Hypolimnetic Upwelling in Coastal Embayments of Lake Ontario; Implications for Restoration

by

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Abstract

Coastal wetlands are an important ecosystem in the Great Lakes basin, providing spawning grounds and warm-water refuge for numerous fish and benthic invertebrate species during cold water upwelling events. Urbanization along the northwestern shore of Lake Ontario has led to a depletion of coastal wetlands, replacing them with artificial embayments. Three artificial embayments, the Credit River estuary, and one coastal marsh in Mississauga, ON were studied to determine if the artificial embayments function as warm-water refuge during upwelling events. Temperature loggers were placed in each study site and temperature was recorded every 15 minutes from July to October 2017. Upwelling events were isolated from the data, and frequency, magnitude, and duration of upwelling was determined. Most study sites had a frequency of 4 upwelling events throughout the study period. The average duration of upwellings varied from 30 to 70 hours, and the average temperature change ranged from -7.1°C to -11.9°C. All of the study sites seemed to buffer upwellings by reducing the magnitude of temperature change and increasing the duration of upwelling events to varying degrees. These results will inform the creation of future wetlands, restoration of existing embayments, and conservation of Great Lakes coastal wetlands.

Keywords: Coastal embayments; coastal marsh; upwelling; warm-water refuge; Lake Ontario; ecological restoration.

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Data used with permission from Credit Valley Conservation Authority 2017.

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Glossary

Coastal Embayment	A small, partially enclosed body of water along the shoreline of a larger body of water. In this document, “coastal embayment” refers to an artificial bay along the shoreline of Lake Ontario.
Ecotone	A transitional zone between two distinct ecosystems, having characteristics of both as well as its own unique characteristics.
Epilimnion	The warmer, less dense water above the thermocline in a temperature stratified lake.
Freshwater Estuary	A constricted area where a river meets a large body of water, with continuous water exchange and the mixing of two distinct bodies of water
Great Lakes	In this document, the term “Great Lakes” refers to the Laurentian Great Lakes (Ontario, Erie, Huron, Superior, and Michigan).
Habitat	An area providing the necessary physical, chemical, and biological conditions to support a specific life stage or activity of a species.
Hypolimnion	The lower layer of cool, dense water in a temperature stratified lake.
Internal Seiche	A standing wave that occurs within a lake along the thermocline.
Seiche	A standing wave within a lake.
Thermocline	The boundary between the hypolimnion and the epilimnion in a temperature stratified lake, in which the temperature gradient rapidly decreases.

Chapter 1. Introduction

Coastal wetlands are an important ecosystem in the Great Lakes, however many of these wetlands have been drained, infilled, or otherwise altered due to urbanization and industrialization. Coastal wetlands are used by a wide variety of native species. These wetlands are particularly important for Great Lakes fish, as they require shallow warm areas for spawning and warm-water refuge. Many coastal wetlands are protected from open lake processes, such as wave action and upwellings that bring cold water from the hypolimnion to the shoreline.

Many areas along the coastline of Lake Ontario have been greatly modified by urbanization. Wetlands and natural shorelines have been dredged and infilled to create marinas, shipping terminals, industrial sites, and residential areas. This has led to a dramatic decline in the amount of warm-water refuge for fish and invertebrates during upwelling events. As an offsetting measure, several areas have been infilled to create artificial embayments with the intention of creating warm-water areas for fish (Murphy et al. 2012b).

The northwestern shore of Lake Ontario from Hamilton to Toronto has been particularly impacted as it is densely populated and highly urbanized. In this study, five sites in Mississauga, ON were studied to assess their effectiveness in providing warm-water refuge during upwelling events. The sites include three artificial embayments, the Credit River estuary, and Rattray Marsh. Temperature loggers were submerged in each study site during the period of stratification in the summer and early autumn of 2017.

This study aims to determine if these sites are effective in creating warm-water refuge during upwelling events. To do so, upwellings were identified and the frequency, duration, and magnitude of upwellings were determined. The objectives of the project were two-fold; 1) to determine the frequency, duration, and magnitude of upwelling within Rattray Marsh, the Credit River estuary, and the constructed embayments, and 2) to determine if areas of warm water thermal refuge exist within the sites. The frequency, average duration, and average magnitude of upwellings were compared across the sites to determine if the sites buffer upwellings. Findings of this study are applied to recommendations for future restoration projects.

Chapter 2. Background

2.1. Great Lakes Coastal Wetlands

Great Lakes coastal wetlands are an integral part of the Great Lakes ecosystem. They are an important ecotone between the open lake and the upland areas. They are similar to inland wetlands in many ways, but are unique in that they are affected by large lake processes such as waves, water level fluctuations, internal seiches, and upwellings (Edsall and Charlton 1997, Maynard and Wilcox 1997, Wilcox and Whillans 1999).

There are several types of coastal wetlands in the Great Lakes. They can be classified by their dominant plant species or by their geomorphology. The most common type based on vegetation are coastal marshes (Maynard and Wilcox 1997). These marshes are dominated by emergent herbaceous hydrophytes, such as cattail (*Typha spp.*), that can tolerate water level fluctuations (Maynard and Wilcox 1997). Coastal swamps, dominated by trees and shrubs, are also common(Maynard and Wilcox 1997)(Maynard and Wilcox 1997)(Maynard and Wilcox 1997)(Maynard and Wilcox 1997), though swamp communities are most often present along the shoreward edge of other coastal wetland communities (Smith et al. 1991, Maynard and Wilcox 1997). Coastal peatlands also exist, however they are uncommon, and none are found along Lake Ontario (Herdendorf 1990, Maynard and Wilcox 1997, Wilcox and Whillans 1999).

Coastal wetlands are formed by numerous geomorphological processes in the Great Lakes. Marshes often form in areas with lower wave action, including unrestricted bay and open shoreline marshes (Maynard and Wilcox 1997). Shallow sloping beach wetlands form in areas where vegetation is protected from strong wave action by sand bars (Jude and Pappas 1992, Maynard and Wilcox 1997). Wetlands can also form along tributaries to the Great Lakes, forming river delta and drowned river mouth wetlands (Herdendorf 1990, Jude and Pappas 1992, Maynard and Wilcox 1997). Wave action can cause sediment deposition, forming a bar across a bay, creating barrier beach and lagoon wetlands (Herdendorf 1990, Smith et al. 1991, Jude and Pappas 1992, Maynard and Wilcox 1997). Inland wetlands with a connection to a Great Lake are also considered coastal wetlands, as they can be influenced by lake processes, such as water level fluctuations (Maynard and Wilcox 1997). Some artificial coastal wetlands have also been created by humans using dikes (Maynard and Wilcox 1997). There are numerous types of coastal wetlands, all of which provide important ecosystem services and functions.

Coastal wetlands are important ecosystems as they have unique community structures, intricate food webs, and high species diversity (Stephenson 1990, Edsall and Charlton 1997). As they are continually affected by water level fluctuations, coastal wetlands are unique in that they do not experience the traditional senescence that inland wetlands do (Herdendorf 1990, Mortsch 1998). Coastal wetlands provide many important ecosystem services, including improving water quality by slowing flows and allowing sediment and contaminants to settle, providing protection against flooding and erosion, and providing habitat for a wide variety of species including provincially significant species and species at risk (Smith et al. 1991, Edsall and Charlton 1997). While coastal wetlands are often small in size, they have a disproportionate ecological role due to the necessity of ecological services that they provide (Sedell et al. 1991). Naturally functioning coastal wetlands should have sediment deposition and disturbance characteristics that support the life histories of native plant and animal species (Sedell et al. 1991).

Due to urbanization, industrialization, agriculture, and recreational development, many Canadian wetlands have been degraded or eradicated completely, and Great Lakes coastal wetlands are no exception. Some coastal wetlands have also been controlled with the use of dikes and flood control structures, which have isolated them from lake level fluctuations, and effectively converted them into inland wetlands (Wilcox and Whillans 1999). Most wetland loss has occurred in urban areas, including the highly urbanized northwestern shore of Lake Ontario (Edsall and Charlton 1997). This area is particularly affected by wetland loss, with 73 to 100% of historic marshes lost between the Niagara River and Toronto (Whillans 1982). Many of the remaining wetlands are currently in a degraded state and also face the constant threat of urban expansion (Stephenson 1990, Jude and Pappas 1992). As such, the amount of wetland loss is likely higher than the percentages recorded in these studies, and the need to restore coastal wetlands is greater than ever.

2.2. Freshwater Estuaries

Freshwater estuaries are an ecotone between rivers or streams and a large body of freshwater, such as Lake Ontario (Herdendorf 1990). Similar to saltwater estuaries, freshwater estuaries can be defined as a constricted area where a river meets a large body of water, with continuous water exchange and the mixing of two distinct bodies of water (Herdendorf 1990). Many freshwater estuaries in the Great Lakes are formed as drowned river mouths, similar to many saltwater estuaries (Herdendorf 1990). In the Great Lakes, many freshwater estuaries have been dramatically altered from their natural state. Many estuaries have been channelized and dredged to facilitate shipping (Sedell et al. 1991).

A naturally functioning freshwater estuary should have sediment accumulation that is conducive to native plant growth and use by native fishes (Sedell et al. 1991). Disruptions within a naturally functioning estuary, including wave action, floods, ice movement, currents, seiches, and upwellings should be of a frequency and intensity that allows native plant and animal establishment, and should support the critical life stages of local fish species (Sedell et al. 1991).

2.3. Coastal Embayments

Coastal embayments are partially enclosed bodies of water along the shoreline of a larger body of water. The morphometry of an embayment often shelters it from open lake processes such as wave action, internal seiches, and upwellings (Klumb et al. 2003). They can be naturally occurring or constructed, and may contain marsh, open water, marinas, and other features (Edsall and Charlton 1997). In this document, the term coastal embayment refers to a small constructed bay along the shoreline of Lake Ontario. Most of these embayments, with the exception of Rattray Marsh, have been either considerably altered from their natural state or artificially constructed.

The temperatures in coastal embayments of Lake Ontario vary greatly (Murphy et al. 2012b). Murphy et al. suggest that the temperature variation among embayments may be caused by bathymetric differences or differences in exchange with the Lake (Murphy et al. 2012b). Depending on their physical characteristics, embayments range in their exposure to open-lake processes, such as upwellings. Some coastal embayments have been constructed to create warm-water fish habitat as compensation projects for shoreline urbanization projects (Murphy et al. 2012b).

