A BIOLOGICAL ASSESSMENT OF ZOOPLANKTON IN ST. PAULS INLET,

AN ESTUARINE ENVIRONMENT IN GROS MORNE NATIONAL PARK, NEWFOUNDLAND

By

© Erin N. Stevens

A Thesis submitted to the

School of Graduate Studies

In partial fulfillment of the requirements for the degree of

Master of Science

Biological Sciences

Memorial University of Newfoundland

March 2017

St. John’s Newfoundland and Labrador

ABSTRACT

St. Pauls Inlet is a fjordal estuary in Gros Morne National Park, Canada. During the summers of 2009 and 2010 four sites within the inlet were sampled for zooplankton as part of Memorial University's Community-University Research for Recovery Alliance (CURRA) project. Objectives were:

- Determine patterns in zooplankton species composition
    - Compare to species data from previous survey
    - Relate to observed longitudinal salinity gradients
    - Compare composition with that of estuaries regionally
- Estimate zooplankton abundance
    - Compare with abundances seen in estuaries globally

Zooplankton species were primarily marine cyclopoida and calanoida, with some brackish-water cladocerans. Cluster Analysis and NMDS showed no strong longitudinal patterns in species assemblages in either season. Only 10 % faunal similarity was observed with estuarine Lake Melville in Labrador, Canada. St. Pauls Inlet does not appear to be a highly productive system, based on low zooplankton abundance (< 4 inds/l), compared with other global sites.

ACKNOWLEDGMENTS

I thank my supervisor, Dr. Christine Campbell, for the guidance and mentoring she gave during the research presented within. Dr. Campbell, along with my supervisory committee, Drs. Grant Gardner and David Schneider, provided excellent support during the planning, research, writing, and revisions of this thesis. Many individuals of the Town of St. Paul's were essential for the completion of the research. I thank in particular Monica Pitman, the town clerk, and Shane Fleming for their assistance with living in St. Paul's with my dog, Hershey. My boat captains, Craig Payne and Willis Payne were a wealth of local knowledge and great at ferrying me around the inlet. Dr. Robin Anderson (Dept. of Fisheries and Oceans) kindly provided the zooplankton samples from Lake Melville. Funding for this CURRA research was supported through Social Sciences and Humanities Research Council of Canada, Memorial University of Newfoundland, the Institute for Biodiversity Ecosystem Science & Sustainability, The Harris Centre at Memorial University of Newfoundland, Centre of Environmental Excellence, Parks Canada, and Fisheries and Oceans Canada. This project is a subcomponent of the overall interdisciplinary Memorial University Community – University Resource for Recovery Alliance (CURRA) project based on the west coast of Newfoundland. The CURRA aims were to *"carry out an innovative program of community-based interdisciplinary research that incorporates knowledge, mobilization, training, and policy development in support of regional efforts to devise and implement a recovery strategy for fish stocks and fishery communities."* CURRA researchers defined recovery as a vibrant future for people, communities, and their natural environment (http://www.curra.ca)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

Chapter 1

Estuaries as important coastal environments

1.1 Estuaries

St. Pauls Inlet is an estuarine system in western Newfoundland that opens out into the Gulf of St. Lawrence. The potential contribution of St. Pauls Inlet to the larger Gulf marine ecosystem was assessed as part of Memorial University's CURRA project focused on fisheries and fishing communities in western Newfoundland. A previous six week survey of the inlet led Carter and MacGregor (1979) to conclude that St. Pauls Inlet was likely representative of other restricted and largely nutrient-poor fjords occurring on the west coast of Newfoundland and should be subject to further scientific investigations, particularly to quantify populations of organisms within the inlet.

Many types of coastal water bodies are broadly estuarine in nature (Knox 1986; Marques et al. 2007). Such estuaries or *tidal inlets* are aquatic coastal regions that can be of great importance to a variety of species (Kennish 1986). Many estuaries are quite productive and can be the location for many types of fisheries as well as feeding grounds for a multitude of species of birds and mammals (McLusky 1989). Some of the larger estuarine systems in the world include the Amazon River in South America, Chesapeake Bay in the United States, the Thames Estuary in Great Britain, and the Gulf of St. Lawrence in Canada. A more rigorous definition of an estuary is a semi-enclosed coastal body of water which has a permanent or periodically open connection with the sea and within which sea water is measurably diluted with fresh water derived from land drainage (Pritchard 1967; Day 1980). Estuaries are dynamic systems, with temporal and spatial

changes in salinity, temperature, oxygen and turbidity which arise from both tidal influences and freshwater inflow (Marques et al. 2007; Almeida et al. 2012).

Estuaries in Atlantic Canada tend to be smaller and protected, rather than the larger estuaries typical of Canada's west coast. An Environment Canada (1990) report "*A Profile of Important Estuaries in Atlantic Canada*", indicated that while most of the estuaries in the Maritimes could be characterized as drowned river valleys, Newfoundland and Labrador's coastal zones are characterized more by large fjords. This fjordal characterization is due to the inland termination of the coastal plain which then rises to form the beginnings of the Long Range Mountains. Within this mountain range there are glacial valleys that run in an east to west direction with some valleys reaching the sea (O'Sullivan 1976). Drainage of rivers in insular Newfoundland averages about 1.22×10^{11} m^3 per year, with much larger drainages coming from the large rivers in Labrador such as the Eagle and Churchill, the latter draining into the estuarine Lake Melville.

1.1.1 Salinity in Estuaries

St. Pauls Inlet (SPI), situated at the northern end of Gros Morne National Park, receives salt water from the sea and has a permanent connection with the sea through an 80 m wide opening (Carter & MacGregor 1979). The neritic feature of the Gulf of St. Lawrence closest to St. Pauls Inlet is called the Esquiman Channel and has a salinity concentration ranging from 32 – 36 ‰ (Galbraith 2006). As well, the inlet receives fresh

water input from highland lakes, rivers, precipitation, and snowmelt. Inlets are a smaller portion of water off a larger body of water with a narrowed entrance between the two (Barnes 1994) and can be a type of estuary.

Estuaries often exhibit a broad longitudinal salinity gradient with high mean salinity at the mouth (seaward, or near the ocean) and low mean salinity at the head (landward, or the furthest point from the ocean). As an estuary has neither a completely fresh nor a completely marine salinity it can be classified as a brackish water environment. Fresh water typically has salinity concentrations of about 0 to 0.5 ‰ (parts per thousand (ppt) by volume), while the average salinity of the ocean is in the range of 33-37 ‰; a concentration in between 0.5 to 30 ‰ is considered to be brackish (Remane & Schlieper 1971; Thurman & Trujillo 2010). The Venice System for the Classification of Marine Waters According to Salinity (1958) details three primary zones of classification: a polyhaline zone (18 ‰ < surface salinity < 30.0 ‰), a mesohaline zone (5.0 ‰ <surface salinity < 18.0 ‰), and an oligohaline zone (surface salinity < 5.0 ‰). Longitudinal salinity gradients found within an estuary can be of high importance to the fish and planktonic organisms living in the water column (McLusky 1989). The interactions of fresh water with salt water create a region of increased mixing and water circulation due to the differences in both the temperature and salinity (and subsequent density) of the water masses. The influx of sea water due to tides can also displace substantial volumes of water which can result in the horizontal and vertical transport of sediments and nutrients (Kennish 1986). During the year, overall salinity in brackish water systems can

fluctuate due to variation in precipitation and freshwater inflow which act to decrease estuarine salinity, in addition to evaporation and saltwater inflow which act to increase estuarine salinity (Heerebout 1970).

Depending on water column depth and water column mixing, there may be a *halocline* (salinity stratification by depth) within the estuarine water column, with heavier salt water lying underneath less dense fresh water. Density of water also increases with decreasing temperature, allowing for warmer, less dense water to lie on top of colder, denser water. Typically in high latitude areas such as Newfoundland, density changes due to temperature are more pronounced in the summer allowing for development of a *thermocline* as surface waters heat up. *Pycnoclines*, or zones of depth within which seawater density changes rapidly, correspond with haloclines and thermoclines because salinity and temperature both influence water density. These layers can separate the estuarine water column into upper water and deep-water masses. When there is layering, a mixed surface layer often occurs due to the surface currents, tides, and waves. The colder, more saline water is found in the deep-water areas. These layers often dictate how the estuarine water masses interact with the adjacent ocean.

Table 1.1 Estuarine Classification Systems (adapted from Day 1980 & Pritchard 1967)

Estuarine Classification Systems			
Geomorphology	**Circulation Patterns**	**Stratification**	**Sedimentation**
Fjordal-type	Positive	Salt Wedge	Positive Filled
Lagoon-type	Inverse (or Negative)	Strongly Stratified	Inverse Filled
Tectonically Produced	Neutral (or Low In-Flow)	Weakly Stratified	Neutral Filled
Drowned River Valley		Vertically Mixed	

1.2 Classification Systems of Estuaries

A number of classification systems have been put forward to identify different types of estuaries (Table 1.1), based primarily on physical and chemical factors such as i) basin geomorphology, ii) circulation patterns within the estuary,
iii) stratification of the estuarine water column, and iv) basin sedimentation.

St. Pauls Inlet would be classified as a positive fjordal-type inlet (Table 1.1) with a tectonic overprint from glacial isostatic rebound (Sella et al. 2007). The inlet is longer than it is wide and contains a shallow sill at the entry which is derived from a terminal moraine, a feature which marks the maximum advance of glaciation during the most recent ice age. It has characteristic steep side walls with relatively shallow outer portions exiting out into a low-lying coastal plain (O'Sullivan 1976).

Fjordal type estuaries like St. Pauls Inlet are common in coastal Newfoundland and Labrador, and are typically located in high latitude coastal areas that have been strongly eroded by glaciers. Due to such erosion the estuarine basins are often deep, with steep rocky sides and a shallow underwater sill at the connection to the sea. The height of the sill determines the extent of deep water exchange with the coastal ocean (Day 1981; Kennish 1986). St. Pauls Inlet has a stronger surface outflow than near-bottom inflow due to the freshwater influx into the system as well as a shallow sill less than 6 m deep at the entry (Carter & MacGregor 1979). Systems in which the fresh water influx from incoming streams exceeds the fresh water loss to the ocean have circulation patterns that are considered *positive* and exhibit a longitudinal density gradient within the estuary.

This gradient causes an outflow of the fresher water to the ocean with a smaller inflow of sea water on the near-bottom (Day 1981; Valle-Levinson 2010). As a consequence of this gradient the head of the estuary is less saline and the mouth is more saline (Kennish 1986; Thurman & Trujillo 2010).

Based on Table 1.1, St. Pauls Inlet may also be characterized as a *vertically mixed* estuary (Pritchard 1967; Kennish 1986; Valle-Levinson 2010). Salinity profiles in this type of estuary are nearly uniform with minimal vertical stratification and the flows are unidirectional with depth. At any given vertical point in the inlet the salinity is relatively uniform however the salinity does change on a longitudinal basis from the head to the mouth of the estuary (Kennish 1986; Thurman & Trujillo 2010). In addition, as with most fjordal-type basins, St. Pauls Inlet can be considered *neutral filled* with respect to sedimentation (Dyer 1979) with little river-transported sediment (positive filled) or nearshore ocean deposition (negative filled) observed by Carter and MacGregor (1979).

1.3 Biological Productivity in Estuarine Basins

Estuaries are essential to nutrient cycling at the land-sea boundary (Day 1981). River inflow supplies organic matter and nutrients (Nielsen & Andersen 2002) and occasionally freshwater zooplankton from upstream (Campbell 2002) to the estuarine system. Organic matter and nutrients brought into the estuary augment the organic matter resulting from the excretion and decomposition of estuarine organisms (Knox 1986). Hence, the concentrations of dissolved solids are more variable than in the ocean (Kennish 1986).

Some estuaries can be highly productive, associated with some of the highest primary productivity on the planet, up to 1500 g m^{-2} yr^{-1} (dry matter) (Correll 1978; Almeida et al. 2012). These high levels of productivity, which can be up to 3.4 % of the total marine primary production, are due to a bountiful supply of nutrients which support the primary production within these estuaries (Burrell 1988). The particulate organic matter produced from the primary production undergoes bacterial decomposition which then provides a nourishing food supply for consumer animals, such as zooplankton and fish (McLusky 1989; Pinckney et al. 2001). The level of fresh water influx from rivers and other sources can modify the estuarine system by altering estuarine circulation patterns, water column stratification, and nutrient mixing, leading to increased primary and secondary productivity (Day 1981; Nielsen & Andersen 2002). This primary production is supplied by three main groups of autotrophs in estuaries: phytoplankton, benthic algae, and vascular plants. Phytoplankton and vascular plants, such as *Zostera* (eelgrass, also known as goosegrass), comprise the main primary producers found in the estuary itself (Alongi 1998). As seen in Table 1.2, phytoplankton production can be limited by light, nutrients, water temperature, mixing processes and grazing. Not all estuaries are affected equally by any limiting factor and nutrient limitation may partially result from nutrient-poor watershed runoff (Pinckney et al. 2001) as well as low nutrient marine inputs.

Table 1.2: Limiting factors for phytoplankton production in estuaries (adapted from Kennish 1986)

Limiting factors				
Light	**Nutrients**	**Water Temperatures**	**Mixing Processes**	**Grazing**
High Turbidity reduces light penetration and decreases the depth of the photic zone	Limited nitrogen availability	Often species have limited temperature ranges for production.	High rates of flushing in the estuary will remove standing populations of phytoplankton	Zooplankton and benthos grazing can restrict population rates

1.4 Zooplankton and Larval Fish in Estuaries

Zooplankton are organisms that drift or weakly swim in the water column because they are too small and too weak to swim independently of water currents. They are the most abundant component of marine and brackish water systems and provide a vital trophic link between phytoplankton primary producers and higher trophic levels such as fish (Calliari et al. 2006; Kibirige et al. 2006; Johnson et al. 2011; Almeida et al. 2012). Zooplankton are often the main food for small or juvenile fishes (Chew & Chong 2011) and there can be seasonality in the abundance and species diversity of zooplankton which correlates with the introduction of juvenile fish into the system (Judkins 1979; Limburg et al. 1997). Anadromous fish, such as Arctic Char (*Salvelinus alpinus*) and Brook Trout (*Salvelinus fontinalis*), develop in the fresh water or brackish water systems of estuaries and feed on the zooplankton. Studies on Striped Bass (*Morone saxatilis*) indicated that the nutritional condition of the juvenile fish within estuaries depends on the abundance of certain copepods and cladocerans (Limburg et al.1997).

This animal portion of the plankton (the zooplankton) consists of two major groups – the holoplankton and the meroplankton. Holoplankton are planktonic throughout their entire life cycle, and include microcrustaceans such as copepods, cladocerans and krill, as well as gelatinous zooplankton (jellyfish, ctenophores, salps, and larvaceans) and arrow worms. Meroplankton, on the other hand, typically spend only their larval or early stages of their lifecycle as part of the plankton. Many organisms such as lobsters, crabs, oysters, and some fish have a planktonic larval and/or juvenile life stage (Thurman & Trujillo 2010).

The diversity of zooplankton taxa found within estuaries is dependent on a variety of physical constraints although many taxa in the higher latitudes are euryhaline, able to tolerate a wide range of salinities, and eurythermic, able to tolerate a wide range of temperatures (Sautour & Castel 1995). One of the main variables influencing the distribution of zooplankton in estuarine environments is salinity (Williams 1984; Uriarte & Villate 2005). Four categories of holoplanktonic copepods have been differentiated on the basis of salinity tolerance (Table 1.3). Common genera in the North Atlantic include *Calanus* sp., *Oithona* sp., *Acartia* sp., *Paracalanus sp.* and *Pseudocalanus* sp. Within the species there are ranges of size, as well as tolerances for salinity and/or temperature differences.

Plankton in estuarine embayments can be physically isolated from more offshore populations and may retain distinct estuarine assemblages (Milligan et al. 2011).

Table 1.3: Classification system for the salinity tolerance of copepods (Johnson & Allen 2005; Uriarte & Villate 2005; Thurman & Trujillo 2010)

Copepod Classification	**Salinity Levels/Tolerance**
True Estuarine	Organisms that can tolerate only estuarine salinities (0.5-30 ‰)
Estuarine and Marine	Organisms that can tolerate estuarine (0.5-30 ‰) and marine salinities (30 ‰+).
Euryhaline marine	Organisms that are found in predominantly marine environments however have a high tolerance for a large range of salinity conditions
Stenohaline marine	Organisms that are found in marine environments and can only tolerate a small range of salinity change

Estuarine regions are important in the life stages of many marine organisms including zooplankton and larval fish (Johnston & Morse 1987; Boehlert & Mundy 1988; Bulger et al. 1993). As these organisms have little ability to control where they are within the water column it is important that they are not exported out of the estuary. This can be a significant recruitment problem and many species of fish or invertebrates have dealt with that dilemma by producing large demersal eggs or by having brief larval stages (Boehlert & Mundy 1988). When either the demersal eggs or larval stages of fish or invertebrates are located at a deep location the marine water from the sea penetrates landward and keeps the organisms within the estuary. Although planktonic organisms cannot move against currents in the water column they can exhibit strong vertical migration within the column (e.g. copepods: Kimmerer et al. 2002). As such, they occupy the landward flow when the circulation pattern allows and in some cases once they reach their limit for salinity/temperature or another factor they will move up towards the surface and be carried towards the sea, only to repeat a migration towards the bottom and be carried

back in towards land (Rogers 1940; Pearcy & Richards 1962; Fortier & Leggett 1982). Additionally, estuarine environments that have low flushing rates benefit the plankton's ability to remain in that habitat.

Numerous species of fish move into the estuary as larvae and make up part of the meroplankton (Deegan 1993). Brackish ponds and fjordal systems often are locations in which fish (such as anadromous salmonids) move from a juvenile life stage in the freshwater environment to a mature life stage within the ocean environment. These estuarine environments are the transition areas in which they move (Kennish 1986). Unfortunately it is unknown if all estuaries in a locale contribute equally to maintaining stocks or if one or a few of them are the primary contributors (Gillanders 2002). Estuaries with low nutrient input and resultant low phytoplankton biomass might be expected to have less primary production available for higher trophic levels such as zooplankton and fish (Knox 1986; Mallin and Paerl 1994; Pinckney et al. 2001).

1.5 Purpose of Study

This study serves as a preliminary step towards assessing the biological contribution of St. Pauls Inlet to the western Newfoundland regional marine ecosystem. By providing a quantifiable assessment of zooplankton populations in St. Pauls Inlet, further studies may be done to determine how St. Pauls Inlet compares regionally in terms of plankton production and diversity. Specifically this study considers zooplankton organisms which belong to the family Crustacea and are of the size range of 3 mm for *Calanus*

finmarchicus down to 0.4 mm for *Evadne nordmanni*; collectively these types of species are classified as microcrustaceans. Attempts were also made to collect larger zooplankton, including larval fish.

An initial inventory of the inlet carried out by Carter and MacGregor (1979) during the planning stages for Gros Morne National Park provided information on the presence of zooplankton species but no quantitative abundance data. The limited nutrient measurements that were taken also suggested that nutrient concentrations in the inlet were very low (below detectability of field kits in some cases) and related to the low concentrations of nitrate, ammonia and phosphate observed by O'Sullivan (1976) in a freshwater inflow to the inlet.

The purpose of the current study, detailed in Chapter 2, is first to determine the existing zooplankton species composition and to compare this with the species composition found in the previous 1979 study, with the hypothesis being that there was no overall change in community composition over time (hypothesis 1). Secondly, species composition throughout the zooplankton taxa in St. Pauls Inlet will not vary in relation to the salinity (hypothesis 2). In addition to comparing the inlet to past conditions, I will be looking at how zooplankton species composition in the inlet compares regionally with similar estuarine systems. As there are few data sets on estuarine zooplankton from Newfoundland and Labrador, specific comparisons will be made with Lake Melville in Labrador (Figure 1.1) for which zooplankton data were available. Zooplankton were

collected similarly by tow net as in this present study. Zooplankton composition will not be largely different between St. Pauls Inlet and Lake Melville (hypothesis 3). In Chapter 3, the abundance/density of zooplankton within the inlet will be compared with other estuarine systems worldwide to place St. Pauls Inlet into a broader context. Biological productivity of the inlet, estimated by zooplankton density (Avila et al 2012), is hypothesized to be low given its likely low nutrient levels and nutrient-poor watershed (hypothesis 4).

The comparison site of Lake Melville (Figure 1.1) can also be classified as a fjord-type estuary as it has a lower salinity than the inner Labrador Shelf and because of a shallow sill in the Narrows at the entrance of the fjord that limits seawater input (Bakus 1951; Vilks & Mudie 1983). This sill has become shallower since glaciation ended approximately 12,000 years ago, and does not allow the more saline inner shelf bottom water to enter Lake Melville (Vilks & Mudie 1983). Both result from glacial action, where the weight of the glacial ice causes the earth's crust to warp downward and post-glacial rebound, where the earth's crust uplifts towards isostatic equilibrium (Sella et al. 2007). Lake Melville receives a large amount of freshwater inflow through the Churchill River. Together, the Churchill and Eagle Rivers in Labrador have a combined drainage area of 140,600 km^2 and an annual average river discharge of 1,740 m^3sec^{-1} (Environment Canada 1990).

Through the larger multidisciplinary CURRA project that involved social and natural sciences, researchers sought to link research and local ecological knowledge to develop and implement recovery strategies for fisheries and fishing communities in the west coast region. The aim of my study was to contribute to a better understanding of the biological components of St. Pauls Inlet, particularly the zooplankton, as a preliminary step towards assessing the potential contribution of St. Pauls Inlet to the wider western Newfoundland marine ecosystem. This study was carried out simultaneously with other CURRA projects on St. Pauls Inlet relating to the history and sustainability of the town of St. Paul's (Kukac 2009; Kukac et al. 2009, Murphy 2009), and the ecology of nearshore fish populations within the inlet (Melanson & Campbell 2012).

Data analysis in the thesis consists of two chapters: Chapter 2 looks at zooplankton species composition within St. Pauls Inlet and in comparison to Lake Melville, while Chapter 3 looks at zooplankton abundance in the inlet on a larger global basis, as well as presenting general conclusions.

(Note while the inlet is officially designated as St. Pauls, the town is listed as St. Paul's).

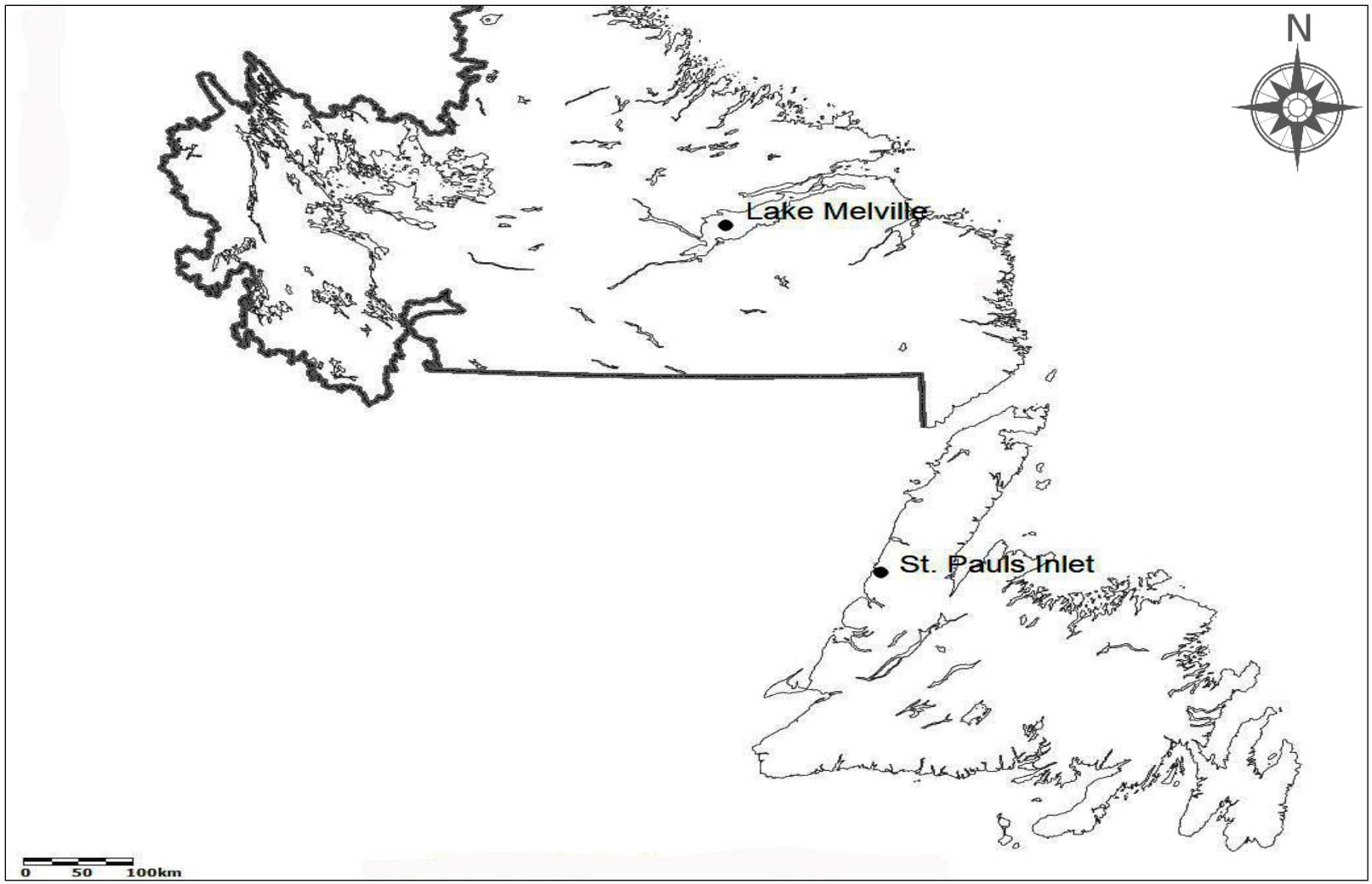


Figure 1.1: Location of St. Pauls Inlet (49.50058° N, 57.47514° W) & Lake Melville (53.6822° N, 59.7486° W) in Newfoundland and Labrador (Adapted from The Geological Survey Division 2014)

1.6 Literature Cited

Almeida, L. R., Costa, I. S., and Eskinazi-Sant'Anna, E. M. 2012. Composition and abundance of zooplankton community of an impacted estuarine lagoon in Northeast Brazil. Brazilian Journal of Biology. 72:13-24.

Alongi, D.M. 1998. Coastal Ecosystem Processes. Marine Science Series, Boca Raton: CRC Press.

Avila, T. R., de Souza Machado, A. A., and Bianchini, A. 2012. Estimation of secondary production in estuarine waters: comparisons between the enzymatic (chitobase) method and mathematical models using crustaceans. J. Exp. Mar. Biol. Ecol. 416/417:144-152.

Bakus, R. H. 1951. New and rare records of fishes from Labrador. Copeia. 4:288-294.

Barnes, R. S. K. 1994. The Brackish-water Fauna of Northwester Europe. Cambridge University Press, New York. USA.

Boehlert, G. W. and Mundy, B. C. 1988. Roles of behavioral and physical factors in larval and juvenile fish recruitment to estuarine nursery areas. American Fisheries Society Symposium. 3:1-67.

Bulger, J., Hayden, B. P., Monaco, M. E., Nelson, D. M., and McCormick-Ray, M. G. 1993. Biologically-based estuarine salinity zones derived from a multivariate analysis. Estuaries. 16:311-322.

Burrell, D. C. 1988. Carbon flow in fjords. Oceanography and Marine Biology Annual Review. 26:143-226.

Calliari, D., Andersen, C. M., Thor, P., Gorokhova, E., and Tiselius, P. 2006. Salinity modulates the energy balance and reproductive success of co-occurring copepods *Acartia tonsa* and *A. clausi* in different ways. Marine Eco Prog. Series. 312:177-188.

Campbell, C. E. 2002. Rainfall events and downstream drift of microcrustacean zooplankton in a Newfoundland boreal stream. Canadian J. Zoology. 80:997-1003.

Carter, J. A. and MacGregor, C. D. 1979. Marine Inventory of St. Paul's Inlet for Gros Morne National Park. Martec Limited, Halifax, NS. Report for Parks Canada.

Chew, L. L. and Chong, V. C. 2011. Copepod community structure and abundance in a tropical mangrove estuary, with comparisons to coastal waters. Hydrobiologia. 666:127-143.

Correll, D. L. 1978. Estuarine productivity. Bioscience. 28:646-650.

Day, J. H. 1980. What is an estuary? South African Journal of Science. 76:198.

Day, J. H. 1981. Estuarine Ecology. AA Balkema, Rotterdam.

Deegan, L. A. 1993. Nutrient and energy transport between estuaries and coastal marine ecosystems by fish migration. Canadian J. of Fisheries and Aquatic Sci. 50:74-79.

Dyer, K. R. 1979. Estuarine Hydrography and Sedimentation. Cambridge University Press, Cambridge.

Environment Canada.1990. Environmental Quality Division. A Profile of Important Estuaries in Atlantic Canada. Environment Canada.

Fortier, L. and Leggett, W. C. 1982. Fickian transport and the dispersal of fish larvae in estuaries. Canadian Journal of Fisheries and Aquatic Sciences. 39:1150-1163.

Galbraith, P. S. 2006. Winter water masses in the Gulf of St. Lawrence. Journal of Geophysical Research. 3:1-23.

Gillanders, B. 2002. Connectivity between juvenile and adult fish populations: do adults remain near their recruitment estuaries? Marine Eco. Progress Series. 240:215-223.

Geological Survey Division, Dept. of Natural Resources, Government of Newfoundland and Labrador. Accessed from http://gis.geosurv.gov.nl.ca/ November 2014.

Heerebout, G. R. 1970. A classification system for isolated brackish inland waters, based on median chlorinity and chlorinity fluctuation. Netherlands Journal of Sea Research. 4:494–503.

Johnson, C. L., Runge, J. A., Curtis, K. A., Durbin, E. G., Hare, J. A., Incze, L. S., Link, J. S., Melvin, G. D., O'Brien, T. D., Van Guelpen, L. 2011. Biodiversity and ecosystem function in the Gulf of Maine: pattern and role of zooplankton and pelagic nekton. PLOS One. 6(1): e16491. doi:10.1371/journal.pone.0016491.

Johnson, W. S. and Allen, D. M. 2005. Zooplankton of the Atlantic and Gulf Coasts: a guide to their identifications and ecology. The Johns Hopkins University Press, Baltimore, MD. USA.

Johnston, C. E. and Morse, M. 1987. Summer ichthyoplankton communities of two estuarine systems of Prince Edward Island. Canadian J. of Zoology. 66:737-745.

Judkins, D. C., Creighton, D. W., and Wayne, E. E. 1979. Composition, abundance, and distribution of zooplankton in the New York Bight, September 1974-September 1975. Fishery Bulletin. 77:669-983.

Kennish, M. J. 1986. Ecology of Estuaries. CRC Press, Boca Raton, Florida.

Kibirige, I., Perissinoto, R., and Thwala, X. 2006. A comparative study of zooplankton dynamics in two subtropical temporarily open/closed estuaries, South Africa. Marine Biology. 148:1307-1324.

Kimmerer, W.J., Burau, J.R., and Bennett, W.A. 2002. Persistence of tidally-oriented vertical migration by zooplankton in a temperate estuary. Estuaries. 25:359-371.

Knox, G. A. 1986. Estuarine ecosystems: a systems approach volume I. CRC Press Inc, Boca Raton, Florida.

Kukac, J. 2009. Capturing the importance of natural resources and future activities in St. Paul's, Newfoundland. M.A. thesis, Dept. of Geography, Memorial University of Newfoundland.

Kukac, J., Korneski, K., and Chuenpagdee, R. 2009. St. Pauls: Past, Present, Future. CURRA Report. Memorial University of Newfoundland, St. John's, NL, Canada.

Limburg, K.E., Pace, M.L., Fischer, D., and Arend, K.K. 1997. Consumption, selectivity, and use of zooplankton by larval striped bass and white perch in a seasonally pulsed estuary. Transactions of the American Fisheries Society. 126:607-621.

Mallin, M.A. and Paerl, H.W. 1994. Planktonic trophic transfer in an estuary – seasonal, diel and community structure effects. Ecology. 75:2169-2184.

Marques, S. C., Pardal, M. A., Pereira, M. J., Goncalves, F., Marques, J. C., and Azeiteiro, U. M. 2007. Zooplankton distribution and dynamics in a temperate shallow estuary. Hydrobiologia. 587:213-223.

McLusky, D. S. 1989. The estuarine ecosystem. Chapman and Hall, New York.

Melanson, R.L. and Campbell, C.E. 2012. Near-shore fish populations within St. Pauls Inlet, an estuarine system in western Newfoundland. Northeastern Naturalist.19:487-500.

