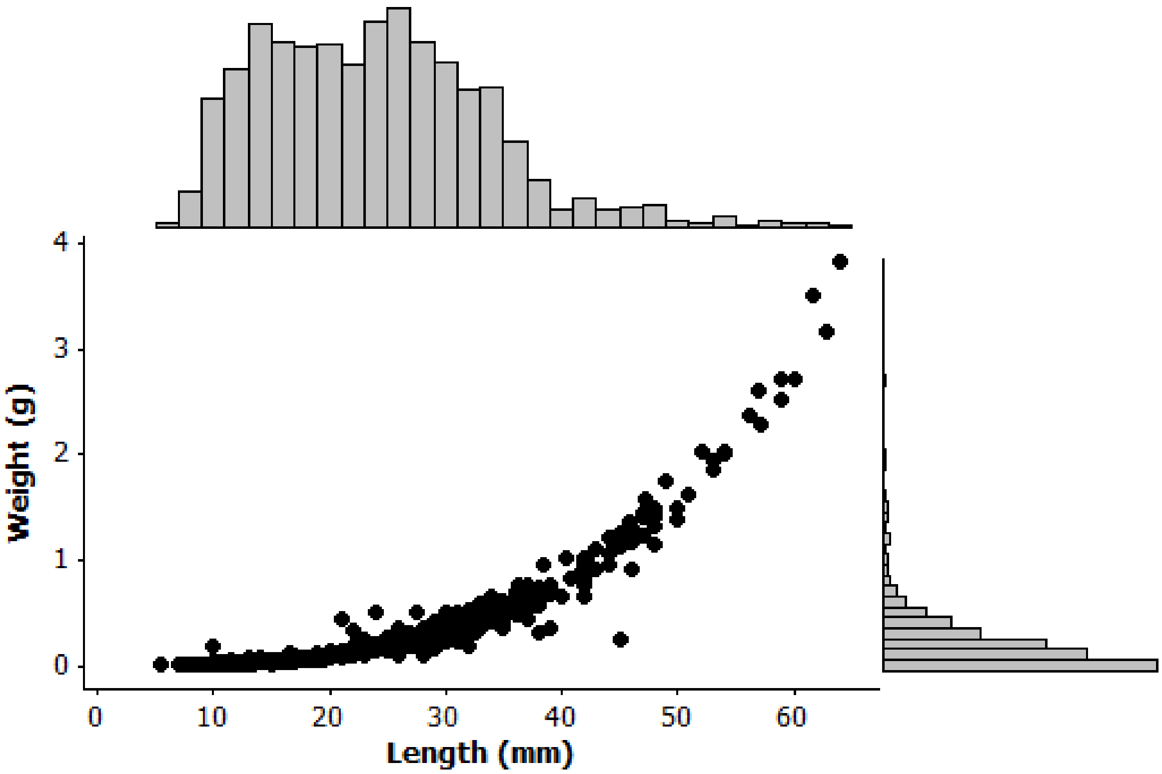


Figure 16. Marginal plot showing larval (< 25mm) to juvenile (> 25mm) length- weight relationship (N= 1001) as well as distribution of lengths and weights. Data sampled over eleven days during 2008. Larval data from 2009 is not included due to low larval abundance. Fitted regression line: Weight (g) = 0.2987 - 0.03715 Length (mm) + 0.001273 Length (mm)**2 (R^2 = 96.1 %).

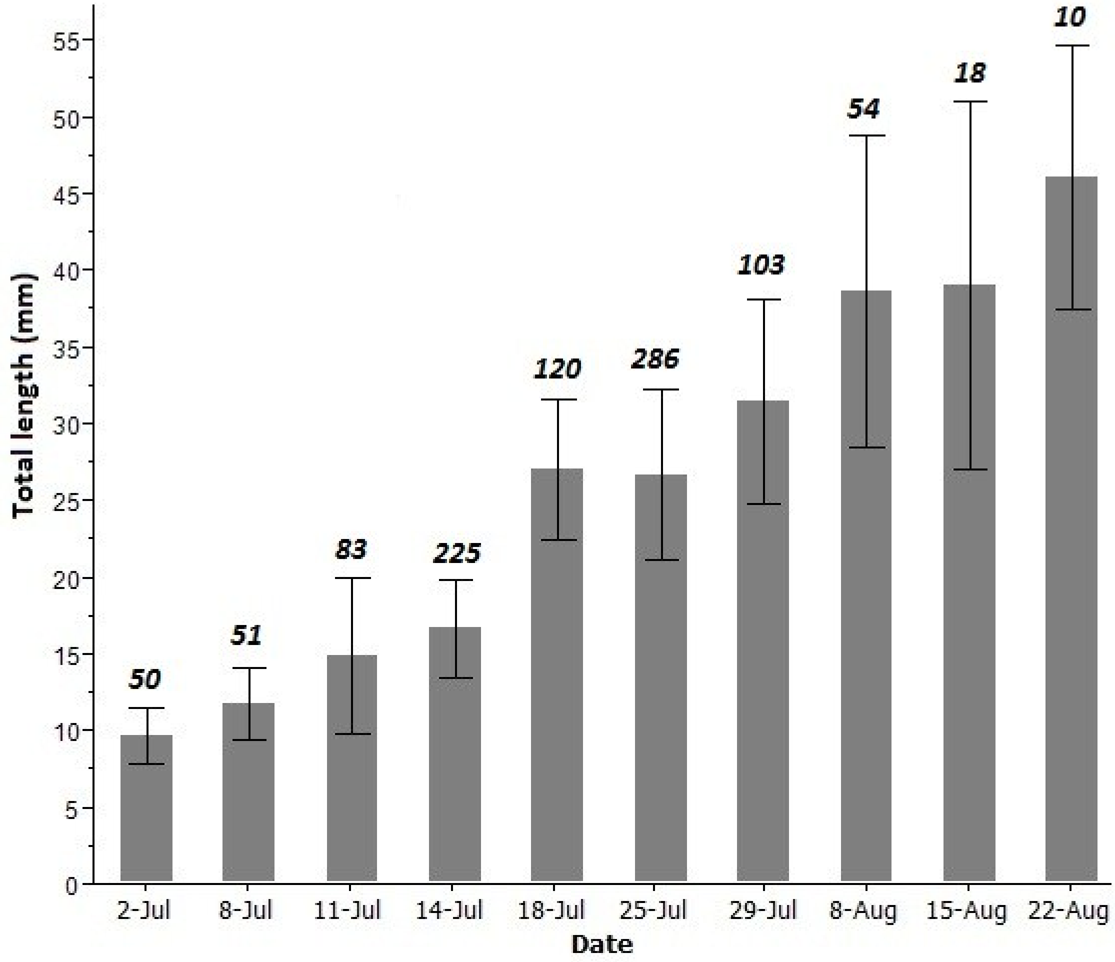


Figure 17. Growth (total length) of larval (< 25mm) to juvenile (> 25mm) striped bass during July and August 2008. Mean lengths (+- SD) across ten days, with the sample size indicated above.

3.5. Discussion

Few published studies (<20) have been conducted on the Shubenacadie - Stewiacke striped bass population, with fewer still focusing on the temporal distribution of early life history stages. Some lab studies (Duston et al. 2004; Cook et al. 2006, 2010; Chanson and Tan 2011) and Department of Fisheries and Ocean stock assessment studies (Bradford et al. 2001; Douglas et al. 2003) have been published with an even smaller group publishing on field conditions (Rulifson and Dadswell 1995; Rulifson and Tull 1999; Paramore and Rulifson 2001; Rulifson et al. 2008). The closest, previously published study on the Shubenacadie striped bass population dealing with temporal distributions was a master's thesis describing the spawning population in the river over the 1994 field season (Tull 1997). In that study, plankton net sampling occurred from a fixed point on the Stewiacke about 500m upstream of the confluence of the Stewiacke and Shubenacadie, and occurred 30min pre- and post- bore and then every 1.5 hours for the remainder of the day (n= 16 per day). The current study is an in-depth continuation of Tull (1997) with similar methodology. Differences in methodology are as follows: 1) rather than sampling on a fix time interval, the sample frequency herein changed over the duration of the ebb tide with respect to salinity, 2) a flow meter was used to gauge the volume of water being filtered through the plankton net during each tow to establish densities from abundances, 3) plankton net tows were restricted to the surface, and 4) no paired bongo nets were used.

Two hypotheses pertaining to striped bass spawning in the Shubenacadie currently exist: that striped bass in the Shubenacadie – Stewiacke watershed require a threshold temperature of 18 °C to initiate spawning and that spawning occurs during the neap tide of the lunar cycle as to provide the smallest tidal range (Rulifson and Tull 1999). Shubenacadie River striped bass spawning data from 1992 reported the highest abundance of eggs on June 1 following an abrupt increase in temperature from 13 to 18 °C over three days (see Rulifson and Dadswell 1995). In 1994, major spawning occurred once temperatures reached 18 °C on June 3 (Rulifson and Tull 1999). The conclusion from these observations was that 18 °C was a 'critical temperature' for spawning on the Stewiacke River, similar to observations on the Roanoake River, North Carolina (Carmichael et al. 1998; Rulifson and Tull 1999). Striped bass from the Annapolis River have also been reported to require an absolute temperature of 18 °C to initiate spawning (Williams et al. 1984). No tidal or lunar phase information was provided regarding the 1992 spawning. Neither a critical temperature of 18 °C nor spawning synchronized to the neap tides were supported herein.