2.4. Hypolimnetic Upwelling and Internal Seiches

Hypolimentic upwelling is a hydrologic phenomenon that occurs in large stratified lakes, including the Laurentian Great Lakes. During the summer, Lake Ontario becomes thermally stratified. Hypolimnetic upwellings occur when the cool, dense hypolimnion rises toward the surface at the shoreline. These upwellings are driven by wind-driven processes within the lake.

Common causes of hypolimnetic upwellings include strong winds and internal waves (Csanady 1977, Landsberg 1977). Prevailing winds generally blow from west to east along Lake Ontario (Simons and Schertzer 1987). Due to the Coriolis force and Ekman transport, the surface water moves south, to the right of the wind (Simons and Schertzer 1987). As the surface water moves south, the thermocline moves upward near the northern shore, causing an upwelling event. These upwelling events are similar to those that occur along the coast of the ocean, however in large lakes, there are other causes of upwelling as well.

In large lakes, upwelling can also be caused by internal waves. Internal waves are caused by numerous factors: prolonged wind, wind variation, seasonal and spatial variation of stability, basin shape, and the Coriolis force (Landsberg 1977). There are four main types of internal seiches in lakes, including uninodal seiches, higher order seiches, transverse seiches, and rotating seiches, many of which occur in Lake Ontario (Landsberg 1977).

Uninodal seiches have a single node, and one standing wave spanning across the entire lake, with maximum amplitudes occurring in the near-shore zones (Landsberg 1977). Higher order seiches have multiple nodes and travel more slowly, with maximum amplitudes occurring at the antinodes (Landsberg 1977). Transverse seiches occur across the width of the lake, and are caused by north-south winds lasting 8 or 24 hours long (Landsberg 1977). Rotating internal seiches are waves that rotate around a lake (Landsberg 1977). In the northern hemisphere, they travel counter-clockwise due to the Coriolis force (Landsberg 1977).

There are four specific types of internal waves that occur in Lake Ontario, including Poincaré waves, quasi-geostrophic waves, short internal waves, and Kelvin waves (Landsberg 1977, Mortimer 2006). Poincaré waves are long internal waves that are generally dominant in the offshore zone (Landsberg 1977). Quasi-geostrophic waves are formed by multiple interacting Poincaré waves, and form a long internal wave in the near-shore zone. Short internal waves are formed by instability at the nodes of Poincaré waves, and are rotating internal waves (Landsberg 1977). Kelvin waves are long rotating uninodal internal seiches, and as such they generally dominate in the near-shore zones (Landsberg 1977). Kelvin waves in Lake Ontario generally have a period of 30 days, however they may have a period of 12 to 16 days when there is interference with quasi-geostrophic waves. In Lake Ontario, Kelvin waves often cause upwelling along the northern shore and downwelling along the southern shore (Landsberg 1977).

2.5. Warm-water Fish and Benthic Invertebrate Utilization of Coastal Wetlands and Freshwater Estuaries

Coastal wetlands and freshwater estuaries are important ecosystems in the Great Lakes for fish and benthic invertebrates. These ecosystems are generally high in species diversity and production (Edsall and Charlton 1997). They are home to resident fish, provide a pathway for anadromous fish, and are temporary feeding, spawning, and rearing areas for other fish species (Stephenson 1990, Sedell et al. 1991, Edsall and Charlton 1997). Stephenson found that 86% of species found in the coastal marshes of Lake Ontario use coastal wetlands for rearing, indicating that the main use of these ecosystems is as rearing habitat (Stephenson 1990). However, coastal marshes are also suitable habitat for invasive species, such as the common carp (*Cyprinus carpio*). Carp are a disruptive invasive species that move into Great Lakes coastal marshes to spawn, and in doing so uproot aquatic vegetation and stir up sediment (Hussey and Goulin 1990).

These coastal wetlands are also important habitat for many benthic invertebrate species. At least 196 taxa of benthic invertebrates have been found in the near-shore areas of Lake Ontario (Barton 1986). The most common benthic invertebrates found in Lake Ontario include: oligochaete worms such as *Vejdovskyella intermedia*, *Chaetogaster diaphanus*, *Potamothrix vejdovskyi*; midges (*Tanytarsus* spp.), *Pontoporeia hoyi*, and *Gammarus fasciatus* (Barton 1986). Coastal wetlands, estuaries, and embayments are important ecosystems for a wide variety of freshwater species.

2.6. Effects of Upwelling on Near-shore Fish and Benthic Invertebrates

Near-shore aquatic fish and benthic invertebrate communities are adapted to a specific range of summer temperatures (Edsall and Charlton 1997). Fish at the northern limit of their range, such as largemouth bass (*Micropterus salmonides*), may need these warm-water areas for survival (Edsall and Charlton 1997). Hypolimnetic upwelling events result in a substantial decrease in temperature over a short period of time, which may have adverse effects on these warm-water fish species. Hypolimnetic upwelling has been found to affect the behaviour and survival of several species of fish and benthic invertebrates (Emery 1970). Many of these species have been found to exhibit behavioural changes during an upwelling. Many species move upward during an upwelling to avoid the cold water intrusion, including white suckers (*Catostomus* *commersoni*), trout perch (*Percopsis omiscomaycus*), yellow perch (*Perca flavescens*), smelt (*Osmerus mordax*), ninespine sticklebacks (*Pungitius pungitius*), alewife (*Alosa pseudoharengus*), and lake whitefish (*Coregonus clupeaformis*) (Emery 1970). When an upwelling occurs, the temperature decrease occurs rapidly, which can be perilous for slow-moving species. During an upwelling, slow-moving mottled sculpins (*Cottus bairdi*) and crayfish (*Orconectes propinquus*) were observed to cease feeding, move erratically, and die (Emery 1970). Benthic invertebrate communities are determined by their susceptibility to temperature changes during upwellings (Barton 1986). Barton (Barton 1986) found a lack of crayfish in his study, and speculated that their absence was due to a high frequency and magnitude of upwellings along the north shore. This speculation is consistent with Emery's study (Emery 1970), in which he observed crayfish mortality during an upwelling. Cold water has also been found to limit the growth and survival of juvenile warm-water fish species such as pumpkinseed (*Lepomis gibbosus*) (Murphy et al. 2011, 2012a). While the effects of cold water intrusion during upwellings have been observed or speculated for some species, the effects on most warm-water fish and benthic invertebrate species are unknown, and further research in this area is required.

2.7. Summary

Hypolimnetic upwellings are a naturally occurring process in Lake Ontario, however they can have adverse effects on warm-water fish and benthic invertebrates. Coastal wetlands provide shelter for fish and benthic invertebrates during upwellings, however many coastal wetlands have been lost. Many coastal embayments have been created in the Great Lakes, for various reasons. It is unknown how they compare to natural wetlands in providing refuge from upwellings. This study compares upwellings in a natural wetland, an altered estuary, and three constructed embayments to determine if the constructed embayments create refuge during upwelling events. The findings of this study will inform the creation of embayments for warm-water refuge in the future.

Chapter 3. Methods

3.1. Study Areas

Five study sites were selected along the northwestern shore of Lake Ontario in the City of Mississauga, ON. The sites include Rattray Marsh, the Credit River estuary, and three constructed embayments located at Port Credit and Lakefront Promenade (Figure 1). Multiple loggers were placed in each site to encompass spatial variation across the sites. The study sites vary in morphology, size, shape, and type.

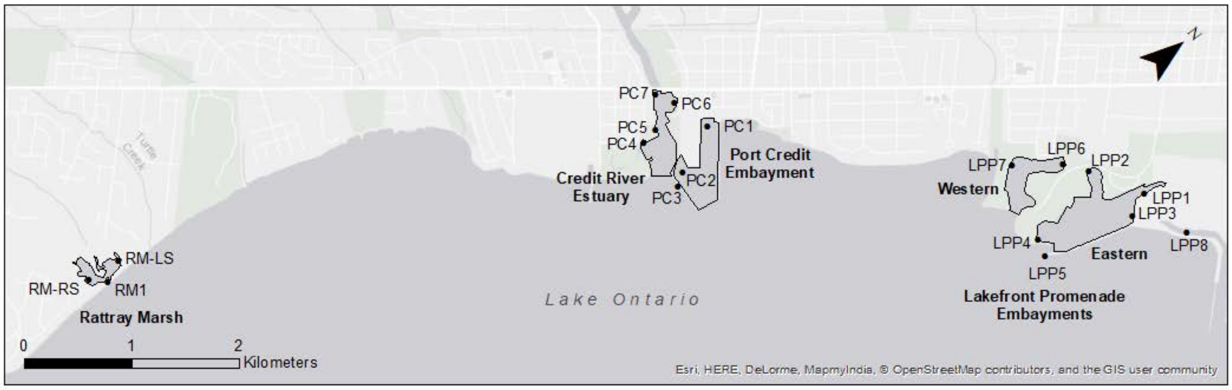

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Figure 1. Study sites and logger locations in Mississauga, Ontario along the northwestern shore of Lake Ontario. Sites include Rattray Marsh, the Credit River estuary, Port Credit embayment, Lakefront Promenade eastern embayment and Lakefront Promenade western embayments.

3.1.1. Rattray Marsh

Rattray Marsh is a Great Lakes coastal marsh that is seasonally connected to Lake Ontario, and is fed by Sheridan Creek (Figure 2). This marsh is a bar-built/lagoon freshwater estuary. The bar is naturally occurring, and was formed by wave action that pushed up flat, smooth, shingle-like stones, creating this 'shingle bar' (Hussey and Goulin 1990). This bar shelters the marsh from open-lake processes, and allows settling of fine sediment (Smith et al. 1991). The marsh is seasonally connected to Lake Ontario, with the bar breaching during a storm event or at high water levels (Hussey and Goulin 1990). There is also some movement of water between the marsh and the lake through the porous shingle bar (Hussey and Goulin 1990). The Sheridan Creek watershed has been highly urbanized, with many impervious surfaces within the watershed. This has caused an increase in urban runoff, altering the annual hydrograph by and Sheridan Creek has become flashy in result (Hussey and Goulin 1990). During heavy rains, this causes erosion of the banks and can cause breaching of the shingle bar (Hussey and Goulin 1990).

