Thermal habitat utilization by northern pike (*Esox lucius*) in Tadenac Bay, Georgian Bay, Ontario, Canada

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Preface

This Masters of Science thesis is composed of 1 chapter and will be submitted as a manuscript for publication in peer-review journals. The chapter focuses on the potential effects of a changing climate on the habitat usage by northern pike within Georgian Bay. The information from this thesis may be combined with previous research conducted in the same study area when publishing this manuscript.

As the author of this thesis, and under the supervision of Dr. Patricia Chow-Fraser, I collected and analyzed all data presented that are not otherwise referenced and wrote the chapter. Data collecting was performed with the assistance of lab technicians.

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Abstract

The northern pike *(Esox lucius*) is a recreationally and ecologically important top predator fish in the Laurentian Great Lakes, where there are still naturally reproducing populations, especially in the relatively undisturbed eastern arm of Lake Huron, Georgian Bay. I conducted a two-year study in a relatively pristine embayment, Tadenac Bay, located in eastern Georgian Bay to determine 1) how thermal habitat suitability changes both seasonally and annually and 2) how radio-tagged northern pike utilize different thermal habitats. During May and June in both years, water temperatures throughout the water column were favourable (13-21°C) for growth of northern pike adults, but during July and August, the surface to 5m was often above favourable temperatures. Yet in both years, during the middle of July (week 30), individual fish were tracked to areas with temperatures >27°C. During the warmer year (2011), the larger females used significantly deeper habitat (2.89±0.46m SE, n=9) than the smaller males (1.93±0.17m, SE, n=27) (one tailed t-test, t(45)=-2.00, p=0.035). During the cooler year (2012), females used deeper habitat (3.60±0.84m SE, n= 8) compared to males (2.45±0.32m, SE, n= 15) but the means were not statistically significant.

A comparison of mean annual water levels of Georgian Bay with variation in global mean surface temperature show that the warmest years to date coincided with sustained low water levels in Georgian Bay since 1999. Global circulation

models predict that these warming trends will continue and will lead to further reductions in water levels. Based on a bathymetric model for Tadenac Bay, a drop in water level of 1 m from current levels (2012) would result in 18% loss of existing habitat. The approach used in this study can be applied to other regions of Georgian Bay to quantify current and projected thermal habitat for northern pike.

Introduction

As fish are ectotherms and must regulate their physiological processes depending on their thermal environment, ambient water temperature is a primary criterion of habitat suitability (Angilletta 2009). Therefore many studies have been conducted to estimate the minimum, optimum and lethal temperatures associated with most of the economically and ecologically important fish species in Canada (Wismer & Christie 1987). Theoretically, by applying this information to field situations, it is possible to estimate the amount of habitat with suitable temperature for any given species. The current threat of global climate change has punctuated the need to study how thermal habitat suitability for important recreational and commercial fisheries in the Laurentian Great Lakes may change as the earth's climate continues to warm.

Northern pike are top predators in many cool-water ecosystems in the northern hemisphere. As an important species both ecologically and economically, managers need to understand their habitat requirements and identify the thermal boundaries that delineate their habitat and survival success. Most of the relevant experiments have been conducted under laboratory conditions, and because of the difficulty in maintaining large adult fish in captivity for such experiments, many of these studies have included smaller immature individuals (Casselman, 1978; Casselman & Lewis 1996; Hokanson at al. 1973). For such sub-adults, the optimum temperature ranged between 19 and 21°C, and the upper incipient lethal temperature was 29.4°C (Casselman 1978). Researchers also found that both the optimal temperature for growth and tolerance for high temperatures decreases as northern pike age (Casselman & Lewis 1996; Casselman 1978). This was confirmed from field studies where the preferred temperature of adult males was calculated to be 8 to 18°C for glacial lakes in South Dakota (Neumann et al. 1994), and 16 to 18°C for large adult males in inland lakes of Minnesota (Pierce et al. 2013) (Table 1). Although a decrease in tolerance of upper incipient lethal temperature has not been confirmed, avoidance of temperatures above 25°C was observed in impoundments in Ohio (Headrick & Carline 1993).

As a keystone species and a top-predator in littoral ecosystems of the Great Lakes, the northern pike is also dependent on wetlands for all of their life stages (Casselman & Lewis 1996). Similar to many fish species, pike use the shallow vegetated areas around wetlands for spawning and nursery habitat. Spawning for pike occurs when the water is between 8 to 12°C, in areas along the shoreline where there is flooded vegetation (Casselman & Lewis 1996). Fluctuating water levels are beneficial to pike because high water levels tend to flood a larger area of vegetation, and this leads to greater spawning success (Inskip 1982). The effect of high water appears to be diminished in the following years, however, if water remains consistently high; an increase of 4 to 10-fold in the first year is often accompanied by decreases in the following years (Bodaly & Lesack 1984). The decrease in spawning success after the initial season of increased water levels suggests that fluctuations in water levels are required for optimal spawning conditions.

As pike grow, their habitat requirements change, and they have a decreased dependency on dense vegetation (Casselman & Lewis 1996). Pike growth is indeterminate and continuous throughout its life cycle; as such, their feeding habits show an ontogenetic shift, and they must spend time simultaneously avoiding predators and searching for prey until they achieve a size where they become the top predator in the system (Craig 2008; Wismer 2008). As adults, pike are primarily piscivores, although they are also known to feed opportunistically on frogs and small mammals. They are ambush predators that hide in submergent aquatic vegetation and wait for suitable prey to come within striking distance (Casselman & Lewis 1996; Craig, 2008). In Georgian Bay, an extended period of sustained low water levels over the past 15 years has resulted in an increase in high-density floating vegetation and a much more homogeneous habitat structure (Midwood & Chow-Fraser 2011). This change in habitat is expected to create a less suitable hiding place for pike and may therefore limit their feeding success. The shift may also negatively impact many other fish, including prey for pike, that require this variable habitat structure (i.e. submerged aquatic vegetation (SAV); Midwood & Chow-Fraser 2012).

Freshwater ecosystems consist of complex, dynamic and often subtle biological and physical interactions that make it difficult to discern the exact effects of climate (Ficke et al. 2007). The global climate change models developed by the

Inter-governmental Panel on Climate Change (IPCC) predict that globally there could be an increase in air temperature of 1 to 7°C over the next 100 years (Ficke et al., 2007), and models specific to the Laurentian Great Lakes predict that the mean annual surface temperature could increase by 4 to 9°C by 2050 (Mortsch & Quinn 1996). An increase in global temperature could have compounding impacts on fish communities through increases in water temperature, a decrease in oxygen concentration, as well as alterations in habitat structure (Casselman & Lewis 1996; Craig 2008).

Fish are exothermic and must regulate their temperature via their environment to remain at a favourable temperature to suit their biological requirements (Casselman & Lewis 1996; Ficke et al. 2007; Anguilleta 2009). To compensate, many fish species move to deeper cooler water in the summer months to maintain optimum/tolerable temperature conditions. These cooler water conditions often occur in deep bodies of water that stratifies during the warmer months of the year where the upper layer (epilimnion) warms to an extent that it stops mixing with the cooler and more dense lower layer (hypolimnion) (Goldman & Horne 1983). As the warmer months end and the epilimnion cools, the density gradient diminishes and mixing during fall disrupts the stratified layers, replenishing lost oxygen in the hypolimnion. One possible outcome of higher water temperature induced by climate change is that stratification may remain beyond the seasonal norms and turnover may be delayed or cease altogether (Croley II 1990).

The hypolimnion may therefore become deprived of oxygen and become uninhabitable by fish such as northern pike.

Increases in global temperatures will not only affect the quality of water by reducing oxygen content, but they will also reduce the quantity/volume of suitable habitat within the Laurentian Great Lakes through reductions in water levels. The recent episode of sustained low water levels may be the beginning of this manifestation. Over the past century, water levels in Lake Michigan-Huron (Georgian Bay) have fluctuated in approximately 30-yr cycles with highs reaching 177.29m above sea level (asl; in 1987) and lows reaching 175.68m (asl; in 1964). Following the high water level of 176.98m (asl) in 1997, however, water levels plummeted to as low as 175.89m (asl) in 2003, and have been low for 14 years (176.09±0.05m, SE (asl) between 1998 and 2012; Figure 1). The highest level in recent years was only 176.26m (asl) which occurred in 2009. There is concern that because of climate change, these current low levels may persist indefinitely (Sellinger et al., 2008). Simulations by Angel and Kunkel (2010) suggest that a further decrease in water levels of up to 1.77 m in Lakes Huron and Michigan may occur over the next seven to eight decades.

The combination of low water levels and unsuitably warm water (>27°C) can be an impediment to the success of northern pike. Since 2000, nine of the ten warmest years globally have occurred during the sustained low water period in Georgian Bay (NOAA 2014). The implications of future declines in water levels and further increase in temperature highlight the need for management and conservation plans to protect fish species with habitats that might be at risk due to alteration by climate change.

Because of the widespread circumpolar distribution of northern pike, (Harvey 2009) many studies have been published on inland lakes and rivers in Europe and North America, with only a few conducted on Great Lakes populations (Table 2). The topics covered in these studies include investigations on aspects of vegetation use, fish movement, feeding, and temperature preferences. There are no known studies that examine the use of thermal habitat by northern pike specifically for Georgian Bay. Given the potential for ecosystem changes under climate change scenarios, it is important to learn about this population now, before further change to the ecosystem occurs for this recreationally and ecologically important fishery.

The overarching goal of my thesis is therefore to define the current boundaries of favourable thermal habitat for northern pike in Georgian Bay, and to predict how they may change in response to lower water levels with global climate change over the next 50 years. I will achieve this goal by conducting a study in Tadenac Bay, a pristine embayment in eastern Georgian Bay that has a large population of northern pike. My first objective is to quantify the amount of thermal habitat available to northern pike in Tadenac Bay and determine 1) the extent to which thermal habitat availability varies seasonally and between years 2) the impact of a 1m drop in water levels on availability of appropriate thermal habitat and 3) the potential growth of fish that could be supported by current thermal habitat. My second objective is to determine if use of thermal habitat by northern pike varies by size and sex of the fish. Information in this thesis will be an important contribution to the body of literature on habitat use by northern pike, and provide insights on how climate change is affecting the ecology of the northern pike populations in Georgian Bay.

Study Site

Georgian Bay is the eastern arm of Lake Huron, and is known to have some of the best quality wetlands in all of the five Great Lakes (Chow-Fraser 2006; Cvetkovic & Chow-Fraser 2011). It has a similar water level regime to that of Lake Huron, and since 1999, Lake Huron and Georgian Bay have both experienced sustained low water levels, which has influenced many components of the aquatic ecosystem (Figure 1). Tadenac Bay is a privately owned bay ($3.4km^2$) that has a hydrological connection with Georgian Bay. Tadenac Bay, like most of the eastern shore of Georgian Bay, is naturally oligototrophic and drains Precambrian Shield bedrock (DeCatanzaro et al. 2009; Weiler 1988). It is surrounded by deciduous forest that was logged until the late 1800s; in 1894, the Tadenac Fishing Club was formed, and since then, the forests have been allowed to regenerate and the lands and water have been managed for hunting and fishing for the club's private members.

Wetlands within Tadenac have been identified as being the least impacted by human disturbance in the Laurentian Great Lakes based on the criteria of the

Wetland Macrophyte Index (Croft & Chow-Fraser 2007) and as a consequence, the area also supports a large northern pike population. Since 1896, the Tadenac Club has regulated the number of members within the club as well as the number of people using the bay at any given time. Management of the fishery within Tadenac Bay is more conservative than the standards set by those by the Ministry of Natural Resources for public waters (Cooper & Riley 2004). This policy as well as the fact that there are only two permanent dwellings on the bay makes Tadenac Bay a valued reference site for wetlands in eastern Georgian Bay, and an excellent location to study northern pike with minimal human impact on the fishery.

Methods

Bathymetric mapping

Bathymetric data are derived from contour maps of water bodies and can be used to generate area and volume information. Such information is essential for mapping fish habitat (BC Ministry of Fisheries 1999) and for this study was collected using the method outlined in the Bathymetric Standards for Lake Inventories (BC Ministry of Fisheries 1999). The bathymetry mapping effort extended over two field seasons; the northern portion of Tadenac Bay was surveyed in 2011 while the southern portion was surveyed in 2012. There were some site-specific variations from the BC Fisheries method due to the rocky nature of Georgian Bay which limited access to portions of shallow water.

I used Hypack for both navigation and data acquisition. Position solutions from a DGPS (WAAS mode) were integrated with sounding data collected with a single-beam echo sounder system operated at 200 kHz (Lowrance, Tulsa Oaklahoma, USA). A shoreline trace was prepared prior to conducting the survey to allow for easier completion of the survey transects that were to follow. To the extent possible, depth soundings were collected at regular intervals (1 sounding per second), following straight-line transects that ran east-to-west in the north basin, and a mixture of north-to-south and east-to-west in the south basin (Figure 3); spacing between transects was approximately 100m to allow coverage of the entire study area within the time available. Proximity to the shoreline depended on the shallowness of the nearshore and the presence/absence of rocky shoals. Surveying was completed over several days which were a function of the size of the area to be surveyed, and the slow boat speed that was required to avoid disturbances around the transducer. The survey was conducted between 17 August and 24 September in 2011, and from 20 September to 21 September in 2012. Over 125,000 spatially referenced soundings were collected to build the bathymetric model for this study.

The bathymetric values were exported from Hypack and integrated with shoreline data (n=4500) which had an assigned depth attribute of 0m. The zero values from the shoreline allowed for interpolation between the shoreline and the shallowest points measured from the boat survey. The combined bathymetric data (survey points and shoreline) were transferred into ArcGIS 10 (ESRI, Redlands, California, USA) and interpolated to create a raster bathymetric map of the northern basin of Tadenac Bay (Figure 4). Babish (2010) recommends using an interpolation method that is best for the site; for this study Natural Neighbors method was selected as it has be shown to work best on a local scale and is able to handle a large amount of data as well as maintaining the original data points within the interpolated model (ESRI 2007).

Temperature data

Buoyed moorings were deployed in a network of stations within Tadenac Bay during the 2011 and 2012 field seasons (Figure 5). Each mooring was equipped with a series of water temperature loggers (TidBit V1 HOBO data loggers, ONSET Corporation) that were mounted at pre-determined intervals. In shallow areas (<3.5 m), the ropes were marked off in 0.5m or 1m intervals for placement of temperature loggers, whereas for the mooring closest to the deep station (Station 9; Figure 5), loggers were placed at the surface and 1 m depth, and then at 2-m intervals between 2 and 12 m; this spacing of loggers was appropriate for monitoring the onset of stratification, the approximate depth of the thermocline, as well as the temperature profiles of the epilimnion, metalimnion and top of the hypolimnion during both seasons. In 2011, loggers were only placed in the northern bay (Stations 1 to 9; Figure 5); in 2012, three of the original stations were retained in the northern basin (Stations 1, 6 & 9-see explanation later) and two additional shallow stations were added in the southern basin (Stations 10 and 11; Figure 5).

The water temperature loggers were set to record every 6 hours with an expectation that there would a continuous data record from the start to the end of the sampling season. There was a scheduled break in data collection for two days at some stations (Stations 1-11) in mid-July (2011 & 2012), during which the tidbits were removed to offload data. I transferred the temperature data to a laptop computer using a proprietary software program Boxcar 4.3 (ONSET). Data collected from 2011 indicated that all of the shallow sites were essentially isothermal and therefore did not require more than a single depth to be monitored in 2012. I also compared temperatures measured at 1 m depth for all stations monitored in 2011 to assess if there was sufficiently strong spatial correlation among sites to justify pooling water temperature data by stations in subsequent years. All stations were highly and significantly correlated with each other; therefore, I only considered the correlations with coefficients r> 0.98 (bolded values in Table 2) to examine possible groupings. Stations 1, 2, 3 and 9, which are all located near the inflow of Tadenac Bay were sufficiently similar that they could be placed in one group; Station 4, located in Pike Alley was also significantly correlated with all of the other shallow stations; Stations 5, 6, 7 and 8, which are located close to the protected shallow coastal marshes in eastern Tadenac Bay were also highly correlated. Based on these correlations, I decided that three stations (Stations 1, 6 &9) were sufficient to describe the water temperature regime in the northern basin in the 2012 field season. I performed a similar correlation analysis among the stations monitored in 2012. The two stations in the southern bay (Station 10&11) were highly correlated with the shallow station (Station 6) in the northern bay (r>0.95) (bolded values in Table 3). This provided credible support for extrapolating the shallow water temperature data collected in 2011 for the northern portion of Tadenac Bay to the southern portion Tadenac Bay. It was also deemed plausible that the temperature isopleth derived for one shallow station could be considered representative of all the shallow embayments within Tadenac Bay.