3.5.1. Spawning

Striped bass spawning in 2008 and 2009 followed a broadly similar time-frame to previous years. Over 10 years of observations, June 1 has often been associated with large spawning activity (Figure 18). Large spawning events in both 2008 and 2009 occurred at temperatures between 12 and 15 °C, and the episodic nature of the spawning over two or more weeks clearly had no synchrony to the lunar cycle and the associated changes in tide height. Additionally, the relative egg abundance in the Shubenacadie, is markedly higher than recent reports of the Chesapeake population (Jahn, 2010) and other published values (Table 1). The marked increase in eggs abundance compared to the Chesapeake, may in part, be a function of the increased dilution from the larger Chesapeake watershed.

Temperature is important for many metabolic functions among fish, including spawning. The striped bass spawning season could be initially cued from rising water temperatures with the rate of temperature rise more important than overall water temperature (Bulak 1994; Robichaud-LeBlanc et al. 1996; Jahn 2010). Both the absolute and rate of change temperature metrics require a threshold temperature before spawning can begin. This threshold value is commonly cited as 18 °C for many populations including the Shubenacadie; indeed the ideal spawning temperature for northern U.S. populations is 18 °C based on hatch rates and larval survival to one day post-hatch (Setzler et al. 1980;

Morgan et al. 1981; Rulifson and Dadswell 1995). Temperature measurements did not occur directly on the spawning grounds, but all three data loggers showed a high degree of similarity (Figure 5).

Striped bass have long been known to spawn during the local springtime (Merriman 1941; Setzler et al. 1980; Rulifson and Tull 1999), however the well cited 18 °C threshold seems to hold more value for southern U.S. populations than northern populations of striped bass (Setzler et al. 1980; Hill et al. 1989). Anecdotal observations attribute an increase in volume of striped bass eggs when water temperature was greater than 18 °C, although not explicitly listed as a critical threshold for spawning on the Pamunkey River (McGovern and Olney 1996). Northern populations, such as the Miramichi population, have also been reported to require 18 °C to induce spawning (Robichaud-LeBlanc et al. 1996). However, all things must be put into context; water temperatures on the Shubenacadie River fluctuated more with the tidal cycle than the progression of the 1994 season (Tull 1997). Indeed, the lower spawning temperatures are consistent with previous accounts of striped bass in the river; that males and females are in spawning condition at water temperatures of 14 and 16 °C, respectively (Rulifson and Dadswell 1995) although more than 40% of all the eggs collected during the 1994 season were collected within the 18.0 to 19.9 °C (Rulifson and Tull 1999). As established through lab-based critical temperature trials; early life history of Shubenacadie striped bass display a broader range of thermal tolerance than southern populations although with an optimum similar to U.S. populations (Cook et al. 2006, 2010). This range exists *in vivo* and is experienced by eggs throughout their temporal distribution (Figure 9). This wider tolerance by the population is important to the survival of YOY, aiding to cope with large temperature differences caused in the nursery habitat by the tidal bore and potentially the colder waters of the inner Bay of Fundy. It would also facilitate differences in habitat that colour morphs inhabit after the first year of growth as both use similar juvenile habitats (Paramore and Rulifson 2001; Morris et al. 2003).

Striped bass spawning on the Shubenacadie River can be delayed with cold water temperatures (Paramore and Rulifson 2001, Duston unpubl. obs.). A decrease of 1.9 °C in mean water temperature at the Alton Project site (15.5 dropping to 13.6 °C) during May 24 to 29, 2009 coincided with a decrease in egg collection, and presumably spawning. Egg abundance resumed in earnest when water temperatures surpassed 15 °C. In contrast, the largest spawning of the 2008 season (June 1, 2008) occurring during a 1.3 °C decrease (14 to 12.7 °C). Similar reports of spawning 'stalling' during bouts of cold water have been reported previously in the Annapolis River (Williams et al. 1984) as well as the Shubenacadie (Rulifson and Tull 1999). A decrease of slightly over four degrees resulted in the suspension of spawning in the Roanoke River (Carmichael et al. 1998).

When temperature requirements for spawning are fulfilled, the oocyte development is regulated on the individual level, with individuals maturing at different speeds depending on photoperiods and water temperatures (Sullivan et al. 1997; Vuthiphandchai et al. 2002). An ability to delay senescence of the oocytes, or 'cold banking' by adults, allows early life history stages a greater chance of avoiding unfavourable environmental conditions which can lower water temperatures on the spawning grounds to sub-optimal ranges. Southern populations of white bass (*Morone chrysops*), striped bass and their hybrid, have exhibited cold banking from temperatures between 10 – 14 °C (Hodson 1995; Sullivan et al. 1997). Striped bass in the Pamunkey River produce large spawns with water temperatures of 16 °C; however, spawning action ceases in Chesapeake Bay tributaries when water temperatures are ≤ 12 °C or > 20 °C (Secor and Houde 1995; McGovern and Olney 1996). The exact temperature and duration required to induce a cold banking response in the Shubenacadie – Stewiacke population is not known, although it might be near the 16 °C threshold where minimal growth occurs in early life history stages of Shubenacadie striped bass (Duston et al. 2004; Cook et al. 2010).

Lab-based trials confirmed the salt range tolerated by recently hatched larval striped bass of the Shubenacadie River to be higher than U.S. populations, although long term exposure and acclimatization beyond the two weeks at high salinities is not documented (Cook et al. 2010). The *in vivo* salinity range is within the limits of those trials (0-35 ‰) with a wide range of salinities (0.1 to 20.0 ‰) experienced by eggs throughout the tidal cycle (Figure 10). Throughout the ebb tide striped bass eggs were found as high as 20.0 ‰ in 2009 (23 eggs/m^3; June 8) and 17 ‰ in the 2008 season (23 eggs/m^3; June 9). Although eggs were found throughout the ebb tide, exceptionally large abundances (>3000 eggs/m^3) tended to be at lower salinities. This could be a function of travel time from the spawning location. The salinity on June 1 2008 was 0.6 ‰, while egg abundance was 3252 eggs/m^3. During 2009 salinities of 2.2 and 1.7 ‰ were recorded with striped bass egg abundance of 4193 and 3859 eggs/m^3 on May 24, while on June 2nd egg abundances of 3549, 4324, and 4620 eggs/ m^3 corresponded with salinities of 4.3, 2.8, and 1.8 ‰ (Figure 7, Figure 8, and Figure 10). Egg viability would have been helpful in determining moribund or eggs in marginal habitat but due to logistical, time and personnel constraints and complications with fixing the eggs in formalin this was not done.

Thus, salinity tolerance of eggs differs among populations. Most eggs in 1994, were collected on the Stewiacke when salinities were ranged 4.0 to 5.9 ‰ whereas, no eggs were found in salinities above 1 ‰ on the Pamunkey River (McGovern and Olney 1996; Tull 1997). Egg survival of the Shubenacadie population was only significantly reduced when salinity was ≥30 ‰, far greater than the 18 ‰ that resulted in egg death for the riverine Savannah River population and greater than the 1.5 – 3.0 ‰ considered the optimum egg development in the Chesapeake Bay (Mansueti 1958; Winger and Lasier 1994; Cook et al. 2010). A numerical model for the brine discharge estimated that salinity, 1000 m downstream, would rise by 0.89 to 3.4 ‰ (depending on tide size) with the brine being vertically mixed within 250 m of being introduced into the river (Martec 2007b). If this estimate is correct, these small changes in salinity should have negligible impact. However, during the summer of 2008, heavy rainfall reduced the overall salinity at the study site (<2 ‰) to far below ambient river salinity used in the modeling (15 ‰) for several weeks (Reesor, unpubl. data).