Figure 2. Aerial view of Rattray Marsh, featuring Sheridan Creek and the porous shingle bar isolating the marsh from Lake Ontario (Google Earth 2016).

Rattray Marsh is an important conservation area, as it provides habitat for many species, and has cultural significance to the surrounding community. It supports many native fish species, including spawning and juvenile suckers (*Catostomus spp.*), brown bullhead (*Ameiurus nebulosus*), northern pike (*Esox lucius*), sunfish (*Micropterus spp., Lepomis gibbosus*), mudminnows (*Umbra limi*), minnows, and others (Hussey and Goulin 1990).

The marsh has a strong cultural significance due to a long history of development threats and battle for conservation. The marsh was initially owned by a series of homeowners including Major Rattray, the namesake of the marsh (Hussey and Goulin 1990). It first faced the threat of development in the early 1960s after Major Rattray's passing (Hussey and Goulin 1990). The marsh was sold for development in 1963 (Hussey and Goulin 1990). There were several failed attempts to protect the marsh and to purchase it for conservation, including doing ecosystem assessments and crowdfunding efforts led by the Nature Conservancy of Canada and the Rattray Estate Preservation Committee (Hussey and Goulin 1990). In 1967, just as the bulldozers were encroaching on the marsh, Ruth Hussey wrote a Letter to the Editor of the Globe and Mail, bringing to light Canada's lack of interest in protecting the marsh (Hussey and Goulin 1990). This letter initiated a petition and fueled public interest (Hussey and Goulin 1990). By 1973, naturalist groups, youth groups, and public citizens had raised enough funds to purchase and protect the marsh (Hussey and Goulin 1990). Due to this long history of conservation, and the urban environment surrounding the marsh, Rattray Marsh has a strong cultural significance to the people of Mississauga.

3.1.2. Credit River Estuary and the Port Credit Embayment

The Port Credit site includes the Credit River estuary to the west and an embayment with Port Credit Harbour Marina to the east (Figure 3). The Credit River estuary has a long history of development and industrialization. The estuary was historically part of an Indian Reserve, however the land was purchased from the Mississaugas in 1820 (Clarkson 1977). At this time, an island existed at the eastern bank of the river (Clarkson 1977). Pine and oak trees in the riparian areas were felled in the 1820s to build ships (Clarkson 1977). In the 1830s, the estuary was dredged and widened to allow passage of large ships, and surrounding land was drained and cleared for urban development (Clarkson 1977). The estuary has been constrained with breakwalls on both banks, as well as a training dyke. Historically, the estuary was likely a drowned river mouth (Herdendorf 1990). The Port Credit embayment is a constructed embayment housing a large marina. It is sheltered from the open lake by a rip rap breakwall.

Figure 3. Aerial view of the Credit River estuary and Port Credit embayment on Lake Ontario (Google Earth 2016).

3.1.3. Lakefront Promenade Embayments

The Lakefront Promenade site encompasses Lakefront Promenade Park and RK MacMillan Park, two municipal parks in the City of Mississauga. Within this area, there are two constructed embayments (Figure 4). The eastern embayment has two marinas, Lakefront Promenade Marina and Port Credit Yacht Club. It is confined by a large breakwall. The eastern embayment contains a small bay separated from the rest of the embayment by a constructed bar (Figure 4). Logger LPP2 was deployed in this bay. The western embayment has sand beaches and is surrounded by park land.

Figure 4. Aerial view of the constructed embayments at Lakefront Promenade, including the western and eastern embayment, in Lake Ontario (Google Earth 2016).

3.2. Temperature Loggers

Temperature loggers were placed in the water column near the bottom of each of the study sites according to Figure 1. Two to five loggers were placed in the sites to provide coverage of the entire site. Two loggers (PC3, LPP5) were placed along the shoreline of the open lake as references for open lake conditions. Loggers PC7 and LPP8 were not placed due to high water levels and access restrictions.

HOBO Water Temperature Pro v2 Data Logger U22-001 loggers were selected for cost effectiveness and continuity with other Credit Valley Conservation Authority projects and similar studies (Murphy et al. 2011). The loggers were placed in the spring of 2017. Sixteen of the loggers began recording on June 1, 2017, and two of the Rattray Marsh loggers began recording on July 2, 2017, as they were placed on July 1, 2017. Temperatures were recorded at fifteen minute intervals until late October/early November when they were removed. A data subset was used to only include data from 0:00 on July 2, 2017 to 23:45 on Oct. 9, 2017 to maintain consistency across sites. Loggers PC5 and LPP2 were not included in the analyses, as they were above the surface for a portion of the study season due to fluctuating water levels, and logger LPP6 was not included, as it was inaccessible due to overgrown vegetation.

3.3. Data Analysis

The temperature data from the loggers was compared to local daily precipitation data to determine if the water temperature trends were reflective of a hypolimnetic upwelling event. Precipitation data was retrieved from the nearest station, Oakville TWN from Environment Canada (Environment Canada 2017). The dates of rain events were compared to the dates of upwellings to determine if they were correlated.

For each logger, upwellings were identified as a sudden sustained temperature decrease of greater than 4^{o}C (Plattner et al. 2006). Temperature change (ΔT) was calculated from the maximum temperature prior to the drop to the minimum temperature following the drop. The duration of the temperature decrease, average ΔT, average duration, and the frequency of upwelling events were calculated.

Descriptive statistics were used for each logger location. Descriptive statistics were chosen because of the limited number of upwelling events, the short study period, small sample size, and inconsistent number of successful loggers within each site. The data from the loggers were used to gain an understanding of the nature of upwellings within the types of sites (i.e. constructed embayment, estuary, marsh, open shoreline), rather than directly comparing between each site.

Chapter 4. Results

The water temperature time series from July 2, 2017 to October 10, 2017 for each data logger was graphed (Appendix A). From these graphs, individual upwelling events were identified. Temperatures were not averaged prior to isolating upwellings to encompass the full magnitude of temperature change during upwelling. Upwellings were defined as a sudden sustained decrease in temperature of over 4°C. The average temperature change (ΔT), average duration, and frequency of upwellings were determined (Table 1).

Table 1 Average magnitude of temperature change (ΔT), average duration, and frequency of upwelling at each logger within the Lakefront Promenade, Port Credit, Credit River, and Rattray Marsh sites in northwestern Lake Ontario from July 2, 2017 to October 10, 2017.

Site	Logger	ΔT (°C)	Average Duration (h:m:s)	Frequency (Events/study period)
Lakefront Promenade Eastern	LPP1	-8.910	53:33:45	4
Lakefront Promenade Eastern	LPP3	-7.081	30:41:15	4
Lakefront Promenade Eastern	LPP4	-9.117	63:11:15	4
Lakefront Promenade Eastern	LPP5	-11.925	42:22:30	4
Lakefront Promenade Western	LPP7	-10.612	60:03:45	4
Port Credit Embayment	PC1	-9.225	64:48:45	4
Port Credit Embayment	PC2	-9.553	68:43:35	4
Port Credit Embayment	PC3	-11.672	39:11:15	4
Credit River Estuary	PC4	-8.742	67:25:00	6
Credit River Estuary	PC6	-7.666	70:00:00	5
Rattray Marsh	RM1	-11.028	48:52:30	2
Rattray Marsh	RM-LS	-8.836	62:00:00	2
Rattray Marsh	RM-RS	-7.468	55:40:00	3

Upwelling events were identified in all thirteen of the successful logger locations. Upwelling frequency was found to be relatively consistent throughout the sites, with 8 sites experiencing 4 upwellings, two experiencing 5-6, and three experiencing 2-3. Two of the Credit River estuary loggers, PC4 and PC6, recorded more than 4 upwellings, and the three Rattray Marsh sites had fewer (Figure 5).

The average duration of upwellings varied from 30 hours, 41 minutes to 70 hours (Table 1). The most rapid upwellings were observed at loggers LPP3, LPP5, PC3, and RM1 (Figure 6). The average ΔT varied from -7.081°C to -11.925°C (Table 1). The loggers with the greatest temperature change were LPP5, LPP7, PC3, and RM1 (Figure 7).

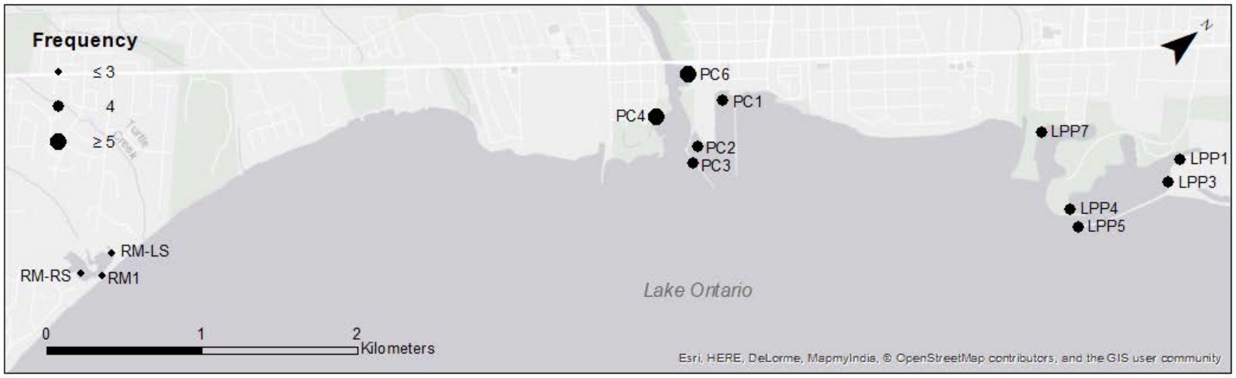

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Figure 5. Spatial distribution of the frequency of recorded upwellings at loggers in Rattray Marsh, the Credit River Estuary, Port Credit embayment, and Lakefront Promenade embayments in Mississauga, ON. Upwellings were recorded between July 2, 2017 and October 10, 2017. The most frequent upwellings were seen in the Credit River Estuary, and the least frequent upwellings were seen in Rattray Marsh.