Mapping of coastal wetlands

Midwood et al. (2012) have already mapped the coastal marshes in Tadenac Bay as part of the development of the McMaster Coastal Wetland Inventory (MCWI); their digitized wetland layer of the MCWI (see Figure 5) was superimposed onto the shoreline map to indicate the location of coastal wetland complexes in relation to the buoys and shallow embayments, which represents critical habitat for northern pike.

Tagging of northern pike

Twelve northern pike were collected with trapnets in Tadenac Bay in early May 2011 and implanted with radio-transmitters MCFT2-3A radio transmitters (46mm length x 16mm diameter) (Lotek Newmarket, ON) as part of the radio-telemetry study to determine habitat use by pike. As externally mounted transmitters are known to affect how fish behave (Jepsen et al. 2002), we used radio-tags that were surgically implanted in the abdominal cavity of the fish. Similar procedures as the ones employed in this study have been used by others with minimal detrimental effects to fish (Cooke et al. 2003, Koed et al. 2006). The northern pike captured with the trapnet were moved to a 60-L container and anesthetised with 60ppm of clove oil in a 20 L solution. The northern pike were sexed as per Casselman (1974) and measured for length (mm) and weight (g) after they stopped responding to external stimuli. The pike were then placed ventral side up in a U-shaped foam surgical table and were kept anesthetized with a maintenance dose of clove oil (30 ppm) over their gills. The tags used were implanted in the body cavity via a 2- to 3-cm incision made to the mid-ventral portion of the abdomen anterior to the pelvic girdle. A 16-gauge needle was used to make an incision in which the trailing whip-antennae from the tag would exit the body of the pike. The incision was closed with 2 interrupted monofilament sutures with at least 2 surgeon knots. The northern pike were then placed on top of the trapnet to recover while being monitored until they were able to swim off on their own. The northern pike that were tagged in this study consisted of 7 males and 5 females. The total length of the tagged fished ranged from 563 to 729 mm and 817 to 962 mm for males and females respectively (Table 4).

Radio-tracking of northern pike

Radio-telemetry tracking began on 24 May 2011 and continued approximately every four weeks for a 4-d period until 24 September 2011. Single-day tracking events occurred opportunistically during the intervening weeks (between 7- to 10-day intervals). The tracking procedure involved early morning, mid-day and early evening sampling sessions. The 12 tagged northern pike were tracked with a hand-held radio antenna (Lotek SRX 600 Telemetry Receiver) from a motorboat. The same tracking procedure was used in 2012, but the frequency of tracking events decreased, with only one tracking event occurring per day. The tracking occurred during at least one week per month from May-August, starting on 14 May and the last tracking point was collected on 9 August 2012. The fish were also tracked once each during the winter of 2012 and 2013, and opportunistically outside of Tadenac Bay.

Thermal habitat classification

Based on my review of the literature (see Table 1), the temperatures that are most ecologically relevant to adult northern pike range between 13 to 27°C. Under laboratory conditions, Casselman (1978) showed that the growth of sub-adult northern pike increased dramatically when temperatures reached 10°C and peaked at between 19-21°C (for both weight and growth), and then decreased and eventually ceased at approximately 27.5°C. Casselman (1978) also found that 2- to 3y-old sub-adult pike had an upper lethal limit of 29.4°C and showed no apparent stress in water temperatures close to freezing while in the field. Past studies have also shown that the optimal temperature for growth as well as tolerance for warm water decreases as northern pike age (Casselman & Lewis 1996; Casselman 1978). In a study of adult pike in inland lakes of Minnesota, Pierce et al, (2013) showed that fish ranging in size from 730 to 1020 mm (TL) preferred water temperatures between 16 to 21°C, while smaller adult fish selected warmer water between 18 to 22°C. In a glacial lake in South Dakota, adult males (459-695mm TL) were found to reach maximum growth rate at 8 to 18°C (Neumann et al. 1994). Given the size of fish in this study (Table 5), I decided that 13 to 21°C would be an appropriate temperature range to be considered favourable for growth, temperatures between 21 to 27°C would be less favourable, and temperatures >27°C would be considered detrimental to pike since they would stop growing at 27.5°C, and are expected to die at 29.4°C (Casselman 1978).

To quantify thermal habitat available to pike, I had to first estimate the total volume of water in Tadenac Bay and then determine the volume of water corresponding to each of the nine 2°C-increments within the relevant temperature range (i.e between 13° and 27°C; see Table7 & 8). The basin was divided into appropriate segments to derive suitable volumes that would account for the irregular contours found in Tadenac Bay; each segment was associated with at least one temperature station and the temperature data collected at each station was used to map the upper and lower limit of the 2°C stratum on a weekly basis throughout the growing seasons of 2011 and 2012. Through integration of the temperature and bathymetric data in a GIS, I was able to generate volumes associated with the 2°C thermal strata for each segment of the bay for each week in

2011 and 2012. I then calculated weekly sums of the volume of each 2°C thermal stratum for the entire bay.

Thermal habitat with a 1m drop

To simulate how the proportion of thermally suitable habitat would change seasonally in response to a one meter drop in water level, I adjusted the shoreline to the 1-m depth contour and assumed that the temperature-depth profile would remain the same as in the "base case" (BC; elevation of 175.86 m, asl), which corresponds to the depths in which the soundings were obtained. Hence, this future scenario will be referred to as "base case minus 1 m" (BCM1). I then used the same approach to calculate volume of water for the nine thermal habitat categories as before.

Growth potential of northern pike

I wanted to investigate how thermal variations within Tadenac Bay might affect the distribution of northern pike within the bay. Since there were no occurrences of fish die-offs during either sampling season, temperatures within Tadenac Bay did not reach lethal levels; however, temperatures were such that adult pike were likely growing sub-optimally. In this study, all of the tagged fish were adults, and therefore larger than the sub-adults used in the 1978 study in which Casselman determined that optimum temperatures for growth were between 19 to 21°C. Previous literature has shown that the optimum temperature for growth of pike decreases with size (assumed to correspond with age) (Casselman & Lewis 1996; Casselman 1978, Hokanson et al. 1973); therefore, I adapted the growth curve of Casselman (1978) for use with the adult pike in this study. Since the temperature for optimum growth in Casselman's study was 19°C, I shifted the entire plot by 2°C so that optimum growth temperature would be 17°C, which is consistent with the temperature reported by Pierce et al. (2013) for "large adult preference". I then applied Casselman's equation to the midpoint of each thermal stratum (e.g. 16°C for the stratum 15 to 17°C) to calculate a growth potential for pike. Since the units of Casselman's growth curve was "percentage change in body weight per day", values were multiplied by 7 to obtain an estimated weekly value. Finally, I weighted all of the values according to the volume of the thermal strata in question. I did not apply the growth curve to temperature data <13°C, since pike did not appear to use this habitat. At temperatures >25°C, the adjusted growth curve would assign negative values so I therefore did not include those in the analysis. I am aware that this adjustment of the growth curve is arbitrary and should be further investigated with a field study specific to Tadenac Bay. My intention is to provide a measure of the potential impact the thermal regime of Tadenac bay may have on the pike population within it. Application of this curve is based on the assumption that published information is relevant to Tadenac Bay, and this has not yet been validated.

Habitat use

Information from the radio-telemetry survey program was limited to only the horizontal location of each fish and not to their vertical position in the water column (i.e. their depth); therefore, I had to derive the associated temperature preference of the fish based on other information. I first overlaid all of the locations of the fish on bathymetric information in ArcGIS. This allowed me estimate the maximum depth corresponding to the location of the fish. I then determined the closest temperature-logging station for each fish; based on the correlations between the buoys, I have confidence that the temperature at the station were similar to that experienced by each fish. The lack of visual confirmation of the pike locations leads to uncertainty in the accuracy of the pike locations, but when applying a buffer of 5m radius to the pike locations, 75% & 90% of the pike locations would have varied by less than 0.8m & 1.3m, respectively within the buffer. I therefore assumed that any slight inaccuracies in the pike location data would not have greatly affected my conclusions. The maximum depth associated with fish locations rarely exceeded 6m (97.5% of the time it did not) and the difference between the surface and 6 m in the majority of cases did not exceed 2.0 °C. Since I could not determine the exact depth of the fish, I calculated the mean temperature associated with up to 6 m of surface water. To control for differences in frequency of observations of all fish, I calculated weekly averages for each fish. All of the temperature data were similarly averaged by week for comparability.

Habitat preference- Ivlev's Electivity Index

Habitat selection is difficult to ascertain in field studies because of the large number of uncontrolled variables. In laboratory settings, researchers have examined habitat preference by examining one factor at a time (i.e. cover or forage; McCauley & Casselman, 1981). Since fish live in a 3-dimensional space, it is difficult to obtain visual confirmation of their location from above the water. Studies reported in literature tend to report the association between fish presence and a particular habitat type (e.g. amount of submerged aquatic vegetation cover). For this study Ivlev's electivity index, (Krebs 1989), was used to indicate habitat preference. Values range from -1 to +1 with negative values suggesting avoidance and positive values representing preference.

Statistical analyses

I imported all temperature data into a statistical program (JMP Version 11, SAS, Cary N.C., USA) to summarize the temperature as isopleth graphs and to analyze the volume of thermal habitat. I determined the degree of correlation between stations with respect to temperatures measured at 1-m depth using correlation analysis. When analyzing habitat use by northern pike, the fish were first grouped by sex; since males tend to be smaller than females (Scott & Crossman 1998; females grow faster and to be a larger size than males) sex and size were effectively linked in this study and it was not possible to account for this confounding effect. The rationale for separating out the sexes is because males are more vulnerable to predation by virtue of their smaller size, and are therefore more likely to seek out habitat in shallower water where they can find refuge from macrophyte cover.

Results

Compared to other embayments in eastern Georgian Bay, Tadenac Bay is relatively large, with a measured total surface area of 3.35km^2 at an elevation of 175.86m above sea level (asl). There is one deep basin, with a maximum depth of 29m (Figure 4), which is located in the northern portion of the bay close to the outflow to Georgian Bay. Since the mean depth of Tadenac Bay is 5.7 m, the majority of the bay is shallow and this feature allows almost the entire southern basin of Tadenac Bay to be colonized by submerged aquatic vegetation down to 4 m (Environment Canada, unpub data). The deeper northern basin also provides important refugium for the larger, older fish to avoid the warmer surface water during summer. Almost the entirety of Tadenac Bay provides excellent habitat for northern pike due to its combination of expansive shallow water submerged aquatic vegetation and coastal wetland complexes as well as a cooler, deep water basin.

Change in stratification characteristics of the deep basin

Like most other northern temperate water bodies, Tadenac Bay is dimictic, with stratified waters in the summer and well mixed water column during the spring and fall turnover. Water temperatures in areas sufficiently deep to stratify, such as the north basin, were monitored at 2-meter depth intervals from surface to 12 m throughout the summer so that changes in the epilimnion (surface 7m), metalimnion (7-10 m) and hypolimnion (10-29 m). The thickness of these layers was representative of conditions measured in July (Figure 6).

Due to an early spring and warming in May 2011, the water column had already begun to thermally stratify by the time data collection began on 14 June (Figure 6a). In 2012, I was able to begin monitoring the temperature earlier and noticed that by 15 May, the bay had already started to stratify, albeit the difference in temperature between the epilimnion and hypolimnion was minimal (Figure 6b). Despite differences in the timing of spring onset of stratification, in both years there was a period in June when surface waters warmed rapidly to temperatures ranging between 21 to 23°C. This was followed by a brief cooling period that brought water temperatures near the surface back to 19 to 21°C by the end of June. Within 4 of 5 days of this cooling, surface temperatures once again increased and exceeded 21°C for the rest of the summer. At peak of summer, the maximum surface temperatures reached >26.5°C in both years, but whereas there were 4 days in 2011, there was only 1 day during 2012. By late September in both years, temperatures in the surface layer had cooled below 21°C.

Change in stratification characteristics of the shallow areas

Similar to the water temperatures at the deepest station in Tadenac, water temperatures in the shallow areas reached the favourable range (13 to 21°C ; Figure 7a) by May 2011; on the same date in 2012, the surface 2 m had already surpassed 21°C (Figure 7b). By 01 July, the entire water column was >21°C and stayed above this temperature until early September in 2011 and mid-September in 2012 (Table 6).

Seasonal changes in thermal habitat

In this study, I operationally defined the favourable temperature for growth of adult pike to range between 13 and 21°C. I tracked how the layer of water in this temperature range changed through the season. At the start of the 2011 season (14 June; Figure 6a), the favourable temperature occurred from surface to a depth of 9 m (a depth that only exists in the deep northern basin within Tadenac Bay). By the middle of August, this layer had been pushed down to 6.5m. During this time, surface temperatures in the shallow embayments were consistently above 25°C and even surpassed 27°C for two days (22 July and 23 July) (Figure 7a & Figure 8). Temperatures that corresponded to the favourable growth range remained at or below the 7 m depth contour until early September when surface water temperatures cooled and the favourable temperature range encompassed the upper 11 m of water (Table 6).

By comparison, spring in 2012 (Figure 6b) was relatively cool; temperatures near the surface did not exceed 15°C until mid-to-late May. I again tracked how the layer of water corresponding to 13 to 21°C changed its depth distribution through the season. These temperatures occupied the surface 4 m at the start of May. As in 2011, this layer of water moved progressively from the surface down to 6.5m in August and then to 8m by the beginning of September (Table 6).

Volume calculations

Another component of the analyses was to quantify the reciprocal changes that represented the components of Tadenac Bay that were either unsuitable or less favourable for growth of northern pike (i.e. below 13°C or above 21°C). Temperatures >27°C were considered to be unsuitable as these approach the physiological limits for northern pike to grow, and survival is threatened (see Table 1). None of the pike in this study appeared to use temperatures <13°C, found only at depths below 8 m during the period of study. It is important to note that 8m is beyond the photic depth in Tadenac Bay, and would therefore no longer support rooted plants, which is a key habitat for northern pike (Casselman & Lewis 1996). I calculated weekly changes in the volume of water that corresponded to the full range of suitable temperatures for the northern pike. As previously mentioned, to ease computations, water temperatures were consolidated into nine categories that were bounded by temperatures >13°C and < 27°C.

There was relative consistency in the amount of unsuitable cool water (i.e. <13°C) in Tadenac Bay throughout the growing seasons in 2011 & 2012 (Figure 9a & b). Due to thermal stratification in Tadenac Bay, water temperatures for this category were only found in the hypolimnion, and only in the deep northern basin (representing between 25 to 46% of the total available habitat). Conversely volumes that exceeded the 27°C threshold represented 14% of the overall potential thermal habitat in July 2011 but only 4% in July 2012 when these maxima occurred. The remainder of the water would be considered thermally favourable, or tolerable (13 to 27°C) and cumulatively accounted for ~65% of the habitat volume throughout the season in both 2011 and 2012. The amount of habitat corresponding to the adult optimum for growth (i.e. 13 to 21°C) was most abundant in June (~60%) and mid-September (~65%) but was severely reduced from late July to early September (weeks 30-36) when it represented on average only 10% of the total habitat available over the 7-week span in 2011, and only 8% of the habitat in 2012 (Figure 9a & b). On average over the same 7-week span, 41% of the habitat in 2011 and 31% of the habitat in 2012 was between 23 to 27°C and therefore probably too warm for large pike to use for any extended period of time. There was noticeably more of the 21-23°C habitat in 2012 (60% by end of August) than in 2011 (38%)(Figure 9a & b)(Table 7).