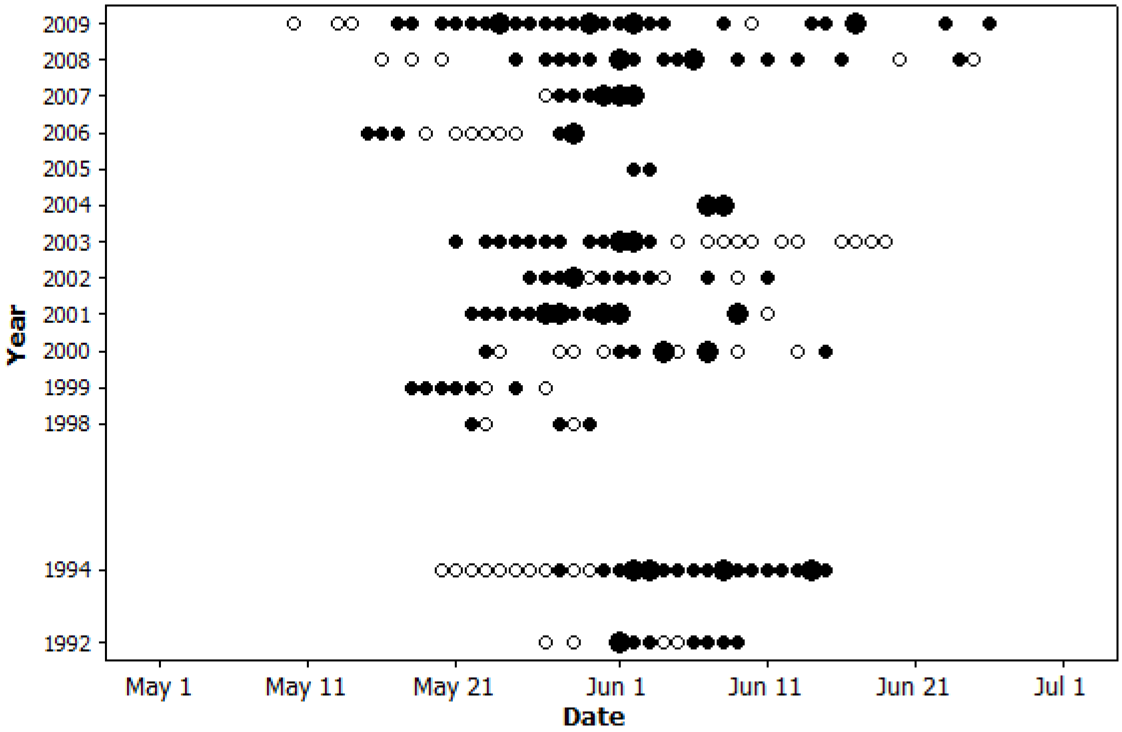


Figure 18. Striped bass spawning activity (solid circles) in the Stewiacke River (1998 to 2009) and Shubenacadie River (2008 to 2009) as judged by either visual observation of adults rolling at the surface or presence of eggs collected in a plankton net. Open circles indicate when no eggs were detected in plankton net tows. Within each year, the larger solid circles indicate a relatively large spawning event based on subjective estimate of egg abundance. Because of these subjective estimates, between 1992 to 2007, comparisons of the magnitude of large spawning events are not valid. **Source of data**: 2008-09: this study; 1998-2007: J. Duston and B. Stone unpubl. observations; 1994: Rulifson and Tull 1999; 1992: Rulifson and Wood unpubl., cited by Rulifson and Dadswell 1995.

Table 1. Peak abundance of striped bass eggs (m^3) associated with four different river systems along the Atlantic coast. Values were converted to eggs per meter cubed where possible and when not possible, asterisks are included before the system's name. Direct comparison between the asterisk systems and those reporting values in eggs/m^3 are not valid. Two northern populations (Bay of Fundy and Gulf of St. Lawrence) are included as are two southern populations (Chesapeake Bay and Lake Texoma), one of which is riverine (Lake Texoma).

Drainage	System	Year	Egg abundance (m^3)	Source
Bay of Fundy	*Annapolis River	1976	1.5 eggs per ten minutes	Rulifson and Dadswell 1995
Bay of Fundy	*Annapolis River	1979	450 eggs per 24h	Rulifson and Dadswell 1995
Bay of Fundy	*Shubenacadie-Stewiacke	1992	147 eggs per 5 minutes	Rulifson and Dadswell 1995
Bay of Fundy	*Shubenacadie-Stewiacke	1994	5000 eggs per second	Rulifson and Tull 1999[†]
Bay of Fundy	*Belleisle Bay	1975	661 eggs per 24h	Rulifson and Dadswell 1995
Bay of Fundy	Shubenacadie-Stewiacke	2008-2009	4620	This study
Bay of Fundy	Shubenacadie-Stewiacke	2001	~1250	Douglas et al., 2003
Gulf of St. Lawrence	Miramichi	1992	0.7	Robichaud-LeBlanc et al., 1996
Chesapeake Bay	Upper Cheasapeake	2001-2003	0.8	Martino and Houde 2010
Chesapeake Bay	Upper Chesapeake	2008	34	Jahn 2010
Chesapeake Bay	Potomac River	1974-1977	5.5	Setzler-Hamilton et al., 1981
Chesapeake Bay	Pamunkey River	1988	8.22	McGovern and Olney 1996
Chesapeake Bay	Pamunkey River	1997-1999	100	Bilkovic et al., 2002
Chesapeake Bay	Mattaponi River	1997-1999	1200	Bilkovic et al., 2002
Lake Texoma	Red River	2001	5	Baker et al., 2009
Lake Texoma	Washita River	2001	34	Baker et al., 2009

[†] Instantaneous egg count. There was no flow meter utilized during this study so direct comparison is difficult to other studies

3.5.2. Critical Habitat

Striped bass tolerate changes to spawning, rearing or overwintering habitats poorly. Loss of Canadian self-sustaining populations is more associated with environmental disruption than other causes (Bradford et al. 2001). Critical habitat designation is important as it provides protection for habitat as well as allows for public education about the species. During the late 1990s, species with designated critical habitat were more than twice as likely to increase their population as those species without the designation (as per Hagen and Hodges 2006). Defining critical habitat can be troublesome as biologically the data does not always align with economic and political forces acting on legislative and policy bodies (Hagen and Hodges 2006). Correctly identifying the critical habitat within the Shubenacadie – Stewiacke estuary is of the utmost importance so that the last remaining spawning population in the Bay of Fundy is conserved. The proposed Alton Project site is likely contained within the critical habitat for this population of striped bass when eggs and larvae are present, conservatively mid-May to mid-July.

Under certain circumstances the Alton Project site might be considered outside of critical habitat. For example a heavy rainfall river discharge shifts the spatial habitat further downstream, and the concomitant shift of salinities below which no larvae were found at the Alton Project site. North *et al*. (2004) found that the salt front in the Chesapeake Bay will be displaced approximately proportional to the change in river flow conditions, with down-estuary movement (i.e. large freshets) yielding a stronger response than droughts or other up-estuary responses. Following a large spawn, subsequent flood and ebb tides may disperse eggs and larvae, expanding the maximum geographic range of the nursery habitat from the head of the tide to potentially Cobequid Bay (Rulifson and Tull 1999), although further study is required to ascertain if a nursery is indeed present at the mouth of the Shubenacadie. Within the limits of the estuary, head of the tide to the river mouth, the geographic range of the nursery habitat can vary depending on the stage of striped bass development, state of the tide, tide height and freshwater discharge volume. Although the Alton Project site may be included within the nursery habitat at one point of the tide, it may be outside this habitat a few hours later. The threshold combination of freshwater discharge and tidal amplitude required for shifting the critical habitat downstream in the Shubenacadie – Stewiacke system is unknown at present.

The Shubenacadie watershed has two distinct subpopulations based on the dorsal colour morphology, unique diets and otolith microchemistry (Paramore 1998), although life-history decisions can potentially be regulated at the individual level (Gemperline et al. 2002). These sub-populations exhibit different life-histories after the first year of growth, but, they use similar habitats for spawning and nursery areas (Paramore and Rulifson 2001; Gemperline et al. 2002; Morris et al. 2003). This could have significant management implications for defining critical habitat. Preserving and improving habitat shared by both colour morph groups would maximize conservation efforts. Both colour morphs share similar spawning grounds (Morris et al. 2003), and a wide variety of year classes use the extended nursery grounds of the Cobequid Bay. Although sub-populations were not specifically examined (Rulifson et al. 2008), both subpopulations grow in the same environment during the first year (Gemperline et al. 2002). It complicates management further if the two colour morph sub populations prove to be genetically different.

The Canadian federal court has taken the precautionary stance that in the absence of "best available information", all known habitat of any given species should be designated as "critical", at least until there is further information suggesting it is not (Campbell 2009). If defining critical habitat on the Shubenacadie – Stewiacke watershed becomes a herculean effort, at some point, it would seem reasonable to work with all stakeholders in the watershed to create a public education campaign and focus on improving general habitat management. Critical habitat is important but the costs associated with defining a habitat for multiple migratory life histories that may be temporally and spatially different might outweigh the concentrated effort to define critical habitat. For instance, during periods of striped bass decline during the

1970s in the Sacramento-San Joaquin Delta the incorporation of pesticide use and contaminant levels resulted in a more efficient recruitment prediction model than conventional models (Bailey et al. 1994). Effluent from heavily developed agricultural areas reduced embryo and larval survival of a west coast population of striped bass as well as a species of *Neomysis*, which served as a primary food source for the juvenile stripe bass in the area (Bailey et al. 1994). Better management practices, such as increase of on-farm holding times to reduce agricultural runoff (see Bailey 1994), strive to protect and preserve the health of striped bass spawning and general habitat. Strong public education campaigns regarding spawning and habitat destruction have helped raise awareness and ultimately aided in the recovery of endangered populations for species such as the piping plover (*Charadrius melodus*) (Abbott 2009) so there is support for similar programs to work for striped bass.

A plausible method for future work to determine bass critical habitat may be through examining otoliths, as daily otolith deposits in Shubenacadie striped bass begin at four days post hatch (Douglas 2001). Otolith microchemistry provides a viable (Secor et al. 1995) and valuable method of examining the migratory history of fish as its capable of detecting variations in ambient salinity which allows small-scale mapping of movements in estuarine fish (Secor and Rooker 2000), although some caution and prior planning should be exercised before examining strontium levels in otolith microchemistry of estuarine inhabitants (Kraus and Secor 2004). The duration in any locale needs to be long enough to allow for adequate otolith growth. As technology progresses, the ability to better describe and discern fish spawning grounds will improve (Secor and Rooker 2000). Examining otoliths of striped bass can provide valuable insights into their life histories and may reveal unknown sub-populations, such as a potamodromous group of striped bass near the Chesepeake region (Secor and Rooker 2000; Secor et al. 2001).

3.5.3. Larvae: Rainfall, Temperature, Tides and Salinity

Striped bass larvae in the Shubenacadie River exist in a complicated system dictated through the interactions of tides and rainfall which, in turn, influence both temperature and salinity. Interplay of these four constraints, as well as the twice daily tidal bore, creates a very dynamic environment and understanding of the five features is crucial to understanding the greater system function.