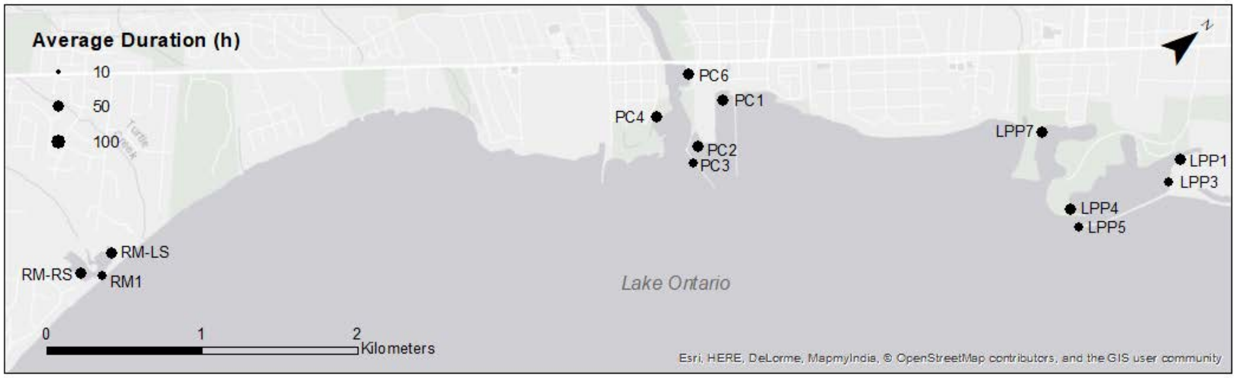

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Figure 6. Spatial distribution of the average duration of recorded upwellings at loggers in Rattray Marsh, the Credit River Estuary, Port Credit embayment, and Lakefront Promenade embayments in Mississauga, ON. Upwellings were recorded between July 2, 2017 and October 10, 2017. Average durations ranged from 30 hours, 41 minutes to 70 hours.

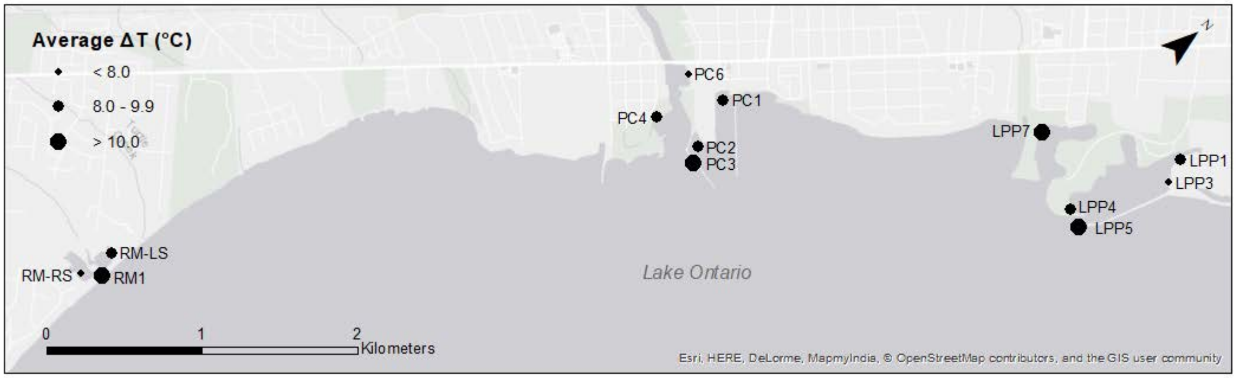

Figure 7. Spatial distribution of average temperature change (ΔT) during recorded upwellings at loggers in Rattray Marsh, the Credit River Estuary, Port Credit embayment, and Lakefront Promenade embayments in Mississauga, ON. Upwellings were recorded between July 2, 2017 and October 10, 2017. The greatest temperature changes were observed at loggers RM1, PC3, LPP7, and LPP5.

The upwellings recorded at each logger were compared to daily precipitation to determine whether the temperature changes were the result of upwelling or simply an influx of cold water (Figure 8). Some of the upwelling events appear to have coincided with rain events, however most of them did not.

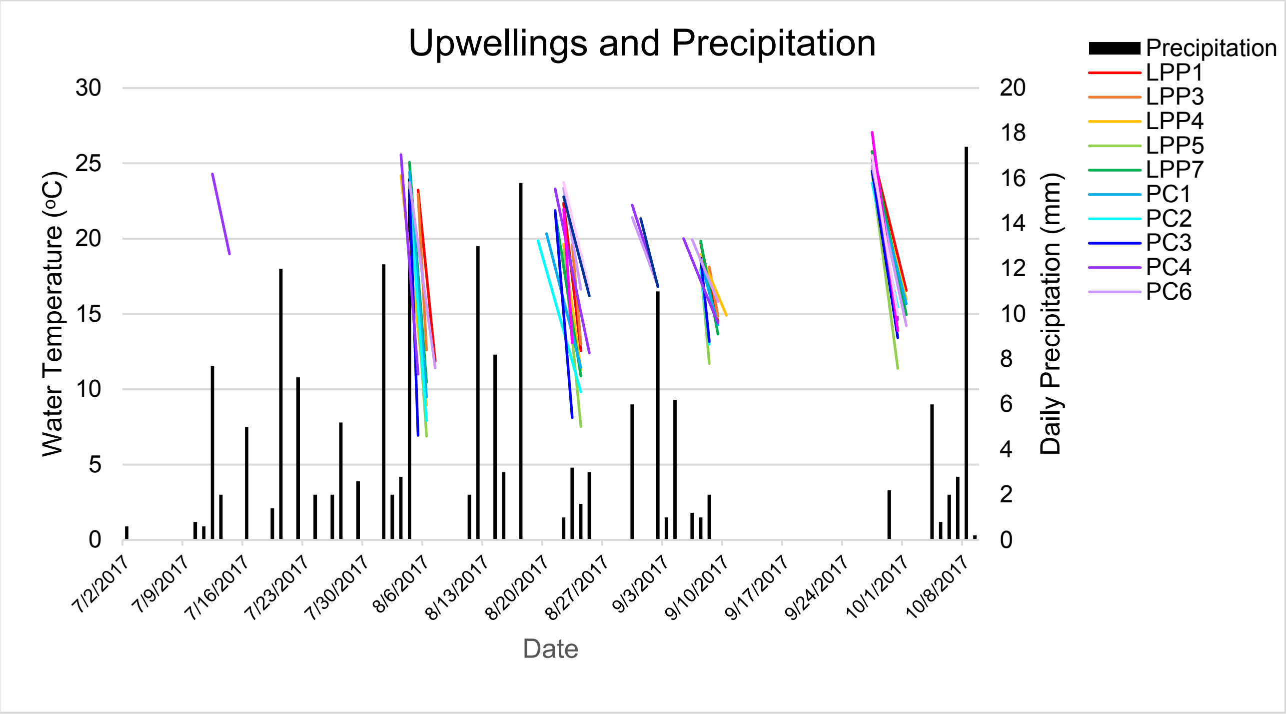

Figure 8. Daily precipitation and upwellings at each site. Black bars indicate total daily precipitation and coloured lines indicate an individual upwelling event at each logger location.

Chapter 5. Discussion

Upwelling events were observed at every logger location. Upwelling frequency was consistent across most of the sites, however two of the Credit River estuary loggers were found to have more upwellings. This may indicate that some of these events may not be upwellings, as they were limited to the estuary. The upwelling events recorded around July 14, 2017 and August 30, 2017 by loggers PC3, PC4, and PC 6 may not be upwellings, and may be caused by changes in the temperature of water flowing through the Credit River. This could be due to a precipitation event as these two events seem to occur just after precipitation (Figure 8). The fewest upwelling events were seen in the Rattray Marsh loggers (RM1, RM-RS, RM-LS). This is likely due to the shingle bar, which isolated the marsh from upwellings in the spring until the unusually high lake level breached the bar.

The average duration of upwellings was relatively consistent, and ranged from 30 hours, 41 minutes to 70 hours. While the average upwelling duration was consistent across most of the logger locations, the shortest upwellings were recorded at loggers LPP3, LPP5, PC3, and RM1 (Figure 6). Three of these loggers (LPP5, PC3, and RM1) are all directly exposed to the open lake. This indicates that the marsh, estuary, and constructed embayments may slow the process of upwelling within them.

The average magnitude of temperature change (ΔT) ranged from -7.081°C to -11.925°C. The magnitude of temperature change was found to be related to the level of connectivity to the open lake (Figure 7). The greatest ΔT was seen in loggers LPP5, LPP7, PC3, and RM1. Of these loggers, three of them are directly exposed to the open lake (LPP5, PC3, RM1). This indicates that the protection provided by the marsh, estuary, and constructed embayments may reduce the magnitude of temperature change during an upwelling when compared to open water areas.

All of the study sites seem to buffer upwellings by reducing the magnitude of temperature change and lengthening the duration of the upwelling. This is likely beneficial to warm-water aquatic species, as the rate of temperature change is reduced. While the marsh, estuary, and constructed embayments all seem to do so, the amount of buffering varies considerably across the sites. The magnitude and rate of temperature change in some of the sites may still be unsuitable to some fish and benthic invertebrate species. Further research is required to determine whether the magnitude of temperature change currently experienced in the study sites is adequately buffered for species of interest.

The barrier bar in Rattray Marsh seems to reduce the frequency of upwellings. It is likely that the barrier bar was breached by high water levels at some point during the study period, however water levels were much higher than average (Government of Canada 2017). Future studies should be done to determine how frequently the bar breaches in an average year, if at all, as the number of upwellings experienced by Rattray Marsh in an average year may actually be lower than those seen in 2017. It would also be of interest to determine if the constructed barrier bar at LPP2 reduces upwelling frequency to the same extent as the natural shingle bar at Rattray Marsh. Unfortunately, there was no reliable data recorded at LPP2 this season.

Further, upwelling is not the only stressor acting on coastal wetland warm-water fish and benthic invertebrate species in Lake Ontario. There are a multitude of other stressors affecting these populations, and it is important that they are assessed prior to commencing restoration efforts of other coastal marshes, estuaries, and embayments.