Milligan, P.J., Stahl, E.A., Schizas, N.V., and Turner, J.T. 2011. Phylogeography of the copepod *Acartia hudsonica* in estuaries of the northeastern United States. Hydrobiologia 666: 155-165.

Murphy, I. 2009. Strategies and Resources for Integrated Community Sustainability Planning in St. Paul's, NL. CURRA Report. Memorial University of Newfoundland, St. John's, NL, Canada.

Nielsen, T. G. and Andersen, C. M. 2002. Plankton community structure and production along a freshwater-influenced Norwegian fjord system. Marine Bio. 141:707-724.

O'Sullivan, W. 1976. Hydrological inventory of Gros Morne National Park, Newfoundland Canada. Inland Waters Directorate, Water Resources Branch.

Pearcy, W. G. and Richards, S. W. 1962. Distribution and ecology of fishes of the Mystic River estuary, Connecticut. Ecology. 43:248-259.

Pinckney, J.L, Paerl, H.W., Tester, P, and Richardson, T.L. 2001. The role of nutrient loading and eutrophication in estuarine ecology. Environmental Health Perspectives. 109:699-706.

Pritchard, D. W. 1967. What is an estuary: physical viewpoint. American Association for the Advancement of Science. 85:3-5.

Remane, A. and Schlieper, C. 1971. Biology of brackish water. Wiley, New York.

Rogers, H. M. 1940. Occurrence and retention of plankton within the estuary. J. Fish. Res. Board Can. 5:164-171.

Sautour, B. and Castel, J. 1995. Comparative spring distribution of zooplankton in three macrotidal European estuaries. Hydrobiologia. 311:139-151.

Sella, G. F., Stein, S., Dixon, T. H., Craymer, M., James, T. S., Mazzotti, S., and Dokka, R. K. 2007. Observation of glacial isostatic adjustment in "stable" North America with GPS. Geophysical Research Letters. 34:1-6.

The Venice system for the classification of marine waters according to salinity.1958. Limnology and Oceanography. 3:346-347.

Thurman, H. V. and Trujillo, A. P. 2010. Essentials of Oceanography – Tenth Edition. Prentice Hall Inc, USA.

Uriarte, I. and Villate, R. 2005. Differences in the abundance and distribution of copepods in two estuaries of the Basque coast (Bay of Biscay) in relation to pollution. Journal of Plankton Research. 27:863-874.

Valle-Levinson, A. 2010. Contemporary Issues in Estuarine Physics. Cambridge University Press, New York.

Vilks, G. and Mudie, P. J. 1983. Evidence for postglacial paleoceanographic and paleoclimatic changes in Lake Melville, Labrador, Canada. Arctic and Alpine Research. 15:307-319.

Williams, R. 1984. Zooplankton of the Bristol Channel and Severn Estuary. Marine Pollution Bulletin. 15:66-70.

Chapter 2:

Zooplankton composition in St. Pauls Inlet: a regional comparison of sites

2.1 Introduction

Within estuarine systems like St. Pauls Inlet, fluctuations in salinity and temperature can result in significant physiological stress for many organisms as well as limit overall species diversity. Varying salinities in particular can impose osmoregulatory challenges for estuarine organisms (Levinton 2014). As well, other chemical and physical gradients within a water body can influence plankton species presence and abundance (Lillick 1937; Heath & Lough 2007). Plankton are aquatic organisms that, due to small size and the inability to swim against water currents, drift within the water column (Green 1968). The plankton community, made up of phytoplankton and zooplankton, is an essential part of the aquatic food web. As phytoplankton are the primary producers within the water column they sustain the zooplankton which in turn sustain larval fish populations. Zooplankton, as the consumer base of the marine food-web, are key players in the food web, transferring energy from the microbial food web and primary producers up to higher trophic levels (Pepin et al. 2011; Richoux 2011). The stress resulting from the many hydrological variations in estuaries strongly influences the composition of the zooplankton communities that develop within such ecosystems. Although estuarine environments often have fewer species and thus lower biodiversity compared with marine or freshwater regions, those estuarine organisms that are able to tolerate the demands are often higher in population density and support higher levels of tertiary productivity. Therefore, it is important to understand what type of zooplankton community is present

within the inlet (Richoux 2011). Numerous studies have indicated that there is a relationship between plankton abundance and survival of larval and juvenile fish (Beaugrand et al. 2003; Heath & Lough 2007). Many species of fish, such as *Gadus morhua*, are planktivorous during their larval and juvenile state. Knowing the taxonomic and functional diversity of the zooplankton will allow for understanding of how changes within the system may propagate up the food chains in such environments (Duffy & Stachowicz 2006).

Holoplanktonic copepods are one of the most abundant and most important zooplankton groups throughout aquatic systems and can dominate the coastal plankton biomass (Rochet & Grainger 1988; Neilsen & Andersen 2002; Marques et al. 2007). The abundance and diversity of zooplankton has been used in past studies to evaluate how mature and ecologically stable an area is. According to Aube et al. (2003), a mature and stable aquatic ecosystem should have a plankton community with an annual cycle that is relatively predictable, an ecological community that is suited to the hydrogeographic status of the region and is not influenced or driven by opportunistic or invasive taxa, and lastly should sustain native fish species either as a nursery for larvae or habitat for other life stages. Zooplankton abundances may directly coincide with the appearances or abundances of various larval and juvenile fish stages (Carter & Dadswell 1983). Zooplankton, a primary fish food source, may become more abundant in the times of year, such as spring, when primary production peaks partially due to higher nutrient availability resulting from increased freshwater flow as well as increased light.

2.2 Objective of Study

The primary objective of this study is to characterize the zooplankton composition of St. Pauls Inlet. St. Pauls Inlet was previously examined during the summer (July to August) of 1977 as well as the spring (May) of 1978 by Carter and MacGregor (1979), following the establishment of Gros Morne National Park in 1973; however, only species composition with qualitative abundance data was determined (abundances were recorded as infrequent, common, or abundant). There have been no other biological studies on the inlet's plankton since that time. My study examines the zooplankton species composition within the inlet and compares the composition with that reported in the 1979 study (Hypothesis 1: There is no overall change in zooplankton community composition over both decadal or seasonal time). Genera such as *Calanus, Pseudocalanus, Paracalanus, Acartia, Oithona,* and *Temora* would be found in marine or brackish systems and are typically the most abundant types in such environments. Carter and MacGregor (1979) suggested that a longitudinal salinity gradient may be present in the inlet during portions of the year. As the freshwater input is greatest during the spring due to the snow melt, the longitudinal salinity gradient would be greatest at that time, decreasing as the season progresses and the freshwater input decreases. Presence vs. absence data of zooplankton species composition of St. Pauls Inlet in the present relative to St. Pauls Inlet from 1979 will be used to infer changes in the inlet over time. This will also allow a comparison of the biodiversity of the inlet to other regional estuaries such as Lake Melville in Labrador (Hypothesis 3: Zooplankton composition will not be largely different between St. Pauls Inlet and Lake Melville).

Lake Melville, the largest estuary in the province of Newfoundland and Labrador, has a surface area of 3,069 km^2 and maximum depth of 256 m (World Lake Database 2014). The lake is a westward continuation of the Hamilton Inlet, which is a fjord-like inlet. It is geographically similar to St. Pauls Inlet although much larger. Both are considered brackish bodies of water that are fjordal inlets with a sill at the entrance and have been formed by glacial erosion (Grant 1975). The marine ecology of both locations is influenced by the adjacent Labrador Sea.

The second objective of this study was to determine if any longitudinal patterns of zooplankton species composition and distributions existed in St. Pauls Inlet from the end of the inlet to the mouth into St. Pauls Bay, and if such patterns related to environmental gradients, such as salinity (Hypothesis 2: Species composition throughout the zooplankton taxa in St. Pauls Inlet will not vary in relation to salinity).

St. Pauls Inlet is the only fjordal estuarine environment within the boundaries of Gros Morne National Park (Carter & MacGregor 1979). In relation to regional estuaries, St. Pauls Inlet might be considered representative of other similar fjordal-type systems such as Parsons Pond and Portland Creek, both further north along Newfoundland's west coast, and part of a larger group of Atlantic estuarine systems that includes Lake Melville in southern Labrador.

2.3 Methods

2.3.1 Sampling Locations for St. Pauls Inlet

The study area, (inlet) is located at the northern end of Gros Morne National Park (see Figure 2.1) and is 11 km long, and 6 km wide at the widest point. The surface area of the inlet is 30 km^2 with the maximum depth in the center of the glacial channel/inlet at 36 m (Carter & MacGregor 1979).

The opening from the inlet to St. Pauls Bay is only 80 m wide, which allows sea water to enter the inlet. Due to the restricted size of this entrance, a natural feature, there can be significant tidal velocity of 2 to 8 knots at the mouth of the inlet with estimated tidal amplitude of 0.6 to 0.9 m (Carter & MacGregor 1979). However, tidal amplitude decreases rapidly further into the inlet meaning that most of the water body is essentially non-tidal (Carter & MacGregor 1979). The freshwater input is from a total of 24 tributaries, with St. Pauls River (aka Bottom Brook), located at the eastern end of the inlet, being the largest inflow (O'Sullivan 1976; Melanson & Campbell 2012).

Consultation on sampling sites, as well as use of boat transport, was provided by community members from the town of St. Paul's. Sampling took place from spring to summer (June to August) in 2009 and in 2010 in St. Pauls Inlet. At the outset of the initial field season in June 2009, three sampling sites were used for weekly sampling. About two weeks into the sampling, an additional site was selected for a total of four sites (Figure 2.2). Sites were selected based upon the location compared to freshwater and

saltwater sources, as well as on accessibility by small boat. These locations were chosen to represent a potential range in salinity as well as bottom substrate type. If a longitudinal salinity gradient exists in the inlet, then the sites chosen should adequately represent it.

The sites chosen were: (Figure 2.2)

- Charles Cove Point (CCP) - close to the inlet mouth opening to the Gulf of St. Lawrence (49.512020N 57.464295W).
- Western Island (WI) - part way up the Inlet but without much direct freshwater input although has a shallow depth (49.493034N 57.464295W).
- Between the Falls (BTF) - approximately halfway up the Inlet with direct fresh water input (49.49684N 57.414223W).
- Bottom Brook (BB) - the farthest from the entrance to the Gulf and with the largest freshwater input (49.493345N 57.394903W).

Bottom Brook is near the head of the inlet, close (100 – 200 m) to the freshwater stream called Bottom Brook. The second site has been labelled Between the Falls, and as the name suggests it is located close (25-50 m) to two waterfalls coming down the cliffs of the fjord. The third site, Western Island, is situated at the buoy near Western Island, which is about halfway between the far end of the inlet and the entrance to St. Pauls Bay. The last point, closest to the salt marshes in St. Pauls Bay and the opening to the ocean, is Charles Cove Point.

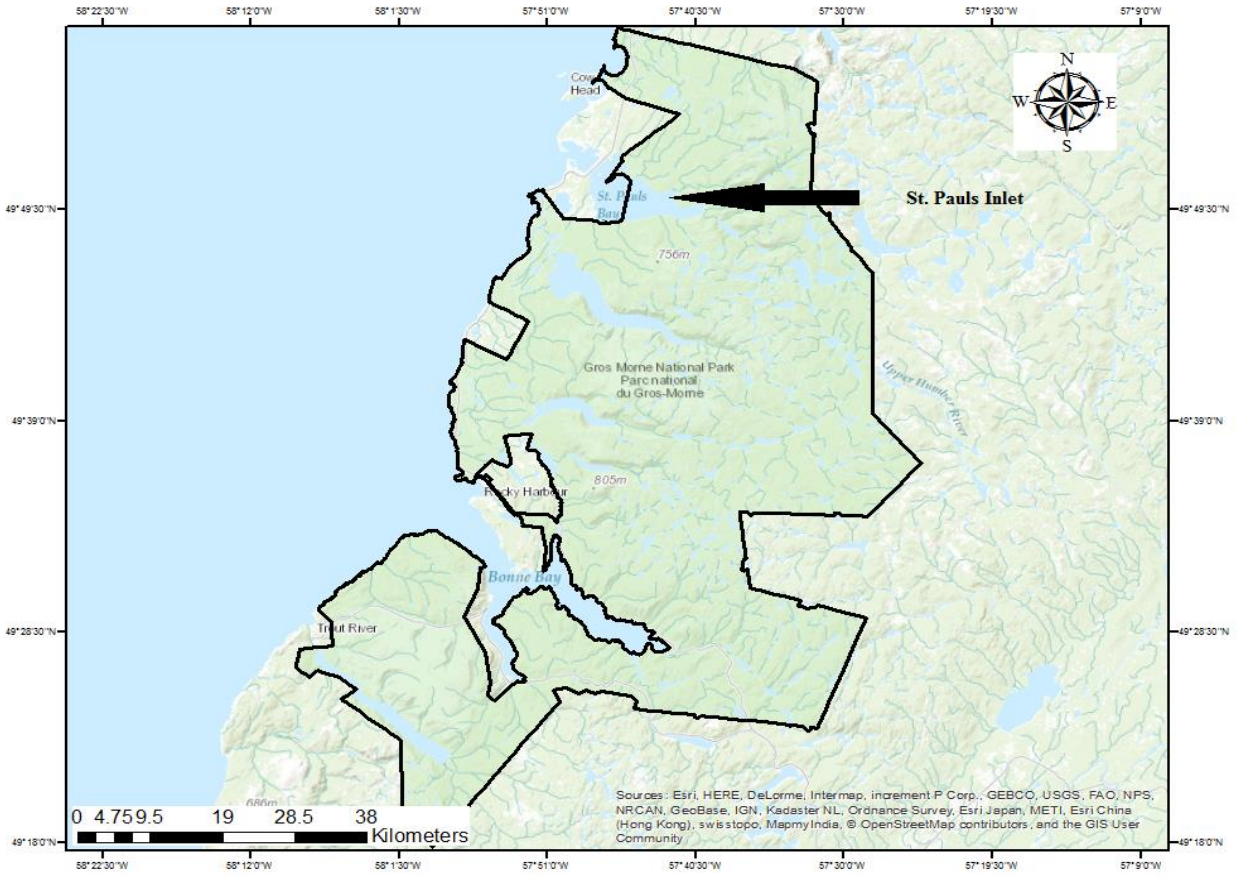


Figure 2.1: St. Pauls Inlet in relation to Gros Morne National Park, NL, Canada. (St. Pauls Inlet Latitude and Longitude 49.50058N 57.45.514W; map data from ESRI 2015)

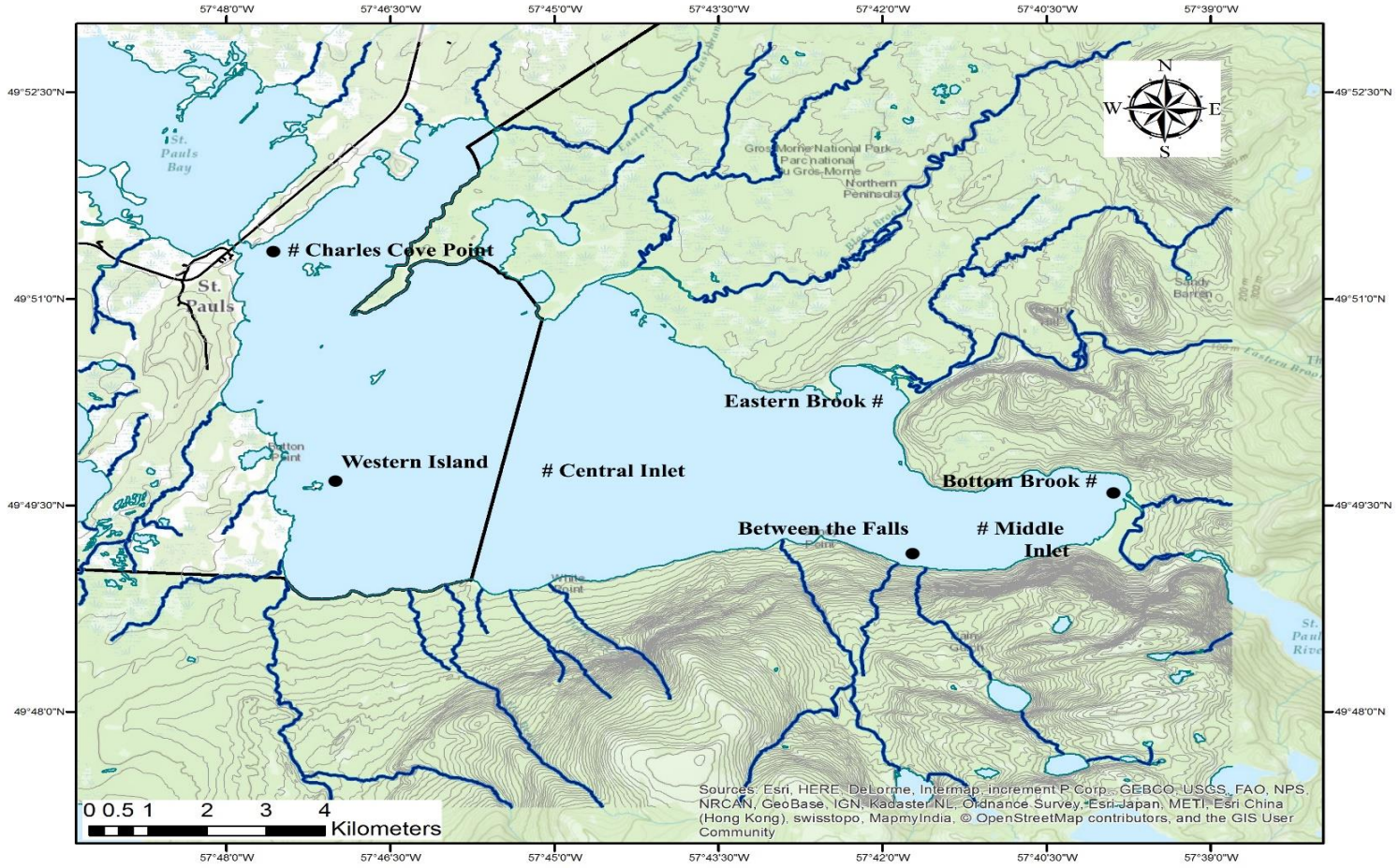


Figure 2.2. Sampling Sites for (●) the 2009 and 2010 Present Study and (#) the 1977 and 1978 Carter & MacGregor Study in St. Pauls Inlet, GMNP, NL, Canada. (Map data from ESRI 2015)

In addition to the reasons listed previously, the sites were chosen to reflect similar sites to the 1979 study. Carter and MacGregor chose 5 sites to sample for plankton (Figure 2.2). One site was located at the entrance to Bottom Brook another site was at the deepest part of the inlet which is a bit offshore from the present Between The Falls, the third site was located at the entrance to Eastern Brook, one was located approximately halfway between the mouth and end of the inlet, and the last point they sampled was at Charles Cove Point.

2.3.2 Sampling Methods for St. Pauls Inlet

Sampling was conducted from a local resident's fishing dory, dependent on the weather and ability to safely access the inlet. As St. Pauls Inlet has limited tidal influence it was not necessary to sample with respect to the tidal cycle (Carter & MacGregor 1979). For each sampling excursion, at each site, salinity (‰) and temperature (^{o}C) were measured at 1 m depth intervals, from surface to bottom, using a portable YSI® 85 Probe, which was calibrated using the 10 mS cm^{-1} conductivity standard for brackish water (YSI Incorporated). Bottom depth at each site was determined with a Speedtech sonar gun. During August of the 2010 season additional sampling for nearshore fish was undertaken utilizing seine nets and minnow traps (Melanson & Campbell 2012).

Zooplankton sampling was carried out at Bottom Brook, Between the Falls, Western Island, and Charles Cove Point once per week for seven consecutive weeks between June 16 and August 26 2009 and for fourteen consecutive weeks between
June 2 and August 11 2010. Unfortunately, due to weather problems, not all sites were

accessible each time. There was significant wind shear when the winds became greater than 20 km/h, causing much higher swells than the dory could safely navigate. At such times sampling was suspended and sites were missed. This difficulty in reaching all the sites all of the time also influenced Carter and MacGregor's ability to sample on occasion. The end result was 237 samples collected over both summer seasons (Table 2.1). See Appendix 1 for full list.

Table 2.1 Sampling Effort per Site for 2009 and 2010 St. Pauls Inlet Seasons (all tows)

2009 Sampling Amounts per Site		2010 Sampling Amounts per Site	
Bottom Brook	11	Bottom Brook	43
Between the Falls	21	Between the Falls	39
Western Island	19	Western Island	42
Charles Cove Point	21	Charles Cove Point	41
Total Sampling Effort	72	Total Sampling Effort	165

Zooplankton samples were taken using horizontal and vertical tows. Vertical tows were used to collect the organisms at a sample site throughout the site water column from a specific depth to the surface; whereas the horizontal tows were used to collect a composite sample of the water column near the surface. Composite sampling is valuable as it can provide more representative estimates of mean concentrations. . Two horizontal tows were taken per site with either a small-mesh conical net (63 µm mesh net, 300 mm mouth diameter, and 1.0 m length) or a large-mesh conical net (500 µm mesh net, 300 mm mouth diameter, and 1.0 m length); see Appendix 1 for all tows and sites. A calibrated General Oceanics® flow meter was attached to both the 500 µm and 63 µm net to allow estimation of the volume of water filtered (Smith et al. 1968). The horizontal tows were carried out for 2 minutes at just below the water surface in 2009. Oblique tows

were taken in 2010 for the same time frame and number of replicates. The sampling method moved from the horizontal tows in 2009 to the oblique as the horizontal tows samples were either empty of any plankton or completely full of only phytoplankton. As I wanted a representative sample of the water column I opted to do oblique tows (Frolander et al. 1973; Judkins et al. 1979; Huntley et al. 1983; Shih et al. 1988). Vertical tows were also done at each site and taken from a moored fishing dory, with a conical net (80 µm mesh net, 200 mm mouth diameter, and 0.5 m length). Filtering efficiency was assumed to be 100 % for the vertical tows in that they never clogged. Two depth of tows were taken per site, one close to 1 meter above the bottom and one down to half of the maximum depth of the sampling site, with two tows per depth range. The net was raised to the surface at approx. 1 m sec^{-1}. Due to the uncertainty of how well mixed the water column was throughout the inlet there was the necessity of replicate tows at differing depths (Pace 1992; Mouny 2002). The mesh sizes of the horizontal tow nets, as well as the vertical tow net, differed in order to collect a range in size of organisms. Although there was no clogging in the tows, the reason for the differing mesh sizes is that the smaller mesh openings can clog more than the larger ones, but small organisms would pass through the larger mesh. Larger mesh results in less of a bow wave in front of the net and hence can catch larger more mobile plankton (De Bernardi 1984; Downing & Rigler 1995). Specifically, it was hoped that the larger mesh size of 500 µm would allow for collection of larval fish, while the smaller mesh would capture mainly zooplankton, as based on other studies (Winkler et al. 2003). However, there was little success in catching larval fish.

2.3.3 Sample Processing for St. Pauls Inlet

Zooplankton samples were pooled for the replicated tows (2 tows at full depth were pooled and the 2 tows at 1/2 depth were pooled) and then were taken to the field station, located at the St. Paul's residence, concentrated through a 25 µm filter, and then preserved within 4 hours in 70 % ethanol (Black & Dodson 2003) in sterile scintillation vials. Samples were well-mixed and diluted to a known volume (20ml) within the vial, then a 1-ml subsample was removed with a graduated pipette. Zooplankton were enumerated under a circular, rotating Plexiglass counting chamber at 250-500x magnification using a dissecting microscope. A minimum of 200 individuals was counted in the samples. In some samples it was not possible to get 200 individuals in the 1-ml subset so additional subsamples were performed until either 200 individuals were reached or the full sample was counted. Quantitative zooplankton density was determined as number of individuals m^{-3}; net volumes were based on either measured velocity (m/s) through flow meters (for horizontal and oblique tows) or on depth of tow. For vertical tows the following equation was used:

$$\textbf{Volume } (m^3) = \pi * (\textbf{Radius of net}^2) * \textbf{Distance towed (m)}$$

Contents of the vials were identified to the lowest taxonomic group possible using a variety of sources and dichotomous keys (Katona 1971; Della Croce 1974; Bradford 1976; Frost 1989; Busch & Brenning 1992; Barnes 1994; Pollock 1998; Bradford-Grieve 1999; Gerber 2000; Taylor et al. 2002; Johnson & Allen 2005; Campbell & Knoechel 2008; Walter & Boxshall 2014). The major microcrustacean groups that were identified

down to the species level were Calanoids and Cladocerans.

2.3.4 Sampling Methods for 1979 Study

The plankton study by Carter and MacGregor was based on samples from July 5 - August 3, 1977 and May 19-26, 1978. Sampling was carried out with a Birge style tow net that was 17 cm in diameter and 108 cm long (mesh size unknown) as well as with Niskin bottles for specific depth sampling that was then sieved through Millipore filters. In addition, a tow net with 80 µm mesh was used for surface tows. During the summer of 1977, sampling was carried out in the afternoon at 5 m intervals from approximately 15-20 m to the surface. During the spring sampling in 1978 only surface tows were conducted, lasting 5 minutes at 3 knots. The qualitative zooplankton abundances for 1977 and 1978 were determined by examining the settled volumes of samples in vials.

2.3.5 Regional Comparison Site and Sampling Methods

Lake Melville was chosen as a regional comparison to St. Pauls as it can be defined as a fjord-type estuarine environment in a similar geologic region of the Canadian Pre-Cambrian Shield (Duthie 1974). Comparable zooplankton samples were obtained from Dr. R. Anderson, Department of Fisheries and Oceans, who collected the Lake Melville zooplankton samples in 2007. Lake Melville is a brackish water lake which stretches 150 km inland from the Hamilton Inlet (Grant 1975; Vilks & Mudie 1983). The Narrows, the connection between the inlet and the lake, is about 30 km long and ranges from 50 m to 28 m deep at the sill. Fresh water enters the lake mainly through the Churchill River at

approximately 58 km^3 yr^{-1}. This discharge, and very slow mixing, results in the surface layer of the estuary having a salinity of 10 ‰ extending almost the length of the lake to the sill. During the summer months the outflow of surface water prevents the saline water from the bay from entering over the sill into Lake Melville (Vilks & Mudie 1983). In fjord-type estuaries the bottom water salinity is determined by the salt content of the water entering from over the sill and the frequency of input. In the case of Lake Melville, there is a very sharp halocline at 25 m with the salinity being 25 ‰ and then at 100 m it increases again to 28 ‰ (Grant 1975; Vilks & Mudie 1983). This shows that the freshwater influx does have some impact on the bottom salinity since the surface salinity of the Narrows is 15 ‰ at the sill and is 31 ‰ at the head of Hamilton Inlet, whereas the bottom salinity is 25 ‰ at the sill and 33 ‰ at the head of Hamilton Inlet. The surface salinity is anywhere from 2 ‰ to 10 ‰ lower than the bottom salinity. These readings indicate that the surface water outflow from Lake Melville decreases the amount of the more saline water from the inlet and bay entering the lake. In addition to the lake having a less saline environment than the Labrador shelf, which ranges for 28.6 ‰ to 34.8 ‰, it also has warmer waters (Vilks & Mudie 1983). These warmer surface waters, 15 ^oC compared with 5 ^oC of the shelf, are due to the freshwater runoff and the sill preventing the colder waters from entering the lake (Vilks & Deonarine 1987).

Lake Melville was sampled over the course of four days in October 2007 by Department of Fisheries and Oceans personnel. As shown in Table 2.2 and Figure 2.3, there were four

locations sampled at 3 depths: just below the surface, 5-8 m depth (just below the pycnocline if present), and approximately 1 m from the bottom with a 202 µm mesh net. Most of the sites chosen were at the head of the lake near the Churchill River with sites 14 and 18 further out into the body of the lake. The areas sampled were a subset of the whole Lake Melville system and strongly influenced by river input. Zooplankton samples were processed the same way as for the 2009-2010 St. Pauls samples.

Table 2.2: 2007 Sampling Data for Lake Melville, Labrador, Canada

Site	Salinity (‰)	Day	Month	Depth (m)	Site Description
1	20.31	12	10	25	Goose Bay 1.9 km North Rabbit Island 53.41679N 60.15797W
3	8.71	12	10	5	
5	1.12	12	10	1	
9	19.60	12	10	15	Goose Bay 1.6 km S R.Is, Churchill mouth 53.38413N 60.14192W
7	11.60	12	10	8	
11	1.00	12	10	1.5	
15	18.30	13	10	7	Cove mouth Kenamu River 53.49416N 59.92350W
16	6.50	11	10	0.5	
14	13.38	13	10	2.5	12.5 km from NW point 53.58099N 59.91738W
18	16.81	13	10	7	

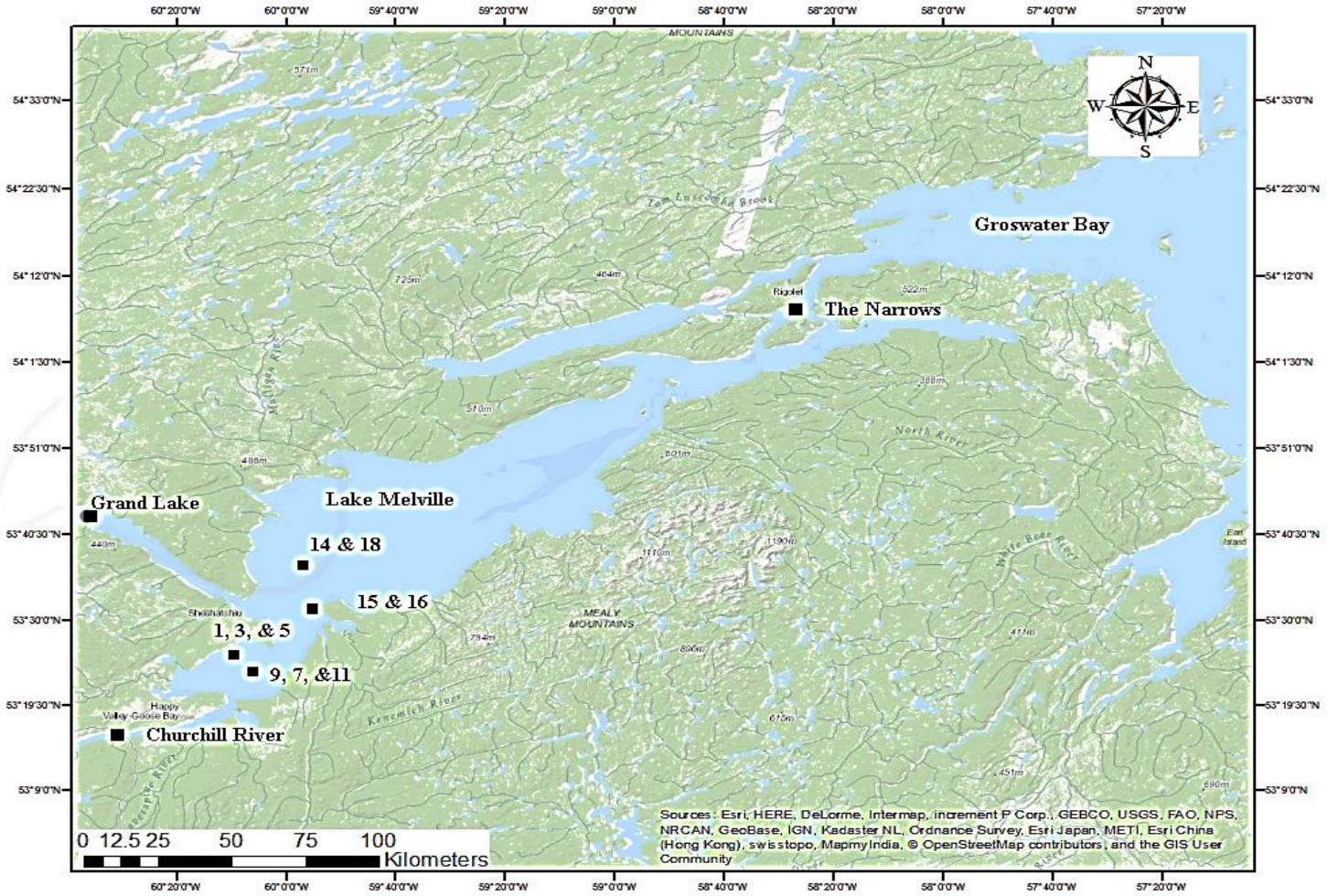


Figure 2.3: Lake Melville, NL (53.41679° N, 60.15797° W) Sampling Sites by DFO in 2007 (map data from ESRI 2015)

2.4 Stream Discharge

To ascertain freshwater inputs and impact on salinity in St. Pauls Inlet, stream discharge rates were measured for the four main freshwater sources (Eastern Brook, Black Duck Brook, Bottom Brook, and Alex Brook; Figure 2.4). These sites were chosen as the main sources due to visual observation, local knowledge, and reference to the Carter and MacGregor 1979 study.