Strong recruitment of striped bass in the Chesapeake was found to be associated with high concentrations of *Eurytemora affinis* (Martino and Houde 2010). *E. affinis*, a euryhaline copepod capable of tolerating hypoxic conditions, is not capable of swimming against general currents but instead behaves like a passive particle, retaining its position in a stratified estuary by undergoing vertical migration (Castel and Veiga 1990). *E. affinis* are present in the Shubenacadie (pers. Obs.), although how they control position in the vertically homogenous Shubenacadie estuary is unclear (no published studies were found) and this thesis did not quantify their abundance due to time and manpower constraints.

Temperature

Temperature on the Shubenacadie River is moderately influenced through the incoming tide and counteracted through river discharge, although the role solar heating and cooling of the mud flats is also significant. The exposed mud flats reflect the state of air temperatures: cool during the night and warm while exposed to the sun during the day; in a 24-hr period, a range of 9 °C in water temperature was not uncommon throughout both years (data not shown). Most often the range was 3 to 6 °C, similar to previous reports of intertidal zone solar heating (Amos and Long 1980; Tull 1997). Mean daily temperature generally increased over the length of the season, albeit with short term (few days) or diurnal volatility (Figure 3 & Figure 11).

In 1994, all but a fifth of larvae were in water cooler than 16 °C (Rulifson and Tull 1999), whereas herein, virtually all larvae detected were in water of temperatures warmer than 16 °C (Figure 13). Lab based trials have shown Shubenacadie striped bass larvae obtain maximum first feeding length if the yolk-sac stage is exposed to temperatures between 14 to 16 °C (Peterson et al. 1996). This is contrary to other lab based trials for the Shubenacadie population, which states 16 °C as a minimal growth threshold for early life history stages (Duston et al. 2004; Cook et al. 2010). The health of larvae and subsequent strength of cohorts spawned in the Pamunkey River during bouts of low water temperatures are unfavourable (McGovern and Olney 1996). On the Patuxent River, increased mortality occurred in larval cohorts subjected to temperatures lower than 15 °C during the first 25 days after hatching (Secor and Houde 1995). Equally troubling can be high water temperatures, with larval cohort mortality increasing when temperatures were greater than 20 °C (Secor and Houde 1995) and although larvae have a sufficiently high tolerance that death is not an immediate concern (Cook et al. 2006), Shubenacadie larval lengths at first feeding were shorter when temperatures exceeded 18 °C (Peterson et al. 1996) which has the potential to impact the ability to forage successfully.

Larval growth must reach a critical threshold of ten centimeters to reduce year class mortalities and allow successful overwintering (Bradford et al. 2001). Larval length and weights collected over eleven days in the 2008 season were examined to see if the relationship was similar to previously reported findings for the Shubenacadie River (Leim 1919 In Rulifson and Dadswell 1995; Paramore 1998) and elsewhere in Canadian and American waters (Setzler et al. 1980; Robichaud-Leblanc et al. 1998). Three-quarters of the larvae were measured mid to late- July, with over half the larvae measured on two days (July 14 and July 29), impeding examining growth by date. More larvae, spanning multiple days would have had to be collected to allow accurate growth per day, similar to Douglas (2001). The growth patterns of larval Shubenacadie striped bass are not different from striped bass in the Miramichi (Douglas 2001). In the Miramichi, striped bass grew >30 fold in length during the summer season, June to October, with grow occurring rapidly during the summer and reduced growth during the fall (Robichaud-Leblanc et al. 1998). The slight bimodal distribution in the length histogram may be a representation of two days, ten days apart, where the number of larvae collected on each day, was greater than 220 (Figure 16). Despite having only one year, the length- weight data contributes significantly to the near vacant body of knowledge on early life history growth in the Shubenacadie watershed.

Salinity

Although Shubenacadie striped bass are subjected to wide ranging salinities during the egg and yolk-sac stage, lab-based trials conducted with Shubenacadie fish have shown salinities of 5 ‰ results in longer first feeding larvae than those reared at either 1 or 10 ‰ (Peterson et al. 1996). Eggs reared at high levels (>20 ‰) of salinity may be negatively affected during larval stages (Cook et al. 2010), but growth rapidly changes to become independent of salinity (Duston et al. 2004; Cook et al. 2010). Swimming ability also develops rapidly (Peterson and Harmon 2001), but still limited compared to the massive tidal forcing that the Shubenacadie undergoes. The increased mobility follows suit with a change in prey preference (Robichaud-LeBlanc et al. 1997; Overton et al. 2009) and the distribution of larvae will likely shift to match habitat preferences or align with specific prey distributions (Robichaud-LeBlanc et al. 1998; Nemerson and Able 2003; North and Houde 2006). In the San Francisco estuary, migration patterns of striped bass larvae matched those of the zooplankton regardless of the flow regime (Bennett et al. 2002).

It is difficult to conclude much on the salinity preferences of Shubenacadie striped bass larvae with abundances low and inconsistent in both years. Instead, the >30-fold difference in abundance speaks more to environmental factors impacting the estuarine habitat (North and Houde 2001; North et al. 2005; Shoji et al. 2005), potential advection (Pace et al. 1992) or shifting the nursery habitat beyond the spatially fixed

Alton Project sampling area (North et al. 2004) as spatial movement can have a larger impact than temporal impact on motility-limited pelagic life (Islam et al. 2006). Gear avoidance is also a possibility, certainly more so with older larvae and young juvenile fish. The difference between 2008 and 2009 was significant supporting large inter-annual variation with striped bass (Martino and Houde 2010). The possibility that the variation is due to fewer spawning adults seems unlikely as egg abundance was greater in 2009 than in 2008, which relates more to an egg season with less rainfall.

Tides

Larvae tended to increase over the course of the ebb tide, although the distribution within the ebb tide suggests a patchy distribution in the river (Figure 12). This distribution shift is not uncommon for striped bass (Setzler-Hamilton et al. 1981). Doing so might have revealed potential gear avoidance behaviour in larvae as swimming ability develops as well as any temporal distribution shifts related to growth and age. Younger larvae might be displaying a gear bias, skewing the distribution so abundance increases over the ebb tide. Larval abundance might have increased over the length of the ebb tide due to narrowing of the river, or perhaps larvae inhabit an area further upriver at high slack.

Data on larval lengths in the Shubenacadie are scarce, and while the initial temporal distribution of larval striped bass has been described in relation to water temperature and salinity, and provides a good preliminary starting point, some caution should be exercised to avoid potentially misleading conclusions. During the 1994 season only 61 larvae were caught yielding speculation that once larvae hatched and transported to the river confluence, further upstream movement did not take place (Rulifson and Tull, 1999). No morphometric data was provided on the 1994 larvae. Despite significantly more larvae found during the study herein (2008 = 45,111 larvae over 38 sampling days; 2009 = 449 larvae over 45 sampling days), further analysis of the temporal distribution is required to better understand larval preferences.

Growth has been described for older fish (> 400 mm FL) of the Shubenacadie population (Paramore 1998) but there is a lack of data on early stages of striped bass from this river.

Larval mean lengths seem to be slightly higher than those reported in Lein (1919) during July and August (Figure 17), although within the range previously reported for this population (Leim 1919 *in* Rulifson and Dadswell 1995). Similar ranges of growth rates were described for Miramichi larvae (Robichaud-Leblanc et al., 1998). Larval lengths collected for this study (9.8 to 46.1 mm TL) were smaller when compared to previous seine net captures between the late 1970s and early 1980s (12 to 80 mm TL) during the same time frame (Figure 17; Dadswell et al. 1984 *in* Rulifson and Dadswell 1995). Differences in larval length and seasonal growth performance are associated with different environmental conditions impacting availability to food sources (Eldridge et al., 1982; Martino 2008). The increase in larval length variability herein (Figure 17) might have resulted from small sample size, sampling across multiple larval cohorts or large growth variation within one cohort, otolith analysis was not undertaken; therefore, determining cohorts was not possible.

Rainfall

The Cobequid Bay exchanges roughly 2 to 2.4 km^3 of water per mean tide over its 43.5 km length (Amos and Long 1980; Gregory et al. 1993). The mean tidal range at the mouth of the Shubenacadie River is 11.9 m (Amos and Long 1980; Gregory et al. 1993), far above the 6 to 9 m required to initial a tidal bore (Chanson 2003). The incoming water up river dampens the magnitude and severity of impacts from freshets.

The Shubenacadie estuary system is greatly influenced by rainfall and is susceptible to large and rapid freshets. Hurricane Bill (August 23, 2009) resulted in a mean temperature drop of one degree per day for six days after 56.5 mm of rainfall. Large rainfall-induced freshets contribute to flushing eggs, larvae and possibly the nursery area, farther downstream than the study site, potentially into Cobequid Bay, for days at a time potentially leading to increased mortality if eggs and larvae are advected from the estuary or critical nursery habitat. The threshold disturbance level required to move the nursery area on the Shubenacadie is unknown at present, although the potential for freshets to disrupt the nursery area is diminished by the overwhelming tidal forces.