Change in availability of thermal habitat with a further drop of 1 m.

Global circulation models of the Great Lakes region suggest that water levels will decline further by up to 1.77m (Angel & Kunkel 2010). To examine how thermal habitat in Tadenac Bay would change in the near future in response to global climate change, the volume of water in the "base case minus 1 m" (BCM1) was only 82% of the volume in "base case" (BC; 175.86 m, asl) (1.614 x 10^7 m^3 vs 1.911 x10^7 m^3 to; see Tables 4 and 5, respectively). When comparing the BCM1 scenario to BC for the warmest part of the summer (late July to early September; weeks 30-36), there were discernible differences in the proportions of habitat as bracketed by water temperature. In 2011 the favourable habitat represented on average 10% of the total compared to 11% under the low water level scenario, and the 23-27°C represented an average of 38% of the total habitat during the base case and 39% with the drop in water level. In 2012 the favourable thermal habitat accounted for 8% of the total habitat over the 7-week period in the base case and an average of 10% with the water level decline. Over the same 7 week period, the less favourable thermal range of 23-27°C accounted for an average of 32% of the habitat in base case and 31% of the total habitat in BCM1 (Table 7 & Table 8).

Applying growth curve to available habitat

As mentioned previously this information is based on the assumption that information from the literature can be used to apply a shift to the growth curve from Casselman 1978. These assumptions have not been validated in the field, but if they hold true, then the following is a reflection of what the growth potential would be within Tadenac Bay.

During mid-summer, the water temperatures increased sufficiently that little growth can be expected for northern pike in Tadenac Bay (Figure 10). By mid-June in both 2011 and 2012 (week 25), the expected percentage change in growth reached the seasonal maximum; values decreased throughout the summer and did not increase again until temperatures cooled in September (week 39). In 2011, the potential for growth decreased gradually with a low during week 32, whereas in 2012, the period of lowest growth potential occurred 2 weeks earlier (week 30). During the end of the summer in 2012, a brief warming period also reduced the growth potential at that time (Figure 10).

Movement of northern pike

Northern pike are known to migrate long distances while they forage and within Tadenac Bay, Midwood (2012) found that they moved up to 3.9 km between wetlands. Tadenac Bay is hydrologically connected to Georgian Bay and some of the radio-tagged fish in this study have been tracked outside Tadenac Bay in the open waters of Georgian Bay during the summer, and we confirmed that they returned to Tadenac Bay during the winter months (Figure 11). A total of 278 pike-locations were recorded during the study window. In 2011 there were 192 pike locations (162 male-locations and 30 female-locations) and 86 pike-locations in 2012 (62 males and 24 females). During this study, two of the tagged fish (pike 14 & 15) had been harvested by recreational fishers, Fish ID 12, 13 & 19 (male, female and male respectively) were last recorded in 2011 whereas Fish ID 11, 16, 17, 21 & 22 were last detected in 2012, and fish ID 18 and 20 were last located in 2013.

Radio-tracked pike locations

Northern pike were tagged in May 2011 and tracking commenced immediately after release of the fish, but only locations that corresponded to times in which temperature data were also collected will be used in this study (starting 13 June, 2011). The males and females appeared to segregate spatially in Tadenac Bay (Figure 12a-d). In 2011, males occupied the shallower embayments, while females occupied in deeper areas, closer to Georgian Bay (Figure 12a, c). In 2012 this trend continued, but female northern pike were observed utilizing the southern portion of Tadenac Bay, where they had not been previously observed in 2011 (Figure 12b, d). It should be noted however that both males and females left Tadenac Bay to venture into the open waters of Georgian Bay during the summer.

The amount of area that would be lost in Tadenac Bay that would be lost with a further 1-m decline in water level in Georgian Bay (174.86m asl) is estimated to be a 24% decrease in area. The habitat that would disappear corresponds to wetlands that are currently used by pike in this study. Therefore, this change will result in a negative impact on a wetland-dependent species such as northern pike (Figure 13).

Habitat used by northern pike based on radio-tracking – Depth

The northern pike appeared to use different habitat types during the two years (Figure 14). The maximum water depth occupied by tagged pike during the summers of 2011 and 2012 was 7.96 m (Table 9). In 2011, the weekly average depth used by males over the season ranged from 0.17±0.03 m SE to 2.51±0.20 m SE. For females, the average depth ranged from 1.35±1.27 m SE to 4.48±0.14 m SE. By comparison, the average depth used by males was much deeper in 2012, ranging from 0.83±0.16 m SE to 6.80±0.98 m SE. Similarly, females used deeper areas in 2012, with weekly average depth ranging between 1.75±0.33 m SE to 6.87m (Table 9).

In 2011, males occupied a significantly shallower depth than females (1.93±0.17 m SE vs 2.89±0.46 m SE, respectively; one-tailed t-test, $t(10)= 1.94$ $p=0.040$)(Figure 15a). In 2012, the difference between sexes was not statistically significant ($t (9) = 1.28$, $p =0.232$) but both sexes were found in deeper habitat compared to 2011 (2.45±0.32 m SE vs 3.60±0.84 m SE, for males and females, respectively) (Figure 15 b). When both sexes were pooled and compared, I found that pike used shallower water in 2011 (2.16±0.18 m SE) compared to 2012 (2.85±0.37m SE) ($t (32) =-1.67$, $p=0.104$).

Habitat used by northern pike based on radio-tracking –Temperature

The hottest temperature used by northern pike over both years was 27.7°C and it occurred during the hottest week of 2011 (25 July to July 31, Table 9). The mean weekly water temperatures experienced by males in 2011 ranged from 17.81°C to 26.91°C. For females, temperatures ranged from a mean of 18.09°C to 24.75°C. By comparison, in 2012, males experienced cooler temperatures that ranged from weekly means of 16.88°C to 25.58°C, and females had a range between 16.55°C to 25.56°C, which were slightly warmer than those in 2011.

I did not find significant differences in water temperatures associated with locations of males and females either year. In 2011, males used habitat with a mean water temperature of 22.36±0.53°C SE, and females used habitat with a mean water temperature of 21.1±0.74°C SE ($t(16)=1.35$, $p=0.200$) (Figure 15a). In 2012, the males used an average water temperature of 21.38±0.92°C SE, whereas females used water temperatures of 20.33±1.25 °C SE ($t(14) = 0.66$, $p= 0.508$) (Figure 15b). The difference between years was not significant ($t(58) =-1.20$, $p=0.238$).

Habitat used by northern pike based on radio-tracking –Change in percent growth

The application of the growth curve to temperature data was to provide a measure of the impact that the water temperature in which the pike were found might affect them physiologically. This information is based on the assumption that pike are using the habitat that they were found, and that the adjusted growth curve is an accurate representation of the growth these pike were experiencing. In 2011, the water temperatures occupied by the male pike corresponded to a potential mean weekly increase in bodyweight of 2.71±0.57% SE, whereas females were predicted to have higher mean weekly body weight growth of 4.04±0.55% SE but these differences were not statistically significant ($t(25)=-1.67$, $p=0.1068$) (Figure 16a). In 2012, males were estimated to have a higher potential growth of 3.11±0.61% SE, and females even higher at 3.85%± SE 0.70 but again these were not significantly different (one-tailed t-test, $t(16)=--0.804$, $p= 0.4326$) (Figure 16b). On average, the potential growth in body weight for northern pike was lower in 2011 (3.05±0.46% SE) than in 2012 (3.37±0.46% SE), but these were not significantly different ($t_{(53)} = -0.491$, $p=0.6250$).

Habitat selection by northern pike

At the start of the sampling season in June2011, both males and females were selecting for the 19-21°C habitat, but males were also showing preference for the cooler water temperatures of 17-19°C (Table 10). As water temperatures increased during the summer, both male and female were found in warmer habitat than what would be considered favourable for growth (13-21°C). In 2011, females did not show any preference for water temperatures >25°C whereas males were found in water temperatures between 25 and 27°C and >27°C, at a time when water temperatures reached its maximum in this study (25 July to July 31) (Table 10).

Habitat utilization was similar for northern pike in 2011 and 2012. At the start of the sampling season in 2012, northern pike were found in cooler water temperatures (Table 10), which were also the most abundant habitat category (Figure 9b). As water temperatures increased and peaked in July, so did the use of warm water habitat by both male and female northern pike. Similar to 2011, female northern pike did not use habitat with temperatures exceeding 25°C whereas the males were found to occupy water temperatures between 23-25°C over a two weeks span(23 July to 5 August).

Discussion

Thermal habitat availability

Water temperature is a key component of habitat suitability for any fish population, and the nearshore habitat is a vital component to many wetland dependent fish species like northern pike. It is therefore of the utmost importance that we understand how these critical habitats areas change both seasonally and annually in their availability of favorable thermal habitat. This is the first study to document the thermal environment of a large embayment in Georgian Bay in such fine detail over two seasons, while simultaneously tracking the movements of adult northern pike during these two years. By combining both aspects in this study, I have provided important insights into how the amount of suitable habitat may change in response to probable water-level scenarios induced by global climate change.

Based on the long-term records kept by the Tadenac Club (Tadenac Club, unpub. data), there is currently a relatively large pike population in Tadenac Bay, but if decline in water levels reduces the availability of suitable thermal habitat, then the health of the population will be jeopardized. In both years, temperatures during May and June were initially suitable for growth for both adult and sub-adult pike throughout the water column. By the middle of July, however, favourable water temperature for growth (13-21°C) was compressed into a region in the northern portion of Tadenac at depths between 6.0 and 9.5 m. Further, towards the end of

July, surface water temperatures in both the deep and shallow stations had exceeded 25°C and were approaching 27.5°C, the temperature when growth of northern pike would essentially cease. Therefore, although favourable temperatures return to the shallow embayments in September, for a large portion of the summer, when other prey items are abundant (Midwood 2012), the thermal conditions in coastal wetlands of Tadenac Bay have been too warm to physiologically accommodate more than a short incursion by northern pike.

Favourable temperatures were only found in deeper areas of the bay during the summer, and this poses a problem because although the temperature was suitable, absence of submerged aquatic vegetation (SAV) at these depths would have limited the suitability of this portion of the water column for pike use (Casselman & Lewis 1996). Casselman & Lewis (1996) found that larger adult pike were less dependent on the presence of vegetation than are smaller adults. I found similar trends in this study, with females using deeper water in both years compared to males. Casselman's (1978) study showed that sub-adults stopped growing at ~27.5°C. Temperatures in the shallow back bay of Tadenac (i.e. Station 6) reached this temperature on 6 occasions in 2011 and on 5 occasions in 2012, and even the shallow station near the outflow (i.e. Station 1) experienced temperatures over 27.5°C for at least one day during both years (Figure 8).

Another way to visualize the availability of thermal habitat for northern pike in Tadenac Bay through the summer is to examine changes in the total volume of water in 9 temperature categories, which was accomplished by applying temperature depth profiles to a hypsographic curve of Tadenac Bay (see methods; Figure 9a & b). The volume of water corresponding to favourable growth for adults (i.e. 13 to 21°C) was relatively small during mid-summer. When weekly temperatures exceeded 27°C, the corresponding stratum of favourable temperature accounted for only 10 and 8% of the total habitat volume in 2011 and 2012, respectively. The amount of thermally favourable habitat was higher in the middle of June and September when it represented approximately 40 to 50% of the total habitat in both years. These observations therefore support the suggestion by Diana (1983) that use of habitat by cool-water top predators in the southern-most range of their habitat may result in a reduction or absence of growth in the middle of the summer due to temperature restrictions.

The mid-summer temperature profile of the relatively pristine Tadenac Bay represents a restriction of favourable thermal habitat for coolwater species such as northern pike that are dependent on access to wetlands and nearshore habitat throughout the summer. Warm temperatures in mid-summer (~27°C) while not fatal to northern pike, encroach upon the 29.4°C threshold determined by Casselman 1978 to be lethal for subadults. Even though the field experiments have not been carried out, it is not difficult to presume that fish would be thermally stressed if they were to remain in these warm temperatures for prolonged periods, since the range of published temperatures associated with thermal optima and preferences tend to fall between 13 to 21°C (see Table 1). Unfortunately, lower water levels induced by climate change may force these wetland-dependent fish into fatally hot temperatures in the not-so-distant future, and this problem deserves further and immediate attention by researchers.

Growth per volume of thermal habitat

I wanted to investigate how the availability of favourable thermal habitat may affect the potential for growth of adult northern pike within Tadenac Bay, given that temperatures did not reach a lethal level. Results from the application of the adjusted growth curve are in accordance with what was expected given the increase in water temperature during mid-summer (Figure 10). There was a pronounced decrease in the weekly percent change in growth from mid-July to mid-August (weeks 29-34) in both years. The ~1% growth in body weight that occurs over these weeks is approximately one third of the growth that occurs at the beginning and at the end of the sampling season (May, June & September). It is important to note that this potential growth only reflected the amount of thermal habitat corresponding to temperatures between 13 and 25°C; temperatures >25°C, which were persistent in the shallow embayments in the middle of summer would have yielded zero growth when the adjusted growth curve was applied. As previously mentioned, areas with favourable temperature in the deeper regions of Tadenac Bay may not have been suitable due to the absence of aquatic plants. Global Circulation Models forecast a further decrease in water levels and an increase in surface water temperature for the Great Lakes region, and it is likely that under these scenarios, the number of weeks with reduced favourable habitat could occur sooner and last longer. The reduction in growth that would attend even a 1°C increase in water temperature has the potential to substantially reduce the success of coolwater fish species like northern pike (Casselman 2002).

Effect of water level drop

I used the bathymetric model and existing thermal profiles to calculate the volume of water for each thermal category assuming a 1m drop in water level. The volume of Tadenac Bay would be reduced to 82% of current capacity and this would also be accompanied by loss of nearshore habitat that pike currently use (see Figure 13). The lower water level also removes hydrologic connectivity between some areas within Tadenac Bay and the open water of Georgian Bay. The area known as Big Bass Bay (Figure 2), located in southwestern Tadenac Bay is already inaccessible by boat due to low water levels, and with a further decrease in water levels, many more areas will either become disconnected or will have greatly reduced access for fish. For instance, Fracz and Chow-Fraser (unpub. data) determined that 66% of wetland habitat in the area known as Pike Alley would no longer be accessible to fish if water levels dropped from 175.9 m to 174.9. Since this decrease depends on local bathymetry of the site, not all of the wetlands would experience this magnitude of loss.

Aside from the 18% decrease in total volume of habitat, the maximum change in proportion of the nine thermal categories was 2% under the BCM1 scenario (Tables 8 & 9). This should be considered a very conservative estimate because I was unable to account for projected changes in temperature-depth profiles under a warmer climate that could raise the temperature of water in the shallow embayments (Mortsch & Quinn 1996). There will likely be an increase in the proportion of water associated with the warmest categories (i.e 25 to27°C and >27°C). The low water levels and accelerated warming, either individually or in combination, could have the potential to greatly reduce the amount of suitable habitat for northern pike.

Northern pike habitat use – Depth

Use of relatively shallow water embayments by the northern pike, despite temperatures there being warmer than optimum for growth, highlight the importance of nearshore habitat to northern pike. In both years, northern pike on average used the surface 4 m of water, probably because that is also where the aquatic vegetation grows (Environment Canada, unpub). The larger females were found to use deeper habitat in both years compared to the smaller males, but the difference in 2011 was not statistically significant (Figure 16a & b). These findings were consistent with Casselman & Lewis (1996), who reported that larger pike using less vegetated habitat compared to smaller individuals. The pike tended to use deeper water in 2012 (2.8±0.37m) compared to 2011 (2.16m±0.18), despite

2011 having a greater number of days with water temperatures in excess of 27.5° (Figure 8). I had expected pike to use the shallower water in a cooler year since temperatures would be closer to the favourable range of 13-21°C. One reason for this discrepancy may be related to the timing of the cooling period between years since temperatures cooled more rapidly in 2011 whereas temperatures remained high for a longer period in 2012. Further field studies must be conducted before we can begin to understand the factors that influence the movements and habitat selection of pike in natural environments.