Each stream site was measured once a month (June, July, and August) with approximately 20-30 days difference between sampling dates. Stream discharge rates were calculated by measuring the volume of water moving down a river or stream per set unit of time (m^3 sec^{-1}). This was typically measured by averaging the determination of the depth with a Speedtech sonar gun at 2 separate rectangular cross-sections of the stream (stream width measured) and then also obtaining the water velocity by a hand-held flow meter (Speedtech Flowatch®). Velocity was measured with the flow meter for 2 minutes at each location. As the substrate was a mix of sandy and rocky terrain, the correlation factor used was 0.85 (Wetzel & Likens 1991). The equation used was:

$$\text{DISCHARGE } (m^3 sec^{-1}) = \text{Velocity } (m\ sec^{-1}) \times \text{Width (m)} \times \text{Depth (m)} \times \text{Correction Factor for Sandy/Rocky substrate}$$

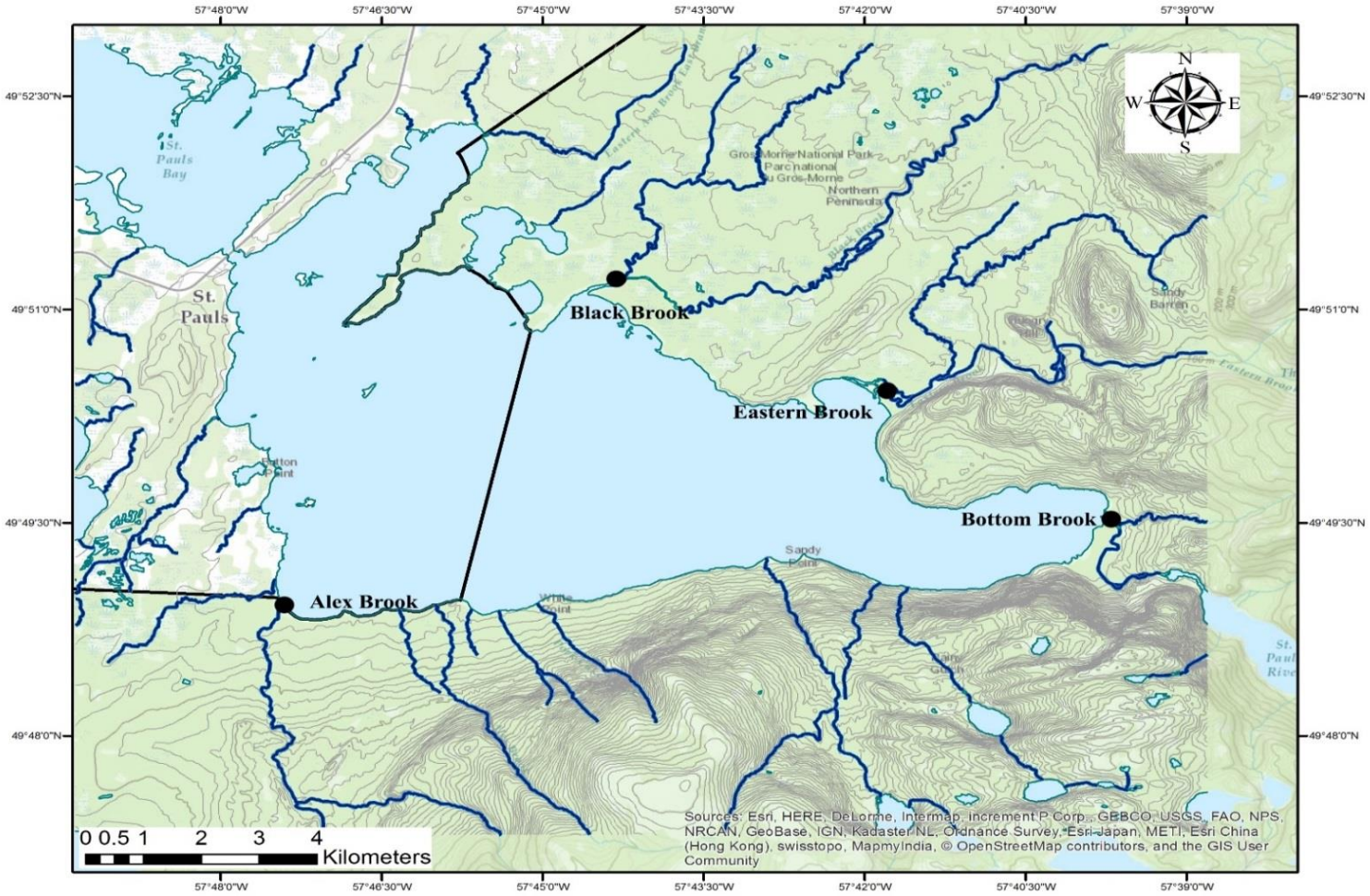


Figure 2.4: The four sites monitored in 2010 for stream discharge into St. Pauls Inlet (adapted from Melanson 2012 and ESRI 2015)

2.5 Statistical Analysis

2.5.1 Zooplankton

To determine if there were spatial patterns in zooplankton species composition within the 2009 and 2010 sampling, as well as in comparison with the 1979 Carter & MacGregor study and Lake Melville, I employed two types of multivariate analysis (one based on classification into groups, one based on looking at spatial patterns of species along ordination axes). Cluster Analysis was used so that similarity among the zooplankton samples could be defined statistically by grouping samples according to their species composition (presence/absence data) (Krebs 1989). Similarity of species composition was calculated using Jaccard's similarity coefficient S_J

$$S_J = \frac{a}{a+b+c}$$

a, b, c = number of species in both samples A & B; in sample B only; in sample A only

Jaccard's is ecologically relevant when using presence/absence data (Legendre & Legendre 1998). Similarity calculated using Bray-Curtis coefficients on abundance data yielded analogous results. I preferentially used Jaccard's since my comparisons of similarity were based on presence/absence data which were available for all sites and years. Jaccard's coefficient is used to determine similarity among samples or sites – the coefficient is based upon the presence and absence of species between a sample pair; 0 indicates no similarity and 1 indicates full similarity (Omori & Ikeda 1984). Using this similarity coefficient, a cluster analysis was performed. The program NTSYS (Rohlf

2009) was used to do a sequential, agglomerative, hierarchical and non-overlapping (SAHN) classification which would assign each sample or site into a group and then arrange those groups into a hierarchical dendrograms. This allowed for any relationships between sites to be visible and to see how they are classified. The method used was the unweighted pair group method with arithmetic averaging (UPGMA) as this is the hierarchical clustering technique recommended when there is no specific reason to choose any other technique (Gauch 1982). Methven et al. (2001), Wroblewski et al. (2007), and Melanson and Campbell (2012) used similar cluster analysis to classify species composition of fishes in estuarine systems in Newfoundland and Labrador. This technique allows all objects in the analysis to receive equal weight in the computation. It assumes that objects in the groups are representative of the larger population under study which works well with the simple random sampling design (Legendre & Legendre 1998). Site sampling in the inlet was considered random.

The other multivariate analysis used was Non-metric Multi-dimensional Scaling (NMDS), an ordination method that graphically represents relationships between objects in multi-dimensional space. Ordination arranges samples so that similar samples are close together and dissimilar samples are far apart, along a number of axes (Krebs 1989). NMDS may be better than cluster analysis when the samples are arranged continuously along environmental gradients (such as salinity, temperature, and depth). It uses distance-based measures like Bray-Curtis or Jaccard's in its analyses and makes few assumptions about the nature of the data (Holland 2008). As with the cluster analysis,

presence/absence data per site were used and similarity between sites assessed with Jaccard's coefficient of similarity. The NMDS ordination was performed on the similarity matrix. Kruskal stress coefficient values, a type of goodness of fit that reflects how well the ordination summarizes observed distances among the samples (Holland 2008), were examined to determine if the stress level is adequate. Stress values that are low (i.e. 0.02 vs. 0.12) generally indicate a very good fit of the objects being tested on the dimension. The level of dimension (number of axes) was identified to be the point at which any additional dimensions did not lower the stress value. In addition, a higher number of dimensions can make the interpretation of the ordination difficult (Kruskal & Wish 1978). NMDS analysis was carried out using NTSYSpc statistical software (version 2.2, Rohlf 2009) based on 100 iterations, the stress was Type 2 and the 3D plot was chosen. This dimensionality was chosen for ease of examination as well as having an acceptable stress value associated with it. An examination of the correlations of the axis values with the environmental factors (salinity, temperature, etc.) was done to determine what the 3D axes might represent. Comparison of past to recent NMDS correlations for St. Pauls Inlet and correlations for the inlet vs. Lake Melville could elucidate any shifts in environmental controls of species richness both in time and in space.

Such analysis may help to determine if there is a spatiotemporal variation in zooplankton species and the extent of any co-variation with the environmental factors reported (analyses similar to Marques et al. (2007) for Mondego estuary in Portugal)... Both the cluster analysis and NMDS ordination were performed to determine what levels of

zooplankton species assemblages' similarity/dissimilarity occur among sites within the inlet over the course of the seasons (i.e. longitudinal variation; hypothesis 2), and among years (1979 vs. 2009/2010, i.e. temporal variation; hypothesis 1). As well, both statistical methods were performed to evaluate similarity between the zooplankton assemblages observed in St. Pauls Inlet and Lake Melville (i.e. regional variation; hypothesis 3).

2.6 Results

2.6.1 Stream Discharge

Stream discharge was evaluated to extrapolate the approximate amount of freshwater input to St. Pauls Inlet during the study period, and to determine if the freshwater input had an effect on the species composition of St. Pauls Inlet. Discharge was measured only in once per month in 2010 although the study covered the two summer seasons of 2009 and 2010. Each stream was measured at two locations, the mouth of the stream and just in from the first tributary or as far in as we could access. As expected, the average seasonal stream discharge rate (m^3sec^{-1}) varied by location with the largest freshwater stream, Bottom Brook, having the highest rate of 8.23 m^3sec^{-1}. Eastern Arm Brook had the second highest freshwater input with a rate of 4.06 m^3sec^{-1}. Discharge rate in Black Brook was recorded at 3.02 m^3sec^{-1} followed by Alex Brook with 0.37 m^3sec^{-1}. The mean discharge differed significantly among the streams (ANOVA $F_{3,16} = 5.06$, $p=0.003$).

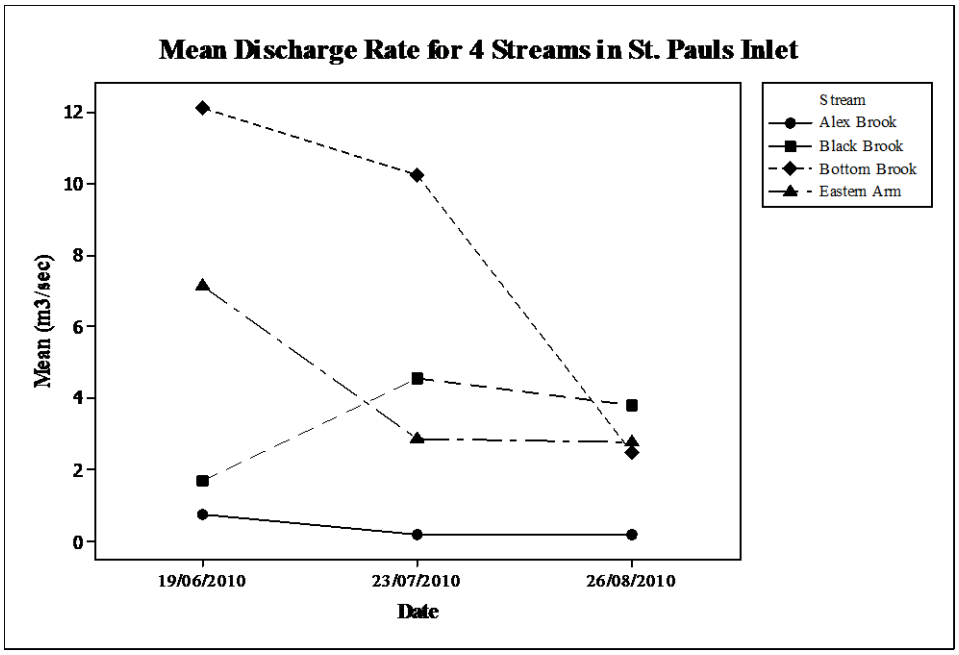


Figure 2.5: Monthly Mean Discharge Rates for 4 Primary Discharge Streams in St. Pauls Inlet for 2010

There was generally a higher discharge rate in June than in the rest of the season, except for Black Brook (Figure 2.5). This is most likely indicative of a spring snowmelt resulting in higher freshwater inflow into the inlet which was also seen in the 1979 Carter and McGregor study. Mean discharge by month (June to August) per stream was 4.40 m^3sec^{-1}in June, 3.82 m^3sec^{-1}in July, and 2.3 m^3sec^{-1}in August, with a mean total discharge of 15.22 $m^3sec^{-1}$for the entire 3 month period. Mean annual discharge draining from the 24 sources into the inlet was previously estimated at 13 m^3sec^{-1} (Carter & MacGregor 1979). The highest flow into the inlet would be in spring with the lowest in February/March similar to the Upper Humber River watershed near the park boundary. Carter & MacGregor assumed that St. Pauls River and drainage basin would show similar flow velocities, with over 47 cm sec^{-1} flow in May but only 5cm sec^{-1} in February. However the flow does vary from season to season and comprehensive winter data for

1979 were unavailable due to ice cover (Carter & MacGregor 1979). According to the Government of Canada's Weather Station in Cow Head the total snowfall levels for the months leading up to the sampling seasons were 471.0 cm for September 2008 - May 2009 and 257.0 cm for September 2009 - April 2010. The maximum accumulation of snow in either the 2009 or the 2010 season was found on February 15-27, 2009 with 100.0 cm. This maximum was reduced to 0.0 cm on the ground by April 4, 2009. This very high snow volume in February translates to high stream discharge in the spring following snow melt. In the following winter the maximum snow was reduced by almost half to 55.0 cm on February 27, 2010. This was reduced to 0.0 cm by March 16, 2010. These figures are for a low lying weather station near the town of Cow Head which is in the coastal plains. It is expected that the snow fall amounts and length of the spring snowmelt would be higher in the elevations surrounding the inlet. The higher snow volume in 2009 vs. 2010 would be expected to cause the stream discharge rate in 2009 to be more than in 2010.

2.6.2 Temperature

Based on temperature profiles observed at all four sites during both years (Figures 2.6-2.9), thermocline development was variable between sites. At Bottom Brook there was a thermocline in 2009 which was not as pronounced in 2010 (Figure 2.6). Between the Falls (Figure 2.7) shows a thermocline in both of the years whereas Western Island (Figure 2.8), as expected due to the shallowness and well-mixed water column at the location, does not show any indication of a thermocline. Lastly, Charles Cove Point

(Figure 2.9) shows only a slight thermocline during the first sampling of June in both years. Overall temperatures were determined by averaging the temperatures at each location by season and depth. These seasonal (spring + summer) temperatures ranged from a minimum of 3.80 ˚C at Charles Cove Point to a maximum of 22.60 ˚C at Bottom Brook. Surface waters (0 to 2.0 m) ranged from 9.6 ˚C at Charles Cove Point to 22.60 ˚C at Bottom Brook. Bottom temperatures (2.0 m up from the bottom) ranged from 3.80 ˚C at Charles Cove Point to 20.70 ˚C at Western Island for bottom waters. Boxplots of temperature (surface and bottom) over both seasons (Figure 2.10a) showed little difference between sites. However, Between the Falls did exhibit more variability in temperature range.

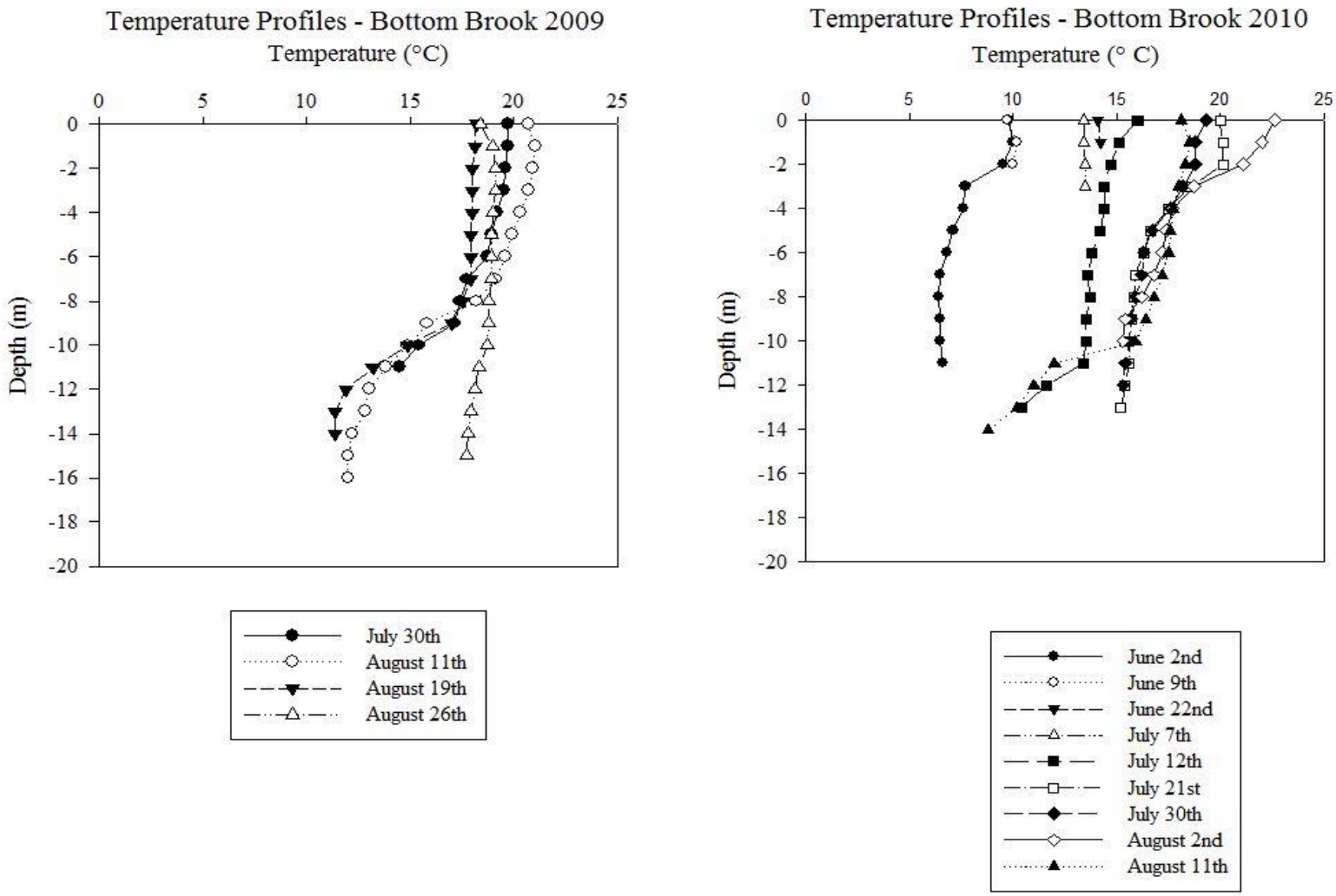


Figure 2.6: Temperature Profiles: Bottom Brook 2009 and 2010

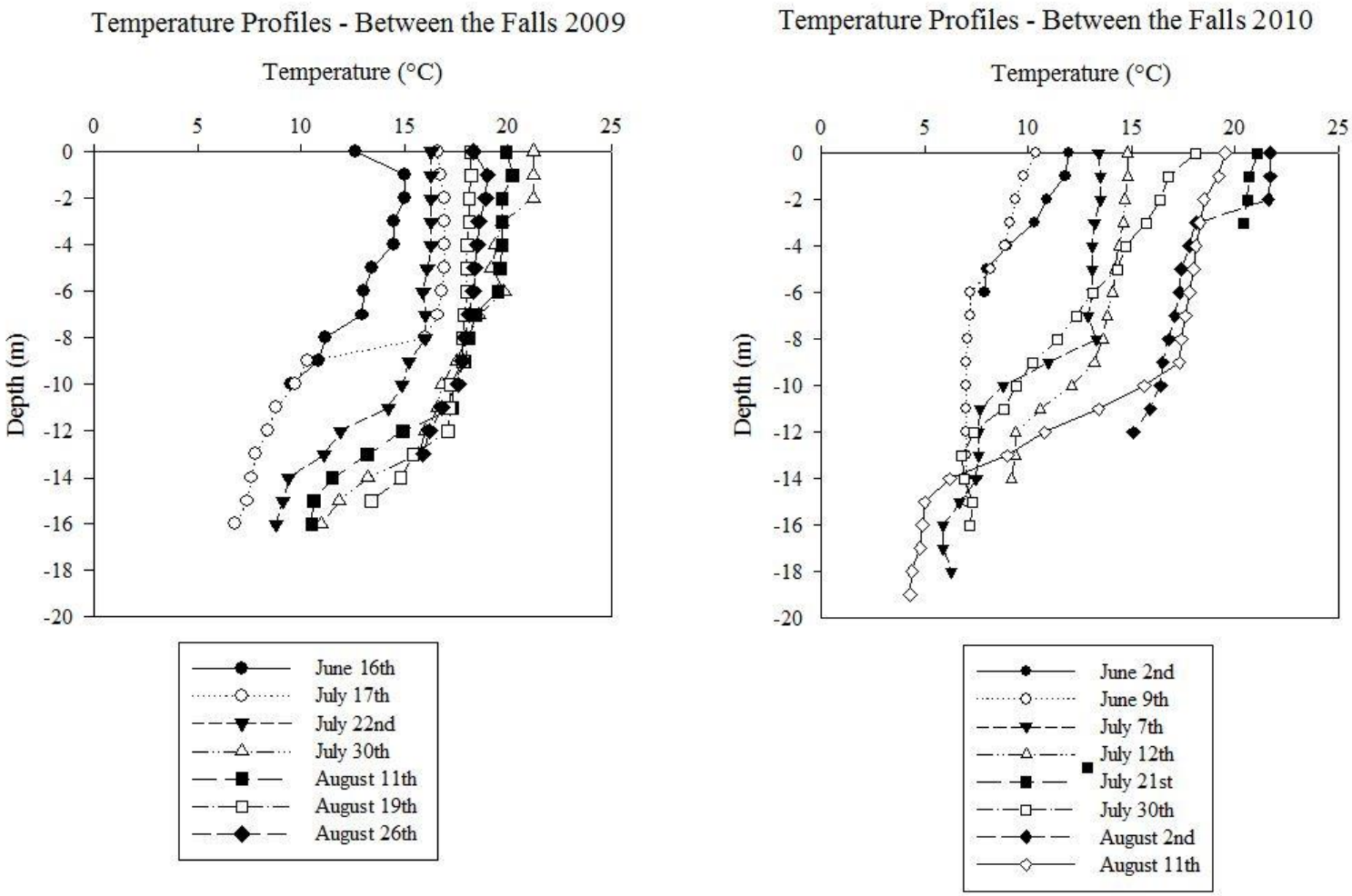


Figure 2.7: Temperature Profiles: Between the Falls 2009 and 2010

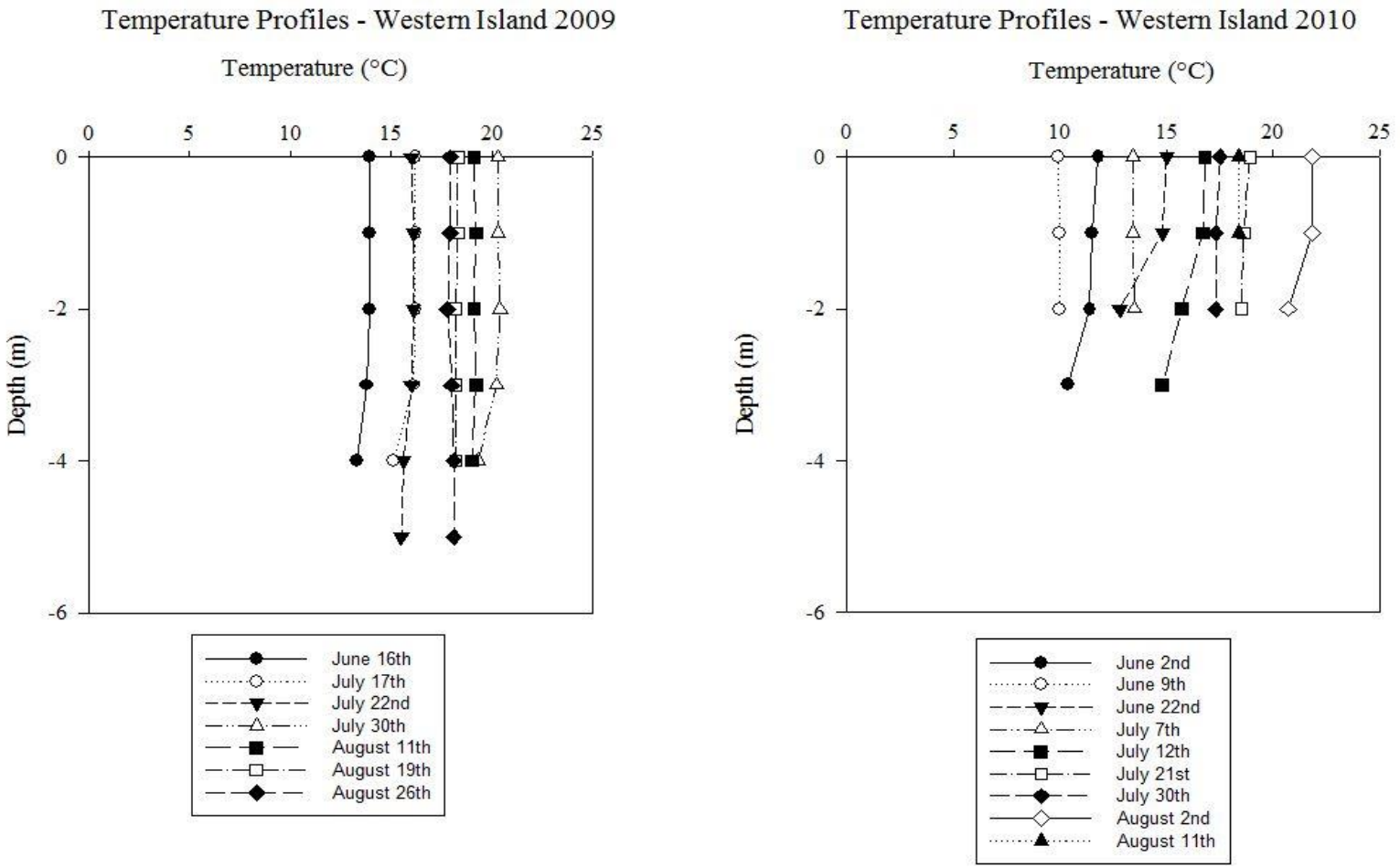


Figure 2.8: Temperature Profiles: Western Island 2009 and 2010

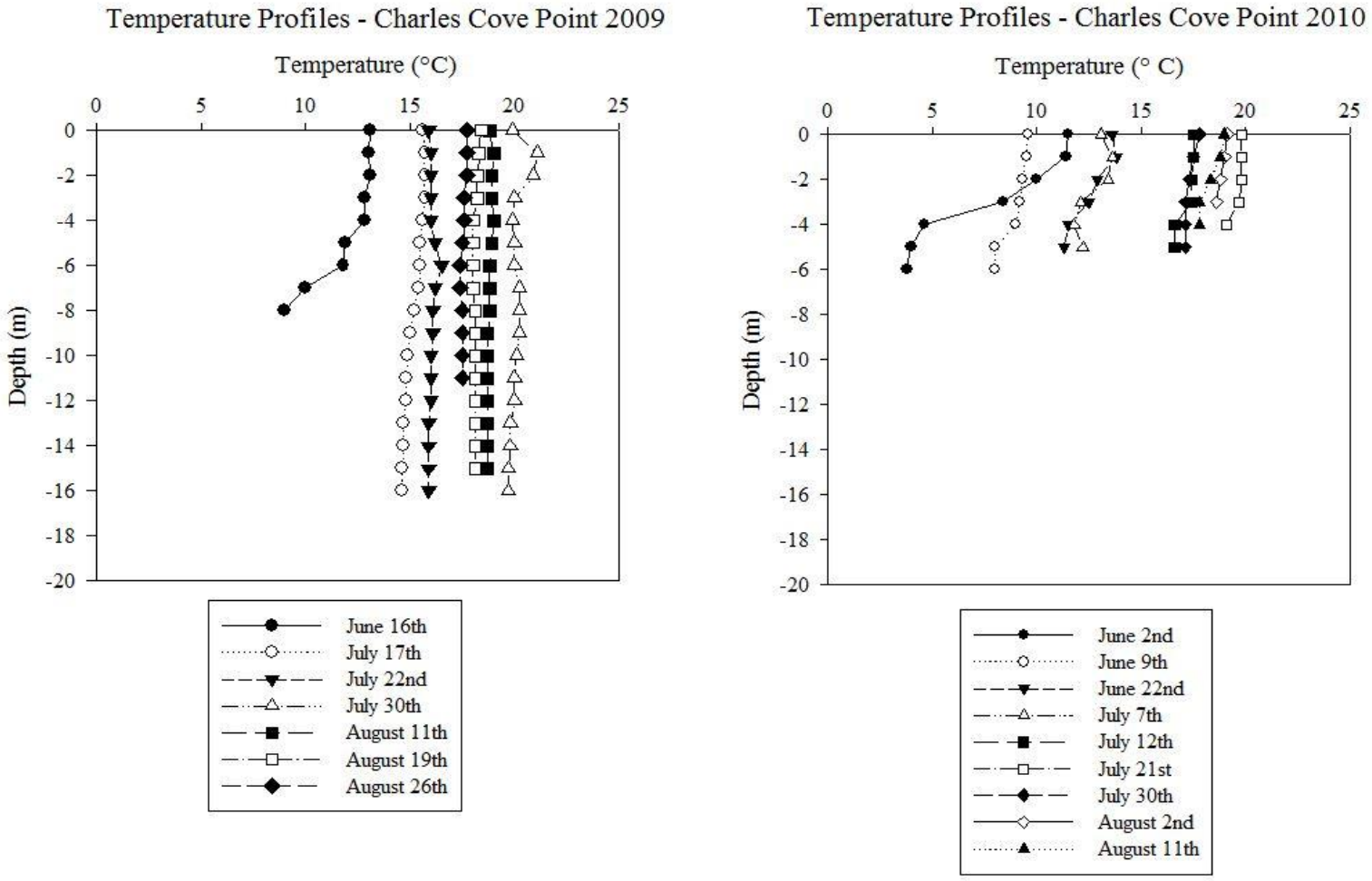


Figure 2.9: Temperature Profiles: Charles Cove Point 2009 and 2010

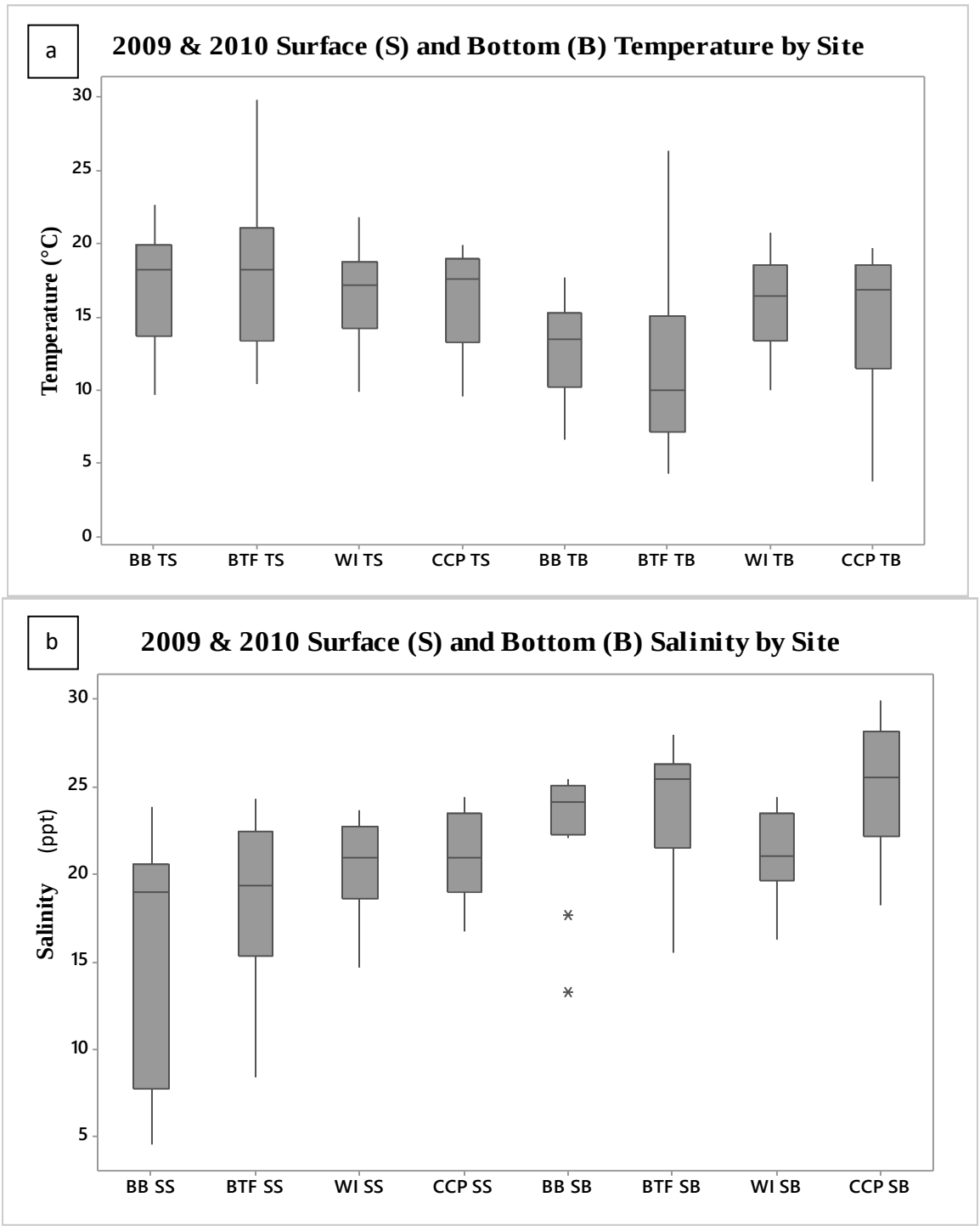


Figure 2.10: a) Boxplots of 2009 & 2010 Surface and Bottom Temperatures (TS & TB) by site; b) Boxplots of 2009 & 2010 Surface and Bottom Salinities (SS & SB) by site. Ends of each box indicate 1st and 3rd quartiles, horizontal line inside box indicates the median, and the ends of the whiskers indicate maximum and minimum values within the upper or lower limit. Outliers shown by *

2.6.3 Salinity

Salinity ranged from a minimum of 4.6 ‰ recorded for Bottom Brook surface water to a maximum of 29.9 ‰ recorded for Charles Cove Point bottom water (see Appendix 2). The mean average salinity sampled from the surface and at depth, was 21.62 ‰ at Bottom Brook, 22.69 ‰ at Between the Falls, 21.07 ‰ at Western Island, and 24.14 ‰ at Charles Cove Point. Bottom Brook and Between the Falls showed higher variability in measured salinities, while there was less freshwater influence at Western Island and Charles Cove Point (Figure 2.10b) . Boxplots of salinity (surface = top 2 meters sampled and bottom = lowest 2 meters sampled) averaged over both seasons showed little difference in median salinities (Figure 2.11).