Despite the high single day values recorded at the Halifax International Airport, the threshold amounts and effects of environmental factors that contribute to a change in salinity of the Shubenacadie are not well documented. River discharge rates on the Shubenacadie increase to their maximums one to two days after rainfall events, with a critical threshold of 5 mm of rainfall needed to impact salinity (Parker 1984); however this did not coincide with the findings herein. Although any given day may result in surpassing the threshold amount of rainfall, salinity might not decrease as the effects are not necessarily immediate: rainfall requires time to travel through a watershed and tributaries. Soil will retain some water after a rainfall event although the amount will vary depending on amount a wide variety of factors such as the type and amount of vegetation, topography, and soil type and moisture condition (Nova Scotia Museum of Natural History 1996). In events of heavy rainfall where soil reaches its saturation point, freshets travel through the watershed largely intact. The strongest effects from a freshet on an estuarine system are within the first week and then diminish over space and time (Islam and Tanaka 2007). The seven day prior rainfall average was higher during the spawning period in 2008 and during the 2009 larval season than the respective 2009 and 2008 seasons. A multi-day average no doubt better represents the lag between rainfall and lowered salinity, and indeed the 7- day lagged average showed significance in both years.

Chapter 4. The Mysid *Neomysis americana*

The mysid, *Neomysis americana* (Family: Mysidae) is common throughout the north Altantic (Hoffmeyer 1990). Female mysids develop a characteristic marsupial pouch, lending to the common name of ‘opossum shrimp’; development takes place entirely within the brood pouch of females (Wortham-Neal and Price 2002). *N. americana* is the dominant species inhabiting the Cumberland basin region of the Bay of Fundy and produce two generations per year, May-June and September-October (Prouse 1986). This species is present at concentrations of 10 individuals per cubic meter of water in Cuberland basin (Prouse 1986).

Mysids are omnivores, primarily relying on visual predation using their well-developed eyes (Abello et al. 2005) and change their diet depending on food size and availability (Froneman 2001; Carrasco et al. 2007). Members of the genus demonstrate behavioural prey switching, changing from suspension feeding and grazing on detritus to foraging on animal prey such as copepods (Frockedey and Mees 1999). *Mysis relicta* (Family: Mysidae) feeds on algae in the water column during the night and sediment during the daytime, and sediment may compose a significant portion of its diet (Lasenby and Shi 2004). Similarly, *N. americana* inhabiting Cumberland Basin is speculated to be sustained on *Spartina* detritus (Prouse 1986). As turbidity increases, dietary changes will also occur in this species.

Mysids have been well documented to exhibit diurnal migration patterns in lakes and in stratified tidal estuaries (Herman 1963; Abello et al. 2005; Boscarino et al. 2009). The speed of ascent and descent is slowed or quickened respectively, to maximize movement under low light (Abello et al. 2005). Vertical migration is a strategy employed to maintain an ideal position in the estuary and responds to existing velocities rather than anticipating changes (Kimmerer et al. 2002). Vertical migration may also be a result of following specific light intensities (isolumes) throughout the water column, avoiding visual predators or maximizing food-energy conversion (Chess and Stanford 1999; Abello et al. 2005; Boscarino et al. 2009). *N. americana* have been found in areas of estuaries where the water column had a light range between 5.38 x 10^0 to 1.08 x 10^{-2} lx. (Herman 1963). Regions of high turbidity may render vertical migration unnecessary as mysids prefer being pelagic rather than in the benthos in water with low transparency (Kimmerer et al. 2002; Horppila et al. 2003). Mysids within the same family as *N. americana* have low survival at high turbidity levels roughly 3x higher than maximum turbidity in the Shubenacadie (300 vs. 1088 NTU; Carrasco et al., 2007). Temporal and spatial data as well as diurnal migration data are lacking on the Shubenacadie estuary and are required to better understand mysid population dynamics in this watershed.

4.1. Results

Mysids, *Neomysis americana*, were common at the Alton Project site. Most developmental stages were collected over the season including juveniles, adults and gravid females although stage determination was anecdotal. Mysids represented the most abundant macro-invertebrate throughout both years from May to November, with peak abundance in some tows >10,000 individuals/m^3 e.g. June 2008 and August 2009. No mysids were found on only three days during 2008 (May 30, September 4, and October 29), and two days in 2009 (May 22 and 31).

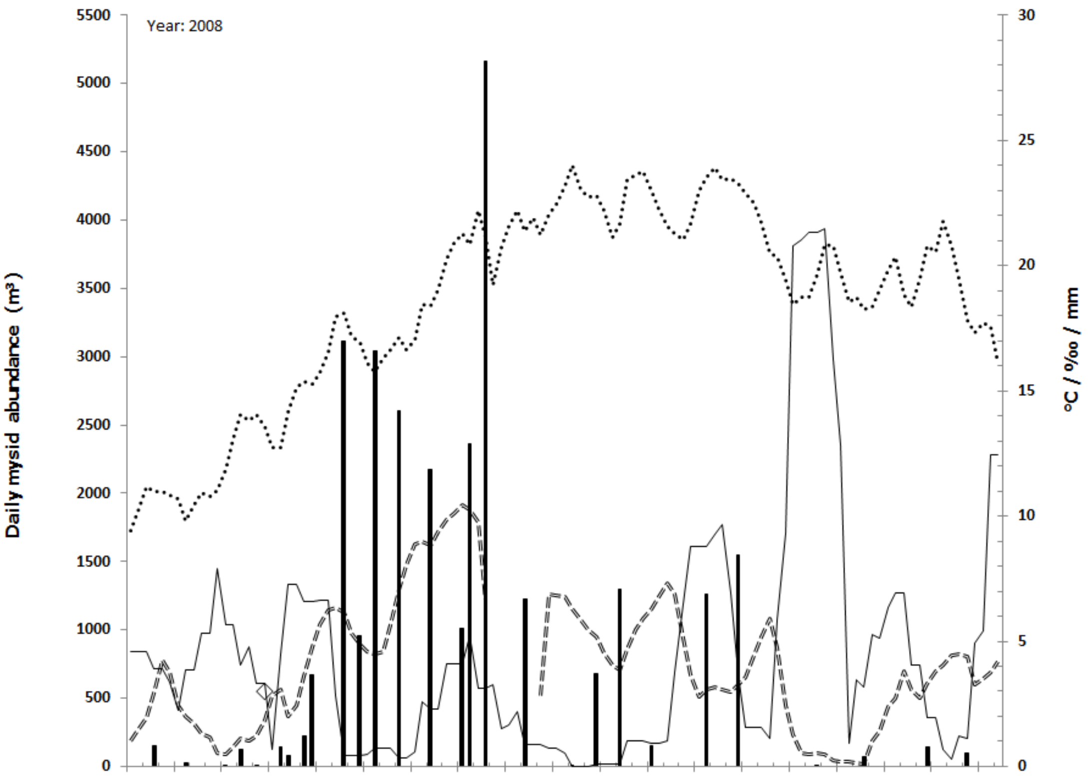
Mysid abundance was high throughout the season, albeit slightly lower in 2009 than 2008 (Figure 19). Daily average mysid abundance increased throughout June 2008 to peak at over 5000 /m^3 on June 27 (Figure 19; upper panel). The mean salinity and temperature corresponding to the large abundance was 6.5 ‰ and 21.1 °C; mean salinity was decreasing gradually as was lagged rainfall (3.1 mm) and temperature. The data logger malfunctioned from June 28 to July 4, 2008 inclusive, most likely from detritus blocking the sensor; values for those dates were removed. The maximum peak in 2009 recorded was on June 4 with over 3200/m^3 at salinity of 13 ‰ (Figure 19; lower panel). The mean salinity and temperature corresponding to the large abundance were 7.5 ‰ and 15.6 °C; mean salinity throughout 2009 was typically higher than 2008 while lagged rainfall was similar to 2008 (3.2 mm). Mean water temperature in 2009 was lower initially than 2008 (Figure 19).

Within each tidal cycle, mysid abundance increased on the flood tide and then decreased over the length of the ebb tide. As an example, on July 11, 2008 the mysid abundance at high slack was 532 mysids/m^3 and peaked ~100 minutes into the ebb tide (>1600 mysids/m^3); 100 minutes later the abundance was 251 mysids/m^3; half that of high slack and less than a sixth of the peak abundance (Figure 20). Abrupt changes in abundance were typical of the 2008 season, although changes in abundance were not always a function of salinity variation. The peak on June 23 2009, was >1400 mysids/m^3 three hours past high slack with a salinity of 14.8 ‰, in the following tow the abundance was less than half (673 mysids/m^3) the initial abundance with a salinity change of only 1.8 ‰ (13.0 ‰; Figure 20). Mysid abundances appear to be heavily influenced by rainfall and freshets. In July and August 2008, mysid abundances remained low (<50 mysids/m^3) and were associated with heavy rain and low salinity at high tide. During the second two weeks of August 2008, mysid abundance increased moderately to a peak of about 240 mysids/m^3 as salinity at high tide returned to >10 ‰. Daily abundances of mysids reflected this lower values as well.