Northern pike habitat use – Temperature

Corresponding temperatures associated with locations and depths at which the pike were found suggest that larger females selected for cooler, deeper water compared with males, and that males in general selected habitat in the shallower, warmer waters and this is consistent with findings of Pierce et al. (2013). Because of the small sample size in this study, however, I was unable to determine significant differences between males and females with respect to water depths they occupied in the water column and their associated temperatures (Figure 15a & b). It is important to note that while the average temperatures used by males and females were in the assumed range for favourable growth (i.e. between 13 to 21°C), there were several weeks in both years when individuals experienced less favourable temperatures that exceeded 24.75°C, and this would have resulted in zero growth during this period. I did not find any significant differences between years with respect to amount of potential growth; in both years, females had a greater potential for growth than males, based solely on water temperatures where they were found (Figure 16). A comparison of Ivlev's electivity index scores shows that females did not select water > 25°C in either year, whereas males were found to occupy water in the two warmest categories (i.e. 25 to 27°C and >27°C) during 2011 (Table 9).

Study limitations

There were several limitations to this study. First, we were informed by local fishers that pike moved in and out of Tadenac Bay into Georgian Bay throughout the year. Therefore, we attempted to monitor the movements of pike in and out of Tadenac Bay by installing a base receiver at the entrance of the bay in May 2011. Unfortunately, towards the end of the summer, the unit malfunctioned and all of the data were lost. Hence, I was unable to track movements in and out of Tadenac Bay during the study period. Nevertheless, our team has tracked the movements of pike on many occasions to the entrance of Tadenac Bay (Figure 14) and based on surveys conducted opportunistically outside of Tadenac Bay, we have ascertained that tagged pike could move more than 2km into the King Bay marina (Figure 11. Therefore, it is very likely that the northern pike left Tadenac Bay in search of more suitable thermal habitat as the summer progressed, and knowing the threshold temperature that might have initiated this migration would have greatly added to the scope of this study.

Another limitation was the type of radio-transmitters used in this study. At the time this study was planned, available radio tags only provided information regarding the horizontal location of the fish. Shortly after this study commence, radio tags became available that could provide information on depth and temperature of the water experienced by the pike. If such equipment had been used in this study, I may have been able to obtain a more accurate representation of the specific thermal characteristic of the water used by the fish. At a minimum, obtaining temperature information would have been easier and I would not have had to derive this information using the temperature depth profiles. The advanced technology would also have provided a more accurate representation of the depth used by the fish. In the current study, I used the maximum depth associated with spatial coordinates of each radio-tracked location, and this is likely an over-estimate of the depth selected by the fish. As previously mentioned the adjusted growth curve that was used may not be a realistic reflection of how adult northern pike grows as a function of water temperature, and therefore may not indicate the growth potential of northern pike within Tadenac Bay.

Implications

Northern pike is a cool-water species that is known to be associated with submerged aquatic vegetation as they are ambush predators (Casselman & Lewis 1996). The combination of low water levels and increased water temperatures predicted by various climate change scenarios will likely reduce the amount of suitable habitat available in Tadenac Bay for northern pike. Casselman (2002) has predicted that as water temperatures warm, the range of cool-water species (e.g. northern pike) will be encroached upon by warm-water species such as smallmouth bass. The northern pike I used in this study were larger than the sub-adults used to determine the optimal growth of 19-21°C for northern pike (Casselman 1978). Therefore, I operationally defined the favourable temperatures to be between 13-21°C for fish in this study since the optimal temperature for pike decreases as pike get larger, but it was not possible for me to determine the precise range for optimal growth (Casselman & Lewis 1996; Casselman 1978; Table 1). Northern pike used habitats within this defined range of "favourable" temperatures, but they were also found in relatively shallow water that was much warmer than the defined range in optimum. Consistent use of warmer than favourable temperature has the potential to inhibit the growth potential of adult northern pike, which has the potential to cause population-wide reduction in size.

If findings in this study were extrapolated to other shallow embayments in Georgian Bay, there could be serious implications for the overall health of the northern pike fishery in Georgian Bay. The coincidental decrease in catch per unit effort of northern pike from fifteen individuals to two between 2000 and 2010 (A. Liskauskas, unpub. data; Ontario Ministry of Natural Resources spring trap netting program) is consistent with the hypothesis that the co-occurrence of hot temperatures and low water levels in the past 10 years been detrimental to the population of northern pike in Georgian Bay. Sub-adults of northern pike from Ohio have been found to acclimate to being raised in warm hatchery ponds over the course of 25 years (Bevelheimer et al. 1985). This apparent ability for northern pike to adapt over the long-term suggests that they may be able to withstand a lake-wide temperature increase if these changes were to occur gradually. The combination of low water levels as well as an increased warming has the potential to cause habitat changes faster than adaptation can occur (Anguilleta, 2009). Therefore, there is an urgency to understand how northern pike use their thermal habitats in a natural setting, and to determine if they are able to adapt to both gradual and rapid changes. Without this information, fisheries managers will not be able to make informed decisions to better protect the critical wetland habitats that are used by northern pike in Georgian Bay.

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Table 1: Range in water temperatures that are ecologically relevant to Northern pike based on literature survey.

Life stage	Category	Temperature °C	Study
Fry	Optimal growth	25.6	Hokanson et al., 1978
Juvenile	Optimal growth	22 to 25	Bevelhimer et al., 1985
Juvenile/sub-adult	Optimal growth	19 to 21	Casselman, 1978
Juvenile/sub-adult	Preferred	23 to 24	McCauley & Casselman 1981
Juvenile/sub-adult	Maximum swimming speed	19 to 20	Casselman 1978
Juvenile/sub-adult	Upper incipient lethal	29.4 30.0	Casselman 1978 Ridenhour 1957
Adult	Spawning	8 to 12	Casselman & Lewis 1996
Adult (male)	Optimal growth	8 to 18	Neumann et al. 1994
Adult (large)	Preferred	16 to 18	Pierce et al. 2013
Adult	Favourable temperature	13 to 21	This study

Table 2: Relevant studies published between 1978 and 2013 that document habitat requirements and habitat use by northern pike

Authors	Topic	Study focus	Location
Casselman 1978	Temperature	Optimal temperature for growth	Laboratory and field tested in Manitoulin
McCauley and Casselman 1981	Temperature	Preferred vs optimal temperature on growth	Laboratory setting
Headrick & Carline 1993	Temperature	Temperature avoidance	Southern Ohio impoundments
Casselman 2002	Temperature	Effects of thermal extremes on reproduction	Lake Ontario
Pierce et al. 2013	Temperature	Use of thermal habitat	Inland lakes in Minnesota
Margenau et al. 1998	Feeding and growth	Environmental effects and prey availability on growth	Small lakes in Wisconsin
Diana 1979	Feeding	Feeding patterns	Alberta
Lucas et al. 1991	Feeding and metabolism	Heart rate, metabolism and feeding	Telemetry study in Scottish lakes
Bevelheimer et al. 1985	Bioenergetics	Bioenergetics model for esocids	Ohio lakes
Inskip 1982	Habitat	Habitat suitability model	Lake and riverine systems
Minns et al. 1996	Habitat	Habitat supply	Hamilton Harbour
Savino & Stein 1989	Habitat	Habitat use in vegetation vs open water	Laboratory
Farrell 2001	Habitat	Sympatric between pike and muskellunge	St. Lawrence River
Pierce & Tomcko 2005	Density and biomass	Basin morphometry	Inland lakes of Minnesota
Koed et al. 2006	Movement	Annual movement patterns	Lowland river in Denmark
Kobler et al 2008	Movement	Movement in summer vs winter	Small lake in Germany
Klefoth et al. 2008	Behaviour	Catch and release effects on short-term behaviour	Lake in Germany

Table 3: Correlation matrix of temperatures measured at 1 m depth for 9 stations established in Tadenac Bay during 2011. All correlation coefficients are statistically significant ($P<0.0001$). Values that are bolded are greater than 0.980.

	Stn 1	Stn 2	Stn 3	Stn 4	Stn 5	Stn 6	Stn 7	Stn 8	Stn 9
Stn 1	--	**0.990**	0.958	0.938	0.932	0.941	0.936	0.926	0.984
Stn 2		--	**0.988**	0.961	0.954	0.963	0.961	0.947	**0.996**
Stn 3			--	**0.985**	0.978	**0.983**	**0.982**	0.969	**0.993**
Stn 4				--	**0.996**	**0.997**	**0.991**	**0.982**	0.974
Stn 5					--	**0.998**	**0.990**	0.976	0.969
Stn 6						--	**0.993**	**0.980**	0.973
Stn 7							--	0.979	0.973
Stn 8								--	0.961
Stn 9									--

Table 4: Correlation matrix of temperatures measured at 1 m depth for 5 stations established in Tadenac Bay during 2012. All correlation coefficients are statistically significant (P<0.0001). Values that are bolded are greater than 0.950.

	Stn 1	Stn 6	Stn 9	Stn 10	Stn 11
Stn 1	--	0.917	**0.972**	0.948	0.860
Stn 6		--	0.937	**0.976**	**0.956**
Stn 9			--	**0.956**	0.882
Stn 10				--	**0.963**
Stn 11					--

Table 5. Summary of total length (mm), weight (g) and sex of northern pike caught initially in May 2011. Amount of time tracked refers to the number of weeks in 2011 and 2012 during which each fish was radio-tracked in Tadenac Bay. Only the weeks in which temperature were also being measured were considered. Total number of weeks sampled were 7 and 6 for 2011 and 2012 respectively.

				Amount of time tracked		
ID #	**Sex**	**Length**	**Weight**	**2011**	**2012**	**Status at end of study**
11	M	632	1540	7	6	Tracked in 2012
12	M	583	1150	4	0	Tracked in 2011
13	F	962	5930	6	0	Tracked in 2011
14	M	773	3170	2	1	Harvested
15	M	563	1170	6	0	Harvested
16	F	912	6420	0	1	Tracked in 2012
17	F	817	4060	0	2	Tracked in 2012
18	F	913	5200	3	4	Tracked in 2013
19	M	574	1110	2	0	Tracked in 2011
20	M	620	1520	6	6	Tracked in 2013
21	F	916	6430	0	1	Tracked in 2012
22	M	729	2560	0	2	Tracked in 2012

Table 6: Range in depths (m) where water temperatures were between 13° and 21°C (optimum temperature for growth of sub-adults) at a deep (Station 9, Figure 5) and a shallow (Station 6, Figure 5) in Tadenac Bay during 2011 and 2012. "--" indicates that water temperatures exceeded 21°C at that time of year.

	2011		2012	
Week of the Year	**Deep station**	**Shallow station**	**Deep station**	**Shallow station**
25	surface to 9.0	surface to 3..5	surface to 7.0	surface to 3.5
26	surface to 9.0	1.0 to 3.5	2.5 to 8.0	surface to 3.5
27	surface to 9.0	1.5 to 3.5	4.0 to 9.0	--
28	3.5 to 9.0	--	4.5 to 9.0	1.5 to 3.5
29	4.5 to 9.0	--	5.5 to 9.0	3.0 to 3.5
30	5.0 to 9.0	--	6.5 to 9.0	--
31	6 .0 to 9.0	--	6.5 to 9.5	--
32	6.5 to 9.0	--	6.5 to 9.5	--
33	6.5 to 9.0	--	6.5 to 9.5	--
34	6.5 to 9.0	--	6.5 to 10.0	--
35	6.5 to 11.5	--	7.0 to 10.0	--
36	6.5 to 11.5	--	7.5 to 10.0	--
37	6.0 to 11.5	1.5 to 3.5	8.0 to 10.0	--
38	6.5 to 11.5	surface to 3.5	8.0 to 11.5	surface to 3.5
39	surface to 11.5	surface to 3.5	surface to 11.5	surface to 3.5

Table 7: Weekly changes in proportion of nine thermal (°C) habitat categories in Tadenac Bay. Proportions were calculated by dividing respective volumes of each thermal habitat category by the total volume of Tadenac Bay (assuming an elevation of 175.86 m (asl) for a calculated total volume of 1.911×10^7 m^3). The shaded area corresponds to the favourable temperature for growth for adult northern pike.

		Proportion of total volume in each thermal habitat category								
Year	Week of the Year	<13	13-15	15-17	17-19	19-21	21-23	23-25	25-27	>27
2011	25	0.35	0.09	0.11	0.15	0.30	0.00	0.00	0.00	0.00
	26	0.37	0.07	0.10	0.10	0.26	0.09	0.00	0.00	0.00
	27	0.36	0.06	0.06	0.13	0.26	0.13	0.00	0.00	0.00
	28	0.36	0.05	0.04	0.03	0.11	0.22	0.19	0.00	0.00
	29	0.33	0.06	0.04	0.03	0.05	0.10	0.20	0.19	0.00
	30	0.31	0.03	0.03	0.03	0.05	0.05	0.21	0.16	0.13
	31	0.33	0.03	0.02	0.02	0.03	0.05	0.14	0.37	0.00
	32	0.33	0.01	0.03	0.02	0.02	0.05	0.12	0.41	0.00
	33	0.35	0.01	0.03	0.01	0.03	0.03	0.25	0.28	0.00
	34	0.35	0.03	0.03	0.01	0.03	0.05	0.44	0.06	0.00
	35	0.39	0.03	0.03	0.01	0.03	0.18	0.26	0.06	0.00
	36	0.38	0.04	0.03	0.01	0.03	0.38	0.13	0.00	0.00
	37	0.32	0.03	0.05	0.04	0.15	0.41	0.00	0.00	0.00
	38	0.36	0.00	0.00	0.07	0.30	0.26	0.00	0.00	0.00
	39	0.31	0.00	0.00	0.29	0.40	0.00	0.00	0.00	0.00
2012	21	0.42	0.16	0.33	0.06	0.00	0.03	0.00	0.00	0.00
	22	0.43	0.10	0.09	0.15	0.19	0.04	0.00	0.00	0.00
	23	0.39	0.12	0.08	0.21	0.18	0.02	0.00	0.00	0.00
	24	0.38	0.08	0.14	0.38	0.00	0.01	0.00	0.00	0.00
	25	0.38	0.05	0.04	0.09	0.26	0.18	0.00	0.00	0.00
	26	0.40	0.04	0.04	0.04	0.12	0.18	0.15	0.02	0.00
	27	0.39	0.03	0.03	0.06	0.06	0.26	0.16	0.00	0.00
	28	0.34	0.06	0.02	0.05	0.03	0.08	0.36	0.06	0.00
	29	0.36	0.03	0.02	0.02	0.04	0.06	0.26	0.21	0.00
	30	0.33	0.01	0.03	0.01	0.02	0.06	0.10	0.40	0.04
	31	0.34	0.01	0.02	0.02	0.02	0.06	0.29	0.24	0.00
	32	0.34	0.03	0.01	0.03	0.03	0.04	0.30	0.22	0.00
	33	0.33	0.01	0.01	0.03	0.03	0.03	0.55	0.00	0.00
	34	0.33	0.01	0.01	0.02	0.04	0.58	0.00	0.00	0.00
	35	0.32	0.01	0.01	0.01	0.04	0.60	0.00	0.00	0.00
	36	0.33	0.03	0.01	0.01	0.03	0.46	0.12	0.00	0.00
	37	0.34	0.02	0.03	0.01	0.02	0.38	0.20	0.00	0.00
	38	0.29	0.03	0.01	0.03	0.10	0.55	0.00	0.00	0.00
	39	0.29	0.02	0.03	0.05	0.62	0.00	0.00	0.00	0.00

Table 8: Weekly changes in proportion of nine thermal (°C) habitat categories in Tadenac Bay. Proportions were calculated by dividing respective volumes of each thermal habitat category by the hypothetical total volume of Tadenac Bay corresponding to a 1-m drop from current water level (total volume of 1.614 x 10^7 m^3). The shaded area corresponds to the favourable temperature for growth of adult northern pike.