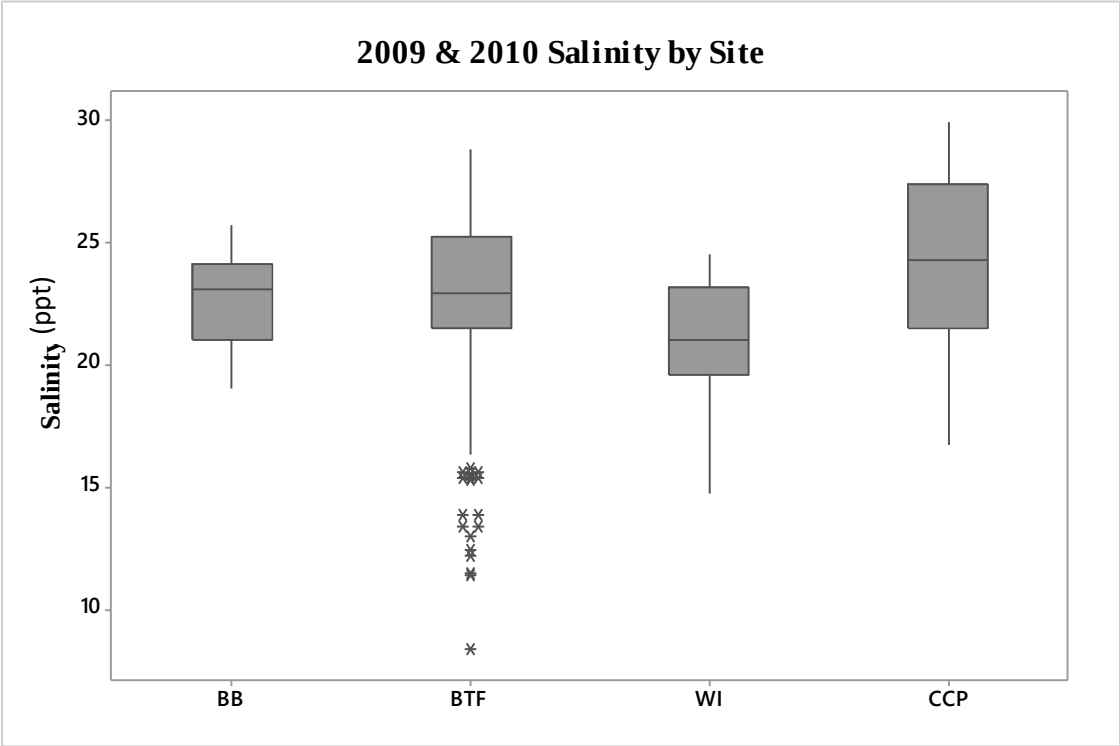


Figure 2.11: Boxplots of Averaged 2009 & 2010 Salinity by Site. Ends of each box Ends of each box indicate 1st and 3rd quartiles, horizontal line inside box indicates the median, and the ends of the whiskers indicate maximum and minimum values within the upper or lower. Outliers shown by *

Compared with the 1979 study which showed a vertical salinity gradient, data for 2009 and 2010 show higher salinity water at the bottom of the inlet indicating some stratification; however, it was not pronounced nor was it present at all sites. As seen in Figure 2.11 the overall salinity did not vary greatly among sites. Figures 2.12 and 2.13 show the two sites, Bottom Brook and Between the Falls, where there was some vertical stratification in salinity (i.e. a halocline). Of the other two sites, Charles Cove Point showed slight early summer stratification (Figure 2.15) while Western Island (Figure2.14), did not exhibit any stratification either year. The salinity gradient in June was as to be expected with the lowest overall salt content being at Bottom Brook and the most saline being Charles Cove Point. This may occur only in June due to the effects of the last of the spring snow melt and thus the peak freshwater influx into the inlet.

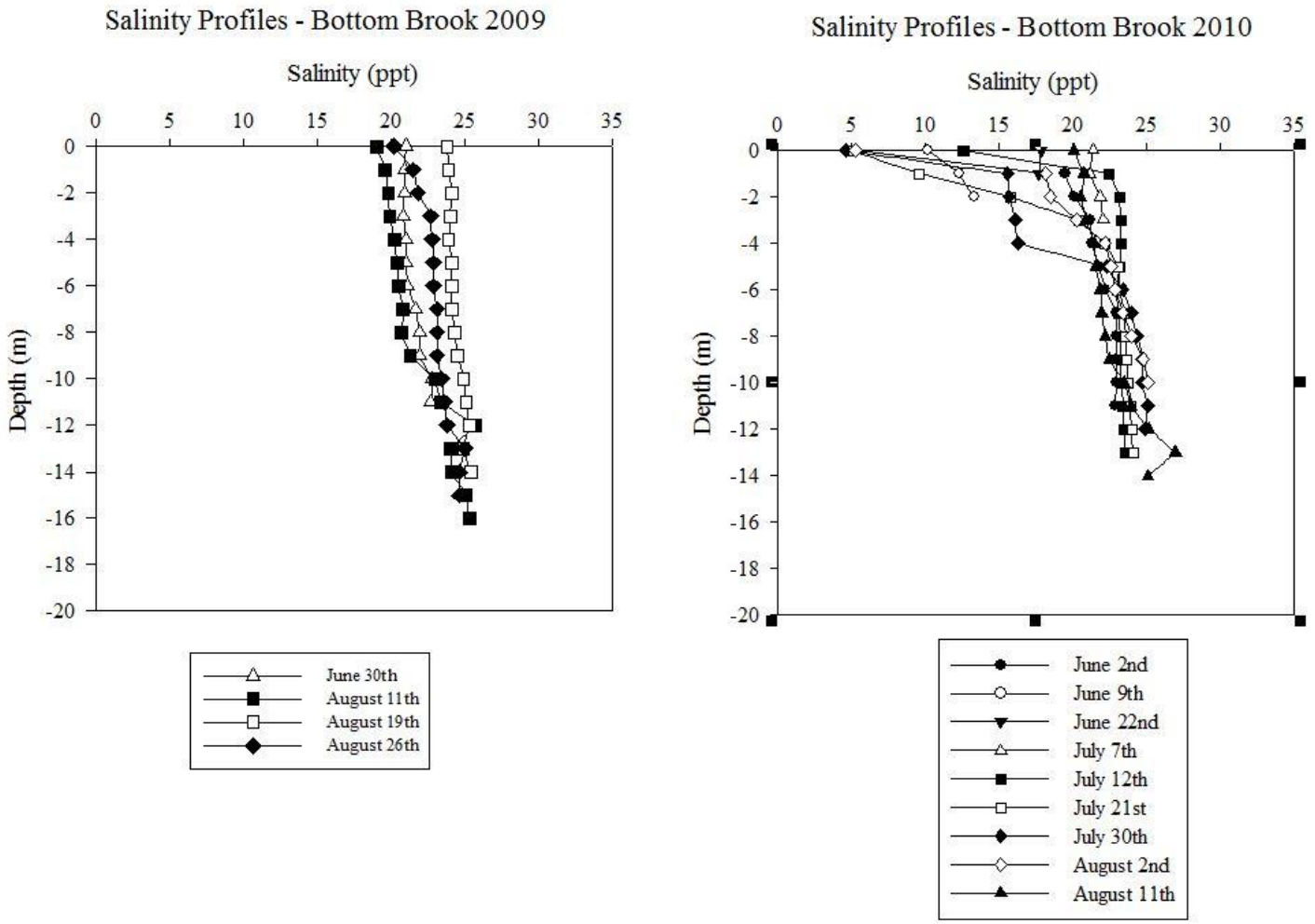


Figure 2.12: Salinity Profiles: Bottom Brook 2009 and 2010

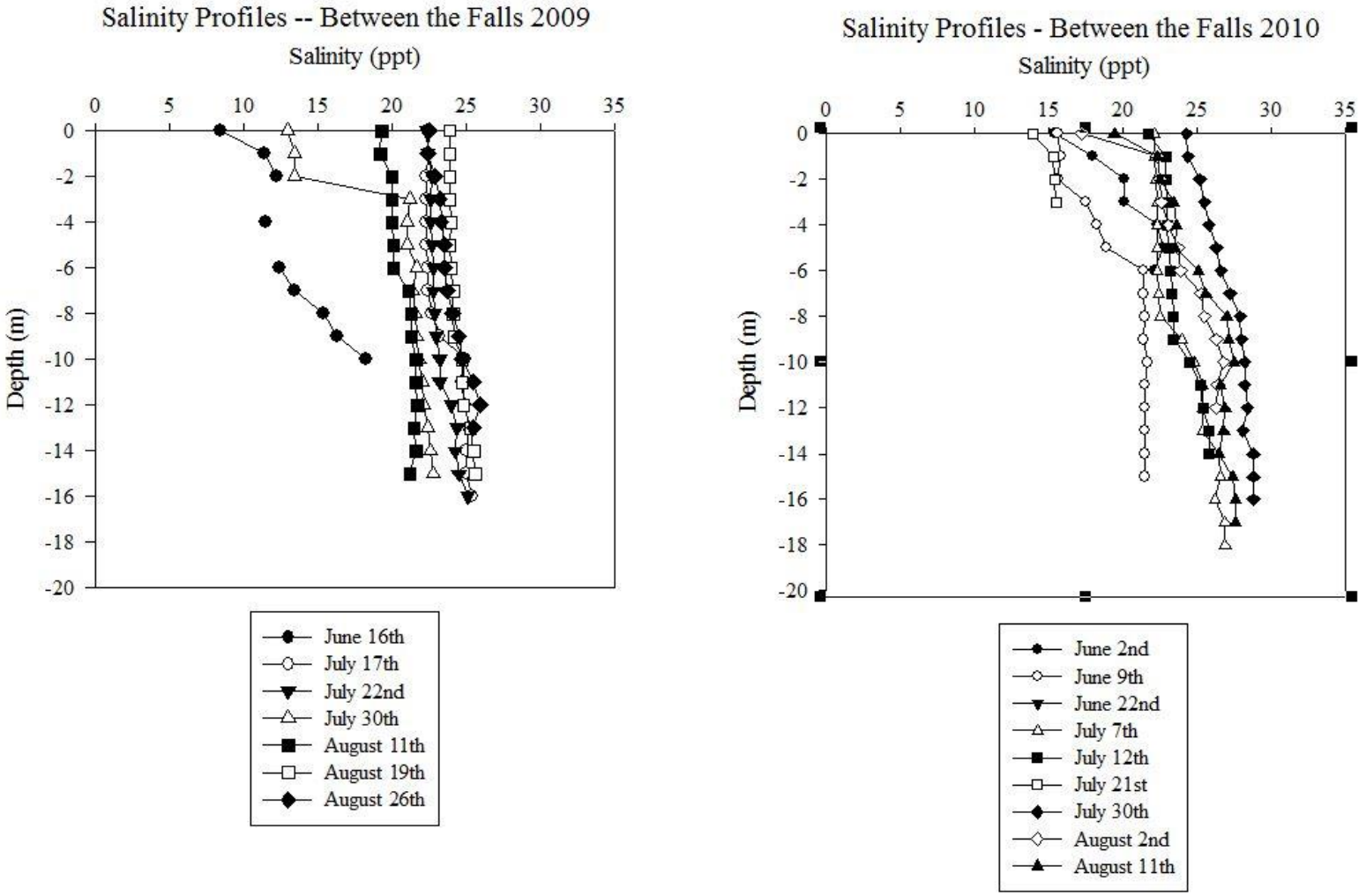


Figure 2.13: Salinity Profiles: Between the Falls 2009 and 2010

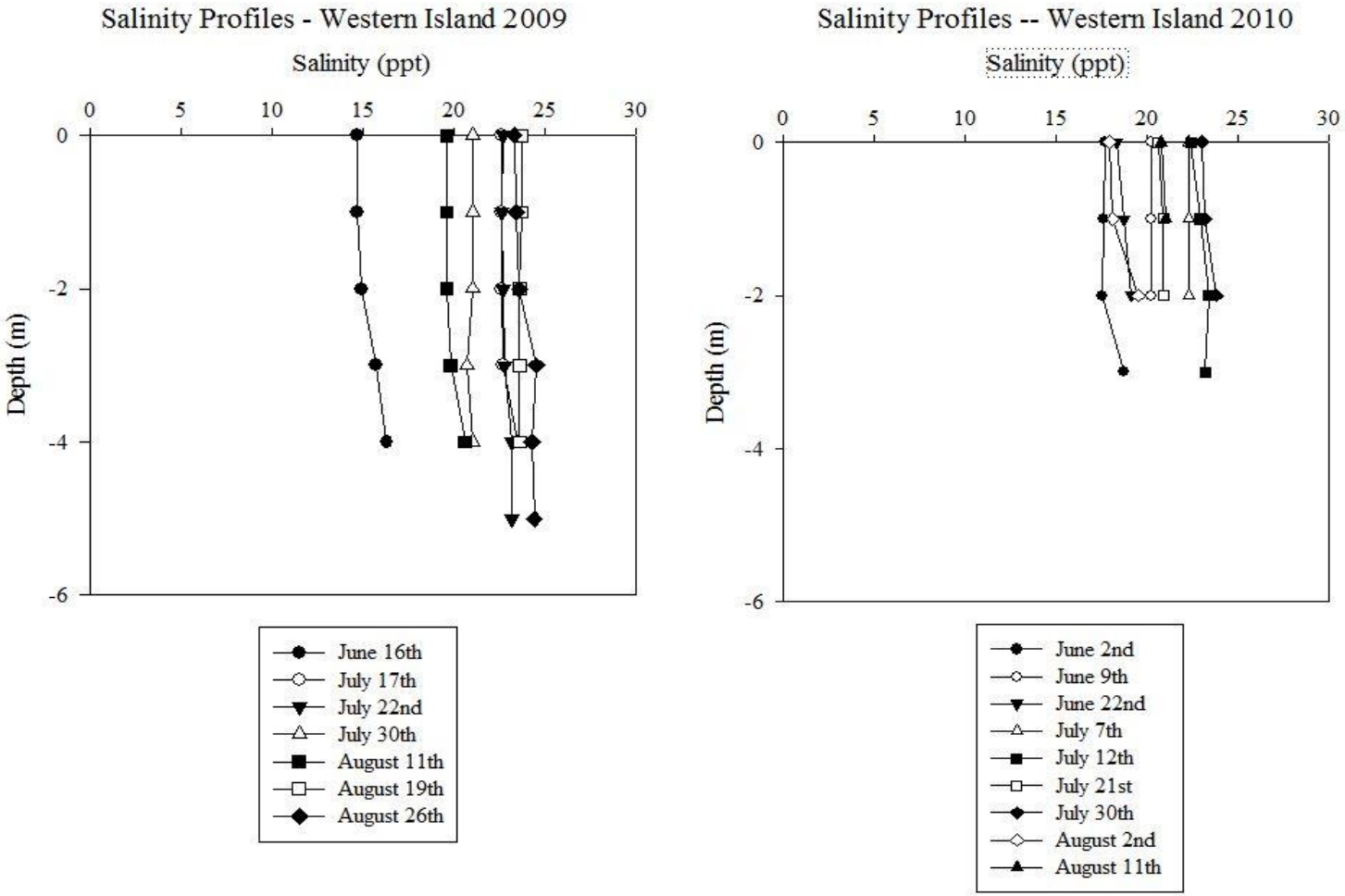


Figure 2.14: Salinity Profiles: Western Island 2009 and 2010

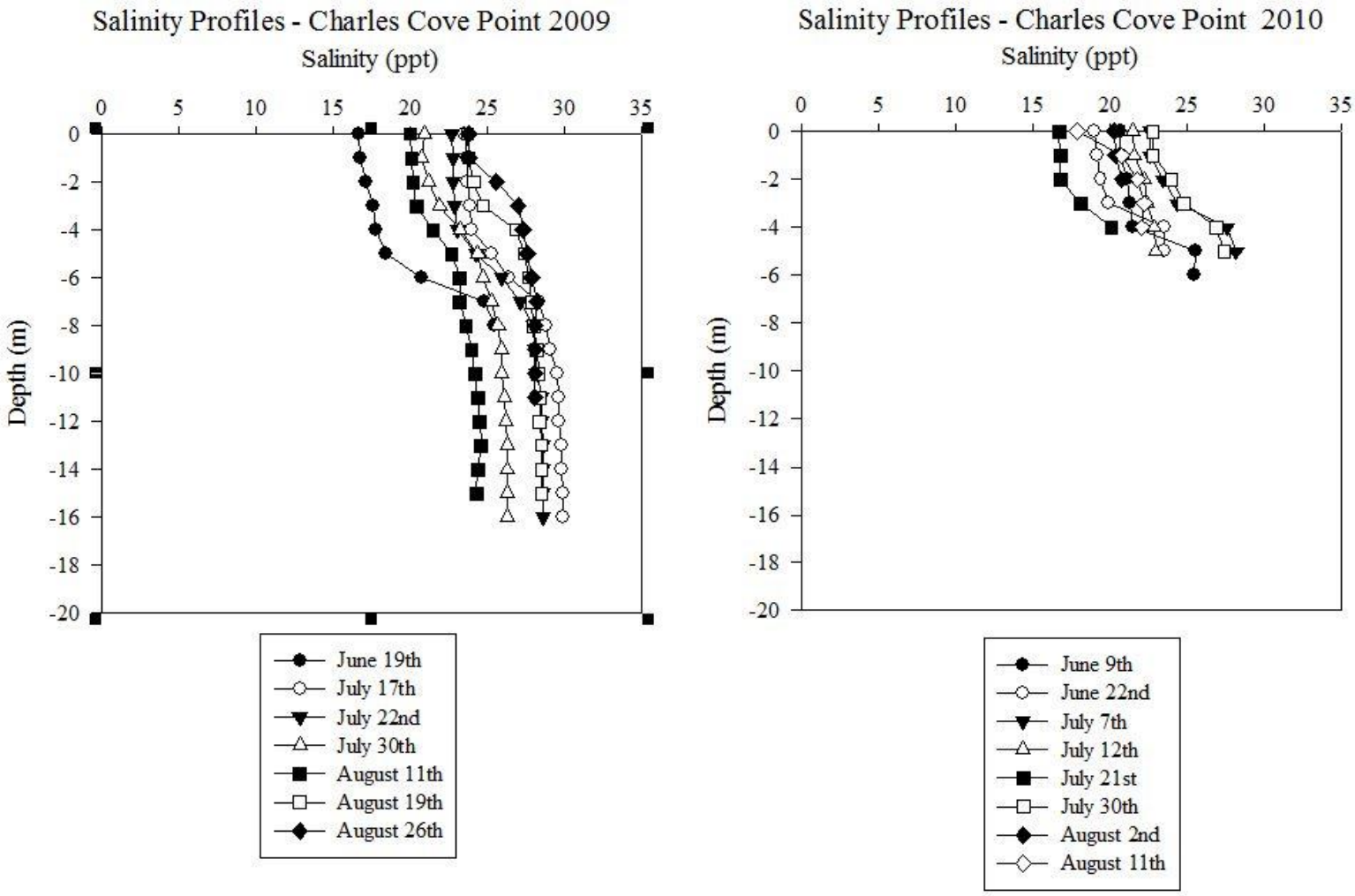


Figure 2.15: Salinity Profiles: Charles Cove Point 2009 and 2010

2.6.4 Zooplankton

A total of 18 zooplankton taxa were identified from St. Pauls Inlet in 1977/1978, whereas only 12 were identified in 2009/2010 (Table 2.3). The 18 taxa listed in 1979 were: Copepods *Acartia hudsonica, Calanus finmarchicus, Eurytemora affinis, Harpacticus chelifer, Oithona similis, Temora longicornis, Oncaea venusta, Pseudocalanus elongatus, Centropages typicus, Macrosetella gracilis, Metridia longa, Metridia* sp., Cladoceran *Evadne nordmanni* and Others: *Aurelia aurita*, Brachyura (Crab) Zoea, *Mysis mixta, Parasagitta elegans* and fish larvae. The taxa listed in the present study were: Copepods *Acartia hudsonica, Calanus finmarchicus, Oithona similis, Temora longicornis, Microsetella norvegica,* Cladocerans *Evadne nordmanni* and *Podon leuckarti,* and Others: *Aurelia aurita*, Brachyura (Crab) Zoea, *Mysis stenolepis, Parasagitta elegans* and fish larvae. Only the microcrustacean species (copepods + cladocerans) were used as comparison in this study.

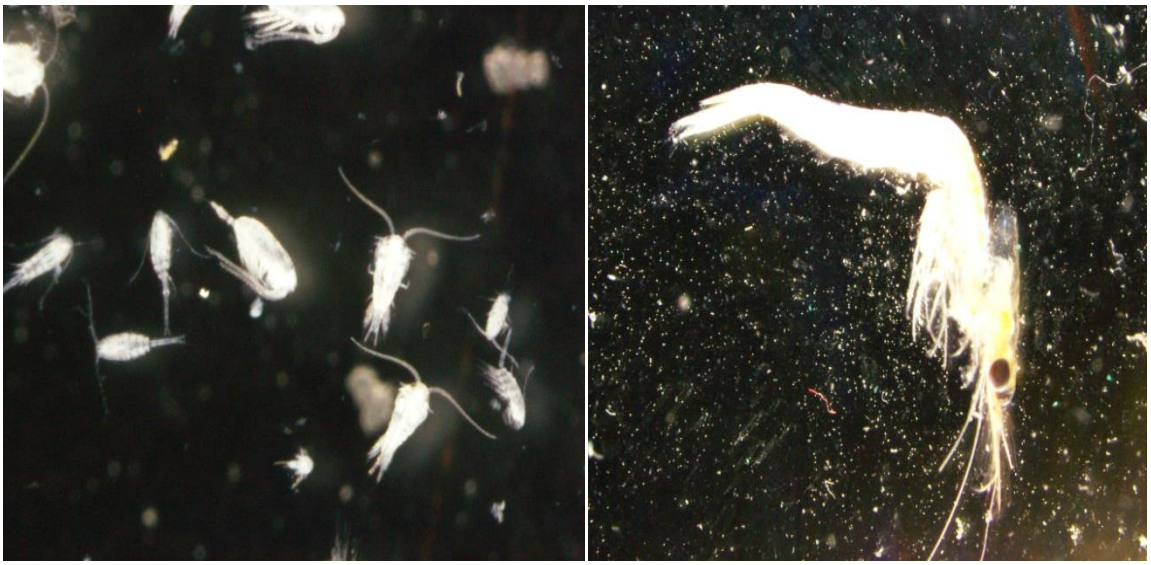


Figure 2.16: Copepods (left) (*Acartia hudsonica* & *Temora longicornis* 30X magnification shots of vertical tow BTF for Aug 11/2010) and (right) *Mysis stenolepsis.*(10X magnification for 500 µm horizontal tow July 15 2009)

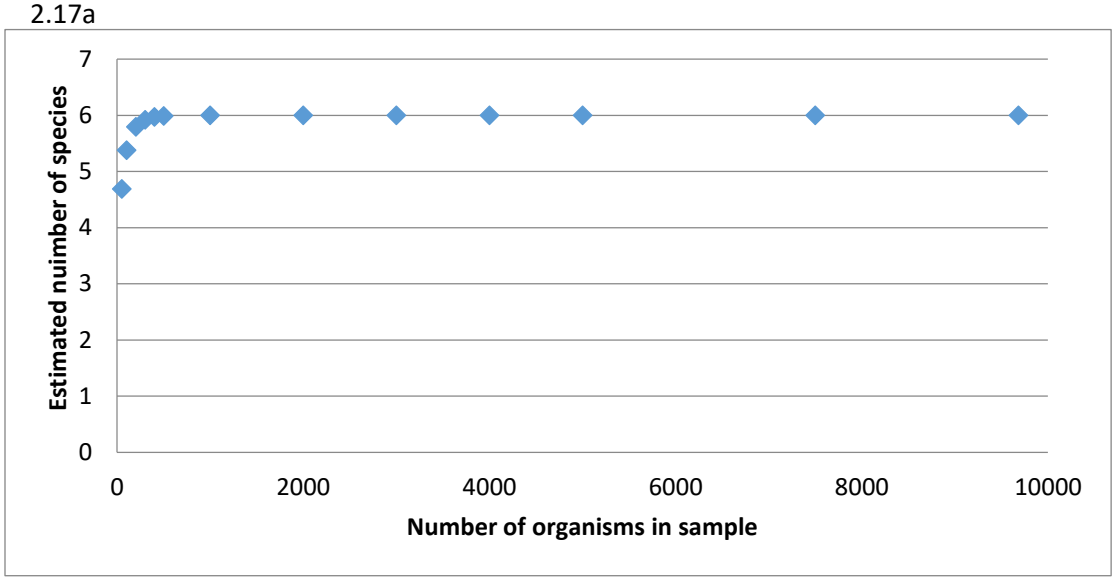
In the 30 year period since the 1979 study by Carter and MacGregor there has been much research on copepod systematics and a number of species have been re-designated (see Gerber 2000; Walter & Boxshall 2014). These re-designations have resulted in the following species for St. Pauls Inlet being revised between studies: *Acartia clausi* (listed by Carter & MacGregor 1979) revised to *A. hudsonica* Pinhey, 1926; and *Eurytemora hirundoides* (listed by Carter & MacGregor) revised to *E. affinis* (Poppe 1880). Also, *Pseudocalanus elongatus* is not likely a valid species according to Frost (1989). Table 2.3 shows an overlap of species between the 2 sampling periods. Additional taxonomic changes have resulted in the chaetognath *Sagitta elegans* now being designated *Parasagitta elegans* (Verill 1873) (Gerber 2000; Katona 1971; Thuesen, 2014). Species designations were upgraded for the St. Pauls Inlet 1977/78 data prior to comparisons with St. Pauls Inlet 2009/2010 data.

The species richness of microcrustacean zooplankton seen in 2009/2010 in St. Pauls Inlet was low with 5 species of copepods and 2 species of cladocerans. Species rarefaction curves were computed (using www2.biology.ualberta.ca/jbrzusto/rarefact.php) to estimate number of species expected in a random collection of individuals.

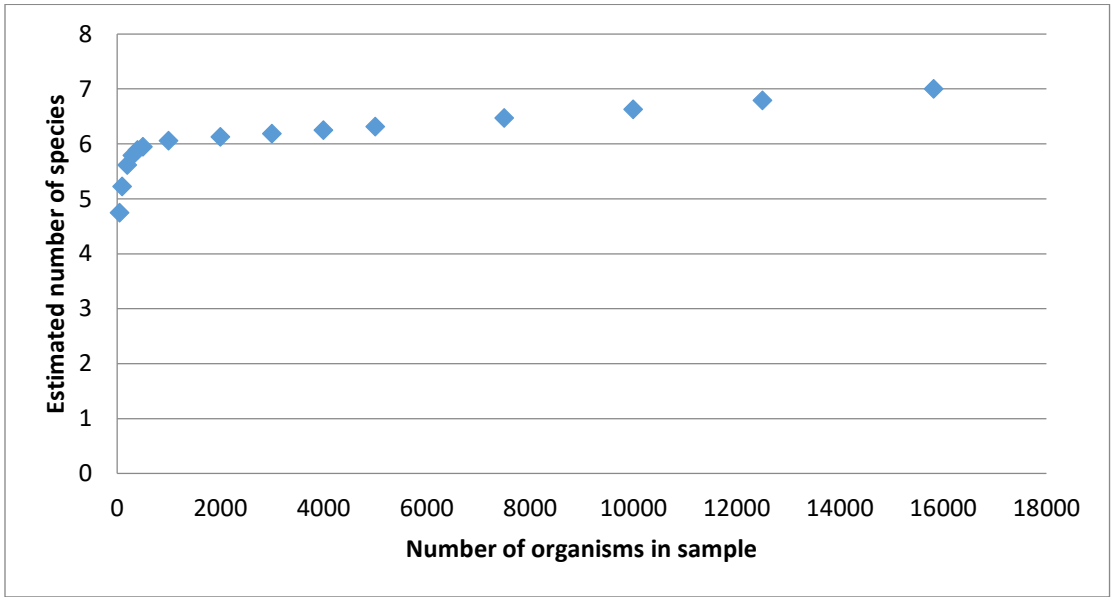
Curves interpolated from total number of individual microcrustaceans collected separately in 2009 and 2010 converged to asymptotes for both years (Figures 2.17a & b); this suggests that total sample size was likely sufficient to account for most species. However, the sampling effort may still have missed some rare species. Consistent with

measured salinities, many of the more common species of microcrustaceans found in St. Pauls Inlet in 2009/2010 are species typically found in estuaries or coastal/estuarine waters. Johnson and Allen (2005) list *Acartia hudsonica* and *Temora longicornis* as two of the species most commonly found in Atlantic coastal waters, being estuarine in nature. As in the 1979 study, *Mysis* were abundant in areas of sandy bottoms with a freshwater

2.17a



2.17b



Figures 2.17: a) 2009 and b) 2010 Species Rarefaction Curves for total microcrustaceans

influence, usually near Bottom Brook. Of the two species of opossum shrimps, *Mysis mixta* is a less common open-water relative of *Mysis stenolepsis* (Johnson & Allen 2005). *M. stenolepsis* (identified in the present study) occupies the intertidal and shallow subtidal area (Wigley & Burns 1971), and is seen in many estuaries of northeastern North America including the St. Lawrence (Winkler et al. 2007) so it is possible that Carter and MacGregor may have misidentified *M. mixta*.

2.6.4.1 Cluster Analysis

A comparison of the 2009 and 2010 study period based on cluster analysis of the microcrustacea (Figures 2.18 & 2.19) indicates no distinct seasonal clustering of sites in either year. There is no strong and obvious grouping of species related to a particular site or to a particular month. The zooplankton taxa are not separated by longitudinal salinity gradients in the inlet. There was no distinct clustering across the five St. Pauls Inlet sites sampled in 1979 (Figure 2.20).

Species composition differences were noted over the 30 year period. In Figure 2.21, two distinct clusters separate out at approximately 30 % similarity. The top cluster includes the aggregated presence/absence data from my study (2009 and 2010) whereas the bottom cluster includes the 1979 data set. Although there are still many of the same species found within the current day inlet as in the past there are a few species that were not found (Table 2.3). Species that were absent from my sampling were: *Centropages typicus, Eurytemora affinis, Harpacticus chelifer, Macrosetella gracilis, Metridia* sp., *Oncaea* sp., and *Pseudocalanus* sp.