5.1. Other Stressors

While upwelling is likely a natural stressor for some fish and benthic invertebrate species, there are countless other natural and anthropogenic stressors affecting these populations that should also be considered in the restoration of these sites. Other potential stressors include eutrophication, dissolved oxygen availability, sediment loading, land use change in the watershed, stream modification, dredging, spawning substrate suitability, water level control, diking, invasive species, et cetera (Francis et al. 1979, Sedell et al. 1991). The Sheridan Creek Watershed is highly urbanized with many impervious surfaces, which has resulted in a flashy creek (Hussey and Goulin 1990). This causes storm surges that result in large influxes of water during a short period of time, which may adversely affect fish and benthic invertebrates, however this has not yet been studied. Contaminants are another stressor in the Great Lakes, and could be a stressor in the study sites (Francis et al. 1979). These stressors, along with climate change, must also be considered and addressed by future restoration efforts.

5.2. Climate Change

Climate change will have profound effects on the Great Lakes, and these effects need to be taken into consideration when considering restoring these sites. Rising air temperatures are predicted to reduce snowpacks, increase winter rainfall, and increase evaporation in the Great Lakes basin (Mortsch 1998, Lam and Schertzer 1999). In the Great Lakes, this will likely lead to an earlier seasonal maximum water level, reduced ice cover, and lower lake levels (Mortsch 1998).

These alterations to the hydrologic regime could greatly affect coastal wetlands and fish populations. Low water levels could impede fish passage into wetlands, and sudden drops in water level could desiccate eggs (Mortsch 1998). Low winter water levels could increase winterkill (Mortsch 1998). While high water levels during spawning and higher water temperatures could increase wetland productivity, increase warm-water fish populations, and increase juvenile fish survivorship, a decrease in water depth and increased competition will further stress these populations (Mortsch 1998).

Unconfined marshes are most likely to adapt to climate change driven water level changes, as their plant communities are adept at relocating (Mortsch 1998). Confined wetlands, such as barrier beach wetlands like Rattray Marsh, may be more prone to desiccation in low water level conditions (Mortsch 1998).

Stratification and upwellings may also be affected by climate change. Periods of stratification may lengthen (Lam and Schertzer 1999, Dove-Thompson et al. 2011). Changes in wind patterns and storm events may alter the frequency and intensity of seiches and upwellings, however these changes are not yet well understood (Dove-Thompson et al. 2011).

5.3. Future Studies

Moving forward, there are many areas of further research that should be explored. While the data collected in 2017 does provide a useful indication of how upwellings affect a coastal marsh, altered estuary, and constructed embayments in Lake Ontario, it is necessary to study the sites over multiple years to ensure that the trends found in this field season are representative of average conditions. This year may not be indicative of an average year, as the Lake Ontario water levels were at a record high (Government of Canada 2017).

Future studies should also include a fish and benthic invertebrate monitoring program to determine if upwellings are negatively affecting fish and benthic invertebrates in the study sites. Fish and benthic invertebrate populations should be monitored prior to, during, and just after an upwelling event, and any indication of mortalities and behavioural changes should be recorded. To predict upwelling events, wind speed, direction, and duration should be closely monitored. A pilot study should be done to determine the correlation between wind conditions and upwelling events. Fish and benthic invertebrates should be sampled consistently throughout the period of thermal stratification and their abundance should be compared to the timing of upwellings. A correlation between upwellings and decreased abundance could indicate that the upwellings are negatively affecting these populations as hypothesized.

Chapter 6. Restoration Recommendations

The findings of this study will help direct future studies and the restoration of coastal marshes and embayments. Moving forward, there are several steps that should be taken: determine the target species, conduct fish and benthic invertebrate studies and surveys, perform a wind-upwelling pilot study, repeat this upwelling study over multiple years, assess upwelling buffering effectiveness of the study sites, and implement restoration techniques at new sites.

6.1. Determine Target Species and Life Stages

A thorough literature review and/or pilot survey should be done to determine the species of fish and benthic invertebrates that are currently and were historically present in coastal marshes of Lake Ontario. From this literature review, a list of species that require coastal marshes and embayments should be compiled, and the life stage at which they use these areas should be noted. From this list, a subsequent list of target species should be written, including species that have high ecological and economic value.

6.2. Fish and Benthic Invertebrate Literature Review and/or Field Studies

The target fish and benthic invertebrate species should be studied to determine their level of tolerance to temperature changes. It is important that the tolerance to temperature change is determined at the life stage in which the species would use coastal wetlands/embayments. While a literature review may be sufficient to determine this information, field and lab studies may be required.

6.3. Targeted Fish and Benthic Invertebrate Studies

Fish and benthic invertebrates should be surveyed prior to, during, and just after an upwelling to determine the effects of an upwelling on these populations. To do targeted surveys, the upwellings must be predicted. The most common process causing upwelling along the northern shore of Lake Ontario is the Kelvin wave, which is predictable in nature (Landsberg 1977). Kelvin waves usually have a period of approximately 30 days (Landsberg 1977), which is consistent with the upwellings seen in this study, reinforcing the notion that they should be predictable. A pilot study should be done to determine the correlation between wind conditions and upwelling events. In this study, wind speed, direction, and duration should be compared to water temperature, to determine when upwellings occur with respect to wind conditions. After this pilot study, a pattern should develop that can be used to predict when an upwelling event will occur.

In the targeted fish and benthic invertebrate studies, fish and benthic invertebrates should be studied before, during, and after an upwelling. Any indications of fish and benthic invertebrate behavioural changes and mortalities should be recorded. It is important to fully understand the effects of upwellings on these populations before restoring wetlands with the goal of buffering upwellings.

6.4. Repeat Upwelling Studies

This upwelling study should be repeated over multiple years to gain a more representative average of upwelling events within the sites. As 2017 was a record high water level year, it is particularly important that upwellings are monitored in successive years with near-average water levels. In future years, the logger at LPP2 should be included to assess the effectiveness of the constructed rip rap bar as an upwelling buffer technique.

6.5. Assess Upwelling Buffering Effectiveness

After determining the target species, their respective target life stages, and assessing the upwellings in the sites over multiple years, the upwelling buffering effectiveness should be assessed. The average temperature change rate should be compared to the tolerances of the target species to determine if the sites provide adequate upwelling buffering. Sites that do provide adequate buffering can be used as reference sites for future embayment creation projects.

6.6. Future Restoration of Coastal Marshes in Lake Ontario

Lake Ontario is a highly degraded ecosystem. Most of Lake Ontario’s coastal wetlands have been lost, which has had many adverse effects on the Lake Ontario ecosystem (Sedell et al. 1991, Jude and Pappas 1992). Restoring the Lake Ontario ecosystem will require the creation of new wetlands that will provide the ecosystem structure and functions that the historical marshes once did.

As much of the shoreline has been dredged or infilled and developed straight to the shoreline, creating new marshes will likely require infilling. When infilling to create a new wetland, the shape of the wetland should be chosen to resemble a natural wetland. The most feasible wetland types to create by infilling include barrier beach and unrestricted bay wetlands. Connected inland wetlands could also be created by excavating an inland area, which is possible in areas where development does not reach the shoreline. Open shoreline and shallow sloping beach wetlands could be restored by creating barrier islands to reduce the impacts of wave action.

When considering which geomorphological type of wetland to create, the needs of the target species should be considered. The amount of upwelling buffering should be considered. Species that require more shelter from upwellings may benefit from a limited connection to Lake Ontario, and a barrier beach or connected inland wetland may be best. Those that require less buffering may find an unrestricted bay or shallow sloping beach wetland suitable. The need for passage should also be considered. If the target species is a fish species that migrates into the marsh to spawn, it is essential that the wetland is accessible during the spawning season. In this case, a barrier beach wetland may not be suitable.

Most of Lake Ontario’s coastal wetlands are marshes with areas of swamp upland of the marsh (Maynard and Wilcox 1997). As such, created wetlands in Lake Ontario should be designed as marshes. When restoring these wetlands, it is important to restore a natural gradient of native plant communities that would have been present in historical coastal marshes. This marsh-to-swamp-to-upland gradient should be followed when seeding, staking, and planting the created marsh, leaving a shallow open water area offshore, followed by emergent marsh vegetation (sedges, cattails, etc.), leading into shrubs and trees in the swamp area, and finally forest farther upland. All plant material, including seeds, live stakes, and rooted vegetation, should be locally-sourced native species.

The target species must also be considered when choosing which habitat features to add to the created coastal marsh. For spawning fish, it may be necessary to add a suitable spawning substrate. For juvenile fish, boulders and large woody debris with large intact root wads will add complexity and cover. Birds of prey, such as osprey (*Pandion haliaetus*), may benefit from standing large woody debris, which they use as perches.

It is important to recognize that Asian carps are a persistent invasive species in Lake Ontario. They travel into coastal wetlands to spawn, and while doing so, disturb the entire marsh ecosystem by uprooting vegetation and suspending sediment (Hussey and Goulin 1990, Stephenson 1990, Jude and Pappas 1992). When creating coastal wetlands in Lake Ontario, it may be necessary to design a system to exclude carp, similar to the exclosure grates at Delta Marsh, MB, or the Fishway at Cootes Paradise Marsh, ON (Ducks Unlimited Canada n.d., Royal Botanical Gardens 1998).

Chapter 7. Conclusion

The frequency, duration, and magnitude of upwelling events were determined for each of the 13 successful temperature loggers. Upwelling frequency was found to be reduced by the shingle bar in Rattray Marsh. Upwelling duration was found to be lengthened within the study sites, and the magnitude of the temperature change during upwelling was found to be reduced within the sites, indicating that the marsh, estuary, and embayments are effectively buffering upwelling, and are creating warm-water refuge during upwelling.

While the patterns seen during the summer of 2017 indicate that the study sites are buffering upwellings, it is important to continue to monitor upwellings over multiple years to determine if the patterns observed are representative of average conditions in Lake Ontario.

The results of this study indicate that restoration of coastal marshes to buffer upwellings is possible. Further research and planning is required to determine the target species, their tolerance to upwellings, and whether or not embayments such as the study sites adequately buffer upwellings. There are many different types of coastal wetlands that can be created in Lake Ontario, providing endless opportunities for restoration.

These coastal embayments, wetlands, and estuaries are very important ecosystems within the Great Lakes, and are particularly important to warm-water fish and benthic invertebrates. Unfortunately, these ecosystems are scarce in Lake Ontario due to urbanization and industrialization, and many of them are degraded. For these reasons, restoration of coastal wetlands, estuaries, and embayments is crucial in the Great Lakes.

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Appendix A.

Temperature Time Series

The figures in this appendix show the temperature time series recorded by each successful logger in the Lakefront Promenade, Port Credit, and Rattray Marsh sites.