		Proportion of total volume in each thermal habitat category								
Year	Week of the Year	<13	13-15	15-17	17-19	19-21	21-23	23-25	25-27	>27
2011	25	0.38	0.10	0.09	0.14	0.29	0.00	0.00	0.00	0.00
	26	0.39	0.08	0.09	0.10	0.26	0.08	0.00	0.00	0.00
	27	0.34	0.06	0.07	0.12	0.30	0.11	0.00	0.00	0.00
	28	0.38	0.05	0.05	0.04	0.10	0.23	0.16	0.00	0.00
	29	0.37	0.03	0.05	0.03	0.06	0.08	0.21	0.16	0.00
	30	0.25	0.03	0.03	0.03	0.05	0.15	0.19	0.16	0.11
	31	0.40	0.03	0.02	0.04	0.03	0.00	0.13	0.36	0.00
	32	0.34	0.01	0.03	0.04	0.01	0.05	0.10	0.40	0.00
	33	0.39	0.01	0.03	0.02	0.03	0.00	0.24	0.27	0.00
	34	0.35	0.04	0.03	0.02	0.03	0.05	0.42	0.06	0.00
	35	0.40	0.04	0.03	0.02	0.03	0.19	0.24	0.06	0.00
	36	0.39	0.04	0.03	0.02	0.03	0.37	0.11	0.00	0.00
	37	0.35	0.03	0.05	0.04	0.12	0.43	0.00	0.00	0.00
	38	0.49	0.00	0.00	0.07	0.16	0.29	0.00	0.00	0.00
	39	0.32	0.00	0.00	0.24	0.44	0.00	0.00	0.00	0.00
2012	21	0.46	0.13	0.32	0.05	0.00	0.04	0.00	0.00	0.00
	22	0.40	0.10	0.07	0.16	0.21	0.06	0.00	0.00	0.00
	23	0.41	0.13	0.07	0.21	0.16	0.03	0.00	0.00	0.00
	24	0.41	0.08	0.16	0.34	0.00	0.01	0.00	0.00	0.00
	25	0.42	0.05	0.05	0.08	0.26	0.14	0.00	0.00	0.00
	26	0.42	0.05	0.05	0.05	0.11	0.18	0.14	0.01	0.00
	27	0.38	0.03	0.03	0.07	0.06	0.29	0.14	0.00	0.00
	28	0.29	0.07	0.01	0.06	0.04	0.09	0.40	0.04	0.00
	29	0.36	0.03	0.05	0.01	0.05	0.07	0.27	0.16	0.00
	30	0.32	0.02	0.03	0.02	0.02	0.07	0.11	0.39	0.03
	31	0.39	0.01	0.02	0.04	0.01	0.03	0.31	0.19	0.00
	32	0.32	0.04	0.02	0.03	0.03	0.05	0.34	0.18	0.00
	33	0.33	0.02	0.02	0.03	0.03	0.04	0.53	0.00	0.00
	34	0.33	0.02	0.02	0.02	0.05	0.57	0.00	0.00	0.00
	35	0.33	0.01	0.01	0.02	0.05	0.58	0.00	0.00	0.00
	36	0.35	0.02	0.01	0.02	0.03	0.45	0.11	0.00	0.00
	37	0.32	0.01	0.04	0.02	0.02	0.42	0.18	0.00	0.00
	38	0.29	0.02	0.02	0.03	0.07	0.56	0.00	0.00	0.00
	39	0.29	0.01	0.03	0.04	0.62	0.00	0.00	0.00	0.00

Table 9: Comparison of depth and water temperature associated with locations of northern pike in Tadenac Bay determined by radio-telemetry during 2011 and 2012. Maximum depth was estimated by superimposing GPS points on a bathymetric map of the bay. Sampling stations (see Figure 5) were closest to the location of each pike obtained based off the maximum depth from the bathymetry at, at the point in which the pike location occurred. Temperature values were based off the values obtained from the buoy that was closest to the pike location.

	Week of		# times locations	Depth (m)		Temperature (°C)	
Year	Year	Sex	confirmed	Maximum	Mean±SE	Maximum	Mean±SE
2011	25	M	6	2.99	2.05±0.35	20.7	19.7±0.34
	26		65	5.77	1.82±0.13	21.2	20.5±0.08
	28		4	2.31	1.44±0.39	24.6	23.9±0.42
	30		46	5.93	2.51±0.20	27.7	26.9±0.12
	34		36	4.76	2.41±0.22	24.7	24.4±0.06
	35		3	2.39	1.59±0.57	23.2	23.1±0.06
	39		2	0.20	0.17±0.03	17.8	17.8±0.0
	25	F	2	2.61	1.35±1.27	19.8	19.8±0.04
	26		11	5.37	2.84±0.46	20.2	19.6±0.17
	28		1	4.00	4.00	22.0	22.0
	30		1	4.23	4.23	24.8	--24.8
	34		12	4.83	3.17±0.26	23.9	--23.9
	35		1	1.88	1.88	22.6	--22.6
	39		2	4.62	4.48±0.14	18.1	--18.1
2012	21	M	23	2.39	0.83±0.16	18.2	16.9±0.28
	25		11	3.91	2.69±0.20	21.2	20.0±0.37
	26		8	3.95	2.78±0.42	23.5	22.7±0.16
	30		8	4.93	4.22±0.17	26.1	25.6±0.20
	31		6	4.75	2.77±0.62	25.6	24.9±0.18
	33		6	6.80	2.55±0.98	24.3	23.9±0.12
	21	F	14	4.43	1.75±0.33	17.9	16.6±0.18
	25		4	3.87	2.70±0.42	20.7	20.3±0.18
	30		2	6.94	6.65±0.29	25.3	25.6±0.77
	31		1	6.87	6.87	24.5	24.50 ±
	33		3	7.96	5.44±2.41	24.2	23.38 ±

Table 10: Analysis of habitat use based on Ivlev's (1961) electivity index. Index scores range from -1.0 to +1.0 with positive values (shown in bold) indicating preference for, and negative values indicating avoidance of, thermal habitat categories. Numbers in each category represent a range in water temperatures (°C).

			Electivity Index							
Year	Week of the Year	Sex	>27	25-27	23-25	21-23	19-21	17-19	15-17	13-15
2011	25	M	--	--	--	--	**0.175**	**0.176**	-1.000	-1.000
	25	F	--	--	--	--	**0.362**	-1.000	-1.000	-1.000
	26	M	--	--	--	**0.206**	**0.230**	-1.000	-0.196	-1.000
	26	F	--	--	--	-1.000	**0.230**	**0.365**	-1.000	-1.000
	28	M	--	--	**0.441**	-0.161	-1.000	-1.000	-1.000	-1.000
	28	F	--	--	-1.000	**0.486**	-1.000	-1.000	-1.000	-1.000
	30	M	**0.394**	**0.285**	-0.356	-1.000	-1.000	-1.000	-1.000	-1.000
	30	F	-1.000	-1.000	**0.538**	-1.000	-1.000	-1.000	-1.000	-1.000
	34	M	--	-1.000	**0.194**	-1.000	-1.000	-1.000	-1.000	-1.000
	34	F	--	-1.000	**0.194**	-1.000	-1.000	-1.000	-1.000	-1.000
	35	M	--	-1.000	**0.213**	**0.051**	-1.000	-1.000	-1.000	-1.000
	35	F	--	-1.000	-1.000	0**.537**	-1.000	-1.000	-1.000	-1.000
	39	F	--	--	--	--	-1.000	**0.405**	--	--
	39	M	--	--	--	--	-1.000	**0.405**	--	--
2012	21	M	--	--	--	-1.000	--	**0.520**	-0.065	-0.249
	21	F	--	--	--	-1.000	--	**0.311**	0**.026**	-0.162
	25	M	--	--	--	-0.185	**0.175**	-1.000	**0.481**	-1.000
	25	F	--	--	--	-1.000	**0.408**	-1.000	-1.000	-1.000
	26	M	--	-1.000	**0.134**	**0.372**	-1.000	-1.000	-1.000	-1.000
	30	F	-1.000	-0.091	**0.551**	-1.000	-1.000	-1.000	-1.000	-1.000
	30	M	-1.000	**0.250**	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000
	31	M	--	**0.155**	**0.068**	-1.000	-1.000	-1.000	-1.000	-1.000
	31	F	--	-1.000	**0.392**	-1.000	-1.000	-1.000	-1.000	-1.000
	33	F	--		-0.246	**0.826**	-1.000	-1.000	-1.000	-1.000
	33	M	--	--	**0.096**	-1.000	-1.000	-1.000	-1.000	-1.000

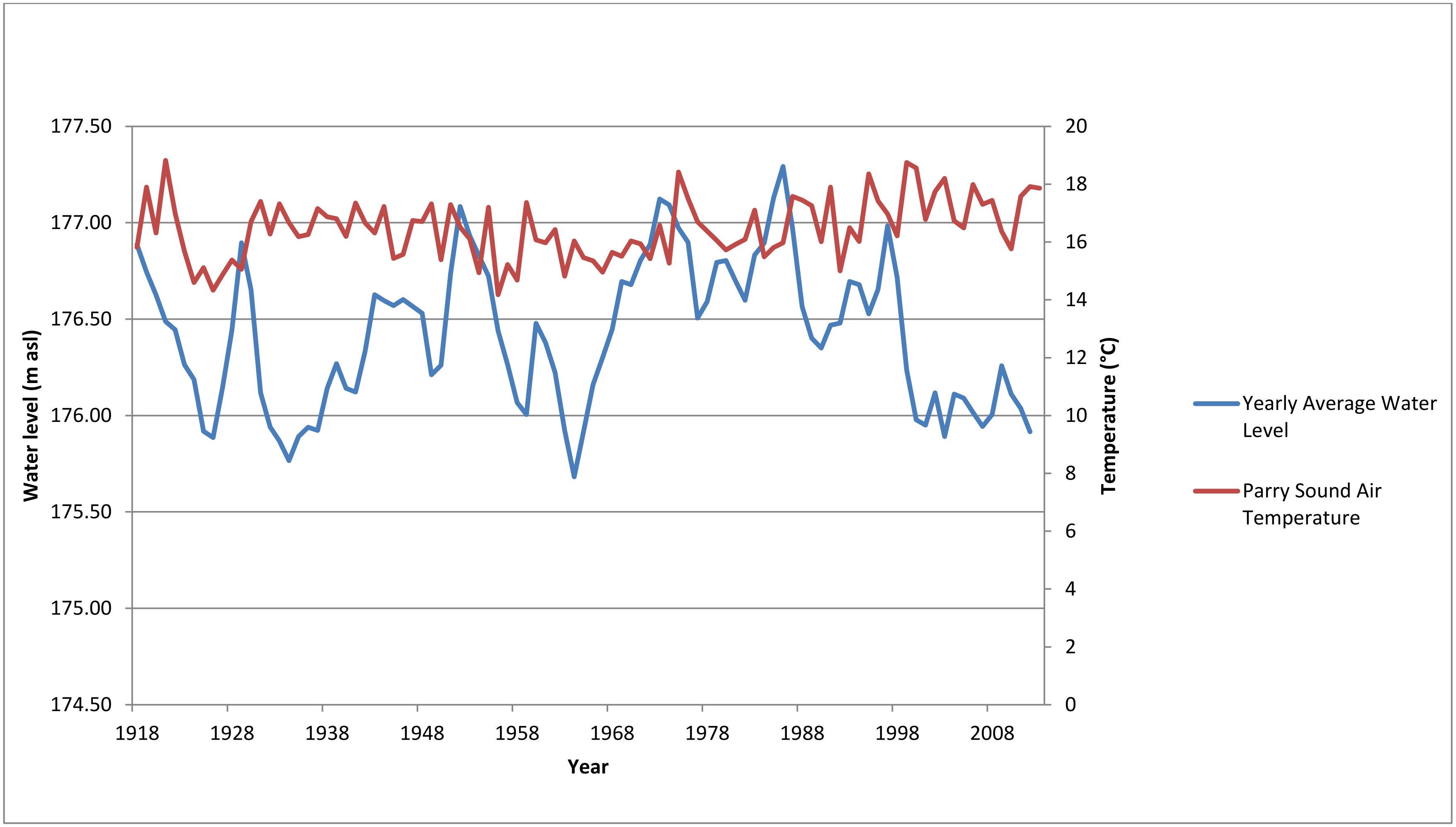


Figure 1: Plot of mean annual water levels of Lake Huron the yearly average of Parry Sound air temperature between May-Sept. Many of the warmest years over the past decade have coincided with extremely low water levels in Lake Huron. Data obtained from both via National Oceanic and Atmospheric Administration (NOAA).

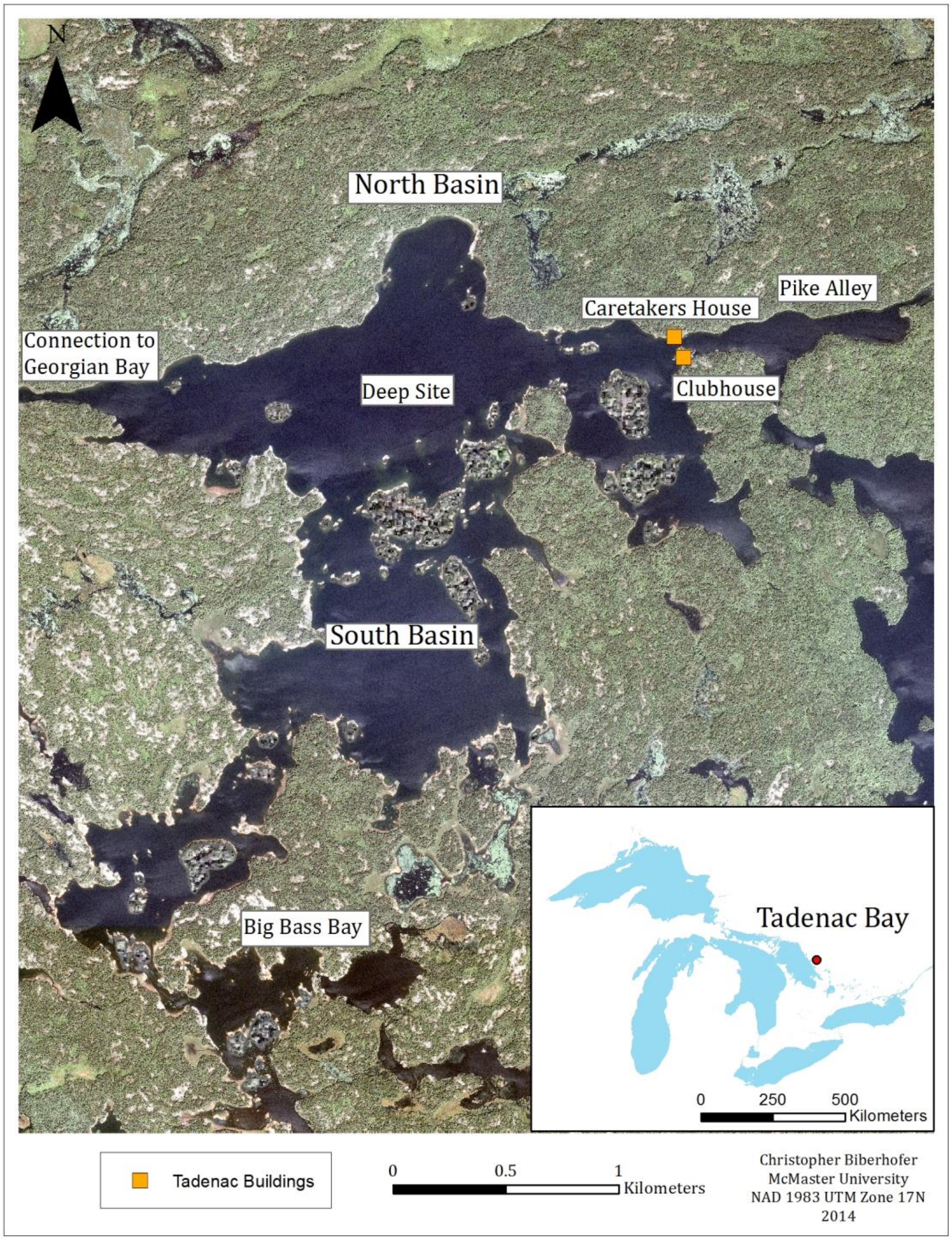


Figure 2: Satellite image of the study site in Tadenac Bay taken in 2002, showing the location of the only two buildings on the property, as well as the deep station established to monitor seasonal changes in the thermal regime of the bay in 2011 and 2012. Inset shows the location of Tadenac Bay in Georgian Bay and the Great Lakes.