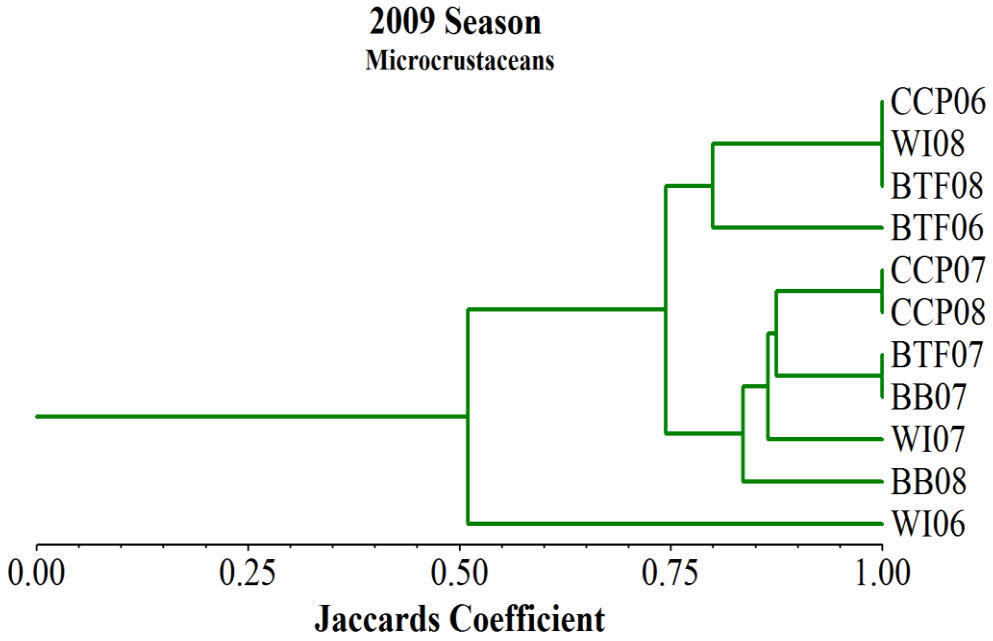


Figure 2.18: Cluster dendograms for 2009 Season for all sites in St. Pauls Inlet, NL. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 06, 07, 08 are June, July, and August respectively)

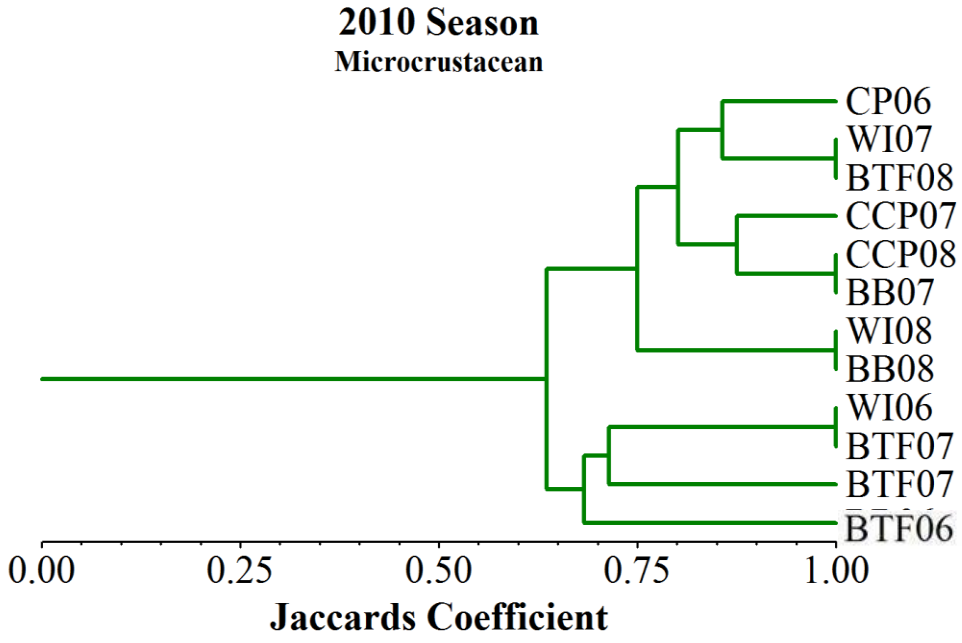


Figure 2.19: Cluster dendograms for 2010 Season for all sites in St. Pauls Inlet, NL. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 06, 07, 08 are June, July, and August respectively)

Although *C. finmarchicus* was present in 2009/2010 and is included in all of the cluster and NMDS diagrams, only one specimen was found during the entire study. This is much different from the "common to abundant at all locations and depths" description of Carter and MacGregor (1979). Species composition in Lake Melville differed somewhat compared to St. Pauls Inlet (Table 2.3). There were some overlapping species; however, there were more distinctly marine or distinctly freshwater zooplankton in Lake Melville that were not in St. Pauls Inlet. Additionally, the clustering of species in the Lake Melville data reflects the discrete depth sampling method used. Microcrustacean taxa identified in Lake Melville include *Acartia hudsonica, Calanus finmarchicus, Centropages hamatus, Chydorus sphaericus, Daphnia longiremis, Eubosmina longispina, Eurytemora affinis, Harpacticus chelifer, Metridia* sp. (probably *M. lucens* Boeck, 1864)¸ *Oithona similis, Pseudocalanus minutus, Pseudocalanus newmani,* and *Temora longicornis.*

Table 2.3: Zooplankton Species Identified across Three Studies. St. Pauls Inlet = SPI and Lake Melville= LM. Species marked with * were used in cluster dendograms and NMDS

Species	Phylum	Class	Salinity Range	SPI 1979	SPI 2009/10	LM 2007
Chydorus sphaericus Müller O.F., 1776*	Arthropoda	Branchiopoda	Marine/ Brackish / Fresh			X
Daphnia longiremis Sars, 1861*	Arthropoda	Branchiopoda	Fresh			X
Eubosmina longispina (Leydig, 1860)*	Arthropoda	Branchiopoda	Fresh			X
Evadne nordmanni Lovén, 1836*	Arthropoda	Branchiopoda	Marine	X	X	
Podon leuckarti (Sars, 1862)*	Arthropoda	Branchiopoda	Marine		X	
Acartia hudsonica Pinhey, 1926*	Arthropoda	Copepoda	Marine	X	X	X
Calanus finmarchicus (Gunnerus, 1770)*	Arthropoda	Copepoda	Marine	X	X	X
Centropages hamatus (Liljeborg, 1853)*	Arthropoda	Copepoda	Marine			X
*Centropages typicus (*Kröyer, 1849)*	Arthropoda	Copepoda	Marine	X		
Eurytemora affinis (Poppe, 1880)*	Arthropoda	Copepoda	Marine	X		X
Harpacticus chelifer (Muller O.F., 1776)*	Arthropoda	Copepoda	Marine	X		X
Macrosetella gracilis (Dana, 1847)*	Arthropoda	Copepoda	Marine	X		
Metridia longa (Lubbock, 1854)*	Arthropoda	Copepoda	Marine	X		
Metridia lucens Boeck, 1865*		Copepoda				X
Copepod Nauplii / copepodites	Arthropoda			X	X	X

Species	Phylum	Class	Salinity Range	SPI 1979	SPI 2009/10	LM 2007
*Microsetella norvegica (*Boeck, 1865)*	Arthropoda	Copepoda	Marine		X	
Oithona similis Claus, 1866*	Arthropoda	Copepoda	Marine/ Brackish / Fresh	X	X	X
Oncaea venusta Philippi, 1843*	Arthropoda	Copepoda	Marine	X		
Pseudocalanus elongatus (Boeck, 1865)*	Arthropoda	Copepoda	Marine	X		
Pseudocalanus minutus (Kröyer, 1845)*	Arthropoda	Copepoda	Marine			X
Pseudocalanus newmani Frost, 1989*	Arthropoda	Copepoda	Marine			X
Temora longicornis (Müller O.F., 1785)*	Arthropoda	Copepoda	Marine	X	X	X
Brachyura (Crab) Zoea	Arthropoda	Malacostraca		X	X	
Mysis mixta Lilljeborg, 1852	Arthropoda	Malacostraca	Marine	X		
Mysis stenolepis S.I. Smith, 1873	Arthropoda	Malacostraca	Marine	X	X	
Parasagitta elegans (Verrill, 1873)	Chaeto-gnatha	Sagittoidea	Marine	X	X	X
Aurelia aurita (Linnaeus, 1758)	Cnidaria	Scyphozoans	> 6 ‰	X	X	
Fish Larvae	Chordata	Osteichthyes		X	X	

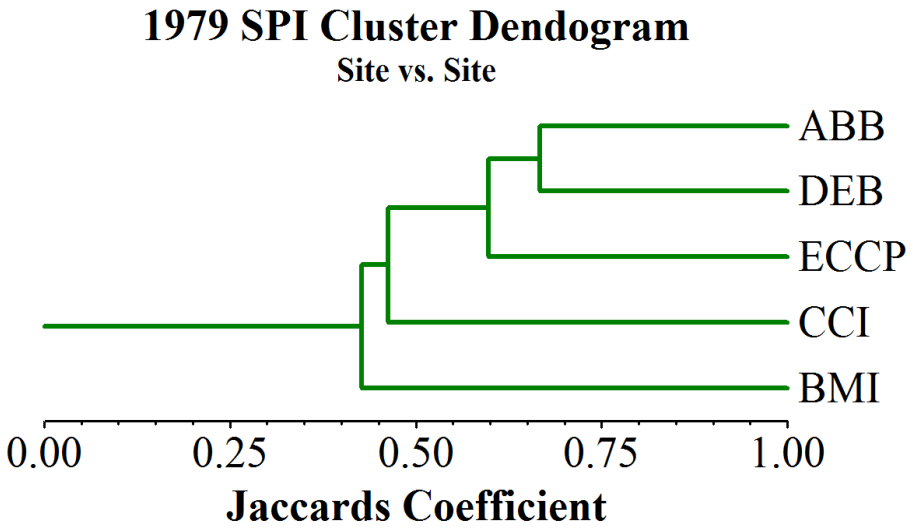


Figure 2.20: Cluster dendogram for 1979 SPI indicating no distinct clustering across sites.

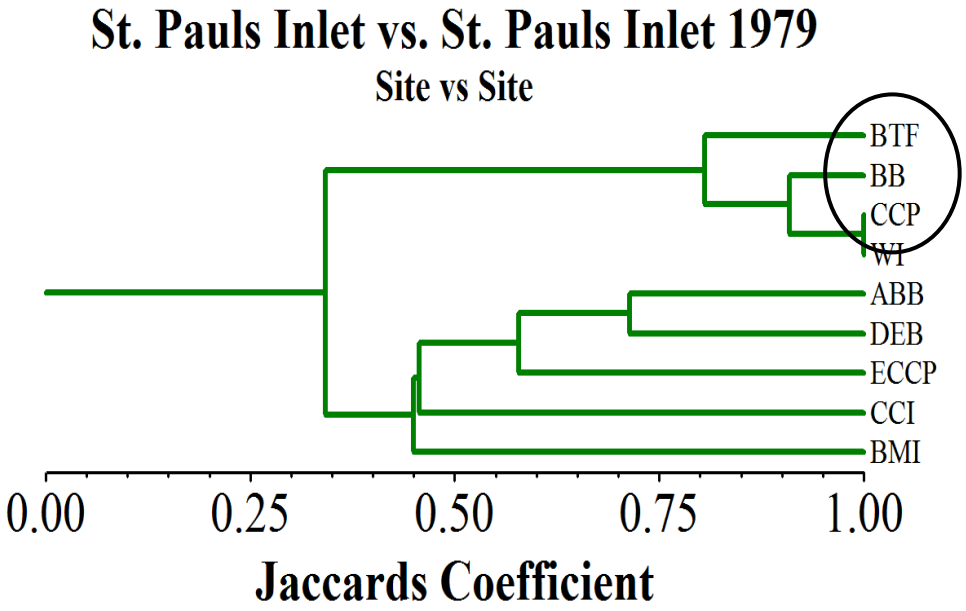


Figure 2.21: Cluster dendogram for SPI Comparison. Comparison of Carter & MacGregor 1979 study and 2009/2010 study by site locations, both in St. Pauls Inlet, NL. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook, ABB = 1979 Bottom Brook, BMI = 1979 Between the Falls, CCI = 1979 Central Inlet, DEB= 1979 Eastern Brook, ECCP = 1979 Charles Cove Point). See previous Figure 2.2 for spatial reference.

As seen in Table 2.4, average salinity in Lake Melville appears to be even lower than in the St. Pauls Inlet Overall Salinity per site. However this is due to a very low salinity at the surface resulting from the freshwater influx from the Churchill River. There is a more distinct halocline, with the heavier more saline water towards the bottom and the freshwater floating on the surface.

Table 2.4: Salinity Data for Lake Melville, Labrador, Canada

Site	Salinity (‰)	Day	Month	Depth (m)	Average Salinity(‰)
1	20.31	12	10	25	
3	8.71	12	10	5	10.05
5	1.12	12	10	1	
9	19.60	12	10	15	
7	11.60	12	10	8	10.07
11	1.00	12	10	1.5	
15	18.30	13	10	7	12.4
16	6.50	11	10	0.5	
14	13.38	13	10	2.5	15.10
18	16.81	13	10	7	

Cluster analysis comparison of microcrustaceans between Lake Melville and St. Pauls Inlet (2009/10) indicated 2 distinct clusters, with 10 % similarity (Figure 2.22). Several species of cladocerans caused this clustering. Only in Lake Melville *Chydorus sphaericus, Daphnia longiremis,* and *Eubosmina longispina* were found, all freshwater species (Campbell & Knoechel 2008). However, only the primarily marine/brackish water cladocerans *Evadne nordmanni* and *Podon leuckarti* (Johnson & Allen 2005) were found in St. Pauls Inlet.

Furthermore, in St. Pauls Inlet, there was only one additional species that was not found in Lake Melville, the harpacticoid copepod *Microsetella norvegica*; whereas in Lake Melville there were 4 additional marine species that were not seen in St. Pauls Inlet: *Eurytemora affinis*, *Harpacticus chelifer*, *Pseudocalanus minutus*, and *Pseudocalanus newmani*. Carter (1965) identified a bimodally sized population of *Pseudocalanus minutus* in Tessiarsuk, a coastal brackish water fjord in northern Labrador. Based on the taxonomic revision of the genus by Frost (1989), it is quite likely that these were the same two species as found in Lake Melville: the larger *P. newmani* and the smaller *P. minutus*. (This would not affect my statistical analysis as I did not directly compare St. Pauls Inlet 1979 with Lake Melville data, and *Pseudocalanus* were not found in St. Pauls Inlet 2009/2010).

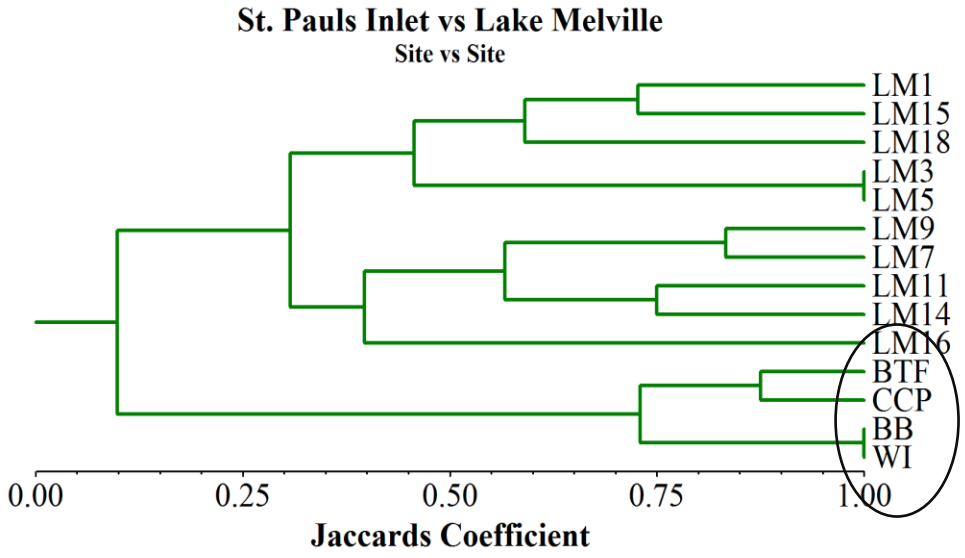


Figure 2.22: Cluster analysis of zooplankton species composition comparing St. Pauls Inlet to Lake Melville (LM). The St. Pauls Inlet (2009/2010) sites cluster together, indicated by the circle. (BTF = Between the Falls, BB = Bottom Brook, WI = Western Island, CCP – Charles Cove Point

Species-salinity relationships are reflected in the cluster patterns for the Lake Melville sites (Table 2.3, Figure 2.22). LM3 and LM5 clustered together – these were surface sites nearest to the river output, and with low salinity (< 9 ‰). As well, sites LM1 and LM15 – the deeper and more saline sites (> 18 ‰) tended to cluster together.

2.6.4.2 Non-metric Multi-dimensional Scaling

NMDS analysis showed similar results to groupings observed in the previous cluster dendograms. As stated earlier the goal when performing NMDS analysis is to produce correlation results with a stress value as close to zero as possible with the smallest number of dimensions. A scree plot (Figure 2.23) shows that for the comparisons of St. Pauls Inlet (present study) to the 1979 Carter and MacGregor St. Pauls Inlet study the near zero stress level that is found with the 3 dimensions. The 4 dimension solution is also close to zero in stress value; however, the addition of the extra dimension would complicate the results without significantly lowering the stress from a 3 dimension analysis. For that reason, all NMDS results are reported for the 3 dimension solution. See Appendix 4 for 2-D Matrix plots.

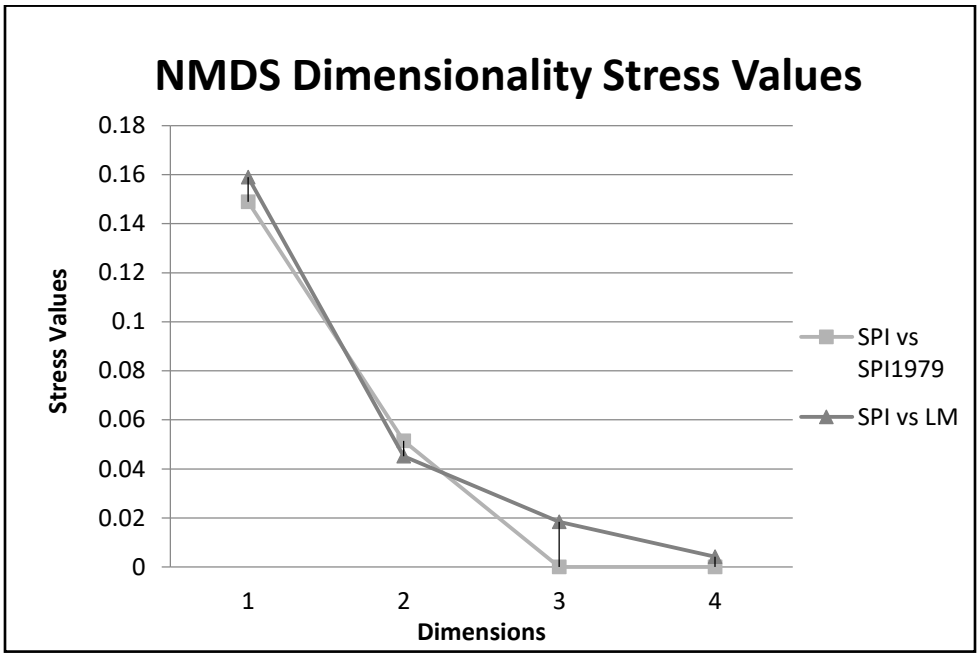


Figure 2.23: Dimensionality and Stress Values for NDMS Parameters for St. Pauls Inlet 2009/2010 (SPI) vs. St. Pauls Inlet 1979 (SPI1979) and St. Pauls Inlet 2009/2010 (SPI) vs. Lake Melville (LM)

NMDS ordinations for 2009 and 2010 separately (Figures 2.24 & 2.25) showed no distinct groupings of sites for either year. Correlations of environmental factors with axes also showed no noticeable patterns between the years (Tables 2.5 and 2.6). In the 2009 season, Axis I was significantly and negatively correlated both with bottom salinity and overall salinity, Axis II was positively correlated with surface temperature, and Axis III exhibited no significant correlations with the tested environmental factors. In the 2010 season, Axis I was negatively correlated with surface temperature, Axis II exhibited no significant correlations, and Axis III was positively correlated with surface, bottom, and overall temperature. See Appendix 4 for 2-D matrix plots between axes. No Bonferroni correction was used because the analyses are intended to be exploratory rather than for hypothesis testing.

Table 2.5: 2009 Season correlations (all sites) between environmental characteristic and NMDS axes

Environmental Characteristics		NMDS Axes		
		Axis I	**Axis II**	**Axis III**
	Surface Salinity	-0.556 0.076	0.515 0.105	0.179 0.618
	Bottom Salinity	**-0.687** **0.020**	0.591 0.056	0.494 0.122
	Overall Salinity	**-0.660** **-0.027**	0.587 0.058	0.354 0.286
	Surface Temp	-0.486 0.129	**0.702** **0.016**	0.183 0.591
	Bottom Temp	-0.436 0.180	0.120 0.725	-0.102 0.766
	Overall Temp	-0.519 0.102	0.432 0.184	0.029 0.931
	Depth	-0.142 0.677	0.591 0.560	0.348 0.294

Cell Contents: Pearson Correlation P-Value (**Bold values significant at p<0.05)**

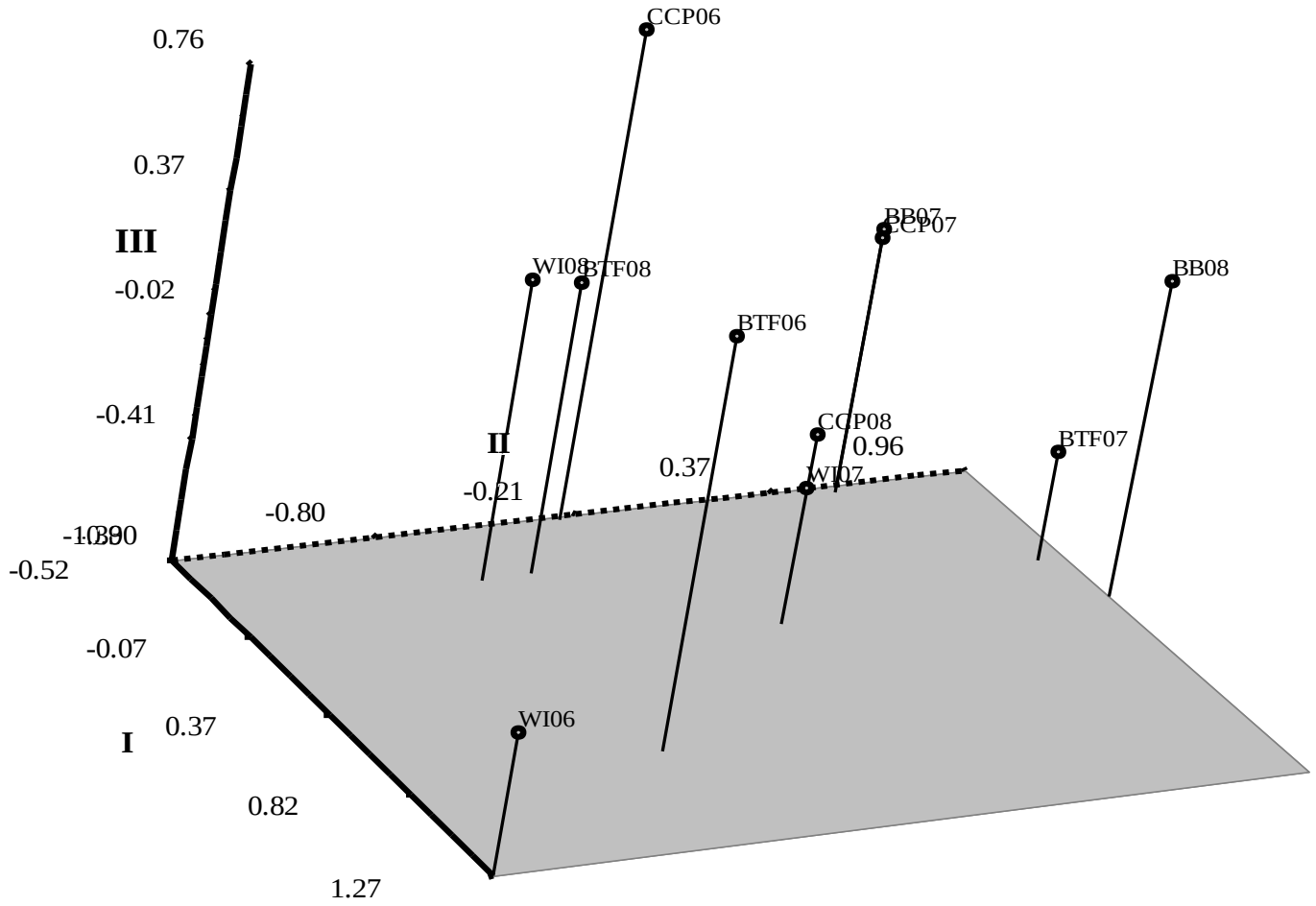


Figure 2.24: 3-D NMDS for SPI 2009 Season. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 06 = June, 07 = July, 08 = August)

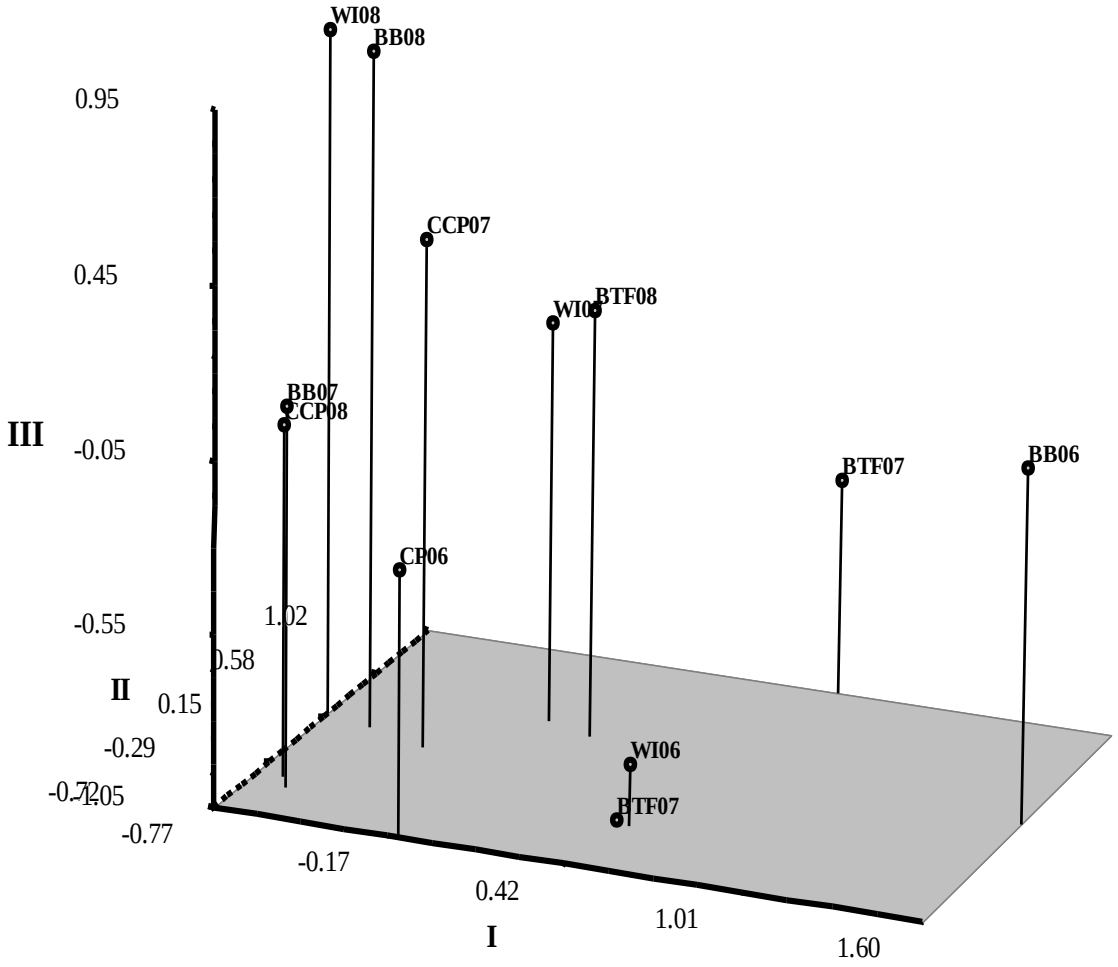


Figure 2.25: 3-D NMDS for SPI 2010 Season. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 06 = June, 07 = July, 08 = August)

Table 2.6: 2010 Season correlations (all sites) between environmental characteristic and NMDS axes

Environmental Characteristics		NMDS Axes		
		Axis I	**Axis II**	**Axis III**
	Surface Salinity	0.056 0.864	0.199 0.535	-0.198 0.538
	Bottom Salinity	-0.510 0.086	0.124 0.701	-0.037 -0.910
	Overall Salinity	-0.299 0.346	0.241 0.451	-0.181 0.573
	Surface Temp	**-0.705** **0.010**	0.284 0.371	**0.757** **0.004**
	Bottom Temp	-0.568 0.054	0.064 0.843	**0.704** **0.011**
	Overall Temp	0.011 0.989	0.187 0.560	**0.809** **0.001**
	Depth	-0.004 0.989	0.223 0.485	-0.178 0.581

Cell Contents: Pearson Correlation

P-Value **(Bold values significant at p < 0.05)**

NMDS ordinations (Figure: 2.26) for St. Pauls Inlet 1979 and St. Pauls Inlet 2009/2010 showed a distinct grouping separating the two time series. Correlations between the environmental variables and the 3 axes for St. Pauls Inlet data (both study periods) were calculated (Table 2.7). Axes I and 2 were significantly correlated with Overall, Bottom and Surface Temperature, while Axis III was positively correlated with temperature and negatively correlated with Bottom Salinity and Depth. See Appendix 4 for 2-D matrix plots between axes.