Lakefront Promenade

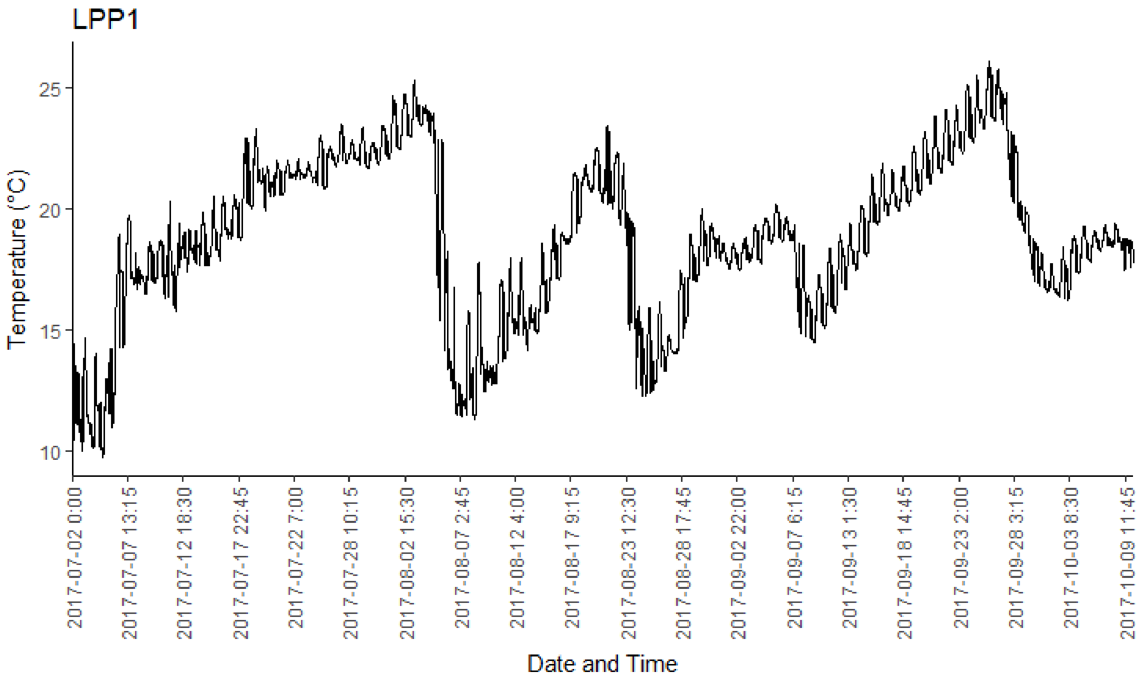

Figure A1. Water temperature in Lakefront Promenade at logger LPP1 from July 2 to October 9, 2017.

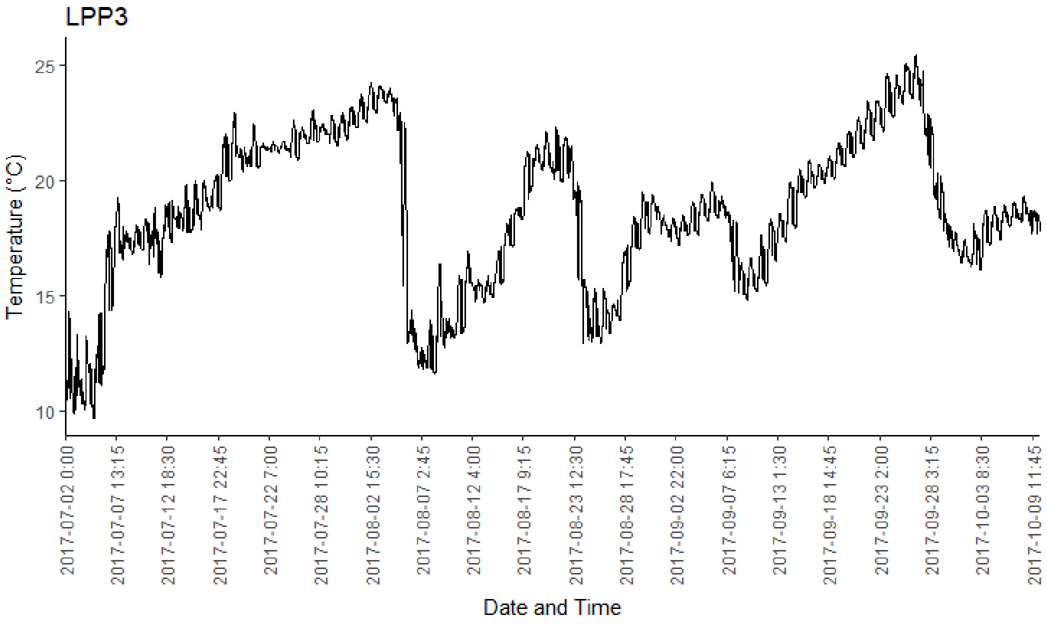

Figure A2. Water temperature in Lakefront Promenade at logger LPP3 from July 2 to October 9, 2017.

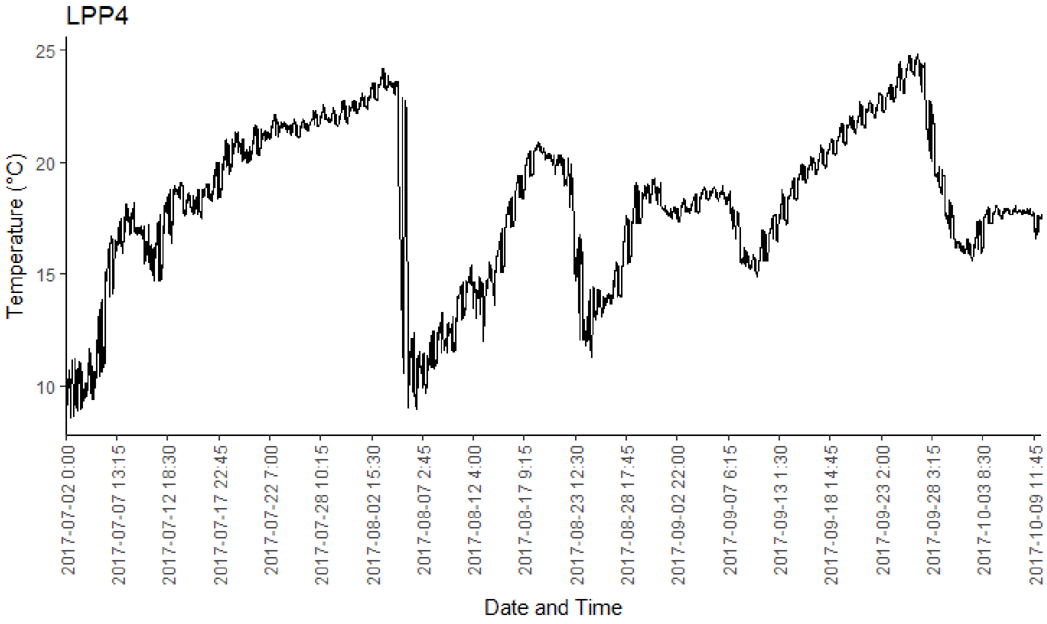

Figure A3. Water temperature in Lakefront Promenade at logger LPP4 from July 2 to October 9, 2017.

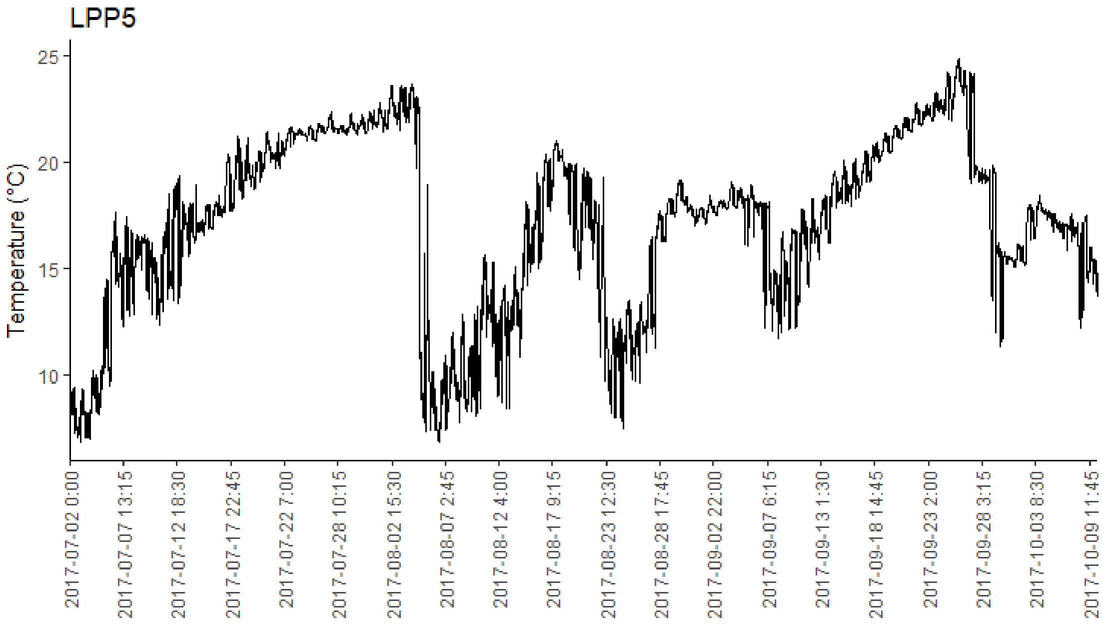

Figure A4. Water temperature in Lakefront Promenade at logger LPP5 from July 2 to October 9, 2017.