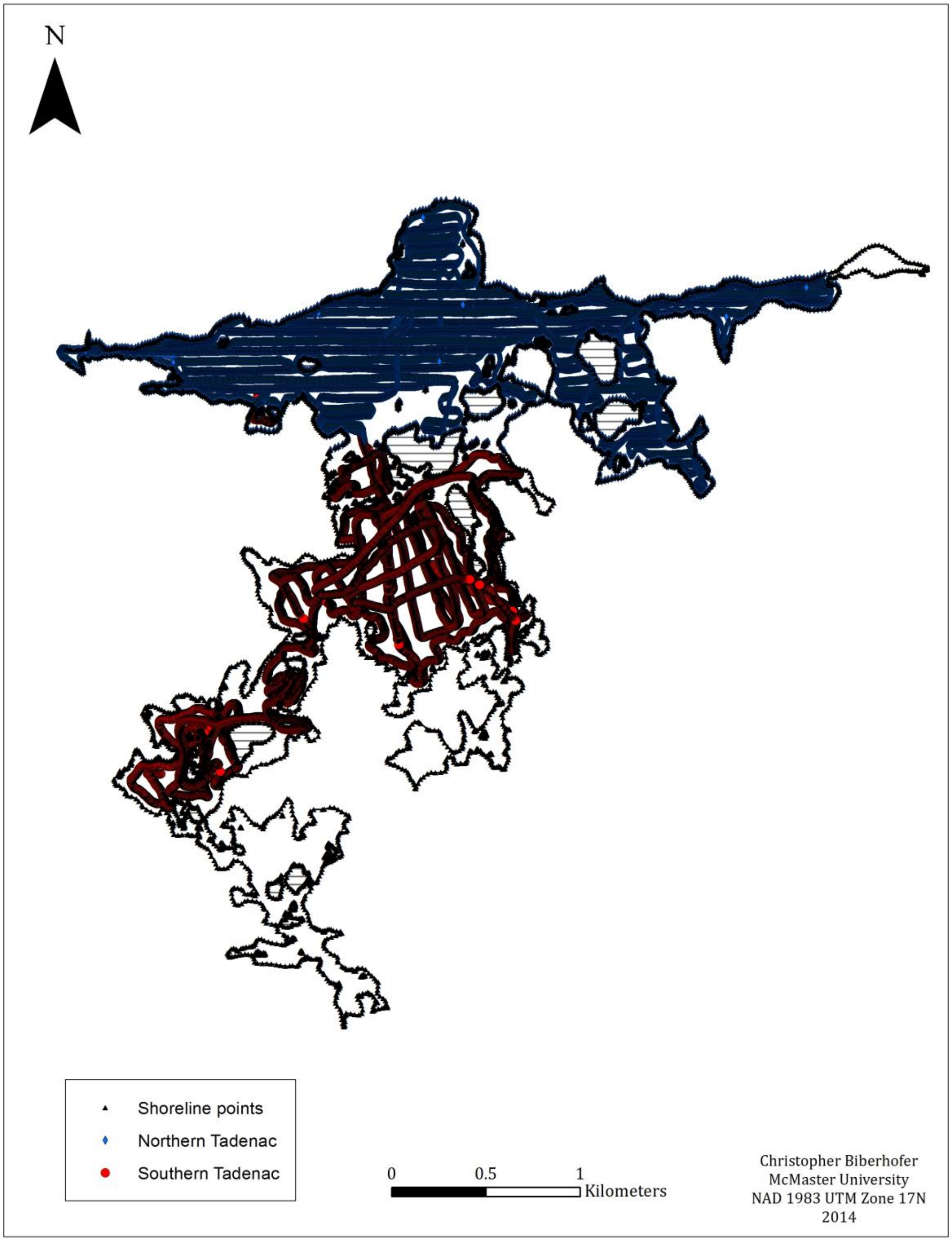


Figure 3: Survey lines of soundings that were taken to collect bathymetric data for Tadenac Bay. Data for northern Tadenac Bay were collected in 2011 and that for southern Tadenac Bay were collected in 2012.

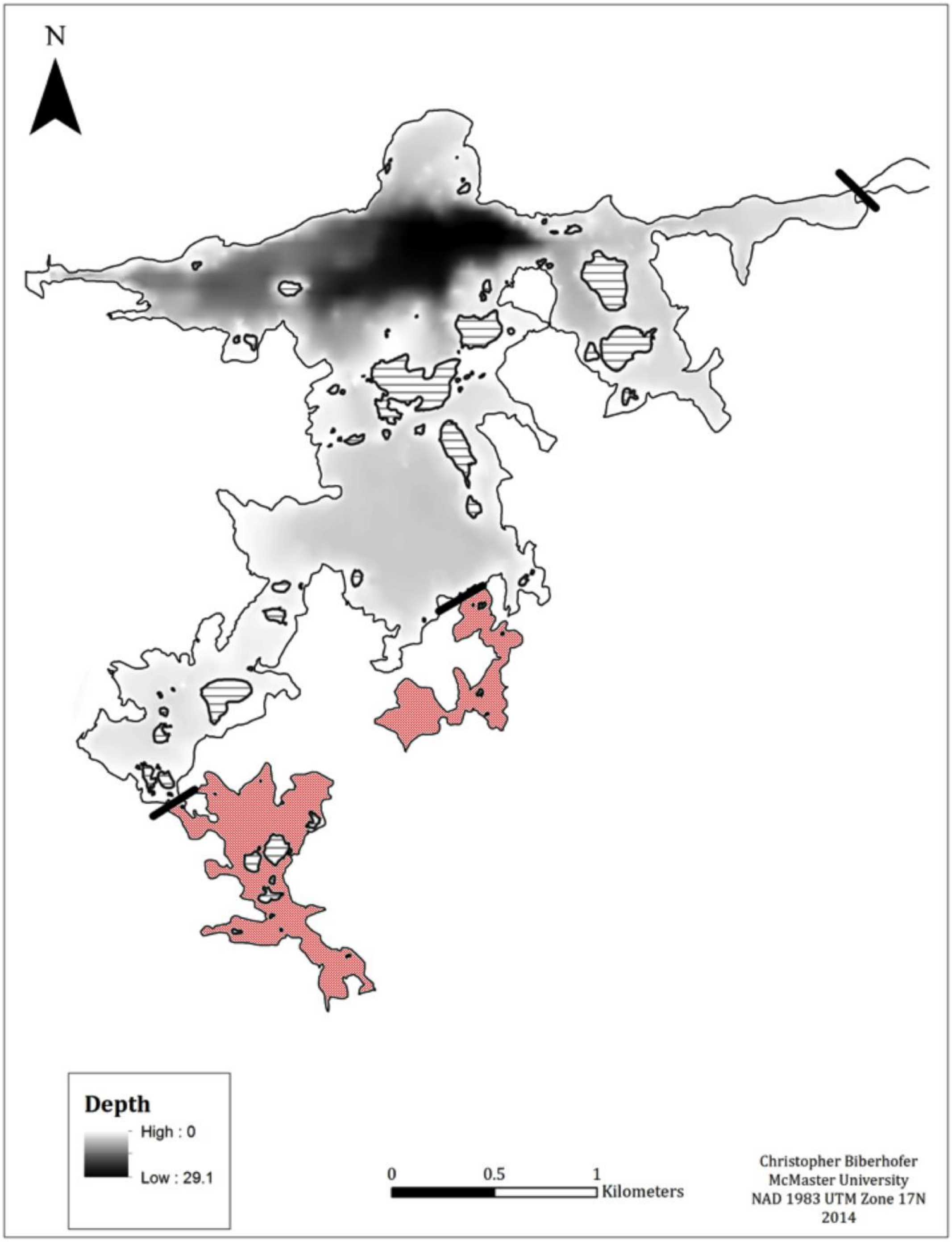


Figure 4: Bathymetric map of Tadenac Bay, showing location of the deepest spot (29.1 m) that occurs in the middle of the northern basin. The red stippled areas located behind the black solid lines could not be accessed by the boat due to the shallow entrance. These areas were known to be habitat for northern pike during periods with high water levels (Tadenac Club, unpub. data).

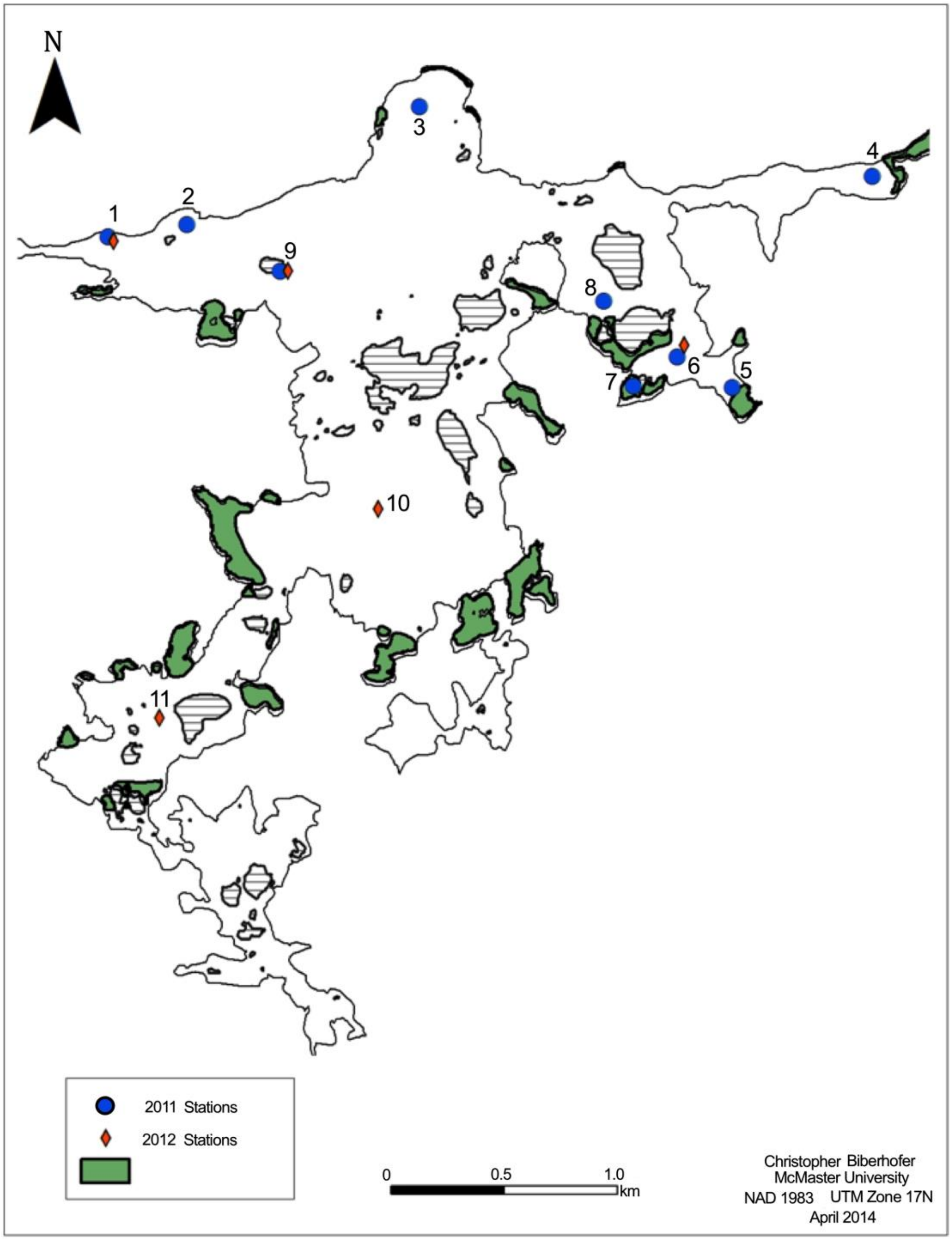
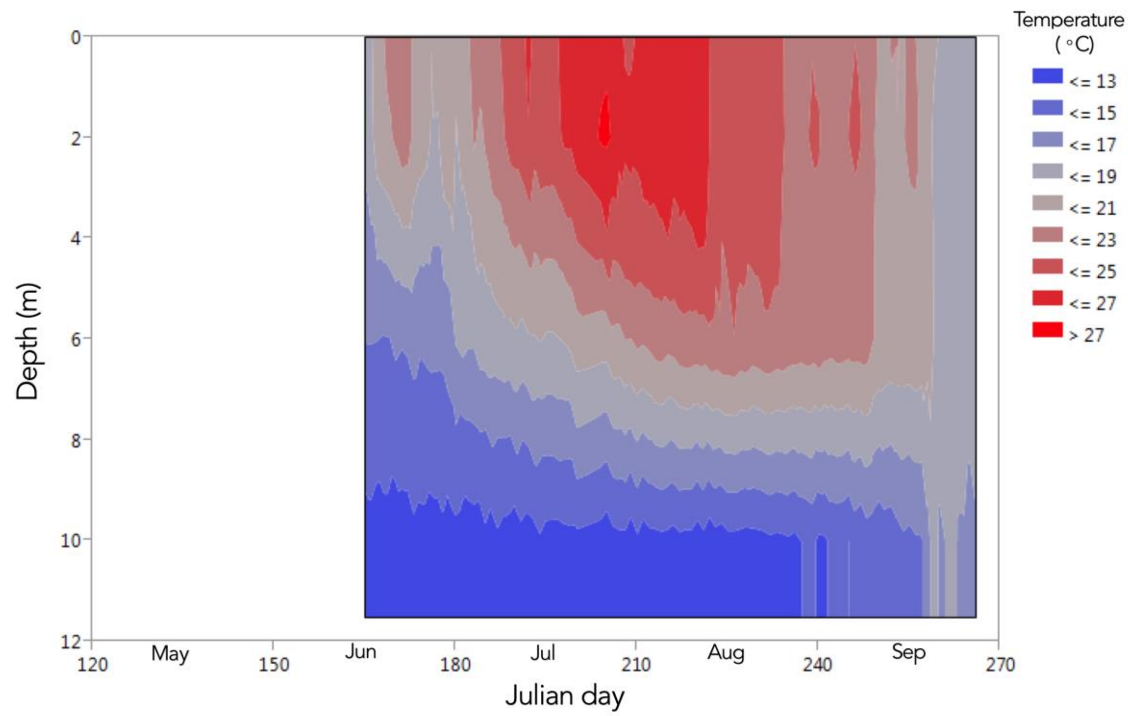


Figure 5: Map showing location of sampling stations established in Tadenac Bay during 2011 and 2012 to monitor seasonal changes in water temperature with depth. Coastal marshes for Tadenac Bay from the McMaster Coastal Wetland Inventory (Midwood et al. 2012) has been superimposed on the map.

a)



b)