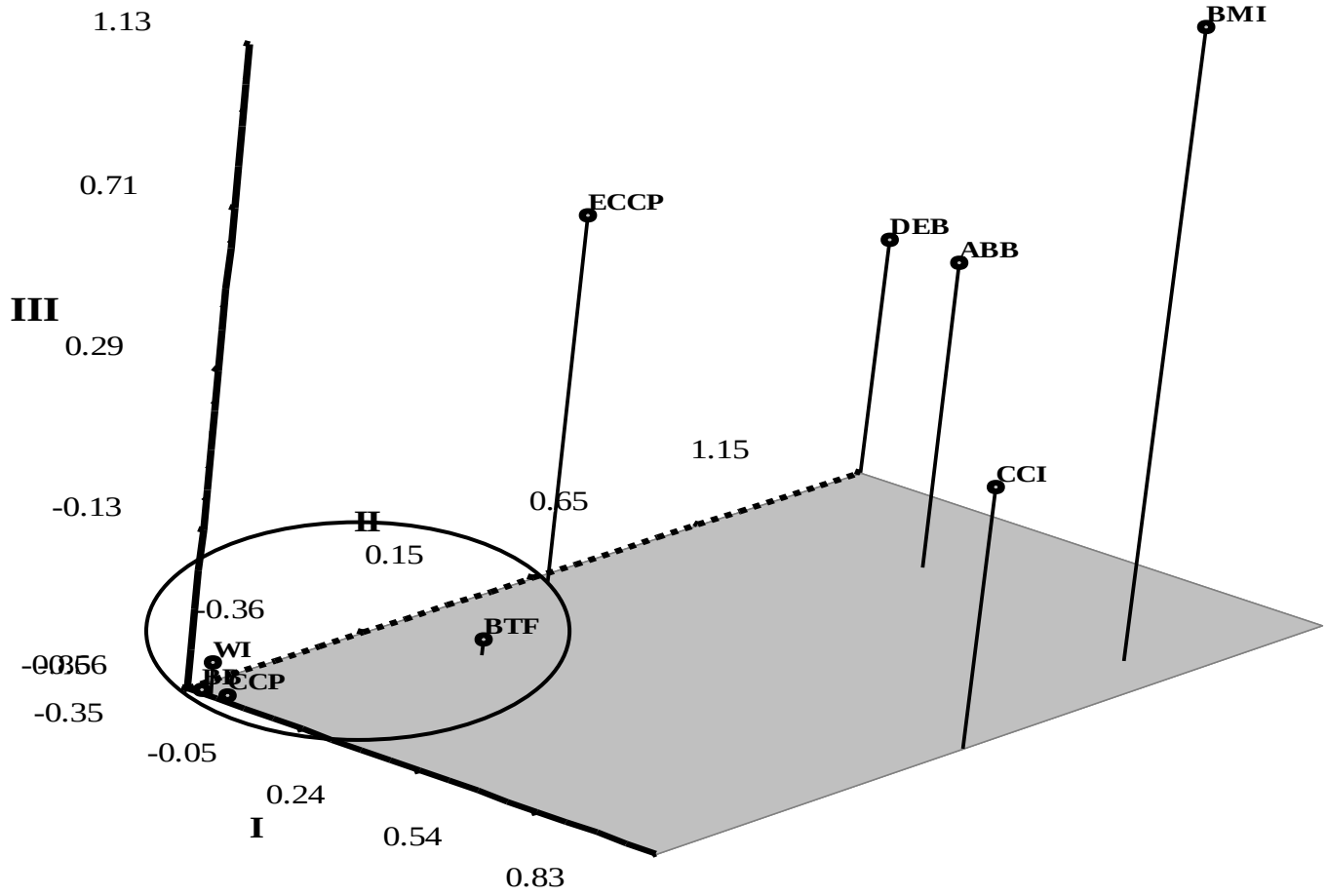


Figure 2.26: 3-D NMDS for SPI 2009/2010 Comparison sites to sites from 1979 SPI. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook, ABB = 1979 Bottom Brook, BMI = 1979 Between the Falls, CCI = 1979 Central Inlet, DEB= 1979 Eastern Brook, ECCP = 1979 Charles Cove Point) Circle shows the SPI 2009/2010 grouping

Table 2.7: Correlations between environmental variables and the axes for NMDS on St. Pauls Inlet 1979 vs. St. Pauls Inlet 2009/2010

		NMDS Axes		
		Axis I	**Axis II**	**Axis III**
Environmental Characteristics	**Surface Salinity**	0.093 0.773	0.369 0.238	0.409 0.187
	Bottom Salinity	-0.277 0.383	-0.510 0.910	**-0.675** **0.016**
	Overall Salinity	-0.008 0.980	0.136 0.672	0.091 0.779
	Surface Temp	**0.663** **0.027**	**0.860** **0.000**	**0.876** **0.000**
	Bottom Temp	**0.665** **0.018**	**0.883** **0.000**	**0.928** **0.000**
	Overall Temp	**0.637** **0.017**	**0.892** **0.000**	**0.913** **0.000**
	Depth	-0.441 0.151	**-0.672** **0.029**	**-0.774** **0.003**

Cell Contents: Pearson Correlation

P-Value **(Bold values significant at p < 0.05)**

Table 2.8: Correlations between environmental characteristics and NMDS axes for Lake Melville vs. St. Pauls Inlet 2009/2010 NMDS Comparison

Environmental Characteristics		NMDS Axes		
		Axis I	**Axis II**	**Axis III**
	Surface Salinity	0.008 0.985	0.309 0.457	-0.310 0.455
	Bottom Salinity	0.199 0.637	0.350 0.395	-0.440 0.275
	Overall Salinity	**0.603** **0.008**	**0.698** **0.001**	**0.523** **0.026**
	Surface Temp	0.377 0.357	-0.531 0.176	**-0.750** **0.032**
	Bottom Temp	-0.052 0.902	0.003 0.994	0.059 0.889
	Overall Temp	0.246 0.558	0.277 0.507	-0.437 0.279
	Depth	0.202 0.421	0.056 0.824	-0.299 0.227

Cell Contents: Pearson Correlation

P-Value **(Bold values significant at p < 0.05)**

NMDS ordination showed strong differentiation between St. Pauls Inlet and Lake Melville samples (Figure 2.27). All axes were significantly and positively correlated with overall salinity (Table 2.8), with Axis 3 also negatively correlated with surface temperature. The more saline sites in Lake Melville (LM1, LM15, and LM18) were located closest to the St. Pauls Sites along Axis 2. See Appendix 4 for 2-D matrix plots between axes.

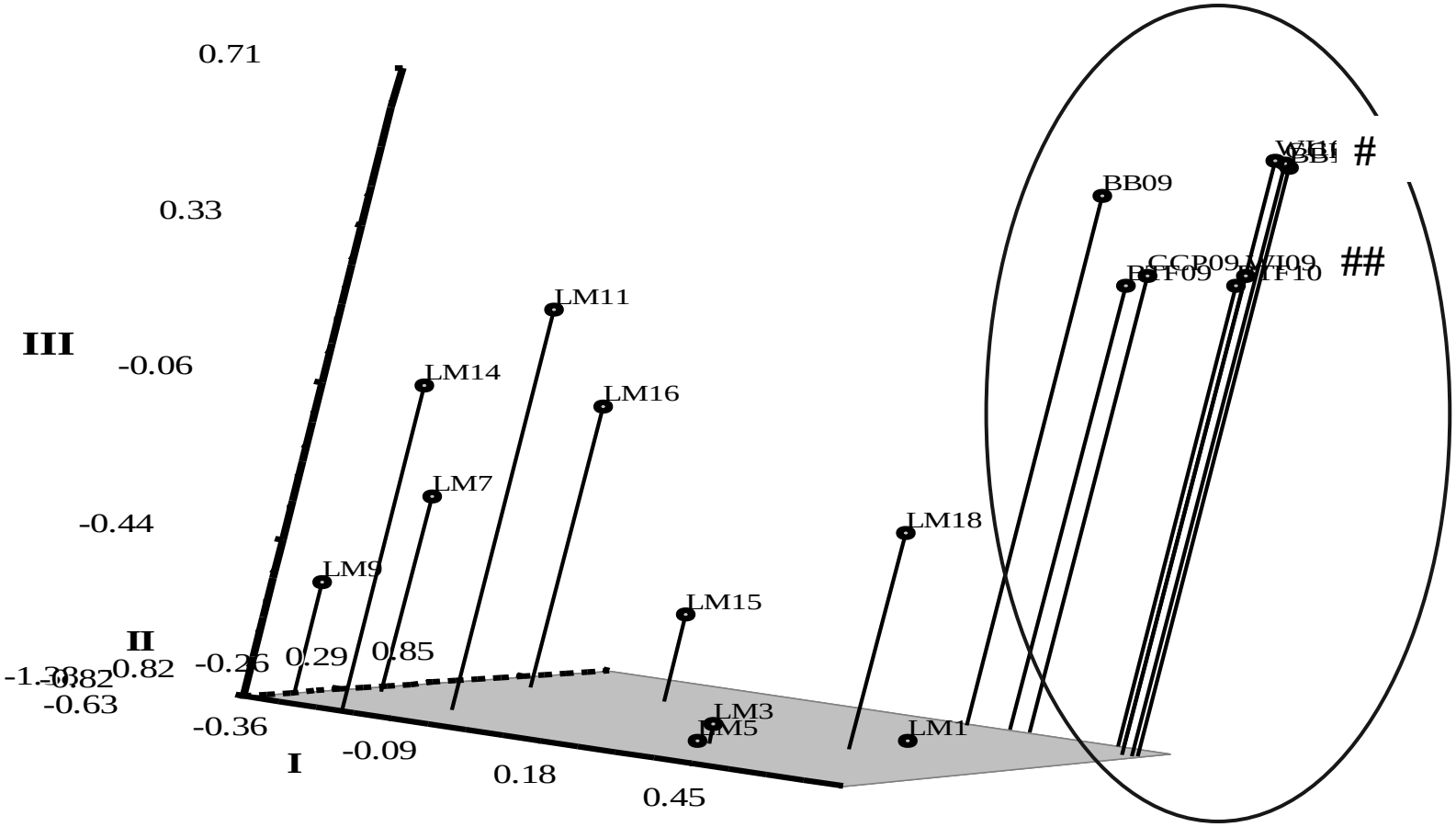


Figure 2.27: 3-D NMDS SPI Comparison to Lake Melville. Comparison is between the sites in SPI from 2009/10 and LM from 2007. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 09 = 2009, 10 = 2010); Lake Melville sampling sites designated LM. Circle is showing SPI sampling sites for 2009 and 2010. (# is overlapping points of BB10, WI10, and CCP10; ## is overlapping points of WI09 & BTF10)

Table 2.9: Yearly Average Air Temperature and Total Precipitation for the years of the two studies of St. Pauls Inlet. (Data from Government of Canada Climate website)

	Year	Average Temp (°C)	Total Precipitation (mm)
Daniels Harbour Station	1976	2.7	1176.9
	1977	3.5	1116.4
	1978	2.6	1231.4
	2009	2.3	728.0
	2010	3.1	843.5
Cow Head Station	2009	3.23	1127.2
	2010	1.33	616.7

2.7 Discussion

Based on its physical and chemical features as well as its zooplankton species composition, St. Pauls Inlet has all the indications of an estuarine system; it cannot be classified as simply a marine or freshwater system. In terms of geomorphology and circulation patterns (Chapter 1), St. Pauls Inlet can be characterized as a weakly-stratified fjordal estuary with only a small exchange of salt water with the Gulf of St. Lawrence due to a shallow sill and narrow entrance (Carter & MacGregor 1979). As a consequence of this small exchange, Carter and MacGregor determined that a limited amount of mixing resulted in spring stratification of the inlet, with the water on the surface of the Inlet approximately half of the salinity of the water at the bottom of the inlet (at least in May). In the current study there was some evidence of a halocline only in the two sites (Bottom Brook and Between the Falls) nearest freshwater inflow. This lack of observed stratification throughout the inlet may indicate either that the physiochemical features of the inlet have changed in the decades between studies or that stratification is brief and occurs only in early spring (a period not sampled in the present study). While there are no

long-term data for inflows into St. Pauls Inlet, historical data are available from Portland Creek Pond, a restricted coastal waterbody approximately 40 km north of St. Pauls Inlet, which show a similar long-term pattern (1984-2014) of higher stream flow in May (Environment Canada https://wateroffice.ec.gc.ca/report).

It is also possible that recent, and potentially ongoing, prevailing weather patterns may have prevented the development of stratification due to the increased occurrence of high energy wind events. Carter and MacGregor postulated that observed stratification was due mainly to very cold and salty marine water entering the Inlet during winter and sinking to the bottom. Local ecological knowledge indicates that during the year prior to and during the years of the current study the inlet did not freeze over during the winter months as is thought to be typical. This accords with physical oceanographic data from the Gulf of St. Lawrence in 2009/2010 that showed numerous above normal near-surface water temperatures and shorter than normal duration of sea-ice (Galbraith et al. 2010; 2011). An extended open-water period in the inlet could result in cooler surface waters with more exposure of the water column to wind energy, thus more mixing. However, average land-based temperatures between the study years show some overlap (Table 2.9). Precipitation in 2009-2010 was almost half that of previous years (Table 2.9); this decreased freshwater input to the inlet could potentially weaken early spring stratification, but it remains unclear why stratification was stronger in 2010 rather than 2009. The historical station for 1977-1979 was Daniels Harbour, which is approximately 50 km north of St. Pauls along the coast. Data for the 2009-2010 years were available

from Daniels Harbour as well as from the Cow Head weather station, approximately 10 km from St. Pauls also along the coast.

Contrary to hypothesis 1, that there was no overall change in community composition over time (hypothesis 1), St. Pauls Inlet may have seen some changes in the last 30 years in species composition of microcrustacean zooplankton. The large marine copepod *Calanus finmarchicus* was common to abundant at all stations and depths during the summer sampling in 1977/78 but was collected only once during my sampling, on July 20, 2010 at the Between the Falls location. The microcrustaceans sampled in both periods and listed as common or abundant, such as *Acartia clausi/hudsonica, Oithona similis* and *Temora longicornis*, indicate that the inlet contains coastal or brackish water species (Johnson & Allen 2005). The only other species that was found during both studies was *Evadne nordmanni*; however it was listed as infrequent in summer 1977 through the outer reaches of the inlet (Carter & MacGregor 1979) unlike the 2009/2010 study where it was quite abundant throughout the inlet. While there was a halocline present briefly at Bottom Brook, on June 2, 2010, no freshwater organisms were found in the upper freshwater layer. The Charles Cove Point location had the highest overall salinity of the sites but did not have salinity over 31 ‰. Salinities in the outer Gulf of St. Lawrence typically range from 29 - 31‰ in the southwest extremity to 33 ‰ in the Strait of Bell Isle (Galbraith 2010). In agreement with hypothesis 2, the cluster analyses may show no distinct grouping among sites, Figures 2.18 & 2.19, because the sites contain species with tolerance to some fluctuation in salinity which can survive throughout the brackish inlet.

Several factors were quite different between the sampling of 1977/1978 and 2009/2010. These sampling differences, such as the type of gear, time of day, and even frequency of sampling, may have resulted in the significant differences between the 1979 inlet study and the present day study in terms of the diversity of species found. The 2009/2010 study attempted to align sampling as much as possible to the 1979 study; sampling months that overlapped with Carter and MacGregor's study were for part of July and August 1977 (summer). Carter and MacGregor sampled infrequently over this period, and also sampled for a one-week period in May 1978 (spring). The copepod *Eurytemora* was abundant in the 1978 May samples; I did not sample in May which may explain the lack of this species in the 2009/2010 survey. Variations in mesh sizes among all three studies (St. Pauls Inlet 2009/2010, St. Pauls Inlet 1979, and Lake Melville) may have influenced the species collected; however Makabe et al. (2012) suggested this is less problematic when only presence/absence data are considered.

Carter and MacGregor (1979) found both a strong halocline and thermocline in May, a month not sampled during my study. Such vertical stratification was less pronounced in July than in June (this study) or May (Carter & MacGregor 1978 study). The environmental correlations that seemed to affect the NMDS axes in the 2009/2010 comparison, Figures 2.24 & 2.25, and then the 2009/2010 to 1979, Figure 2.26, study was most related to temperature. This is in line with other studies that have found that estuarine zooplankton species composition are influenced by the temperature more so than by salinity or stratification patterns (Marques et al. 2007; Menéndez et al. 2012).

In disagreement with hypothesis 3, St. Pauls Inlet is also different in species composition compared with Lake Melville. Although the two water bodies share similar physical features, Lake Melville has a distinct species composition of zooplankton, as indicated by both the cluster dendograms, Figure 2.22, and the NMDS graphs. These differences are due to a noticeable presence of strictly freshwater species, as well as some predominantly marine species as opposed to the more estuarine species typical of St. Pauls Inlet. Due to the large rivers in its catchment, there is a larger freshwater drainage into Lake Melville - the Churchill River provides 58 km^3 yr^{-1} freshwater inflow or 90% of the input, which is substantially higher than the estimated 0.41 km^3 yr^{-1} (13 m^3sec^{-1}) coming into St. Pauls Inlet from Bottom Brook (Carter & MacGregor 1979; Vilks & Mudie 1983). Many of the samples from Lake Melville were taken close to the mouth of the Churchill River, as seen in Figure 2.3, this sampling is not a representation of all of Lake Melville. Both cluster analysis and the NMDS ordination show two distinct groupings – one being the species composition of St. Pauls Inlet and the other being the species found in Lake Melville. Four microcrustacean species occurred at both sampling sites; these were the copepods *A. hudsonica, C. finmarchicus, O. similis,* and *T. longicornis.* Not surprisingly due to the location of the sampling, Lake Melville had distinctly freshwater species as well, such as the cladocerans *Daphnia longiremis, Chydorus sphaericus* and *Eubosmina longispina.* Presence of these species might suggest downstream drift of zooplankton via the Churchill River, similar to that found by Campbell (2002) in a Newfoundland stream. Differences in salinity have been correlated with differences in zooplankton faunal compositions in other estuaries and bays (Harvey et al. 2001; Marques et al. 2007).

Overall salinity was correlated with the different clusters between Lake Melville and St. Pauls Inlet. Another complicating factor related to differences in species composition was seasonal differences as Lake Melville samples were available only for October.

In addition, Lake Melville appears to be more strongly stratified, with fresh water at the surface lying on deeper marine water. Surface salinities in Lake Melville in October 2007 ranged from 1 to 6.5 ‰, with deeper water salinities ranging from 9 to 20 ‰ (Table 2.4), while St. Pauls Inlet, as seen in Appendix 2, showed a range in surface salinity between 4.6 ‰ – 25.6 ‰ and a minimum salinity for bottom waters being 13.3 ‰ and maximum being 29.9 ‰ . (Ranges of 8 to 25 ‰ for surface, and 25 to 31 ‰ for bottom waters > 24 m, were observed by Carter and MacGregor in 1977/78). Lake Melville is also quite a bit deeper than St. Pauls Inlet (maximum depths 256 m vs. 36 m).

Salinity and temperature are often cited as factors affecting zooplankton species composition clustering and spatial patterning within estuaries (e.g. Vieria et al. 2003; Menéndez et al. 2012; Sutherland et al. 2013). Based on NMDS analysis, Almeida et al. (2012) found two distinct groups of copepod species in a Brazilian estuary – one coastal/neritic group associated with salinity ~ 34 ‰, and one coastal/estuarine associated with salinity ~ 24 ‰. However, observed gradients in either salinity or temperature were seemingly not strong enough within St. Pauls Inlet to result in noticeable clustering in zooplankton spatial distribution. A temperature effect may be detectable more with ordination than with binary clustering data.

A lack of consistent spatial or seasonal patterns in zooplankton community structure has been observed in other estuaries (e.g. Mallin 1991; Gómez-Erache et al. 2000; Primo et al. 2009; Paul et al. 2016). General factors leading to the absence of any longitudinal or marked vertical patterns in zooplankton species composition are i) little freshwater input (Primo et al. 2009; Paul et al. 2016) and ii) well-mixed water column due to wind and currents (Mallin 1991; Gómez-Erache 2000). The absence of observed longitudinal patterns in zooplankton composition in St. Pauls Inlet in either 2009 or 2010 then is not overly surprising. Its relatively shallow depth, coupled with the observed high winds and a wind-exposed broad basin, likely renders the inlet well-mixed both vertically and horizontally. Any longitudinal salinity gradient would appear to occur briefly after the spring melt, after which freshwater discharge may be much decreased leading to destratification and resulting in a horizontally and vertically homogenous water body in terms of temperature and salinity.

2.8 Literature Cited

Almeida, L. R., Costa, I. S., and Eskinazi-Sant'Anna, E. M. 2012. Composition and abundance of zooplankton community of an impacted estuarine lagoon in northeast Brazil. Brazilian Journal of Biology. 72:13-24.

Aube, C. I., Locke, A., and Klassen, G. J. 2005. Zooplankton communities of a dammed estuary in the Bay of Fundy, Canada. Hydrobiologia. 548:127-139.

Barnes, R. S. K. 1994. The Brackish-water Fauna of Northwestern Europe. Cambridge University Press, New York. USA.

Beaugrand, G., Brander, K. M., Lindley, J. A., Souissi, S., and Reid, P. C. 2003. Plankton effect on cod recruitment in the North Sea. Nature. 426:661–664.

Black, A. R. and Dodson, S. I. 2003. Ethanol: a better preservation technique for *Daphnia*. Limnology and Oceanography: Methods. 45-50.

Bradford, J. M. 1976. Partial revision of the *Acartia* subgenus *Acartiura* (Copepoda: Calanoida: Acarthiidae). N.Z. J. of Marine and Freshwater Research. 10:169-202.

Bradford-Grieve, J. M. 1999. *ICES Identification Leaflets for Plankton*. International Council for the Exploration of the Sea. Leaflet No. 181.

Busch, A. and Brenning, U. 1992. Studies on the status of *Eurytemora affinis* (Poppe, 1880) (Copepoda, Calanoida). Crustaceana. 2:13-38.

Campbell, C.E. and Knoechel, R. 2008. Species occurrences of microcrustacean zooplankton in Labrador, Canada. Verhandlungen Internationale Vereinigung für Theoretische und Ange-wandte Limnologie. 30:77-81.

Carter, J. A. and Dadswell, M. J. 1983. Seasonal and spatial distribution of planktonic crustacea in the Lower Saint John River, a multibasin estuary in New Brunswick, Canada. Estuaries. 6:142-153.

Carter, J. A. and MacGregor, C. D. 1979. Marine Inventory of St. Paul's Inlet for Gros Morne National Park. Martec Limited, Halifax, NS. Report for Parks Canada.

Carter J. C. 1965. The ecology of the calanoid copepod *Pseudocalanus minutus* Kroyer in Tessiarsuk, a coastal meromictic lake of Northern Labrador. Limnology and Oceanography. 10:345-353.

De Bernardi, R. 1984. Methods for the estimation of zooplankton abundance. Chap. 3 *in* Downing, J.A. and Rigler, F.H. (eds) A Manual on Methods for the Assessment of Secondary Productivity in Fresh Waters. 2nd ed. Blackwell Scientific Publications. Oxford. 1995.

Della Croce, N. 1974. Zooplankton Sheet 143. ICES Identification Leaflets for plankton. International Council for the Exploration of the Sea. Copenhagen.

Downing, J.A. and Rigler, F. H. (eds) A Manual on Methods for the Assessment of Secondary Productivity in Fresh Waters. 2nd ed. Blackwell Scientific Publications. Oxford. 1984. pp. 336-412.

Duffy, J. E. and Stachowicz, J. J. 2006. Why biodiversity is important to oceanography: potential roles of genetic, species, and trophic diversity in pelagic ecosystem processes. Marine Ecology Progress Series. 311:179-189.

Duthie, H. C. and Ostrofsky, M. L. 1974. Plankton, chemistry, and physics of lakes in the Churchill Falls region of Labrador. J. of Fish. Res. Bd. Canada. 31(6):1105-1117.

ESRI 2015. ArcGIS Desktop: Release 10.3.1 Redlands, CA: Environmental Systems Research Institute.

Frolander, H. F., Miller, C. B., Flynn, M. J., Myers, S. C., and Zimmerman, S. T. 1973. Seasonal cycles of abundance in zooplankton populations of Yaquina Bay, Oregon. Marine Biology. 21:277-289.

Frost, B. W. 1989. A taxonomy of the marine calanoid copepod genus *Pseudocalanus*. Canadian Journal of Zoology. 63:525-551.

Galbraith, P.S., Pettipas, R.G., Chassé, J., Gilbert, D. Larouche, P. Pettigrew, B., Gosselin, A., Devine, L. and Lafleur, C. 2010. Physical oceanographic conditions in the Gulf of St. Lawrence in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/035. iv + 73 p.

Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Brickman, D., Pettigrew, B., Devine, L., Gosselin, A., Pettipas, R.G., and Lafleur, C. 2011. Physical oceanographic conditions in the Gulf of St. Lawrence in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/045. iv + 82 p.

Gauch, H. G. 1982. Multivariate analysis in community ecology. Cambridge University Press. Cambridge, MA. USA.

Gerber, R. P. 2000. An identification manual to the coastal and estuarine zooplankton from Passamaquoddy Bay to Long Island Sound. Acadia Productions, Brunswick, Maine.

Gómez-Erache, M., Norbis, W. and Bastreri, D. 2000. Wind effect as forcing factor controlling distribution and diversity of copepods in a shallow temperate estuary (Solis Grande, Uruguay). Scientia Marina. 64: 87-95.

Government of Canada Climate. Government of Canada. Accessed from climate.weather.gc.ca November 2014.

Grant, A. C. 1975. Seismic reconnaissance of Lake Melville, Labrador. Canadian Journal of Earth Science. 12:2103-2110.

Green, R. H. 1968. Mortality and stability in low diversity subtropical intertidal community. Ecology. 49:848-854.

Harvey, M., Therriault, J-C., and Simard, N. 2001. Hydrodynamic control of late summer species composition and abundance of zooplankton in Hudson Bay and Hudson Strait (Canada). Journal of Plankton Research. 23:481-496.

Heath, M. R. and Lough, R. G. 2007. A synthesis of large-scale patterns in planktonic prey of larval and juvenile cod (*Gadus morhua*). Fish. Oceanography. 16:169-185.

Holland, S. M. Non-metric multidimensional scaling (MDS). Department of Geology. University of Georgia, USA. http://www.uga.edu/~strata?software/pdf/dstutorial/pdf/ (June 2014).

Huntley, M., Strong, K. W., and Dengler, A. T. 1983. Dynamics and community structure of zooplankton in the Davis Strait and Northern Labrador Sea. Arctic. 35:143-161.

Johnson, W. S. and Allen, D. M. 2005. Zooplankton of the Atlantic and Gulf Coasts: a guide to their identifications and ecology. Johns Hopkins University Press, Baltimore, MD. USA.

Judkins, D. C., Creighton, D. W., and Wayne, E. E. 1979. Composition, abundance, and distribution of zooplankton in the New York Bight, September 1974-September 1975. Fishery Bulletin. 77:669-983.

Katona, G. 1971. The developmental stages of *Eurytemora affinis* (Poppe, 1880) (Copepoda, Calanoida) raised in laboratory cultures, including a comparison with the larvae of *Eurytemora americana* (Williams, 1906) and *Eurytemora herdmani* (Thompson Scott, 1897). Crustaceana. 21:5-21.

Krebs, D. J. 1989. Ecological Methodology. Addison-Welsey Educational Publishers Inc. California, USA.

Kruskal, J. B. and Wish, M. 1978. Multidimensional Scaling. Vol 11. Sage.

Legendre, P. and Legendre, L. 1998. Numerical Ecology 2nd edition. Elsevier Science B.V. Amsterdam, The Netherlands.

Levinton, J. C. 2002. Marine Biology: Biodiversity, Ecology. Oxford Uni. Press. UK.

Lillick, L. C. 1937. Seasonal studies of the phytoplankton off Woods Hole, Massachusetts. Biology Bulletin. P488-503.

Makabe, R., Tanimura, A., and Fukuchi, M. 2012. Comparison of mesh size effects on mesozooplankton collection efficiency in the Southern Ocean. Journal of Plankton Research. doi:10.1093/plankt/fsb014.

Mallin, M. A. 1991. Zooplankton abundance and community structure in a mesohaline North Carolina estuary. Estuaries. 14:481-488.

Marques, S. C., Pardal, M. A., Pereira, M. J., Goncalves, F. Marques, J. C., and Azeiteiro, U. M. 2007. Zooplankton distribution and dynamics in a temperate shallow estuary. Hydrobiologia. 587:213-223.

Melanson, R.L. and Campbell, C.C. 2012. Near-shore fish populations within St. Pauls Inlet, an estuarine system in Western Newfoundland. Northeastern Naturalist. 19:487-500.

Menéndez, M. C., Dutto, M. S., Piccolo, M. C., and Hoffmeyer, M. S. 2012. The role of the seasonal and semi-diurnal tidal cycle on mesozooplankton variability in a shallow mixed estuary (Bahia Blanca, Argentina). ICES J. of Marine Science. 69:389-398.

Methven, D. A., Haedrich, R. L., and Rose, G. A. 2001. The fish assemblage of a Newfoundland estuary: diel, monthly and annual variation. Estuarine, Coastal and Shelf Science. 52:669-687.

Mouny, P. and Dauvin, J-C. 2002. Environmental control of mesozooplankton community structure in the Seine estuary (English Channel). Oceanologica Acta. 13-22.

Nielsen, T. G. and Andersen, C. M. 2002. Plankton community structure and production along a freshwater-influenced Norwegian fjord system. Marine Bio. 141:707-724.

Omori, M. and Ikeda, T. 1984. Methods in Marine Zooplankton Ecology. Wiley and Sons. New York, NY. USA.

O'Sullivan, W. 1976. Hydrological inventory of Gros Morne National Park, Newfoundland Canada. Inland Waters Directorate, Water Resources Branch.

Pace, M. L., Findlay, S. E. G., and Lints, D. 1992. Zooplankton in advective environments: the Hudson River community and a comparative analysis. Canadian Journal of Fisheries and Aquatic Science. 49:1060-1069.

Paul, S., Wooldridge, T. and Perissinotto, R. 2016. Evaluation of abiotic stresses of temperate estuaries by using resident zooplankton: a community vs. population approach. Estuarine, Coastal and Shelf Science. 170:102-111.

Pepin, P., Colbourne, E., and Maillet, G. 2011. Seasonal patterns in zooplankton community structure on the Newfoundland and Labrador Shelf. Progress in Oceanography. Doi:10.1016/j.pocean.2011.01.003.

Pollock, L. 1998. A practical guide to the marine animals of northeastern North America. Rutgers Univ. Press. New Jersey.

Primo, A.L, Azeiteiro, U.M., Marques, S.C., Martinho, F.M. and Pardal, M.A. 2009. Changes in zooplankton diversity and distribution pattern under varying precipitation regimes in a southern temperate estuary. Estuarine, Coastal and Shelf Science 82:341-347.

Richoux, N. B. 2011. Trophic ecology of zooplankton at a frontal transition zone: fatty acid signatures at the subtropical convergence, Southern Ocean. Journal of Plankton Research. 33:491-505.

Rochet, M. and Grainger, E. H. 1988. Community structure of zooplankton in eastern Hudson Bay. Canadian Journal of Zoology. 66:1626-1630.

Rohlf, F. J. 2009. NTSYSpc Numerical taxonomy and multivariate analysis system version 2.21L. Exeter Software, Setauket, New York. USA.

Shih, C., Marhue, L., Barrett, N., and Munro, R. 1988. Planktonic copepods of the Bras d'Or Lakes system, Nova Scotia, Canada. Hydrobiologia. 167/168:319-324.

Smith, P. E., Counts, R. C., and Clutter, R. I. 1968. Changes in filtering efficiency of plankton nets due to clogging under tow. Journal du Conseil/Conseil Permanent International pour l'Exploration de la Mer. 2:232-248.

Sutherland, K., Wooldridge, T. H., and Strydom, N. A. 2013. Composition, abundance, distribution and seasonality of zooplankton in the Sundays Estuary, South Africa. African Journal of Aquatic Science. 38:79-92.

Taylor, D. J., Ishikane, C. R., and Haney, R. A. 2002. The systematics of Holarctic bosminids and a revision that reconciles molecular and morphologic evolution. Limnology and Oceanography. 47:1486-1495.

Thuesen, Erik V. (2014). *Parasagitta elegans* (Verrill, 1873). Accessed through: World Register of Marine Species at http://www.marinespecies.org/aphia.php?p=taxdetails&id=105440 on 2014-11-30

Vieira, L., Azeiteiro, U., Re, P., Pastorinho, R., Marques, J. C., and Morgado, F. 2003. Zooplankton distribution in a temperate estuary (Mondego estuary southern arm: Western Portugal). Acta Oecologica. 24:163-173.

Vilks, G. and Deonarine, B. 1987. Labrador shelf bentich Foraminifera and stable oxygen isotopes of *Cibicides lobatulus* related to the Labrador Current. Canadian Journal of Earth Science. 5:1240-1255.

Vilks, G. and Mudie, P. J. 1983. Evidence for postglacial paleoceanographic and paleoclimatic changes in Lake Melville, Labrador, Canada. Arctic and Alpine Research. 15:307-319.

Walter, T.C. and Boxshall, G. (2014). World of Copepods database. Accessed at http://www.marinespecies.org/copepoda on 2014-06-12.

Wigley, R.L. and Burns, B.R. 1971. Distribution and biology of mysids (Crustacea, Mysidacea) from the Atlantic coast of the United States in the NMFS Woods Hole Collection. Fishery Bulletin. 69:717-745.

Winkler, G., Dodson, J. J., Bertrand, N., Thivierge, D., and Vincent, W. F. 2003. Trophic coupling across the St. Lawrence River estuarine transition zone. Marine Ecology Progress Series. 251:59-73.

Winkler, G., Martineau, C., Dodson, J.J., Vincent, W.F. and Johnson, L.E. 2007. Trophic dynamics of two sympatric mysid species in an estuarine transition zone. Marine Ecology Progress Series. 332:171-187.

Wetzel, R. G. and Likens, G. 1991 Limnological Analyses, 2nd ed. Black & Dodson 2003.

World Lake Database. Lake Melville. Accessed from International Lake Environment Committee Foundation. http://wldb.ilec.or.jp/Lake.asp?LakeID=SNAM160&RoutePrm=0%3A%3B4%3Aload%3B on June 2014.

Wroblewski, J. S., Kryger-Hann, L. K., Methven, D. A., and Haedrich, R. L. 2007. The fish fauna of Gilbert Bay, Labrador: a marine protected area in the Canadian subarctic coastal zone. Journal of the Marine Biological Association of the United Kingdom. 87:575-587.

Chapter 3

Zooplankton abundance in St. Pauls Inlet: a global comparison

3.1 Introduction

Estuarine environments are important transition zones between river and marine ecosystems. They can be characterized by high productivity, as well as by environmental fluctuations resulting from marine and freshwater influxes bringing nutrients, organic matter, and inorganic sediments from adjacent rivers, oceans, and land (Almeida et al. 2012; Menéndez et al. 2012). The classical definition of an estuary is a semi-enclosed and coastal body of water with free communication to the ocean and within which ocean water is diluted by freshwater derived from land (Pritchard 1967; Valle-Levinson 2010). Temperature, salinity, and nutrient concentrations in estuaries can vary highly both spatially and temporally (Knox 1986; Almeida et al. 2012). There is often a longitudinal gradient throughout the estuary with zones of differing salinity. Sea water that enters the estuarine environment contains calcium, magnesium, sulphur, potassium, and other trace elements that can be used by the primary producers. Many estuaries receive sizeable amounts of the nutrients phosphorus and nitrogen from freshwater runoff (Correll 1978). The variability of the estuarine environment will often influence the composition, abundance, and size structure of higher trophic levels such as zooplankton, as well as fish and bird species (Methven et al. 2001).