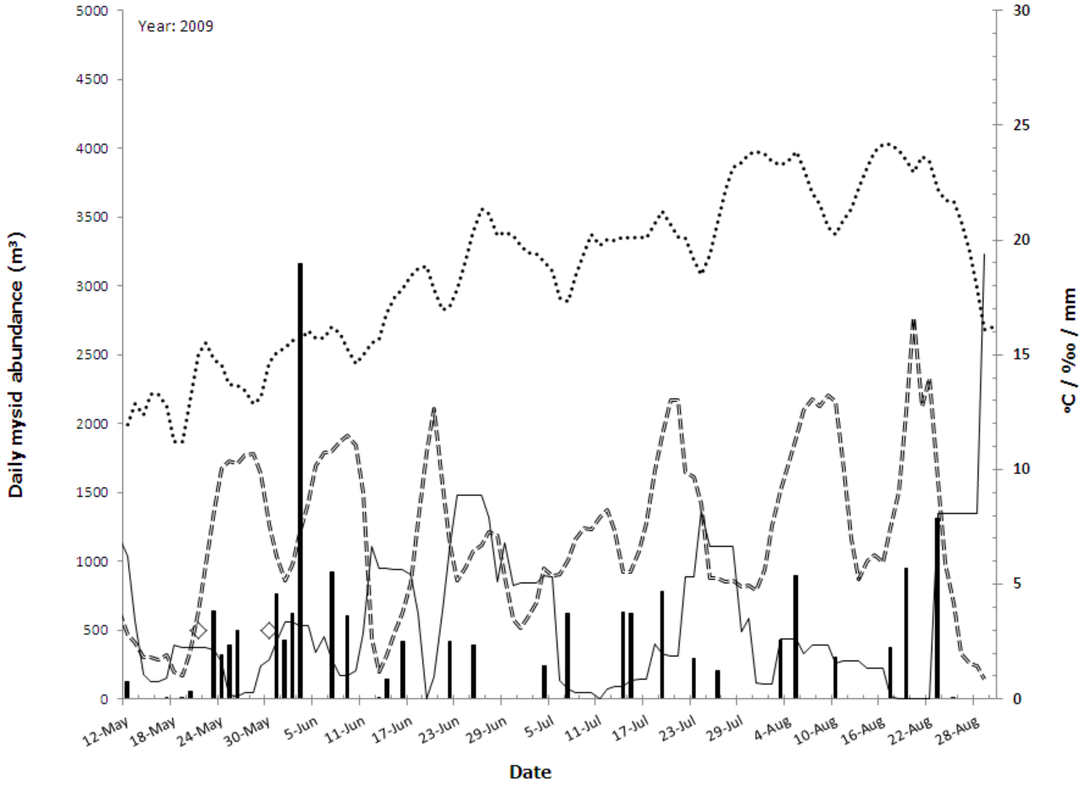
Neomysis americana were collected from similar salinity ranges over both years, although 2008 (0.1 to 23.1 ‰) was slightly larger than 2009 (0.1 to 20.8 ‰). Mysids were very common whenever salinity was >1 ‰ but abundances diminished below 5 ‰ with rapid decay beneath 3.5 ‰ (Figure 21). The curve plateaus at roughly 1000 mysids/m^{3}of water. Overall, abundances of mysids were lower in 2009 than 2008, although the relationship between years is very similar, and differences were associated with greater rainfall and lower salinities (Figure 21).

Mysid abundances over the 2008 season, May 16 to Nov 13, was recorded over a wide range of temperatures (6.9 to 26 °C) although abundance was greatest between temperatures of 16 to 25 °C (Figure 22). Likewise, mysid abundance during 2009 sampling, May 5 to Oct 29, spanned a similar range of temperatures (10.1 to 27.4 °C) as that in 2008. Despite less overall abundance, abundances were greater at lower temperatures in 2009 than those in 2008 (Figure 22).

Figure 19. Daily mysid abundance (columns) with respect to water temperature (dotted line), salinity (dashed line) and lagged rainfall (thin line). Coordinates show the daily total number of mysids collected from up to nine (2008) or twelve (2009) tows over several hours. Tow duration: 1.5 to 3 mins. Upper panel: 2008. Lower panel: 2009. Open diamonds indicate when sampling occurred but no mysids collected.



Year: 2008
Daily mysid abundance (m³)
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
°C / ‰ / mm
30
25
20
15
10
5
0



Year: 2009
Daily mysid abundance (m³)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
°C / ‰ / mm
30
25
20
15
10
5
0
12-May
18-May
24-May
30-May
5-Jun
11-Jun
17-Jun
23-Jun
29-Jun
5-Jul
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10-Aug
16-Aug
22-Aug
28-Aug
Date

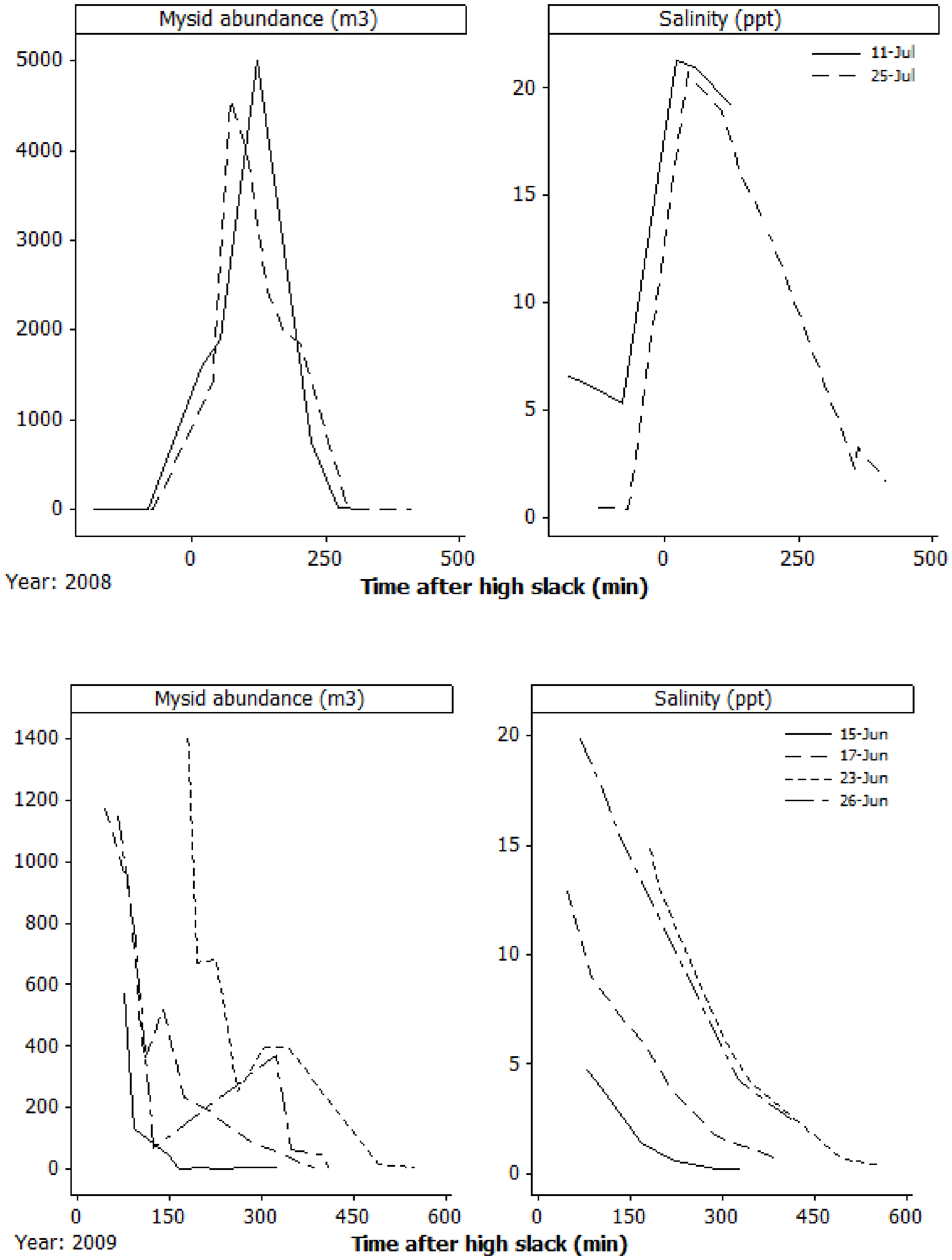

Figure 20. Mysid abundance (mysids/m^3) with respect to salinity (‰) during the ebb tide in 2008 and 2009 field seasons, upper and lower panels respectively.