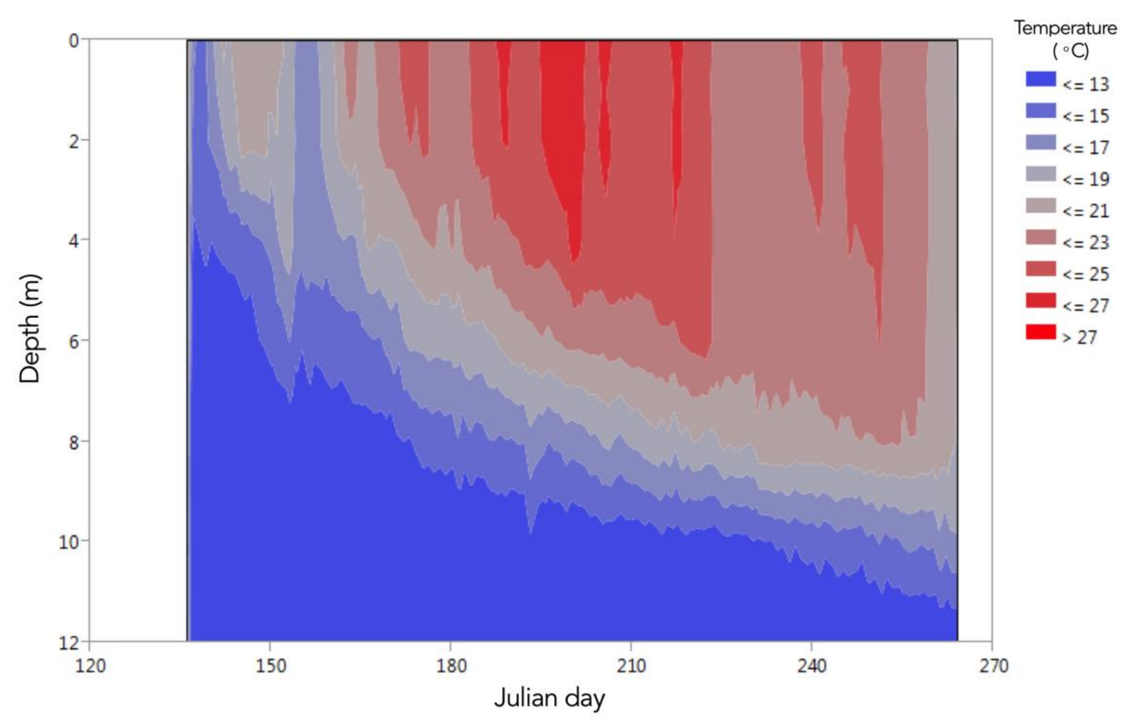
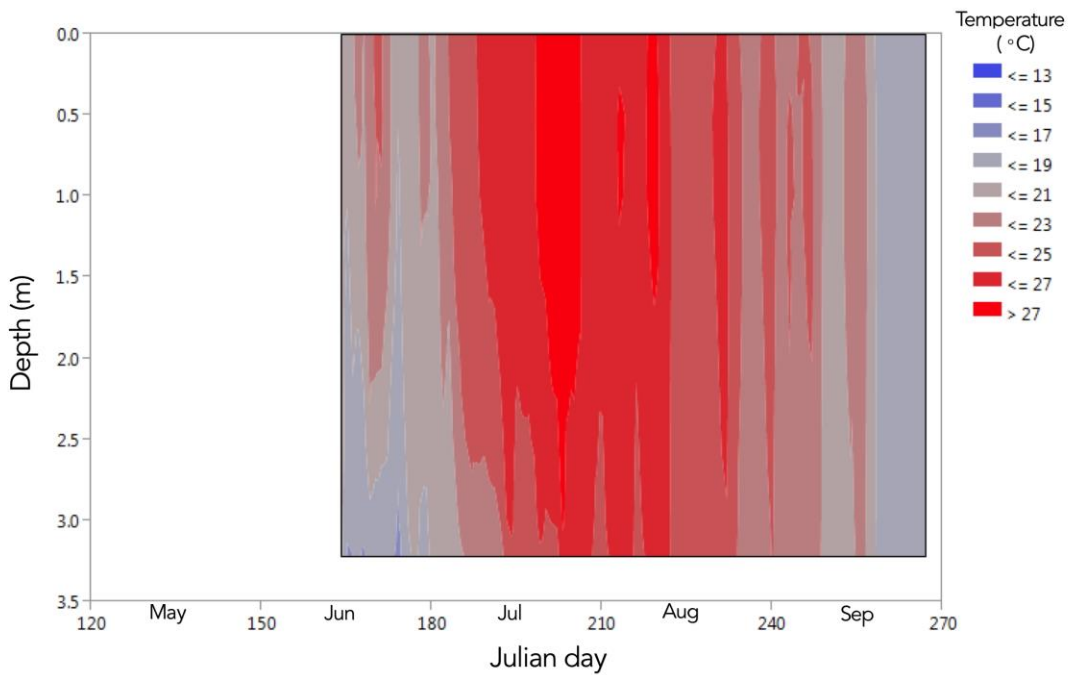


Figure 6: Temperature isopleths of northern Tadenac Bay for data collected at the deep station (Station 9 in Figure 2) in a) 2011 and b) 2012.

a)



b)

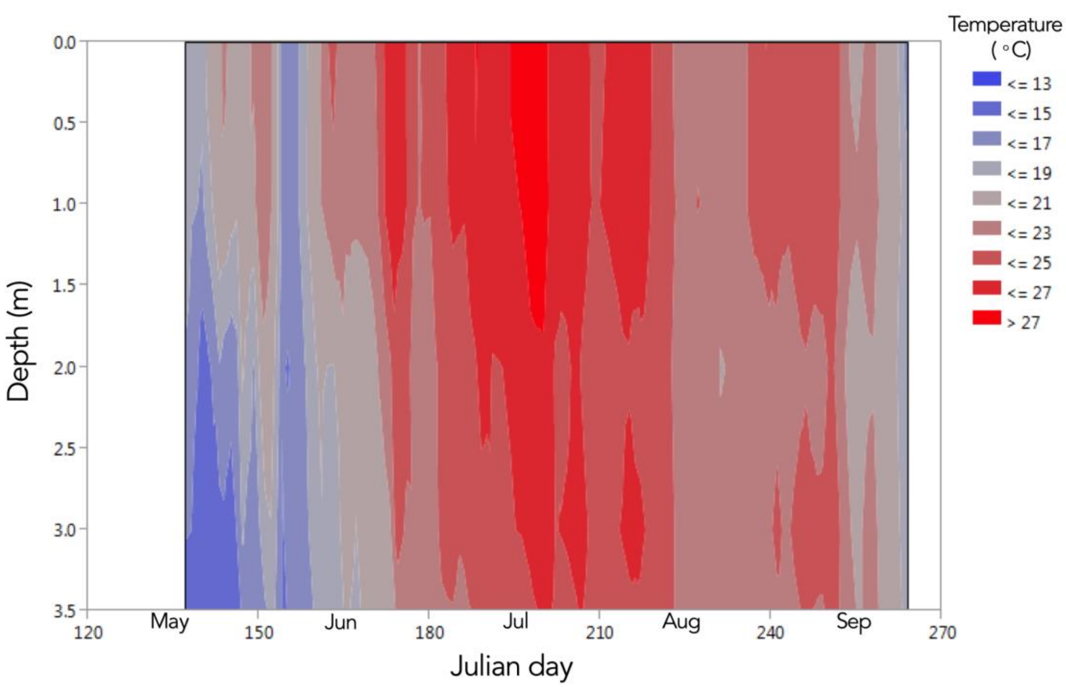


Figure 7: Temperature isopleths of northern Tadenac Bay for data collected at the shallow station (Station 6 in Figure 5) in a) 2011 and b) 2012.

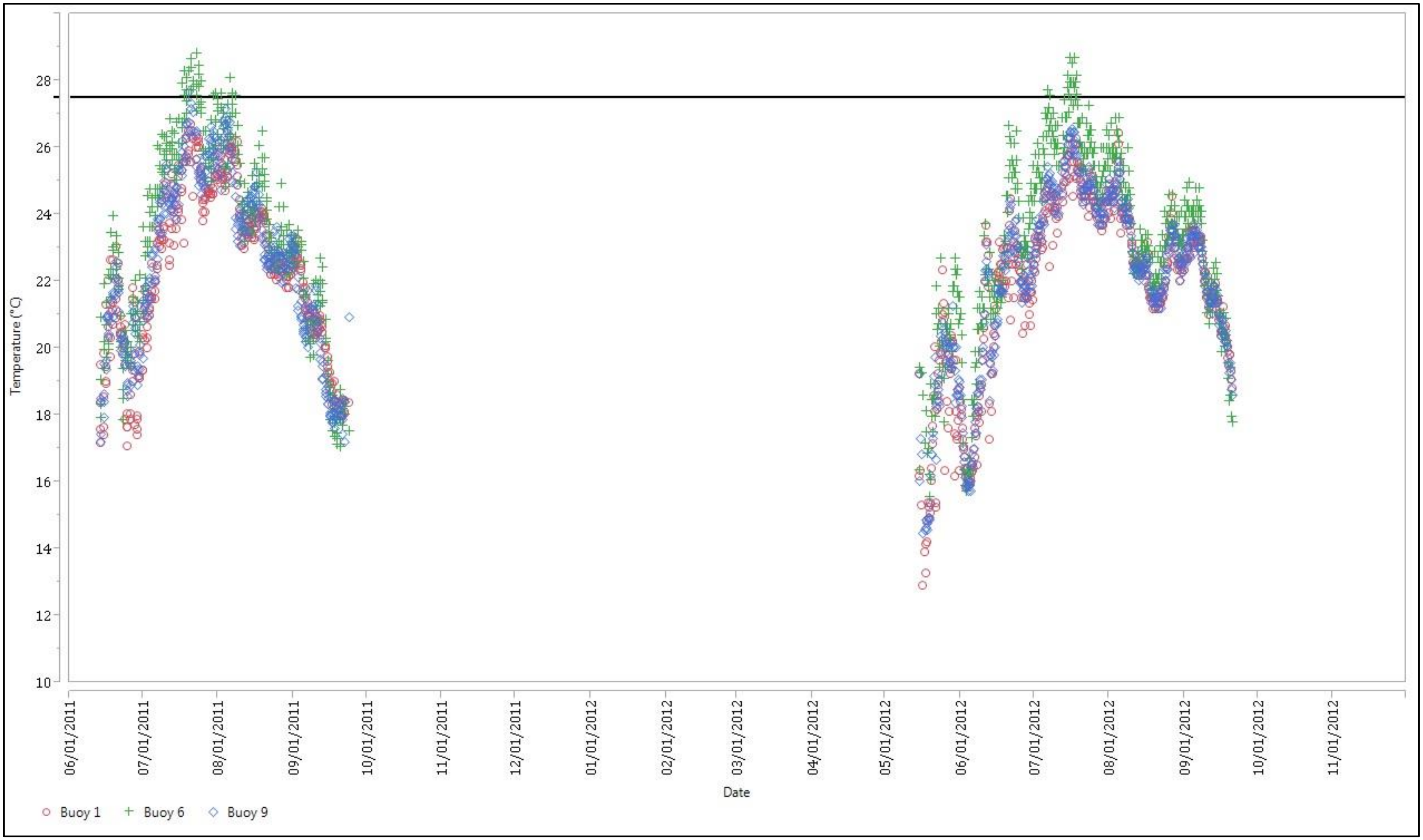
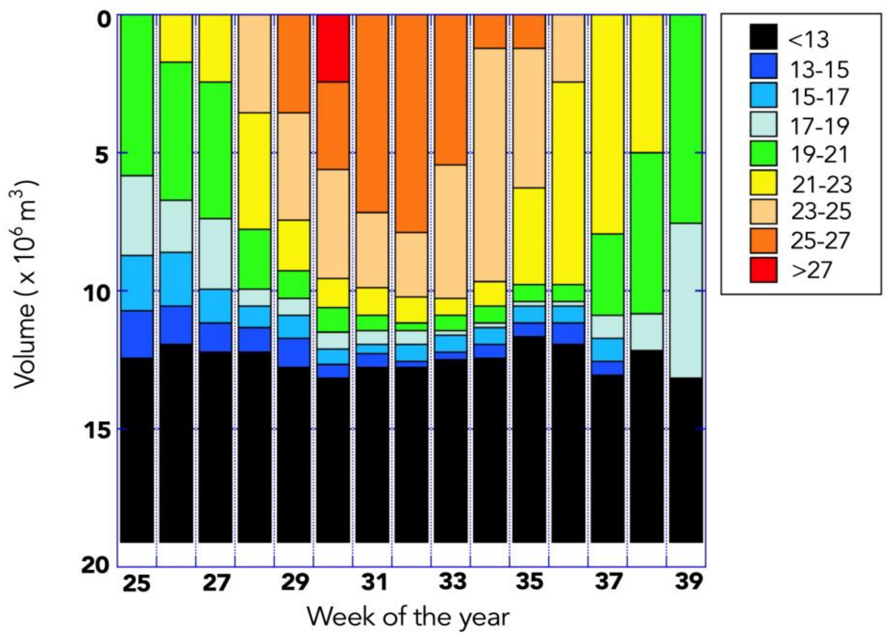


Figure 8: Daily temperatures measured at 6-h intervals at Stations 1, 6 and 9 for both 2011 and 2012. The black line indicates 27.5°C which is at the temperature in which northern pike would cease to feed.

a)



b)

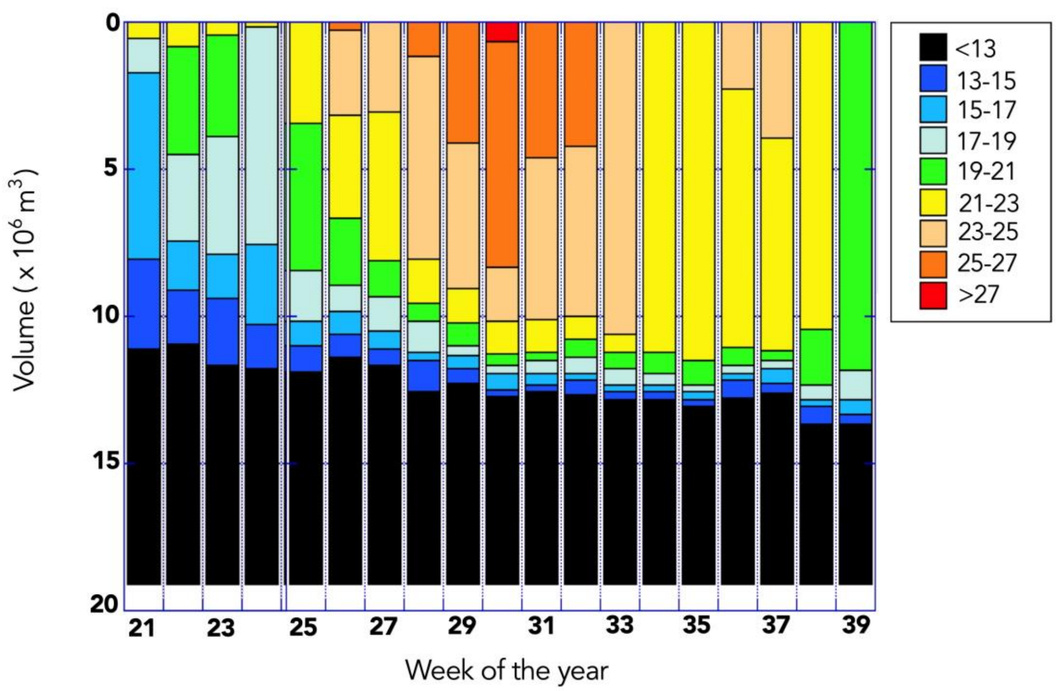


Figure 9: Stacked histogram showing weekly changes in volume of the thermal habitat categories in Tadenac Bay during a) 2011 and b) 2012. Volumes were calculated assuming water level of 175.86 m, asl (base case).