Estuaries are some of the most productive ecosystems on earth with mean primary production globally of 1,500 g m^{-2} yr^{-1} (dry matter) (Correll 1978). The next most

productive ecosystem is cultivated land with 650 g m^{-2} yr^{-1} (dry matter) and the other aquatic ecosystems come in far below with 125 g m^{-2} yr^{-1} (dry matter) for the open ocean, 360 g m^{-2} yr^{-1} (dry matter) for continental shelf waters, and 400 g m^{-2} yr^{-1} (dry matter) for lakes and streams (Correll 1978). Several processes that can enhance estuarine productivity include: i) input of nutrients from inflowing freshwater rivers, as well as marine inputs, ii) circulation patterns within estuaries that can lead to the system acting as a nutrient trap, iii) tidal and other mixing leading to recirculation of nutrients from bottom sediments, and iv) retention of nutrients in associated tidal marshes, mud flats, and vascular plants (Knox 1986). Due to such productivity, many estuaries can be nurseries or spawning grounds and transition zones for anadromous fish such as salmon as well as feeding grounds for other organisms (Day 1981; Beck 2001). However, it should not be assumed *a priori* that an estuary is a highly productive system, as nutrient input from river inflows and tidal mixing can vary widely among systems. The estuarine St. Pauls Inlet, for example, may be representative of other restricted and largely nutrient-poor fjords occurring on the west coast of Newfoundland (Carter and MacGregor 1979).

Zooplankton can be abundant in brackish estuarine systems and flourish in locations that have high food concentrations (Bradford-Grieve 1999). Zooplankton are an important link between the photosynthetic energy fixed by phytoplankton and the higher trophic level consumption of fish and crustacean species (Miller 1983). Based on diet, zooplankton abundance in estuaries can be related to two main food sources – phytoplankton and detritus/bacteria (Knox 1986). Hence, zooplankton productivity

reflects both photosynthetic productivity of phytoplankton and heterotrophic activity associated with bacterial breakdown of detritus. The abundance or density of zooplankton can therefore be assessed as a general correlate of overall biological production in an estuary (Avila et al. 2012). As a preliminary step towards assessing the potential contribution of St. Pauls Inlet to the wider western Newfoundland and Labrador marine ecosystem, I examined zooplankton abundance over 2 open water periods in the inlet, a brackish pond/estuary located in insular Newfoundland. The Inlet opens through a narrow mouth into St. Pauls Bay and the Gulf of St. Lawrence. The biological productivity of St. Pauls Inlet, estimated by zooplankton abundance, is hypothesized to be low compared with other temperate estuaries (Hypothesis 4). This study examines the microcrustacean zooplankton assemblage in St. Pauls Inlet with a view to assessing:

1. How this estuarine system of likely low nutrient levels and nutrient-poor watershed compares on a global scale with other temperate estuaries in terms of mean zooplankton abundance.
2. How proportion of dominant taxa, such as copepods, in the inlet compares with that seen in estuaries with higher biological productivity

3.2 Methods

The primary study site, as seen in Figures 2.1 & 2.2, was St. Pauls Inlet, Newfoundland. The specific study sites and methods are detailed extensively in Chapter 2. Samples were taken roughly biweekly from June to August 2009 and June to August 2010 from 4 sites (Figure 2.2). Zooplankton were identified to the lowest taxonomic group possible using a

variety of sources and dichotomous keys (Katona 1971; Della Croce 1974; Bradford 1976; Frost 1989; Busch & Brenning 1992; Barnes 1994; Pollock 1998; Bradford-Grieve 1999; Gerber 2000; Johnson & Allen 2005; Campbell & Knoechel 2008).

Zooplankton abundance was determined as population density (inds m^{-3}) with sampled volumes determined by either measured flow through flow meters (for horizontal and oblique net tows) or extrapolated from depth of vertical tow as follows:

$$\textbf{Volume } (m^3) = \pi * (\textbf{Radius of net}^2) * \textbf{Distance towed (m)}$$

Mean microcrustacean abundance data for each of the two seasons, 2009 and 2010 separately, were plotted and examined visually on normal probability plots which show ordered response values graphed against statistical means. Since the data met the assumptions of parametric testing (i.e. normality and even distribution of the residuals), two-way analyses of variance (ANOVA) were used to determine if there were differences in the mean abundances between months and between sites. ANOVAs were carried out using MINITAB 16.

Zooplankton abundance data from another 23 estuaries were obtained from 9 studies in the literature for comparison; see Appendix 3 and Figure 3.1 for locations. Particular focus was given to estuaries that were similar to the St. Pauls Inlet study in terms of:

1. Location – temperate region, both North and South (Figure 3.3)
2. Zooplankton sampling methodology
3. Zooplankton numbers recorded as inds-m^{-3}

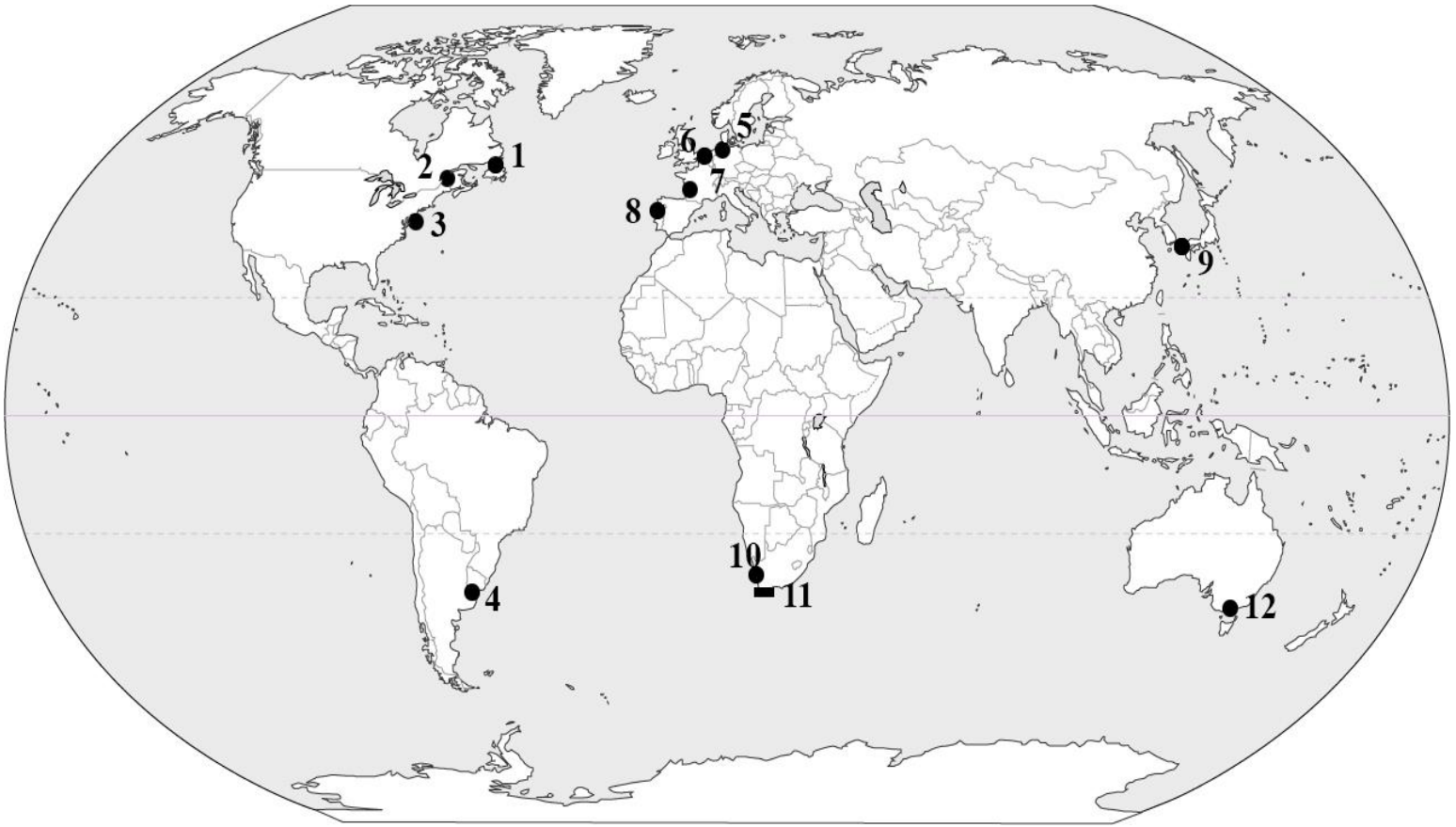


Figure 3.1: St. Pauls Inlet and comparison site locations, all in temperate areas (Adapted from Johomaps 2014). Site 1: St. Pauls Inlet; Site 2: St. Lawrence Estuary, CA (Winkler et al. 2003); Site 3: Hereford Inlet, NJ, USA (Herman & D'Apolito 1985); Site 4: Bahia Blanca, AR (Menéndez et al. 2012); Sites 5 & 6:Ems & Westerschelde, Netherlands; Site 7: Gironde Estuary, FR (Sautour & Castel 1995); Site 8: Mondego Estuary, PT (Uriarbe & Villate 2005); Site 9: Chikugo Estuary, JP (Islam et al 2006); Sites 10 & 11: Goukou, Breede Heuringnes, Great Berg, Oilfants, Klein, Bot, Lourents, & Diep Estuaries, ZA (Montoya-Maya & Strydom 2009); Site 12: Yarra, Maribyrnong, Werribee, & Patterson Rivers, AU (Neale & Bayley 1974)

Inevitably, the studies did show some differences in terms of mesh size of sampling device, depth and seasonality of sampling, all of which can influence zooplankton abundance estimates (Kennish 1986; Riccardi 201; Makabe et a. 2012). I attempted to minimize these differences by selecting studies that used roughly similar mesh size to that used in the St. Pauls Inlet research, and sampled most of the water column. As well, seasonalilty was partially addressed by focussing mainly on studies that encompassed an entire year or more, or at least focussed on spring and summer as in St. Pauls Inlet. Nevertheless, it is important to emphasize that the overall zooplankton abundances generated are likely only rough estimates of the biological productivity of the different estuaries.

3.3 Results

3.3.1 St. Pauls Inlet, Newfoundland, Canada

The predominant species found in St. Pauls Inlet were copepods, totaling 84 % of total zooplankton enumerated (all microcrustaceans) (see Figure 3.2), with *Acartia hudsonica* at 57 % of the total abundance and *Temora longicornis* at 25 %. The next two highest abundances were the cladocerans *Evadne nordmanni* and *Podon leuckarti* with 8.5 % and 5.9 % respectively. *Oithona similis* was present in the estuary with about 1.4 % of the total abundance (Table 3.1). The salinity and temperatures for all sites are listed in detail in Chapter 2. Mean microcrustacean abundance did not differ significantly either among sites (Location) or among the summer months sampled, for either of the two seasons (Table 3.2).

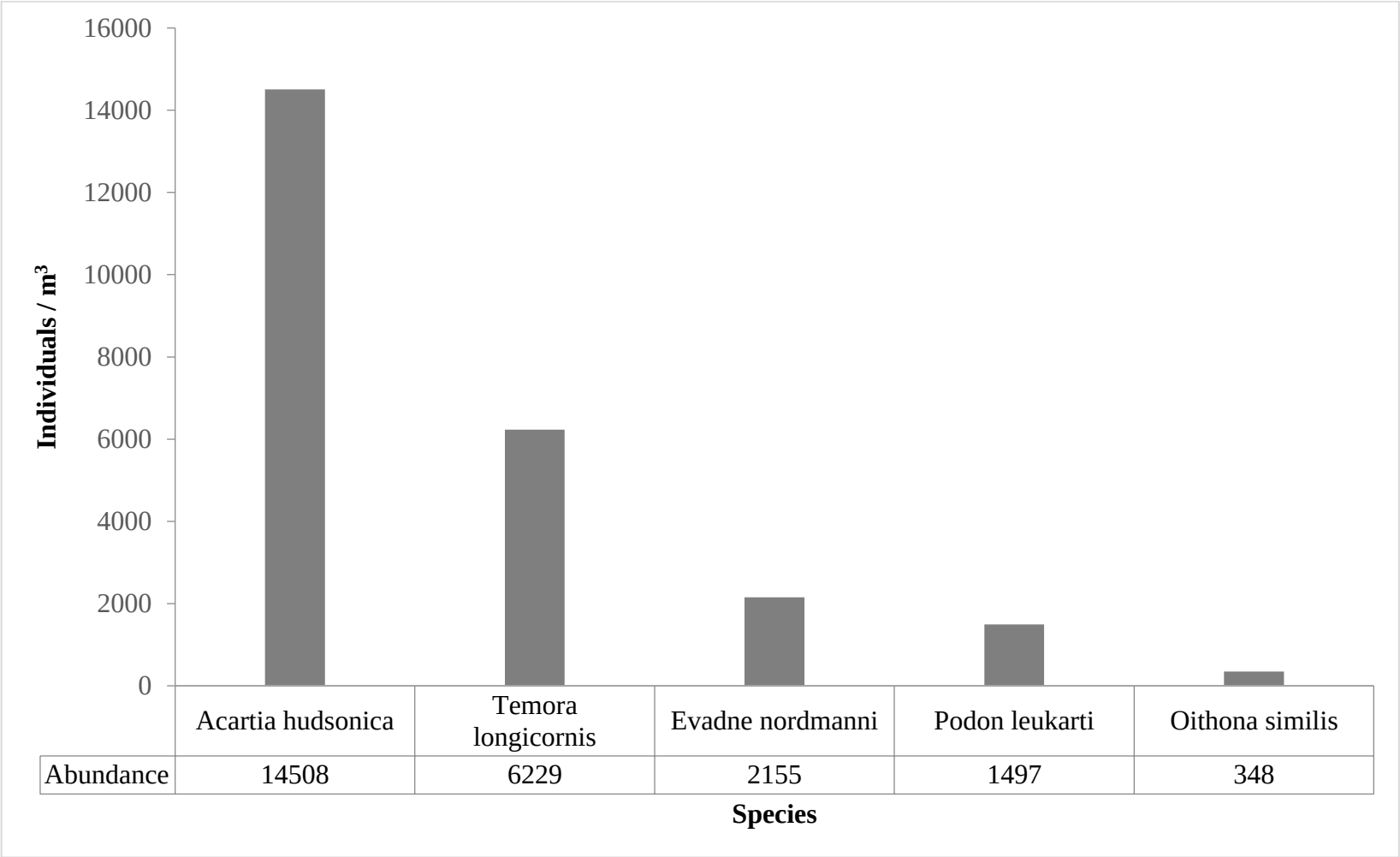


Figure 3.2: Total species abundances (individuals / m^3) in St. Pauls Inlet of the most common species found, from all samples.

Table 3.1: Estuarine comparison studies & associated zooplankton densities (inds m^{-3}, for total zooplankton, microcrustacea only, & copepod only). Values given are overall means for each study if available, otherwise ranges. Percent Copepod refers to mean % out of total zooplankton. Bracketed numbers are maximum values used in computation of means, or maximum values listed by authors. Data not available in all cases; listed as n/a

Study Site	Mesh Size (µm)	Total Zooplankton	Micro-crustacean	Copepod	% Copepod
-St. Pauls Inlet, NL, CA *(present study)*	63,80, & 500	3,798	3,495	3190 (max 482,735)	84
-St. Lawrence Estuary, CA *(Winkler et al. 2003)*	63 & 500	16,402	15,018	14,853	88
-Hereford Inlet, NJ, USA *(Herman & D' Apolito 1985)*	203	9,244	8,559	7923 (max 26,883)	89
-Bahia Blanca, AR *(Menéndez et al. 2012)*	200	1,786	1,538	1577 (max 5,923)	86
-Ems & Westerschelde, NL *(Sautour & Castel 1995)*	200	n/a	n/a	(max 38,800)	n/a
-Gironde Estuary, FR *(Sautour & Castel 1995)*	200	n/a	n/a	(max 19,400)	n/a
-Mondego Estuary, PT *(Uriarte & Villate 2005)*	63 & 125	22,426	17,225	17,210	76
-Chikugo Estuary, JP *(Islam et al 2006)*	100	n/a	n/a	range 7,900-32,600	80+
-Goukou, Breede, Heuringnes, Great Berg, Oilfants, Klein, Bot, Lourents, & Diep Estuaries, ZA *(Montoya-Maya & Strydom 2009)*	200	6,872	6049	n/a	87
-Yarra, Maribyrnong, Werribee, & Patterson Rivers, AU *(Neale & Bayley 1974)*	158	16,000	n/a	5980 (max 12,960)	81

Table 3.2. Two-Way ANOVA Results for Microcrustacean Abundance 2009 & 2010

Year	Mean Abundance (inds m^{-3})		p
2009	By Month (June 5170.9, July 5250.6, August 6553.0)	$F_{2,5} = 0.31$	0.75
	By Location (CCP 2005.7, WI 9465.3, BTF 4453.1, BB 7477.4)	$F_{3,5} = 5.47$	0.06
2010	By Month (June 1375.3, July 4484.8, August 27190.8)	$F_{2,6} = 2.36$	0.18
	By Location (CCP 4819.1, WI 3519.0, BTF 7389.6, BB 29340.2)	$F_{3,6} = 1.21$	0.38

3.3.2 Comparison Sites

In the St. Lawrence Estuary 88 % of total zooplankton species found were copepods with *Ectinosoma curticorne* (now *Halectinosoma curticorne)* and *Eurytemora affinis* being the most abundant (Table 3.1). Samples from the Hereford Inlet consisted of 89 % copepods with four species (*Oithona similis, Temora longicornis, Acartia tonsa,* and *Pseudocalanus minutus*) making up the largest portions of the 89 %. In the Bahia Blanca Estuary there were two species *Acartia tonsa* and *Eurytemora americana* made up 40-97% of the mesozooplankton. The zooplankton in the Bahia Blanca Estuary was comprised of 86 % copepods. Copepods made up 76% of the samples from the Mondego Estuary in Portugal (Table 3.1).

The most abundant copepods found in the Mondego Estuary system were *Oithona nana, Acartia tonsa, Acartia clausi, Euterpina acutifrons, Oithona similis, Temora longicornis, Clausocalanus arcuicornis, Paracalanus parusus,* and *Acartia bilfosia* var. *inermis.* Islam et al. (2006) listed 6 copepod species that made up 80^{+} % of all the copepods collected from the Chikugo Estuary in Japan. Two of these copepods were identified by the authors as true estuarine (*Sinocalanus sinensis* and *Pseudodiaptomus inopinus*) while

the other four (*Acartia omori, Oithona davisae, Paracalanus parvus,* and *Pseudodiaptomus marinus*) were considered more marine species. In the South African estuaries of Goukou, Breede, Heuringnes, Great Berg, Olifants, Klein, Bot, Lourents, and Diep copepods comprised 87 % of the zooplankton sampled. The two dominant species were *Pseudodiaptomus hessei* (51 %) and *Acartia africana* (12 %). Finally in the Yarra, Maribyrnong, Werribee, and Patterson Rivers in Australia 13 species of copepods made up 81 % of the total zooplankton densities.

The abundance data for St. Pauls Inlet shows that the plankton concentration is generally lower than most of the other studies examined. Bahia Blanca showed a lower abundance during their winter sampling as well as during the high and low tides. During their summer months they showed much higher numbers that coincided with peak current velocities in the inner zone of the estuary (Menendez et al 2012). The mean abundance of 3,495 adult microcrustacean individuals m^{-3} was lower than most of the other estuarine systems (Table 3.2) and was comprised of 84 % copepods which is in the same percentage range for all the studies (between 75-90 %). The comparison studies were predominantly comprised of mostly marine species with a few truly estuarine or an occasional freshwater species. Copepods were the dominant component of the zooplankton in all sites except the Patterson Estuary which experienced severe flooding during sampling and is prone to flooding, and thus had larger numbers of freshwater cladocerans (Neale & Bayley 1974).

3.4 Discussion

Mean values of zooplankton abundance in estuaries can be quite wide-ranging, as a reflection of often large environmental fluctuations. For example, Mallin (1991) compared 6 estuaries in the southeast US and found total zooplankton densities to vary from 4,000 to 34,530 inds m^{-3}. Similarly, Turner (1982) observed a range of 1,320–52,500 inds m^{-3} for 6 estuaries, over 10 studies, in the northeast United States. A high relative abundance of copepods is typical of most estuaries, including St. Pauls Inlet. Most of the studies used for this comparison had similar sampling techniques in that they did a combination of horizontal, vertical, and oblique tows as were done in St. Pauls Inlet. One of the primary differences between the comparison and St. Pauls Inlet studies was in the mesh size of the plankton nets. Other than the sampling done by Winkler et al. (2003) and the present one, the mesh sizes ranged from 100 - 200 µm. Turner (1982) noted that a mesh that is too coarse would not sample many meroplankters or immature holoplankters. Most of the comparison studies used only a single mesh size and would have underestimated the numbers of small adults and the developmental forms such as nauplii (Herman & D'Apolito 1985; Riccardi 2010; Makabe et al. 2012). According to Gallienne & Robins (2001), larger sizes of mesh (200 µm) are likely only to catch 7 % of the total zooplankters that are between 200 µm and 20 µm in dimension; Riccardi (2010) found that the percentage was closer to 11 % of the total; Makabe et al. (2012) found that a 330 µm net produced a collection efficiency of 2.0 - 5.6%. Gallienne & Robbins (2001) also suggested that an 80 µm net will collect 90 % of total zooplankton abundance and that finer mesh nets may result in reduced estimates of larger taxa. The present study in

St. Pauls used both a coarse (500 µm) and fine (63 µm) mesh oblique tow nets, as well as 80 µm vertical tow nets. Even though the finer mesh size was used in this study, I had similar or lower abundances than the comparative studies that used only the coarser mesh size. It is acceptable to postulate, that if my study had utilized just the coarser mesh, the abundances would have been even lower due to the underestimation of small organisms such as nauplii.

Many of the study sites were different from St. Pauls Inlet in that the sites studied were often heavily influenced by freshwater or tides whereas St. Pauls Inlet has little influence of tidal mixing as Carter and MacGregor (1979) indicated and as was shown by my salinity readings. The St. Lawrence Estuary has a great tidal influence (Winkler et al. 2003), whereas the Chikugo Estuary has a very large catchment from numerous rivers (Islam et al. 2006). The Hereford Inlet has no freshwater input and is very shallow which results in a high salinity from the incoming tides. It also has no endemic community; the source of the zooplankton is the coastal waters (Herman & D'Apolito 1985).

Tidal mixing in estuaries leads to recirculation of bottom sediments and is one of the dominant variables that determine salinity distribution. However, when there is little to no tidal forcing, such as in St. Pauls Inlet, there is little occurrence of deep water exchange with the coastal ocean (Day 1981; Kennish 1986). The restricted entrance to the inlet may allow sea water to enter only during high tide (Carter & MacGregor 1979). Additionally, the sea water entering from the Gulf of St. Lawrence and Esquiman

Channel area off the west coast of Newfoundland also has low primary production and nutrient concentrations compared to other regions of the Gulf (Carter & MacGregor 1979; Dunbar 1972; Savenkoff et al. 2001). Measurements of nutrients in surface waters of Bonne Bay, a nearby marine body of water that is deeper and more stratified than St. Pauls Inlet, indicated low concentrations of nitrate, ammonia and phosphate (see Table 3.3). This suggests similarly low nutrient input to St. Pauls Inlet from marine sources.

Table 3.3: Nutrient Concentrations for St. Pauls River and Gros Morne National Park surface fresh waters and for marine Bonne Bay surface waters. (adapted from O'Sullivan 1976; Tables 2 & 3 Carter & McGregor, 1979, maxima for GMNP and Bonne Bay)

Location	**Nutrient Concentrations**		
	Nitrate (ppm N)	**Ammonia (ppm N)**	**Phosphate (ppm P)**
St. Paul's River	0.07	0.07	0.01
Gros Morne Park	0.3	0.1	0.04
Bonne Bay	0.32	0.02	0.04

The steep portions of St. Pauls Inlet are mostly surrounded by metamorphic rocks, gneiss, and quartzite, while the broader gently sloping terrain around the inlet is surrounded by Paleozoic limestone and siltstones (Daley 1992). Metamorphic rock are resistant to weathering and thus do not contribute a large sediment load into the inlet via the rivers (O'Sullivan 1976; Carter & MacGregor 1979). Since St. Pauls inlet does not have significant sedimentary deposit from rivers or the nearshore ocean therefore it would be considered a neutral filled basin and thus is nutrient poor (Thurman & Trujillo 2010). The rivers providing the freshwater influx also have very low levels of nutrients (O'Sullivan 1976), see Table 3.3. Additionally, there is low tidal input (Carter & MacGregor 1979).

Western Brook Pond, a lake close to St. Pauls Inlet, has been classified as ultra-oligotrophic with low levels of phosphorus (1.7 – 2.1 µg l^{-1}; Kerekes 1978), and low phytoplankton chlorophyll *a* (0.43 µg l^{-1}; Wells 2001). Western Brook Pond is a fjordal system similar to St. Pauls Inlet; however, it is no longer connected to the sea and hence is entirely fresh water. Mean copepod abundances in Western Brook Pond were recorded as 7,983 inds m^{-3}(more than twice the abundance recorded in St. Pauls Inlet 2009-2010), with microcrustacean abundance of 8,650 inds m^{-3} (Wells 2001). Both Western Brook Pond and St. Pauls Inlet are similar in having relatively small drainage area per water body size, with steep sides typical of fjords. It can therefore be surmised that input of nutrients from fresh water is similarly limiting in St. Pauls Inlet.

Zooplankton abundance n St. Pauls Inlet is demonstrably lower than many other estuaries. The observation of the low zooplankton abundances in light of the limiting factors listed in the studies raises the question of whether St. Pauls Inlet has sufficient primary and secondary production to support higher trophic levels. Many juvenile and larval fish use locations such as the eel grass beds located just outside the inlet in St. Pauls Bay as nurseries because these locations typically have high levels of primary and secondary production (Beck 2001). As discussed in Chapter 2 although the inlet was sampled for larval fish there were none in the samples. The vertical and horizontal tows performed during the 2009 and 2010 sampling period may have not been adequate to accurately sample for larval fish although similar sampling techniques were used in studies of the St. Lawrence Estuary (Winkler 2009). Many studies, such as Campfield &

Houde (2011) performed oblique tows for 5-20 minutes with nets that had a much larger opening; others used beam or otter trawls for similar time intervals (Bakus 1951; Krygier 1986). Thus the mesh sizes used in this study may not have been able to sample adequately for larval fish. Focusing on adults, Melanson and Campbell (2012) were able to identify 15 species of nearshore fish (representing 9 families) within St. Pauls Inlet using beach seines, minnow traps and gillnets. Six of the 15 species accounted for 98 % of the total fish sampled: 60 % *Pungitius pungitius* (Ninespine stickleback), 18 % *Gasterosteus aculeatus* (Threespine stickleback), 7 % *Gasterosteus wheatlandi* (Blackspotted stickleback), 7 % *Apeltes quadracus* (Fourspine stickleback), 4 % *Tautogolabrus adspersus* (Cunner), and 2 % *Myoxocephalus octodecimspinosus* (Longhorn sculpin). In order to estimate higher trophic level productivity then, future studies should be done to estimate juvenile and larval fish abundance within the inlet as well as to further sample just outside the inlet in St. Pauls Bay and salt marshes.

In conclusion, changes in zooplankton species composition over time were observed in St. Pauls Inlet (Chapter 2) meaning that null hypothesis 1 was not supported. However null hypothesis 2 (did species composition throughout the inlet show lack of variation with longitudinal salinity) was supported (Chapter 2). Lastly, in Chapter 3, the data did indicate that zooplankton abundance in St. Pauls Inlet was lower than in other estuarine systems worldwide, thus disproving hypothesis 3. It is interesting then that the temporal variability over decades seems more important than the spatial variability across kilometers in this estuarine system.

3.5 Literature Cited

Almeida, L. R., Costa, I. S., and Eskinazi-Sant'Anna, E. M. 2012. Composition and abundance of zooplankton community of an impacted estuarine lagoon in Northeast Brazil. Brazilian Journal of Biology. 72:13-24.

Avila, T. R., de Souza Machado, A. A., and Bianchini, A. 2012. Estimation of secondary production in estuarine waters: comparisons between the enzymatic (chitobase) method and mathematical models using crustaceans. J. Exp. Mar. Biol. Ecol. 416/417:144-152.

Bakus, R. H. 1951. New and rare records of fishes from Labrador. Copeia. 4:288-294.

Barnes, R. S. K. 1994. The brackish-water fauna of northwestern Europe. Cambridge University Press, New York. USA.

Beck, M. W., Heck Jr., K. L., Able, K. W., Childers, D. L., Eggleston, D. B., Gillanders, B. M., Halpern, B., Hays, C. G., Hoshino, K., Minello, T. J., Orth, R. J., Sheridan, P. F., and Weinstein, M. P. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. Bioscience. 51:633-641.

Bradford, J.M. 1976. Partial revision of the *Acartia* subgenus *Acartiura* (Copepoda: Calanoida: Acarthiidae). N.Z. Journal of Marine and Freshwater Res. 10:169-202.

Bradford-Grieve, J. M. 1999. *ICES Identification Leaflets for Plankton*. International Council for the Exploration of the Sea, Leaflet No. 181.

Busch, A. and Brenning, U. 1992. Studies on the status of *Eurytemora affinis* (Poppe, 1880) (Copepoda, Calanoida). Crustacean. 2:13-38.

Campbell, C.E. and Knoechel, R. 2008. Species occurrences of microcrustacean zooplankton in Labrador, Canada. Verhandlungen Internationale Vereinigung für Theoretische und Ange-wandte Limnologie. 30:77-81.

Campfield, P. A. and Houde, E. D. 2011. Ichthyoplankton community structure and comparative trophodynamics in an estuarine transition zone. Fish. Bull. 109:1-19.

Carter, J. A. and MacGregor, C. D. 1979. Marine inventory of St. Paul's Inlet for Gros Morne National Park. Martec Limited, Halifax, NS. Report for Parks Canada.

Correll, D. L. 1978. Estuarine Productivity. Bioscience. 28:646-650.

Daley, L.A. 1992. Geology, Topography and Vegetation of Gros Morne National Park. Geological Survey of Canada. Miscellaneous Report 54.

Day, J. H. 1981. Estuarine Ecology. AA Balkema, Rotterdam.

Della Croce, N. 1974. Zooplankton Sheet 143. ICES identification leaflets for plankton. International Council for the Exploration of the Sea. Copenhagen.

Dunbar, M. J. 1972. The Gulf of St. Lawrence. Bedford Institute of Oceanography Biennial Review 1971/72:34-57.

Frost, B. W. 1989. A taxonomy of the marine calanoida copepod genus *Pseudocalanus*. Canadian Journal of Zoology. 63:525-551.

Gallienne, C. P. and Robins, D.B. 2001. Is *Oithona* the most important copepod in the world's oceans? Journal of Plankton Research. 23:1421-1432.

Gerber, R. P. 2000. An identification manual to the coastal and estuarine zooplankton from Passamaquoddy Bay to Long Island Sound. Acadia Productions, Brunswick, Maine.

Herman, S. S. and D'Apolito, L. M. 1985. Zooplankton of the Hereford Inlet Estuary, southern New Jersey. Hydrobiologia. 124:229-236.

Islam, Md. S., Ueda, H., and Tanaka, M. 2006. Spatial and seasonal variations in copepod communities related to turbidity maximum along the Chikugo estuarine gradient in the upper Ariake Bay, Japan. Estuarine Coastal and Shelf Science. 68:113-126.

Johnson, W. S. and Allen, D. M. 2005. Zooplankton of the Atlantic and Gulf Coasts: a guide to their identifications and ecology. The Johns Hopkins University Press, Baltimore, MD. USA.

Johomaps. World Maps. Accessed from http://johomaps.com/world/worldblank_bw.html November 2014.

Katona, G. 1971. The developmental stages of *Eurytemora affinis* (Poppe, 1880) (Copepoda, Calanoida) raised in laboratory cultures, including a comparison with the larvae of *Eurytemora Americana* (Williams, 1906) and *Eurytemora herdmani* (Thompson Scott, 1897). Crustaceana. 21:5-21.

Kennish, M. J. 1986. Ecology of estuaries. CRC Press, Boca Raton, Florida.

Kerekes, J. 1978. Aquatic resources inventory Gros Morne National Park, Part 5 limnological conditions. Canadian Wildlife Service, Ottawa.