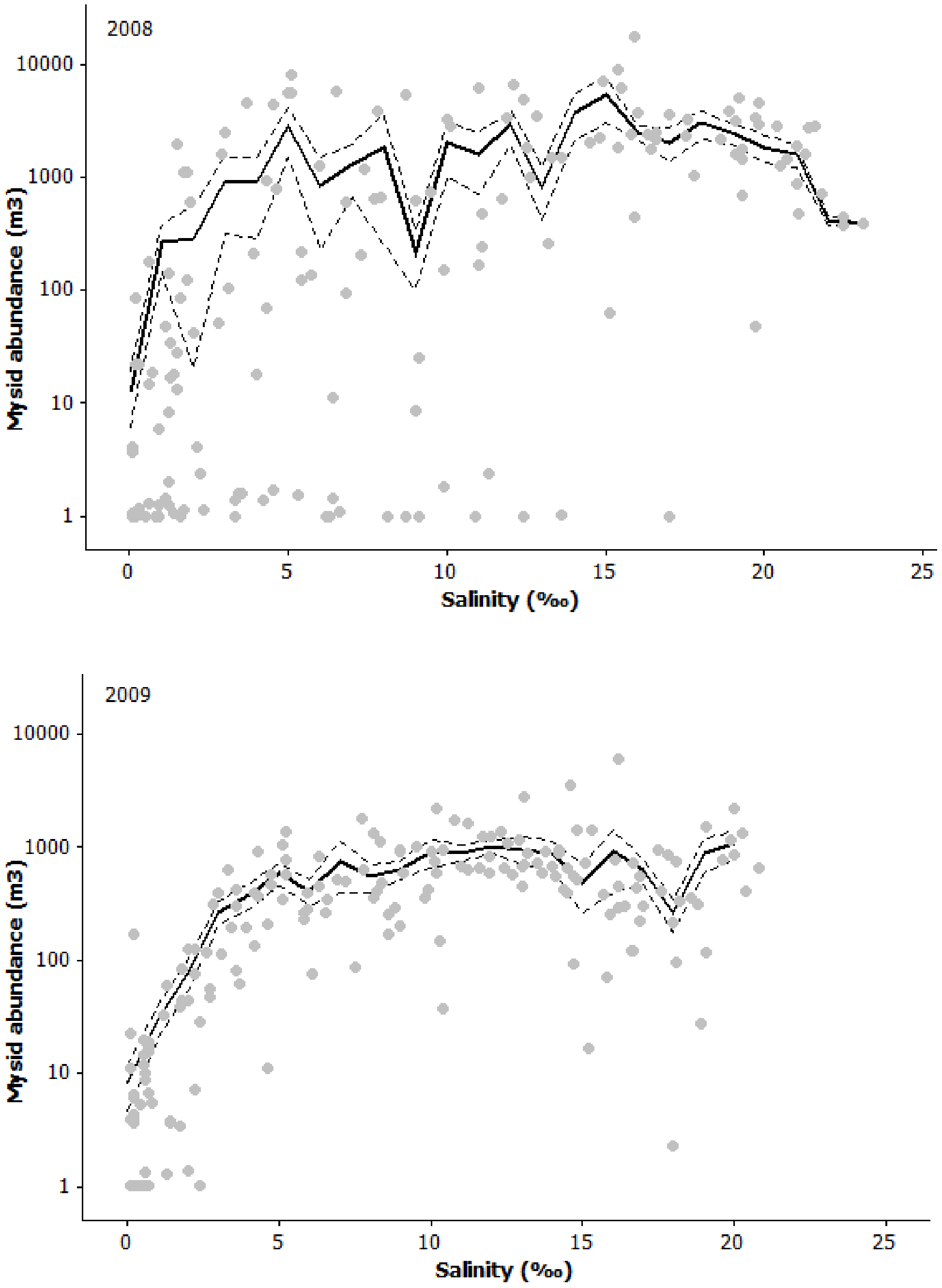

Figure 21. Salinity distribution of *Neomysis americana* at the Alton Project site during the 2008 and 2009 field seasons, upper and lower panels respectively. Each dot represents an individual tow; whereas the solid line represents the mean abundance (±SE) for the season as pooled at each salinity point. Note the log scale.

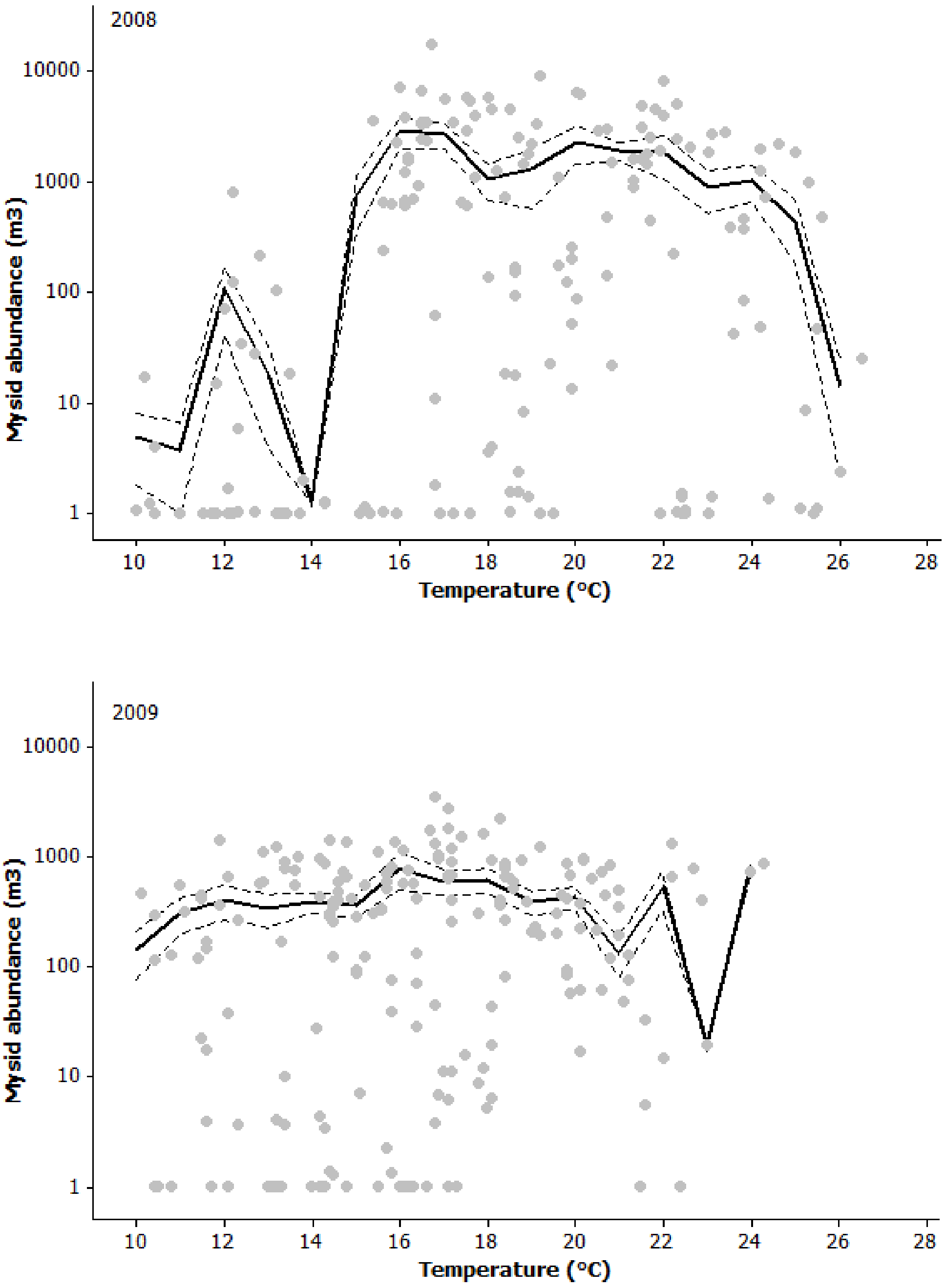

Figure 22. Thermal distribution of *Neomysis americana* detected at the Alton Project site during the 2008 and 2009 field season upper and lower panels respectively. Each dot represents an individual tow; whereas the solid line represents the mean abundance (±SE) for the season as pooled at each salinity point. Note the log scale.

4.2. Discussion

The pervasive and consistently high abundances of mysids in the Shubenacadie are similar to reports of mysids from the Delaware River, where they were found in high abundance throughout the year and present on all cruises undertaken over a two year period (Cronin et al. 1962). Similar abundances to the 2009 daily mean value have been reported in the Delaware River (3000 mysids/m^3), although the second year of that study reported only 800 mysids/m^3 as the maximum (Hopkins 1965). Abundance of mysids in the Delaware have also been reported to peak at 72 mysids/m^3; far lower that the peak numbers in the Shubenacadie during this study but closer to the reported abundance from the inner Bay of Fundy (Hulburt 1957; Prouse 1986).

The difference in mysid abundance between 2008 and 2009 is not unexpected. Large inter- annual variations in abundance are common with mysid populations (Hopkins 1965; Heubach 1969; Orsi and Knutson Jr. 1979). Habitat size and food availability have been speculated as the controlling factors in mysid populations, which, is turn, is mediated through freshets (Orsi and Knutson Jr. 1979). *N. americana* is speculated to have two generations during the summer months and one during the winter months on the Delaware River; although the Cumberland basin population only produces two generations a year (Hopkins 1965; Prouse 1986). It is unclear if the inter-annual year class fluctuations on the Shubenacadie River can be explained through habitat size and food supply, through a higher fecundity and low generational time, or another cause; further study is required.

Mysids appear to be quite abundant irrespective of temperature throughout the season in both years. This is remarkable as mysids generally prefer colder waters. *Mysis relicta* from Lake Ontario completely avoid water temperatures of > 16 °C, limit movement into waters above 12 °C unless prey is present and prefer temperatures 6 to 8 °C (Boscarino, et al. 2007). Herein, some mysids were collected in water with temperatures of nearly 27.5 °C. Water temperature > 22 °C were unfavourable to *Neomysis awatschensis*

(Heubach 1969); however, some field data has contradicted this value finding *N. awatschensis* in water up to 25 °C (Orsi and Knutson Jr. 1979). During lab trials, immature *N. americana* from the Bay of Fundy displayed > 50 % mortality across salinities when water temperature was greater than 25 °C, which is consistent with other species in the genus (Pezzack and Corey 1982). Body condition or similar index for assessing health of mysids was not done to see if they were moribund or inhabiting marginal habitat. Further studies are required to assess the temperature optima and range of *N. americana* in the Shubenacadie system.

The rapid change in mysid abundance in the Shubenacadie in both 2008 and 2009 during the ebb tide suggests that their distribution has some degree of spatial patchiness, which could result from passive particle transport. Swarms of *Neomysis integer* have been found along sections of the Shubenacadie river with current velocities as high as 12 cm/s, although they can only maintain swimming speeds of 6 cm/s with short term sprinting up to 27 cm/s by some individuals (Roast et al. 1998). This relatively poor swimming ability, compared to the large tidal forcing of the Shubenacadie, suggests that mysids behave as a passive particle in the estuary similar to smaller copepods (Castel and Veiga 1990) and that spatial patchiness may be more a result of a flow pattern than swimming ability.