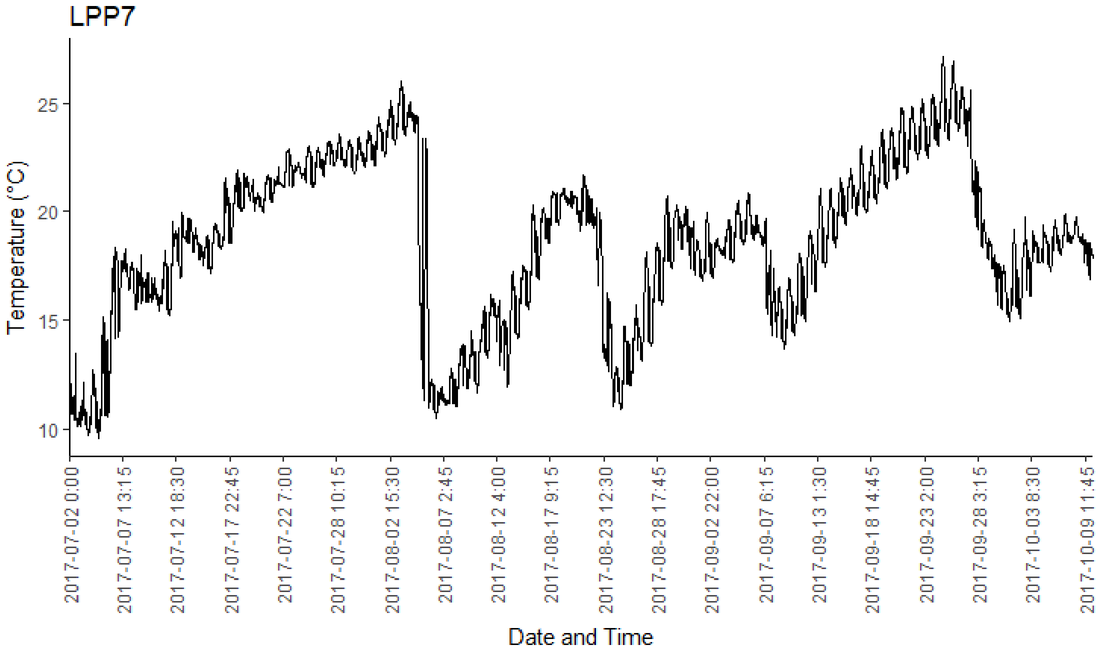

Figure A5. Water temperature in Lakefront Promenade at logger LPP6 from July 2 to October 9, 2017.

Port Credit

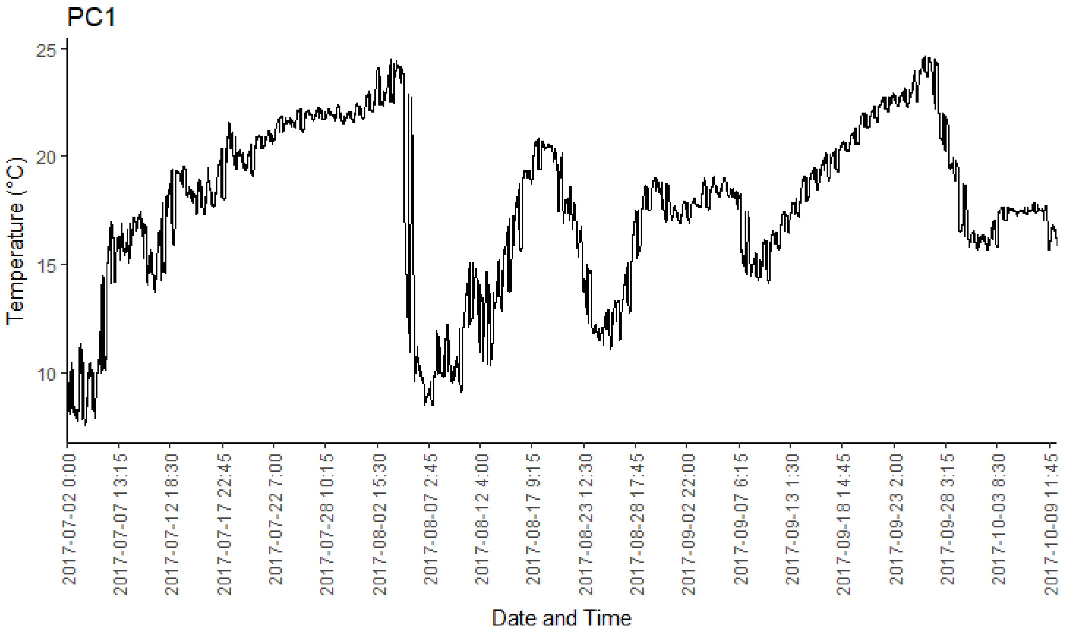

Figure A6. Water temperature in Port Credit at logger PC1 from July 2 to October 9, 2017.

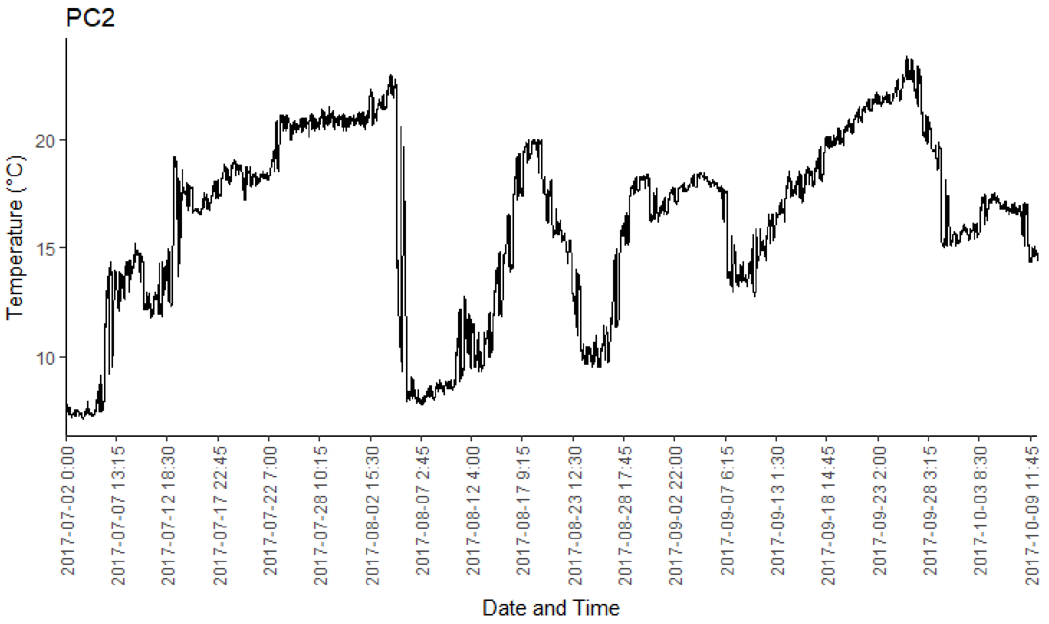

Figure A7. Water temperature in Port Credit at logger PC2 from July 2 to October 9, 2017.

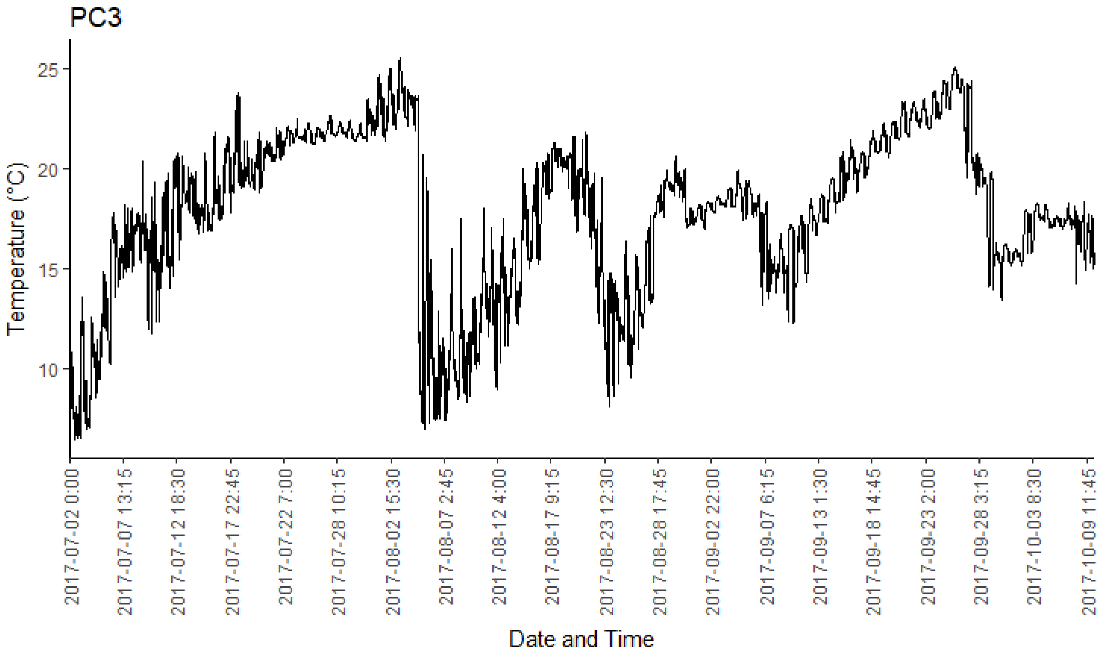

Figure A8. Water temperature in Port Credit at logger PC3 from July 2 to October 9, 2017.

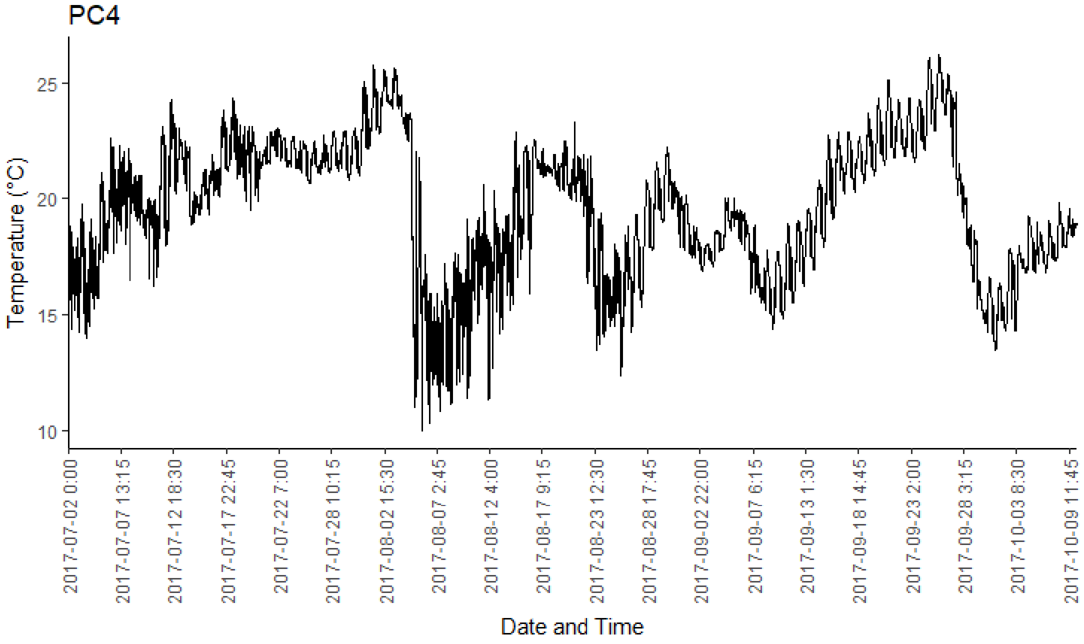

Figure A9. Water temperature in Port Credit at logger PC4 from July 2 to October 9, 2017.