Knox, G. A. 1986. Estuarine ecosystems: a systems approach volume I. CRC Press Inc., Boca Raton, Florida.

Krygier, E. E. and Pearcy, W. G. 1986. The role of estuarine and offshore nursery areas for young English Sole, *Parophrys vetulus* Girard, of Oregon. Fish Bull. 84:119-132.

Mallin, M. A. 1991. Zooplankton abundance and community structure in a mesohaline North Carolina estuary. Estuaries. 14:481-488.

Makabe, R., Tanimura, A., and Fukuchi, M. 2012. Comparison of mesh size effects on mesozooplankton collection efficiency in the Southern Ocean. Journal of Plankton Research. doi:10.1093/plankt/fsb014.

Melanson, R.L. and Campbell, C.C. 2012. Near-shore fish populations within St. Pauls Inlet, an estuarine system in Western Newfoundland. Northeastern Naturalist. 19:487-500.

Menéndez, M. C., Dutto, M. S., Piccolo, M. C., and Hoffmeyer, M. S. 2012. The role of the seasonal and semi-diurnal tidal cycle on mesozooplankton variability in a shallow mixed estuary (Bahia Blanca, Argentina). ICES J. of Marine Science. 69:389-398.

Methven, D. A., Haedrich, R. L., and Rose, G. A. 2001. The fish assemblage of a Newfoundland estuary: diel, monthly and annual variation. Estuarine, Coastal and Shelf Science. 52:669-687.

Miller, C. B. 1983. The zooplankton of estuaries. In, Ketchum, B. H. (ed.) Ecosystems of the World - 26 estuaries and enclosed seas, Elsevier, Amsterdam, p103-149.

Montoya-Maya, H., and Strydom, N. A. 2009. Zooplankton composition, abundance and distribution in selected south and west coast estuaries in South Africa. African Journal of Aquatic Science. 34:147-157.

Neale, I. M. and Bayly, I. A. E. 1974. Studies on the ecology of the zooplankton of four estuaries in Victoria. Australian Journal of Marine and Freshwater Res. 25:337-350.

O'Sullivan, W. 1976. Hydrological inventory of Gros Morne National Park, Newfoundland Canada. Inland Waters Directorate, Water Resources Branch.

Pollock, L. 1998. A practical guide to the marine animals of northeastern North America. Rutgers Univ. Press. New Jersey.

Pritchard, D. W. 1967. What is an estuary: physical viewpoint. American Association for the Advancement of Science. 85:3-5.

Riccardi, N. 2010. Selectivity of plankton nets over mesozooplankton taxa: implications for abundance, biomass and diversity estimation. Journal of Limnology. 62:287-296.

Sautour, B. and Castel, J. 1995. Comparative spring distribution of zooplankton in three macrotidal European estuaries. Hydrobiologia. 311:139-151.

Savenkoff, C., Vezina, A. F., Smith, P. C., and Han, G. 2001. Summer transports of nutrients in the Gulf of St. Lawrence estimated by inverse modeling. Estuarine, Coastal and Shelf Science. 52:565-587.

Turner, J. T. 1982. The annual cycle of zooplankton in a Long Island Estuary. Estuaries. 5: 261–274.

Uriarte, I. and Villate, R. 2005. Differences in the abundance and distribution of copepods in two estuaries of the Basque coast (Bay of Biscay) in relation to pollution. Journal of Plankton Research. 27:863-874.

Valle-Levinson, A. 2010. Contemporary issues in estuarine physics. Cambridge University Press, New York.

Wells, D. A. 2001. Spatial heterogeneity in zooplankton populations in Western Brook Pond – potential impacts from increase boat traffic? B.Sc. Honours, Grenfell Campus – Memorial University of Newfoundland, Corner Brook, NL.

Winkler, R., Dodson, J. J., Bertrand, N., Thivierge, D., and Vincent, W. F. 2003. Trophic coupling across the St. Lawrence River estuarine transition zone. Marine Ecology Progress Series. 251:59-73

Appendix 1: Sample Dates, Site Locations, and Tows for all samples in St. Pauls Inlet 2009 and 2010. BB – Bottom Brook, BTF – Between the Falls, WI – Western Island, CCP – Charles Cove Pt. V80 - Vertical Tow 80um, H63 - Horizontal/Oblique Tow 63 μm, H500 – Horizontal/Oblique Tow 500 μm

Sample Date	Site Location	Sample Date	Site Location	Sample Date	Site Location
16/06/2009	BTF V80	30/07/2009	BTF H63 & H500	11/08/2009	CCP V80
16/06/2009	BTF V80	30/07/2009	BB H63	11/08/2009	WI H63
16/06/2009	CCP V80	30/07/2009	BB V80	11/08/2009	WI V80
16/06/2009	CCP V80	30/07/2009	CCP V80	17/08/2009	BTF V80
16/06/2009	WI V80	30/07/2009	CCP V80	19/08/2009	BTF V80
15/07/2009	CCP H500	30/07/2009	WI H63	19/08/2009	BTF V80
17/07/2009	BTF V80	30/07/2009	WI V80	19/08/2009	BTF H63
17/07/2009	BTF V80	30/07/2009	WI V80	19/08/2009	BB H63
17/07/2009	CCP V80	07/08/2009	BTF V80	19/08/2009	BB V80
17/07/2009	CCP V80	07/08/2009	BTF H63	19/08/2009	BB V80
17/07/2009	WI V80	07/08/2009	CCP H63	19/08/2009	CCP H63
17/07/2009	WI V80	07/08/2009	CCP V80	19/08/2009	CCP V80
20/07/2009	BTF V80	07/08/2009	CCP V80	19/08/2009	CCP V80
20/07/2009	BTF V80	07/08/2009	WI H63	19/08/2009	WI H63
20/07/2009	CCP H63	07/08/2009	WI V80	19/08/2009	WI V80
22/07/2009	BTF V80	07/08/2009	WI V80	19/08/2009	WI V80
22/07/2009	BTF V80	11/08/2009	BTF V80	26/08/2009	BTF V80
22/07/2009	BB H63	11/08/2009	BTF V80	26/08/2009	BTF V80
22/07/2009	CCP V80	11/08/2009	BTF H63	26/08/2009	BB V80
22/07/2009	CCP V80	11/08/2009	BB H63	26/08/2009	BB V80
22/07/2009	WI H63	11/08/2009	BB V80	26/08/2009	CCP V80
22/07/2009	WI V80	11/08/2009	BB V80	26/08/2009	CCP V80
22/07/2009	WI V80	11/08/2009	CCP H63	26/08/2009	WI V80
30/07/2009	BTF V80	11/08/2009	CCP V80	26/08/2009	WI V80

Appendix 1: Sample Dates, Site Locations, and Tows for all samples in St. Pauls Inlet 2009 and 2010. BB – Bottom Brook, BTF – Between the Falls, WI – Western Island, CCP – Charles Cove Pt. V80 - Vertical Tow 80um, H63 - Horizontal/Oblique Tow 63 μm, H500 – Horizontal/Oblique Tow 500 μm

Sample Date	Site Location	Sample Date	Site Location	Sample Date	Site Location
02/06/2010	BTF H63	09/06/2010	WI H63	22/06/2010	WI H63
02/06/2010	BTF H500	09/06/2010	WI V80	22/06/2010	WI H500
02/06/2010	BTF V80	09/06/2010	WI V80	22/06/2010	WI V80
02/06/2010	BTF V80	17/06/2010	BTF H63	22/06/2010	WI V80
02/06/2010	BB H63	17/06/2010	BTF H500	01/07/2010	BTF H63
02/06/2010	BB H500	17/06/2010	BTF V80	01/07/2010	BTF H500
02/06/2010	BB V80	17/06/2010	BTF V80	01/07/2010	BTF V80
02/06/2010	BB V80	17/06/2010	BB H63	01/07/2010	BTF V80
02/06/2010	CCP H63	17/06/2010	BB H500	01/07/2010	BB H63
02/06/2010	CCP H500	17/06/2010	BB V80	01/07/2010	BB H500
02/06/2010	CCP V80	17/06/2010	CCP H63	01/07/2010	BB V80
02/06/2010	CCP V80	17/06/2010	CCP H500	01/07/2010	BB V80
02/06/2010	WI H63	17/06/2010	CCP V80	01/07/2010	CCP H63
02/06/2010	WI H500	17/06/2010	CCP V80	01/07/2010	CCP H500
02/06/2010	WI V80	17/06/2010	WI H63	01/07/2010	CCP V80
02/06/2010	WI V80	17/06/2010	WI H500	01/07/2010	CCP V80
09/06/2010	BTF H63	17/06/2010	WI V80	01/07/2010	WI H63
09/06/2010	BTF V80	17/06/2010	WI V80	01/07/2010	WI H500
09/06/2010	BTF V80	22/06/2010	BB H63	01/07/2010	WI V80
09/06/2010	BB H63	22/06/2010	BB H500	01/07/2010	WI V80
09/06/2010	BB H500	22/06/2010	BB V80	07/07/2010	BTF H63
09/06/2010	BB V80	22/06/2010	BB V80	07/07/2010	BTF H500
09/06/2010	BB V80	22/06/2010	CCP H63	07/07/2010	BTF V80
09/06/2010	CCP H63	22/06/2010	CCP H500	07/07/2010	BTF V80
09/06/2010	CCP V80	22/06/2010	CCP V80	07/07/2010	BB H63
09/06/2010	CCP V80	22/06/2010	CCP V80	07/07/2010	BB H500

Appendix 1: Sample Dates, Site Locations, and Tows for all samples in St. Pauls Inlet 2009 and 2010. BB – Bottom Brook, BTF – Between the Falls, WI – Western Island, CCP – Charles Cove Pt. V80 - Vertical Tow 80um, H63 - Horizontal/Oblique Tow 63 μm, H500 – Horizontal/Oblique Tow 500 μm

Sample Date	Site Location	Sample Date	Site Location	Sample Date	Site Location
07/07/2010	BB V80	21/07/2010	BTF H500	30/07/2010	WI H500
07/07/2010	BB V80	21/07/2010	BTF V80	30/07/2010	WI V80
07/07/2010	CCP H500	21/07/2010	BTF V80	30/07/2010	WI V80
07/07/2010	CCP V80	21/07/2010	BB H63	30/07/2010	BTF H63
07/07/2010	CCP V80	21/07/2010	BB H500	02/08/2010	BTF H500
07/07/2010	WI H63	21/07/2010	BB V80	02/08/2010	BTF V80
07/07/2010	WI H500	21/07/2010	BB V80	02/08/2010	BTF V80
07/07/2010	WI V80	21/07/2010	CCP H63	02/08/2010	BB H63
07/07/2010	WI V80	21/07/2010	CCP V80	02/08/2010	BB H500
12/07/2010	BTF H63	21/07/2010	CCP V80	02/08/2010	BB V80
12/07/2010	BTF H500	21/07/2010	WI H63	02/08/2010	BB V80
12/07/2010	BTF V80	21/07/2010	WI V80	02/08/2010	CCP H63
12/07/2010	BTF V80	21/07/2010	WI V80	02/08/2010	CCP H500
12/07/2010	BB H63	21/07/2010	BTF H63	02/08/2010	CCP V80
12/07/2010	BB H500	30/07/2010	BTF H500	02/08/2010	CCP V80
12/07/2010	BB V80	30/07/2010	BTF V80	02/08/2010	WI H63
12/07/2010	BB V80	30/07/2010	BTF V80	02/08/2010	WI H500
12/07/2010	CCP H63	30/07/2010	BB H63	02/08/2010	WI V80
12/07/2010	CCP H500	30/07/2010	BB H500	02/08/2010	WI V80
12/07/2010	CCP V80	30/07/2010	BB V80	02/08/2010	BTF H63
12/07/2010	CCP V80	30/07/2010	BB V80	11/08/2010	BTF H500
12/07/2010	WI H63	30/07/2010	CCP H63	11/08/2010	BTF V80
12/07/2010	WI H500	30/07/2010	CCP H500	11/08/2010	BTF V80
12/07/2010	WI V80	30/07/2010	CCP V80	11/08/2010	BB H63
12/07/2010	WI V80	30/07/2010	CCP V80	11/08/2010	BB H500
21/07/2010	BTF H63	30/07/2010	WI H63	11/08/2010	BB V80

Appendix 1: Sample Dates, Site Locations, and Tows for all samples in St. Pauls Inlet 2009 and 2010. BB – Bottom Brook, BTF – Between the Falls, WI – Western Island, CCP – Charles Cove Pt. V80 - Vertical Tow 80um, H63 - Horizontal/Oblique Tow 63 μm, H500 – Horizontal/Oblique Tow 500 μm

Sample Date	Site Location
11/08/2010	BB V80
11/08/2010	CCP H63
11/08/2010	CCP H500
11/08/2010	CCP V80
11/08/2010	CCP V80
11/08/2010	WI H63
11/08/2010	WI H500
11/08/2010	WI V80
11/08/2010	WI V80

Appendix 2: 2009 & 2010 Combined Salinity & Temp. data for all four sites in SPI.

Variable	Location Name	Mean	Minimum	Maximum
Overall Salinity (ppt)	Bottom Brook	21.62	4.60	25.7
	Between the Falls	22.69	8.40	28.80
	Western Island	21.07	14.70	24.50
	Charles Cove Point	24.14	16.70	29.90
Surface Salinity (ppt)	Bottom Brook	15.42	4.60	23.80
	Between the Falls	18.76	8.40	24.30
	Western Island	20.68	14.70	23.70
	Charles Cove Point	20.97	16.70	24.40
Bottom Salinity (ppt)	Bottom Brook	22.74	13.30	25.4
	Between the Falls	23.77	15.50	28.00
	Western Island	21.33	16.30	24.40
	Charles Cove Point	24.57	18.20	29.90
Overall Temp. (° C)	Bottom Brook	15.80	6.40	22.60
	Between the Falls	13.99	4.30	21.70
	Western Island	16.43	9.90	21.80
	Charles Cove Point	16.16	3.80	21.10
Surface Temp. (° C)	Bottom Brook	16.82	9.7	22.60
	Between the Falls	13.99	10.40	21.70
	Western Island	16.58	9.90	21.80
	Charles Cove Point	16.28	9.60	19.90
Bottom Temp. (° C)	Bottom Brook	12.68	6.60	17.70
	Between the Falls	10.30	4.30	20.40
	Western Island	15.93	10.00	20.70
	Charles Cove Point	14.88	3.80	19.70

Appendix 3: Estuaries used as comparisons for zooplankton abundance: an outline of sampling methods and salinity ranges.

Location	Zooplankton Sampling	Salinity range
North & South America	Vertical and horizontal tows	
St. Pauls Inlet, NL *(present study)*	Tow net (v) 20 cm diameter, 80 µm mesh Tow net (h) 30 cm diameter, 63 µm mesh June – August 2009, June – August 2010	4-30 ppt
St. Lawrence Estuary *(Winkler et al. 2003)*	Horizontal tows, surface, mid-depth, bottom Trawl, 0.03 m^2 opening, 63 & 500 µm mesh	0 – 6 PSU
Hereford Inlet, NJ, USA *(Herman & D'Apolito 1985)*	June 2003 and June 2004 Horizontal tows, surface Tow net 50 cm diameter, 203 µm mesh	28 – 31 ppt
Bahia Blanca, Argentina *(Menéndez et al. 2012)*	May 1973-April 1974 Horizontal pumps, surface and bottom Tow nets, 200 µm mesh	28 – 37 ppt
Europe & Asia		
Ems &Westerschelde, Netherlands *(Sautour & Castel 1995)*	December 2004 – April 2006 Oblique tows Tow net 50 cm diameter, 200 µm mesh	0-30 PSU
Gironde estuary, France *(Sautour & Castel 1995)*	March – June 1992 Oblique tows Tow net 50 cm diameter, 200 µm mesh	0-30 PSU
Mondego estuary, Portugal *(Uriarte & Villate 2005)*	March – June 1992 Horizontal tows 2 tow nets, 63 and 125 µm mesh	9.5 – 32 ppt
Chikugo estuary, Japan *(Islam et al. 2006)*	July 1999 – June 2000 Oblique tows Tow net 45 cm diameter, 100 µm mesh	1- 31 ppt
Africa & Oceania		
Goukou, Breede, Bot, Diep, Heuringnes, Great Berg, Olifants, Klein, Laurens, South Africa *(Montoya-Maya & Strydom 2009)*	April 2004 – March 2005 Horizontal surface tows Tow net 57 cm diameter, 200 µm mesh June 2003 – March 2004	0-36 PSU
Yarra, Maribyrnong, Werribee, Patterson River, Australia *(Neale & Bayley 1974)*	Oblique tows Tow net 12.89 cm diameter, 158 µm mesh February-July 1971	6-30 ppt

Appendix 4: 2-D NMDS Matrices

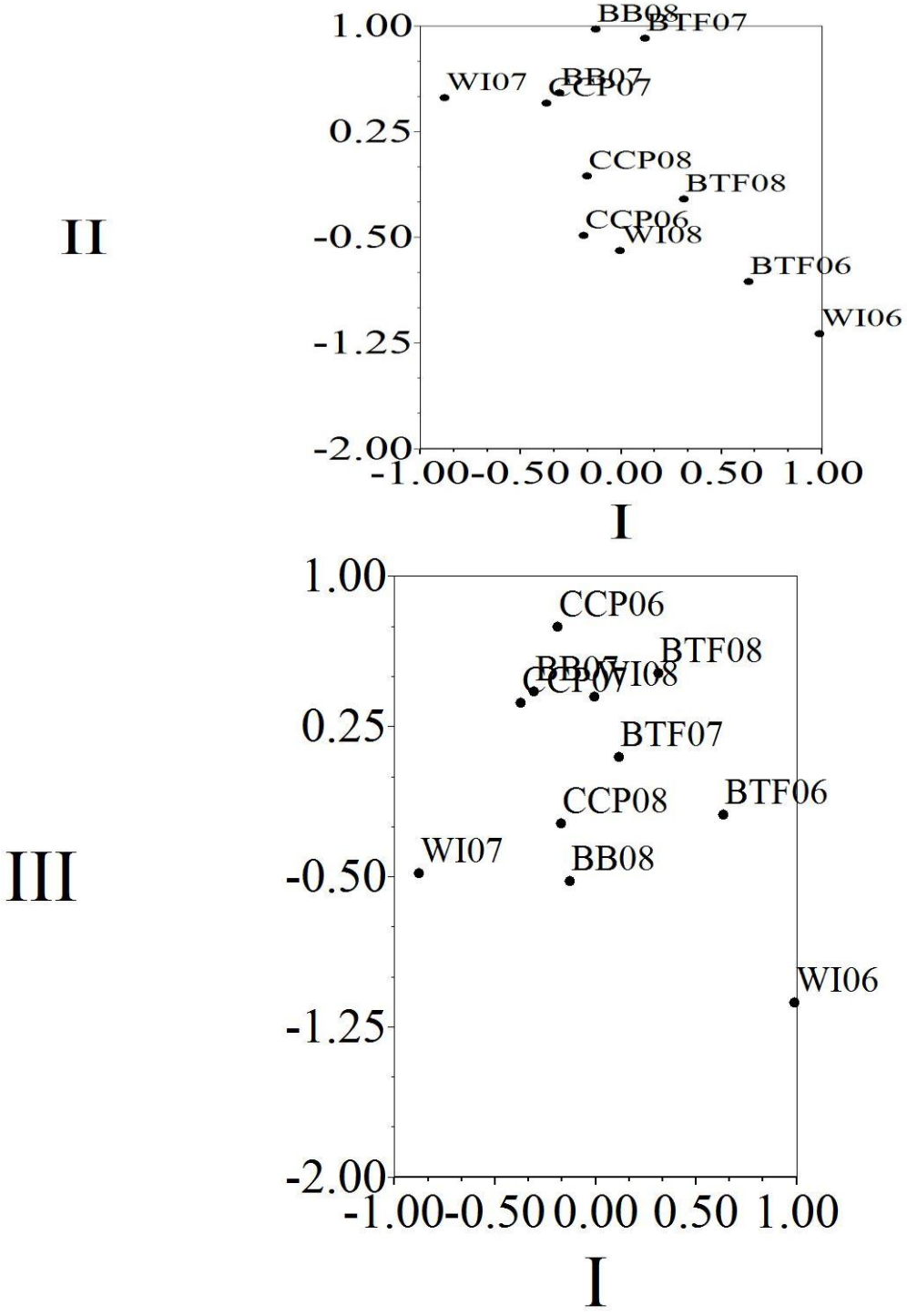


Figure A-1: 2-D NMDS for SPI 2009 Season. Axis I vs. Axis II and Axis I vs. Axis III. Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 06 = June, 07 = July, 08 = August)

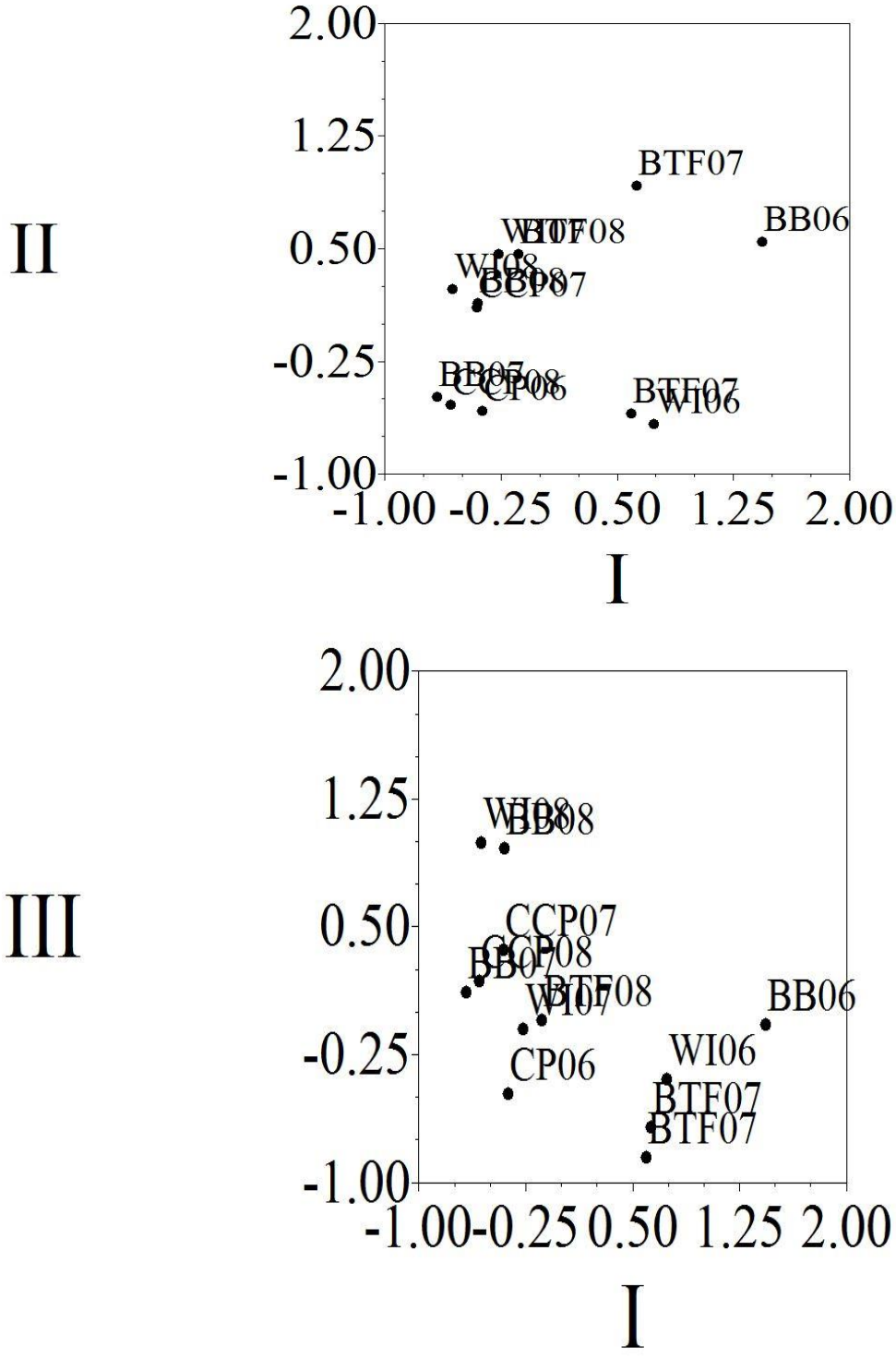


Figure A-2: 2-D NMDS Plot for SPI 2010 Season. Axis I vs. Axis II and Axis I vs. Axis III. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 06 = June, 07 = July, 08 = August)

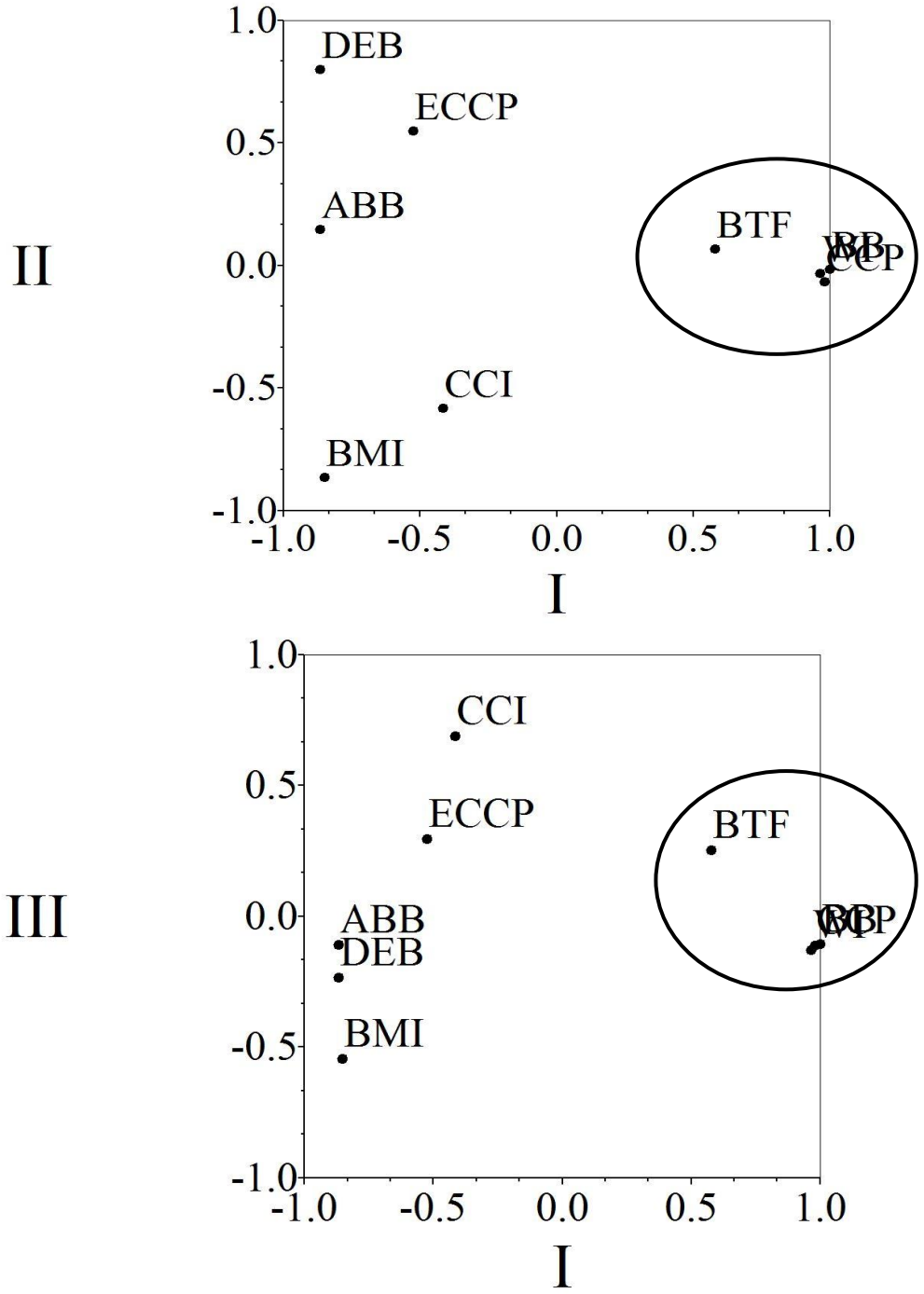


Figure A-3: 2-D NMDS for SPI 2009/2010 Comparison sites to sites from 1979 SPI. Axis I vs. Axis II and Axis I vs. Axis III. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook, ABB = 1979 Bottom Brook, BMI = 1979 Between the Falls, CCI = 1979 Central Inlet, DEB= 1979 Eastern Brook, ECCP = 1979 Charles Cove Point) Circles show the SPI 2009/2010 groupings.

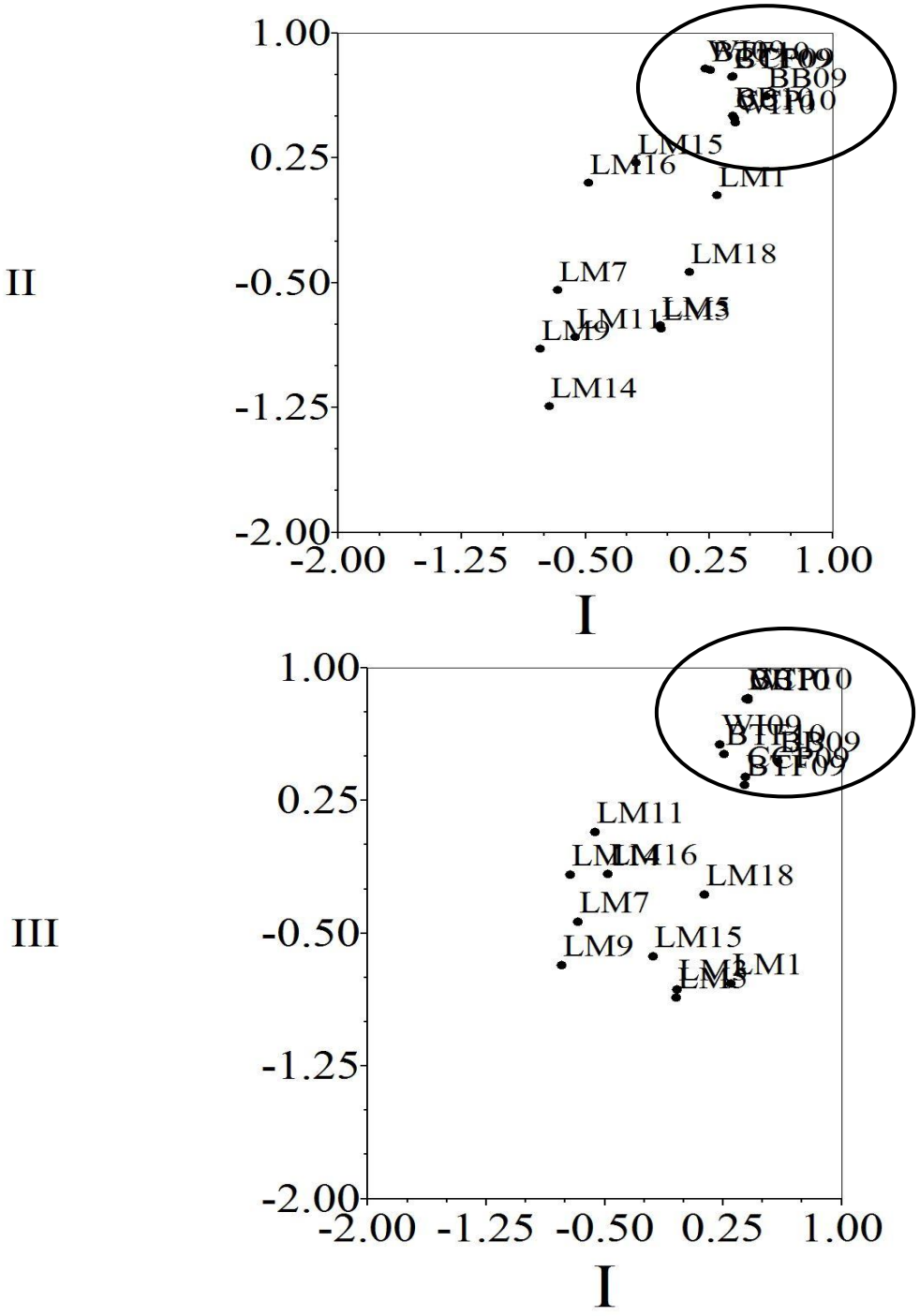


Figure A-4: 2-D NMDS SPI Comparison to Lake Melville. Comparison is between the sites in SPI from 2009/10 and LM from 2007. (Codes: CCP = Charles Cove Point, WI = Western Island, BTF = Between the Falls, BB = Bottom Brook; 09 = 2009, 10 = 2010); Lake Melville sampling sites designated LM. Circles are showing SPI sampling sites for 2009 and 2010.