Perhaps instead of a passive particle, mysids in the Shubenacadie – Stewiacke river system employ another type of position maintenance. When the rate of change in salinity on the Shubenacadie due to the incoming tidal bore is considered, it seems unlikely that the incoming flood tide has such a high stocking level of mysids to be able to increase the abundance so quickly. In higher currents, position maintenance can encompass utilization of the substrate, burrowing through mud and utilizing waves formed from sand to protect from current velocities (Roast et al. 1998). Similar behaviour might be occurring on the Shubenacadie. Further studies are required to test this hypothesis as well as to see if passive particle or active position maintenance are used in combination or mutually exclusive.

Beyond an initial sharp rate of change when salinity is between zero to five, mysids are ubiquitous. Mysids were collected in salinities ranging from 5 to 25 ‰ on the Delaware River (Cronin et al. 1962), similar to the ~20 ‰ range that mysids were collected from during 2008 and 2009. Typically mysids are mesohaline, requiring some intermittent salinity to survive. In the Delaware River estuary, most mysids were not in salinities of less than 4 ‰ (Hulburt 1957) although a few individuals were collected in salinity <1 ‰ (Cronin et al. 1962), whereas in the Shubenacadie they were present at salinities <1 ‰. The highest abundance of mysids collected in the Delaware was between 15 and 20 ‰ (Cronin et al. 1962). This contradicts another estuarine member of the genus, *N. mercedis*, where abundance is greatest in fresh water to slightly over seven parts per thousand, and least abundant in waters with salinities over 18 ‰ (Heubach 1969).

Chapter 5. Conclusions

Striped bass in the Shubenacadie – Stewiacke watershed spawn in response to changes in water temperature. Water temperature is currently the best predictor when spawning may occur. Eggs were collected at 15 °C, slightly lower than other reported populations and contrary to the 18 °C previously cited as required to induce spawning. Further study is required to generate a model to predict the onset of spawning from either heat accumulation (Neuheimer and Taggart 2007) or rapid change in temperature caused from freshets (see Jahn 2010). A validated model would lend insight into the basic biology of this fish.

Both years showed egg abundance peaking within the last week of May and first week of June, despite the 2009 spawning starting a week earlier. Within the ebb tide, time after high slack is the best predictor for egg abundance, with a direct relationship present throughout both years. Throughout a tidal cycle, egg abundance was consistently lowest at high tide and increased progressively through the ebb tide as salinity decreased, irrespective of spawning size and whether they were newly fertilized or 24h-old eggs. Egg abundance showed a decrease at roughly 300 minutes, although whether the decrease represents a biologically or simply a statistical threshold is unknown at present. Further studies to examine time after high slack versus ontogenetic changes in eggs would yield more insight into potential changes of egg distributions.

In both years larvae were detected at the proposed Alton Project site for 38 days, albeit with a >30 fold difference in abundance between years. Striped bass larvae displayed temporal patchy distribution and a high inter-annual variability. Within the ebb tide, time after high slack is the best predictor for larval abundance; however, as they development their distribution appears to shift perhaps to align with food sources. Further study is required to assess changes in temporal distribution through ontogeny. Most larvae were detected in water warmer than 16 °C, aligning with a purported minimum growth requirement for the Shubenacadie River system. Conclusions regarding larvae and their salinity preference are hindered because of patchy distributions during 2008 and low abundances in 2009. The colder water and larger tidal range of June 2009, coupled with heavy rainfall during the larval season contributed to larval mortality or advection from the Shubenacadie estuary; possible explanations for the over 30-fold lower abundance than in 2008. Another possibility is that the nursery area was shifted outside the sampling location and the few larvae caught were potentially moribund or were outliers who inhabited marginal habitat. The possibility of fewer spawning adults seems unlikely as egg abundance was greater than in 2008.

Mysid abundance was greatest within the initial four hours of the ebb tide, although time after high slack may not be the best predictor of mysid abundance as the sample intensity was greatest during the initial four hours after high slack. Most likely mysid abundance dynamics in the Shubenacadie are similar to those of Cumberland basin where no difference in abundance was observed between both the flood and ebb tides (Prouse 1986), although freshets and low salinities may make a significant impact on total abundance. Mysid abundance on the Shubenacadie seems independent of temperature when temperature was ≤ 25 °C, and salinity when salinity was ≥5 ‰. Further investigation into the effect and interaction of environmental variables on mysid abundance would provide greater insight to habitat use and retention mechanisms. The high abundance of mysids when salinity is over 3.5 ‰ is interesting as the rapid rate of salinity change suggests that a mechanism of position maintenance other than passive particle may be employed such as regulating their position in the estuary through burrowing in the substrate.

The Shubenacadie – Stewiacke watershed is highly susceptible to freshets. When a large rainstorm occurs, salinity at the Alton Project site decreases and pelagic life typically is not seen in high abundances;

presumably because suitable habitat shifts downriver. Rainfall lagged by seven days showed a significant relationship with respect to salinity in both years; however, the duration of any apparent habitat shift as well as the minimum volume of rainfall required for this shift and the tidal counterpoint are subjects for further study and characterization.

5.1. Ideas and Further Study

An interesting question arises from this study. How do pelagic organisms with limited motility remain within the estuary, specifically suitable habitat areas near the Alton Project site? Pelagic organisms with limited motility are very sensitive to spatial movement (Islam et al. 2006). For example, during the 1991 spawning season on the Paxtuant River, a seven kilometer stretch immediate upriver of the salt front, accounted for 78 % of the total egg production (Secor and Houde 1995). Other cohorts along the same river experiencing unfavourable environmental conditions experienced high mortality (Secor and Houde 1995).

Various species exhibit day/night differences in offspring abundance, primarily to reduce visual predation (Forward and Tankersley 2001). Striped bass eggs from the Shubenacadie increase in abundance throughout the night with the largest number of viable eggs collected between 00:00 and 02:59 h (Tull 1997). Striped bass juveniles and adults caught in the inner Bay of Fundy showed a preference for dusk and dawn (Rulifson et al. 2008), although this might have been due to gear type and/or habitat avoidance. Diurnal differences were not observed herein due to logistical issues with night sampling, although these differences might well exist in the Shubenacadie – Stewiacke watershed. Mysids also exhibit diurnal vertical migration patterns, rising to the surface only at night (Herman 1963). By contrast, in the highly turbid and turbulent Shubenacadie, mysids displayed high abundances in the top 0.5 m of the water column during the day, although this is also exhibited in the Cumberland Basin of the Bay of Fundy (Prouse 1986). I speculate that the shallowness of the study site in combination with the powerful tidal bore might make any attempts at vertical migration for position maintenance useless. Furthermore the shallow photic zone, high degree of turbidity coupled with the large amount of turbulence reduces, if not negates, potential fitness advantages from vertical migration (Kimmerer et al. 2002; Horppila et al. 2003) for mysids inhabiting the Shubenacadie.

Different tidal stream transport regimes might occur because of ontogenetic changes in egg buoyancy that controls vertical distribution and allows selective dispersion from residue currents and the tidal bore (Laprise and Dodson 1990; Rulifson and Tull 1999; Chanson and Tan 2011). Evidence herein suggests that the tidal bore acts as a rolling estuarine turbidity maximum as there is no estuarine turbidity maximum in the upper and middle portions of the Shubenacadie estuary (Parker 1984; Tull 1997). This hypothesis is in agreement with a previous retention hypothesis relating to the Shubenacadie (Tull 1997).

The mechanism of this hypothesis is as follows: as the bore travels up river, it ‘pushes’ a packet of fresh water further upriver, containing eggs and young larvae, which remain in that packet ahead of the bore. Eggs retained in the system for a short while and early stage larvae being retained in lower salinity waters can ‘ride’ these packets of fresh water ahead of the bore (also see Tull 1997). Water depths at the Alton Project site suggest that an ‘impulse’ of water surges ahead of the bore rather than waves forming a typical sinusoidal tidal action (Martec, 2007b). As the bore moves up river, it ensures that any dilution and water clarity resulting from freshets are thoroughly mixed providing the turbulence and high prey abundance that is beneficial to young larvae (Schubel 1968; Robichaud-LeBlanc et al. 1996; North et al. 2005), which is where the older eggs and younger larvae end up as their specific gravity changes (Rulifson and Tull 1999; Chanson and Tan 2011). The river length between the spawning grounds to the mouth of the

Shubenacadie estuary, aids in reducing the likelihood of eggs being removed to the inner Bay of Fundy on the ebb tide (Rulifson and Tull 1999) and increases the probability of those eggs being retained in the estuary by a successive tidal bore. To better understand these retention techniques, development of the ‘rolling estuarine turbidity maximum’ hypothesis is warranted.

Further areas of study on the Shubenacadie – Stewiacke watershed could focus on further defining the spatial and temporal distribution of striped bass with respect to ontogenetic changes incorporating growth and increased swimming ability, which could lead to a more apt description of habitat needs. Examining spatial histories of different stages of development and colour morph sub-populations would provide insight to identify critical habitats. Additional characterization of spawning and the environmental cues under which it occurs would provide a better understanding of the biology of a northern population of striped bass through the development of models. If regular night time plankton net sampling were done, possible diel differences in abundance of eggs and larvae could be detected and a clearer picture of the temporal distribution immediately following a spawning could be achieved.

Assessing mysids with regard to structure and number of cohorts within a summer season as well as describing abundances closer to the bore and during flood tide would be beneficial to understanding this potentially key prey species. Assessing mysid health temporally on the ebb tide would allow inference about the quality of habitat within which they were found.

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