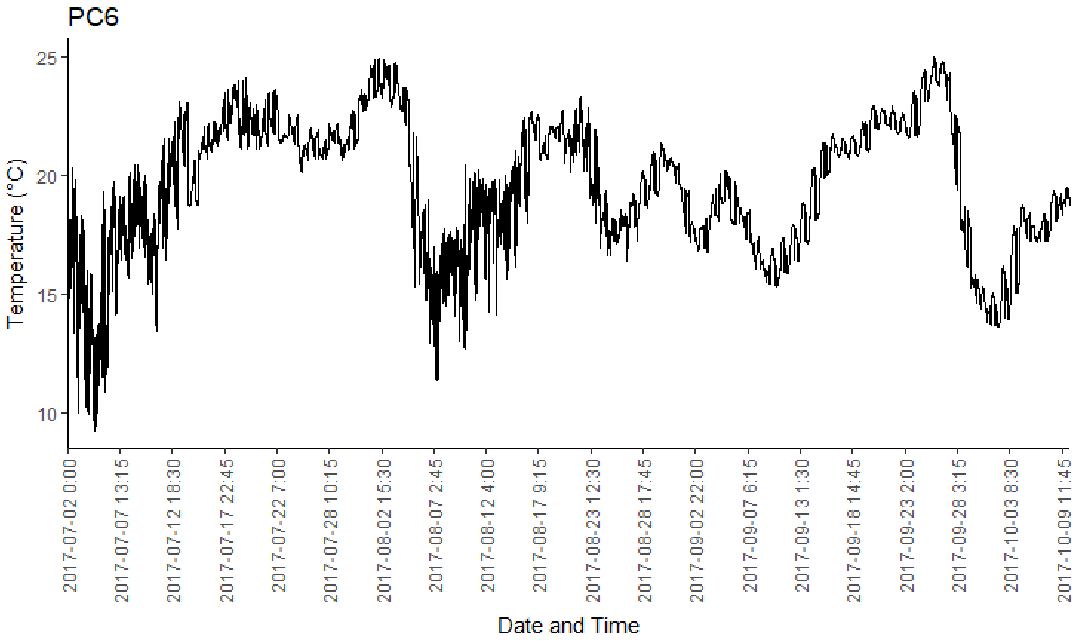

Figure A10. Water temperature in Port Credit at logger PC6 from July 2 to October 9, 2017.

Rattray Marsh

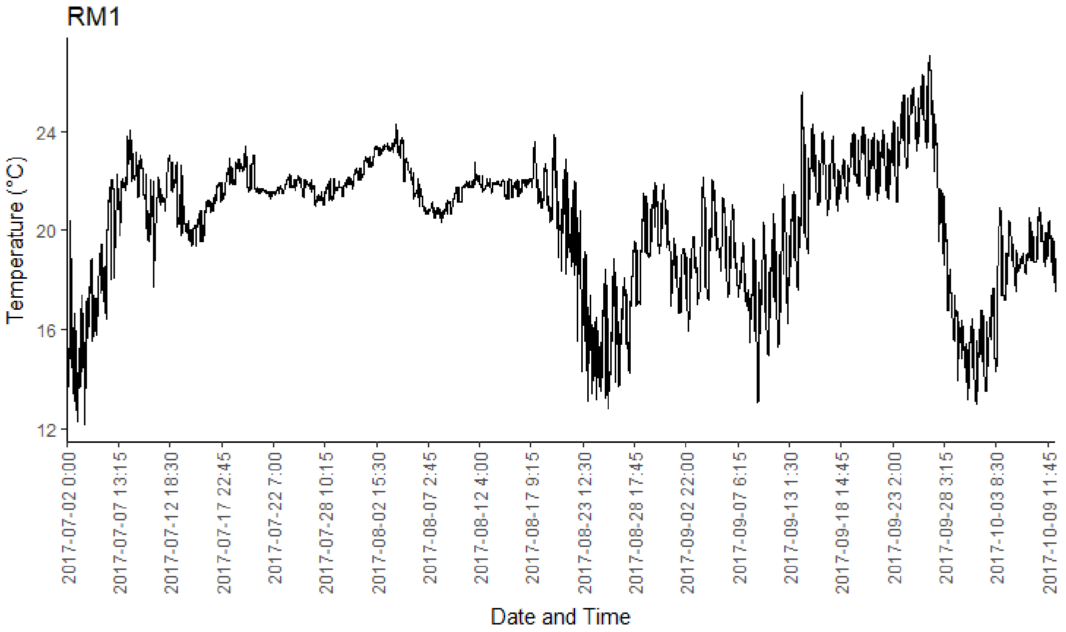

Figure A11. Water temperature in Rattray Marsh at logger RM1 from July 2 to October 9, 2017.

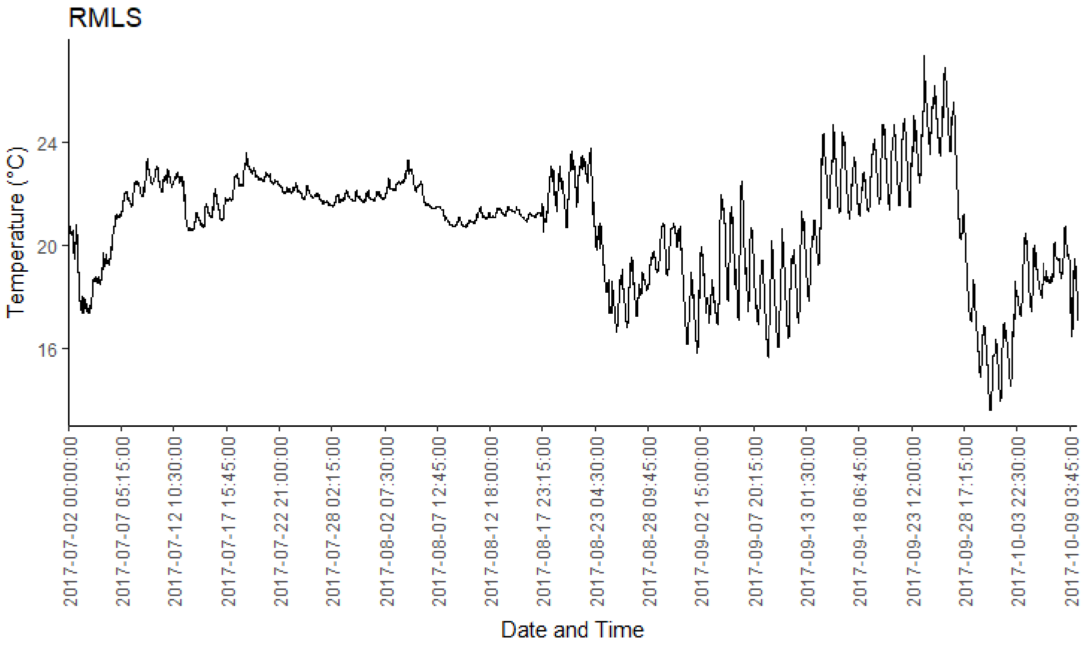

Figure A12. Water temperature in Rattray Marsh at logger RM-LS from July 2 to October 9, 2017.

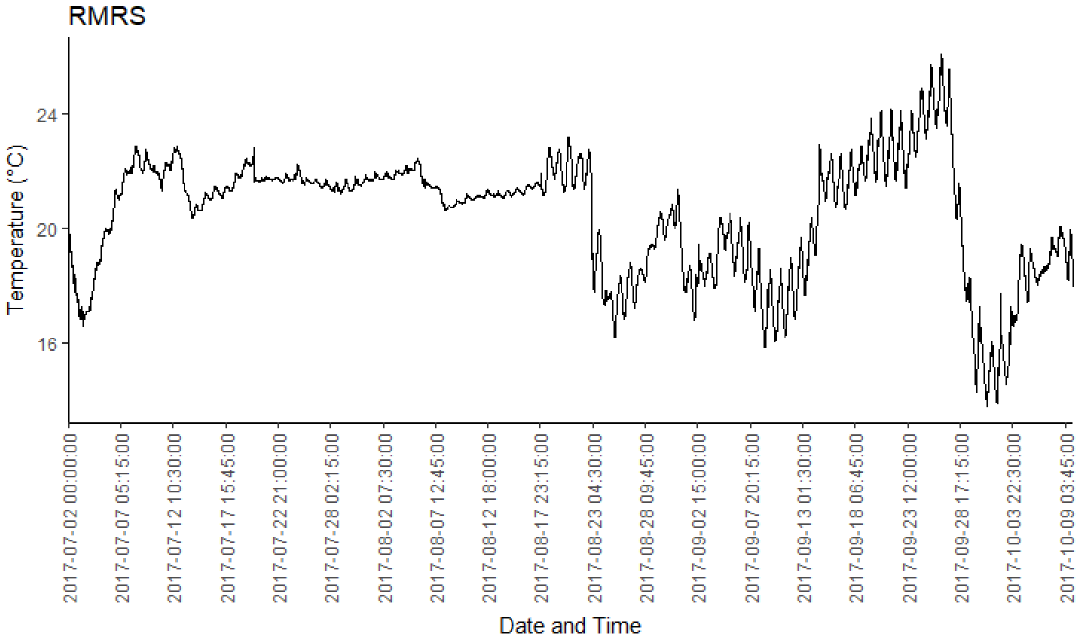

Figure A13. Water temperature in Rattray Marsh at logger RM-RS from July 2 to October 9, 2017.