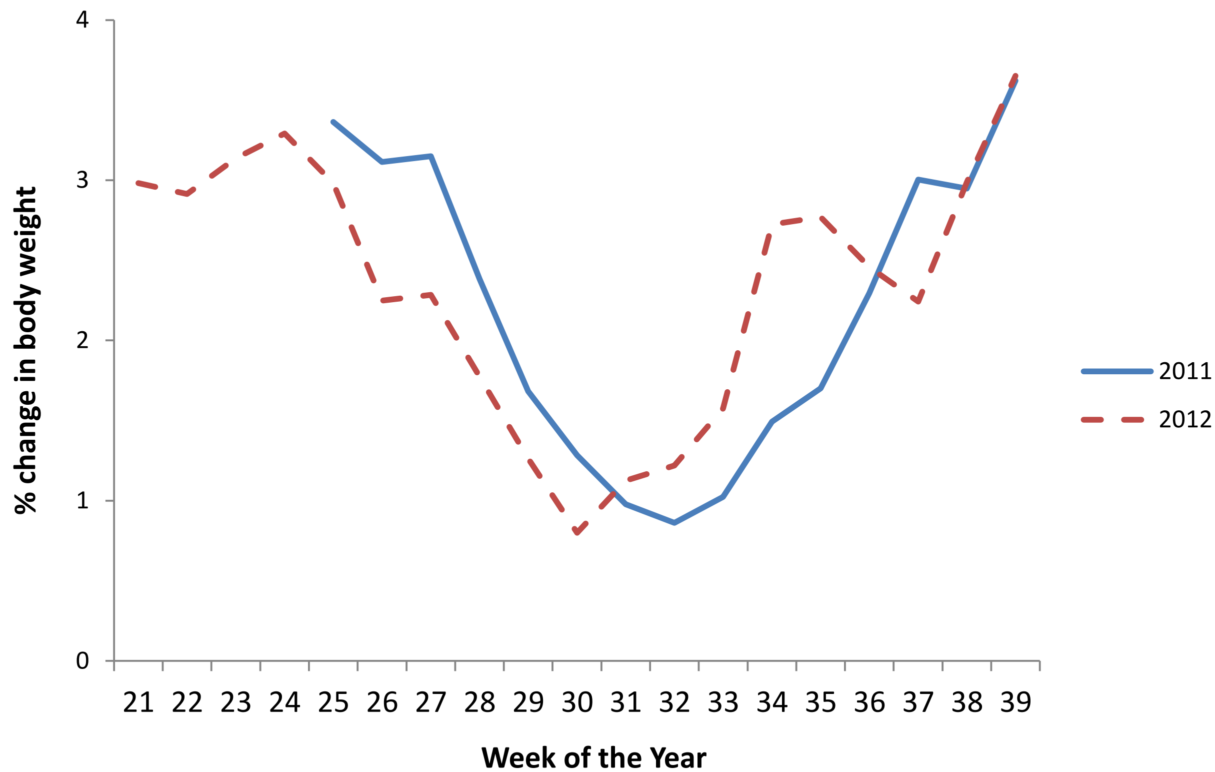


Figure 10: Percentage change in body weight of northern pike (male and females) calculated on a weekly basis during the growing season. Changes in body weight were calculated by determining the range of water temperatures occupied by northern pike each week and estimating the growth corresponding to these temperatures provided in Casselman (1978). Only temperatures between 13 and 25°C were included in this analysis because northern pike were not observed in water temperature <13°C and at temperatures >25°C growth does not occur (based on the growth curve adjusted for adults).

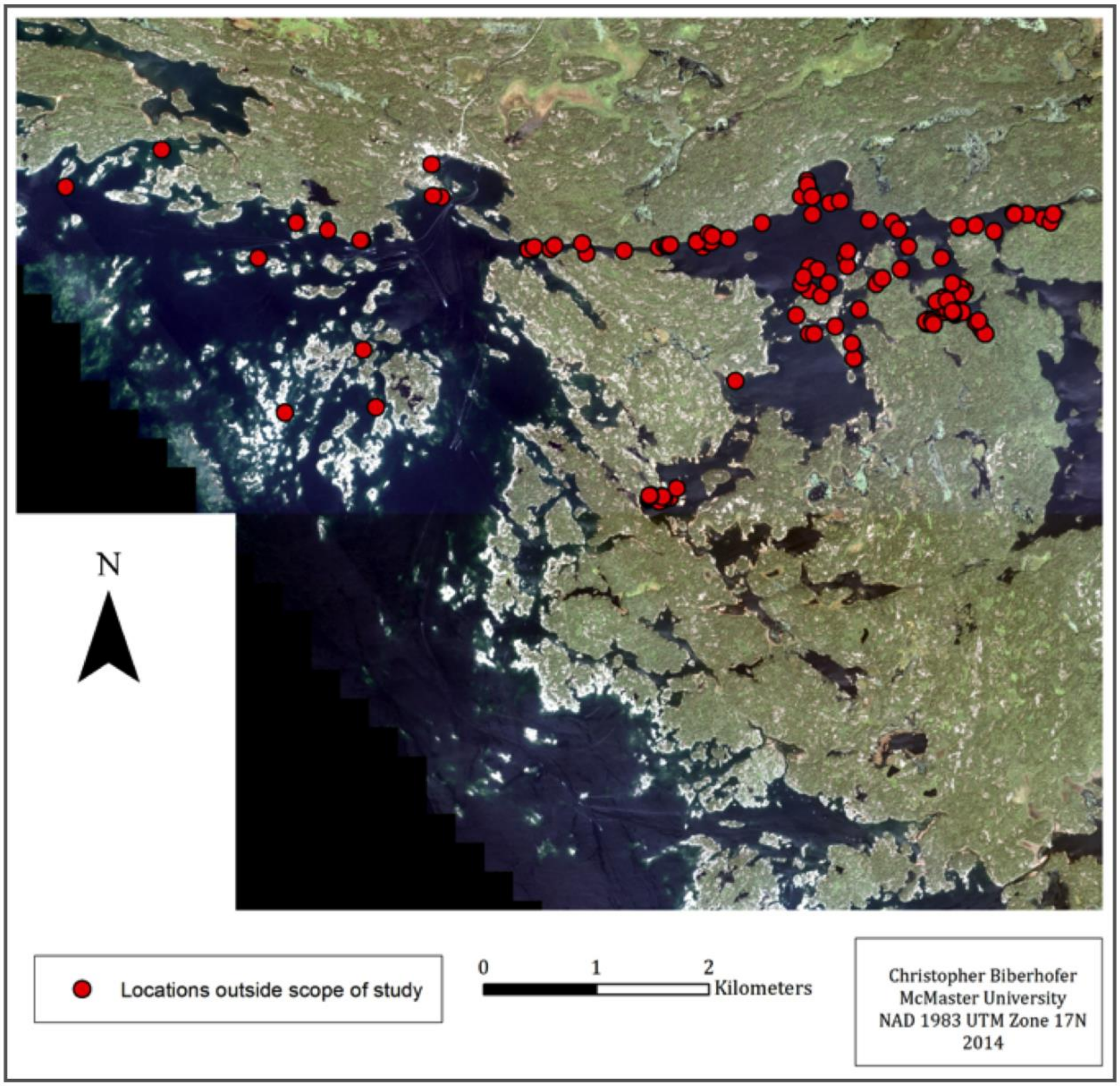


Figure 11: All radio-tracked locations of northern pike in Tadenac Bay and in the general vicinity of the outflow to Georgian Bay. Data include those obtained outside the growing seasons of 2011 and 2012 as well as three surveys conducted in the fall and winter of 2012 and 2013

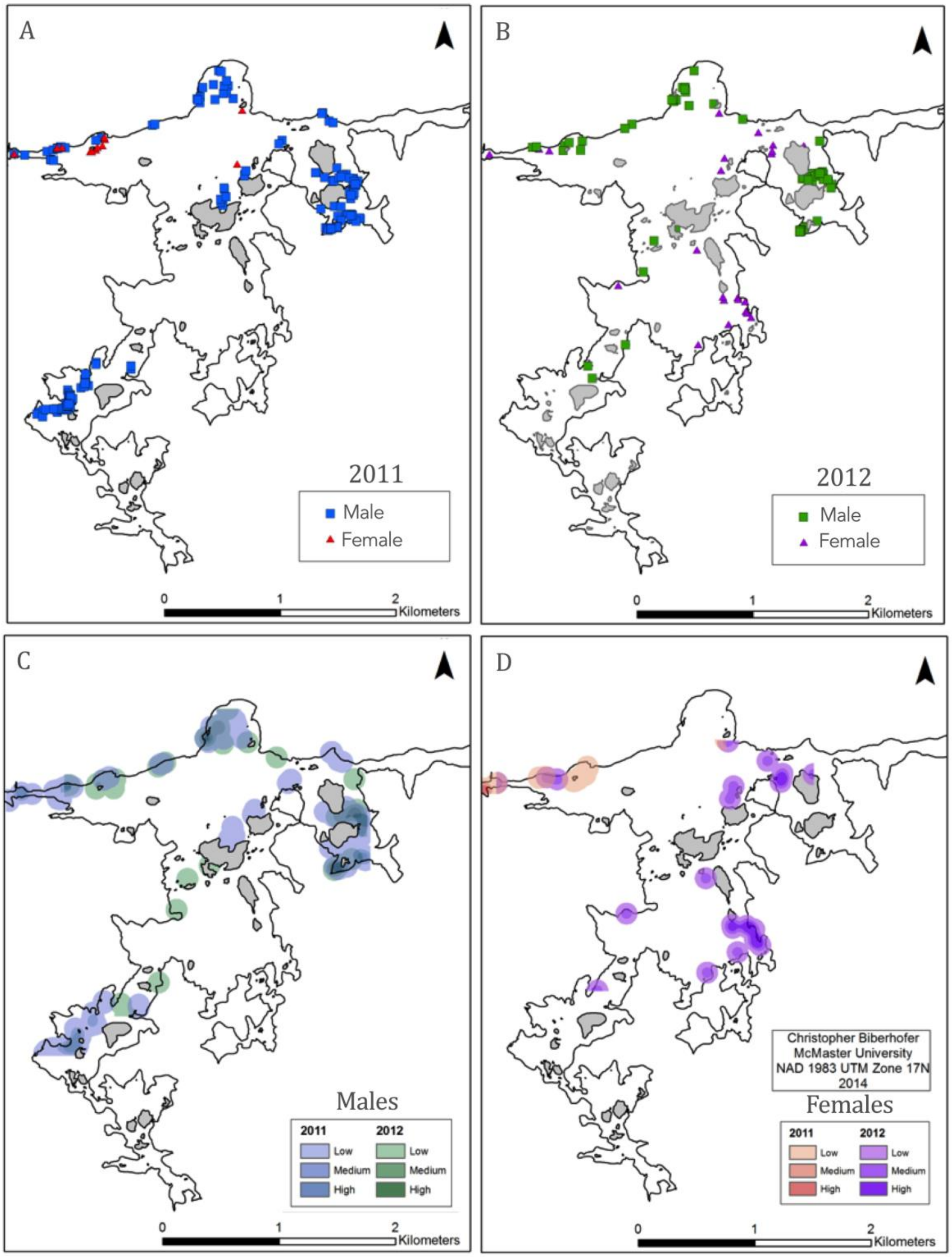


Figure 12: Radio-tracked locations of northern pike during the growing season in A) 2011 and B) 2012. Density maps of C) male and D) female pike based on radio-tracked locations.

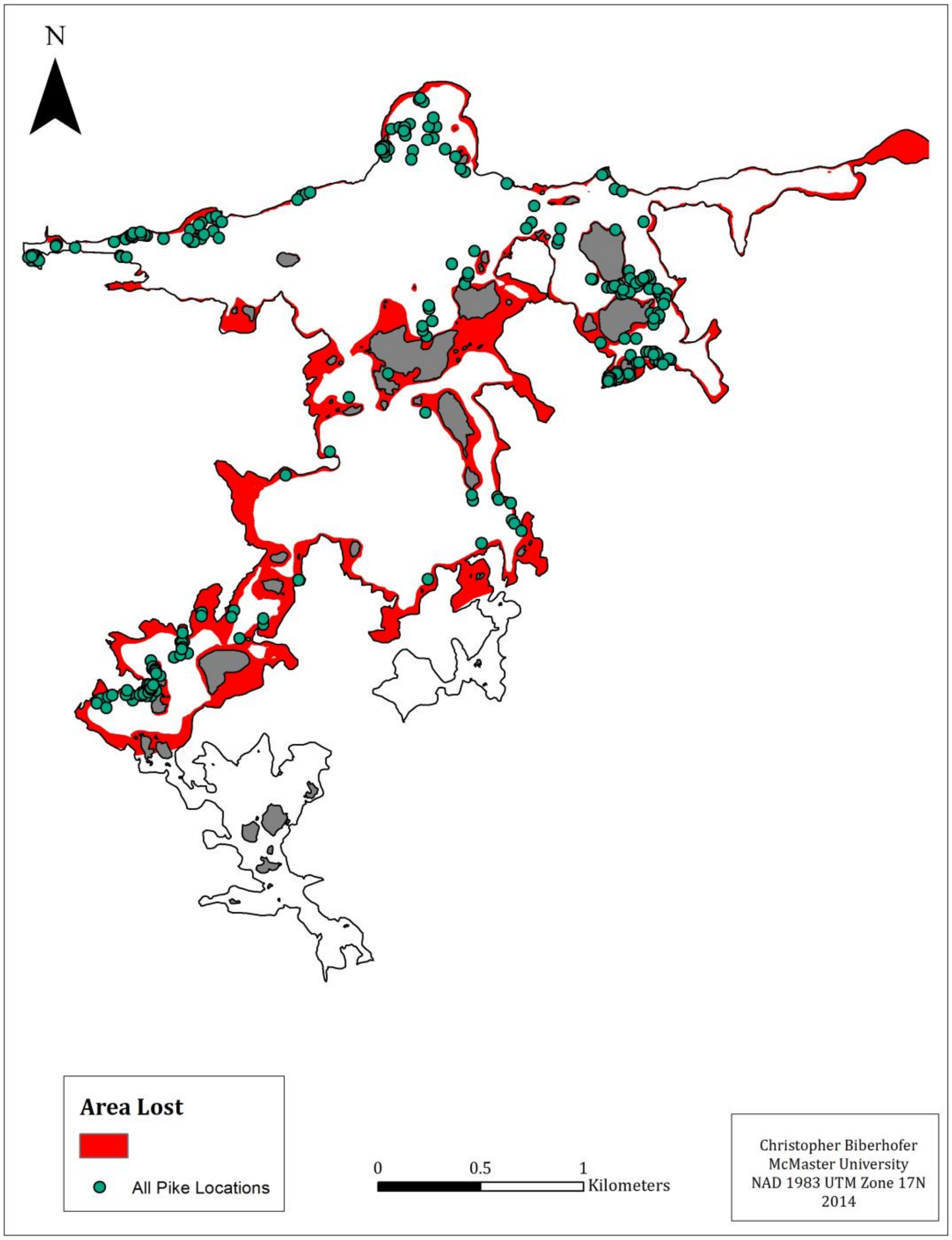
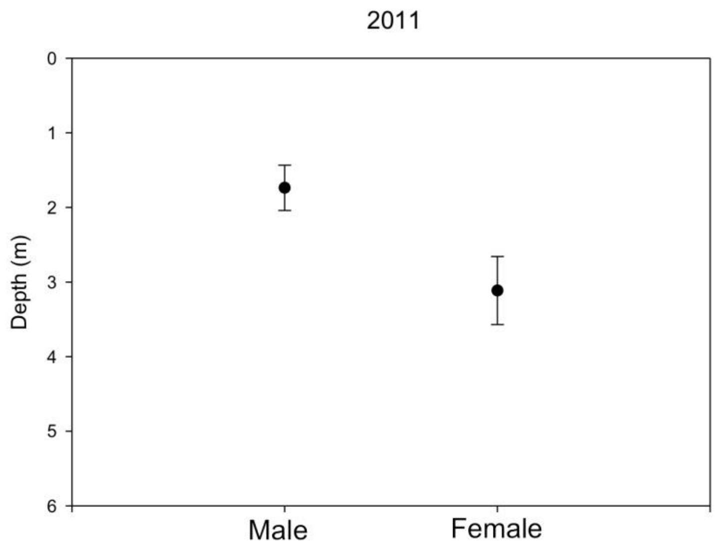


Figure 13:. Map showing areas (in red) that would be lost to northern pike if water levels were to drop an additional meter from base case (i.e. BCM1). Radio-tagged locations of all northern pike obtained in this study are superimposed to show which areas are most affected by this change in water level.

a)



b)

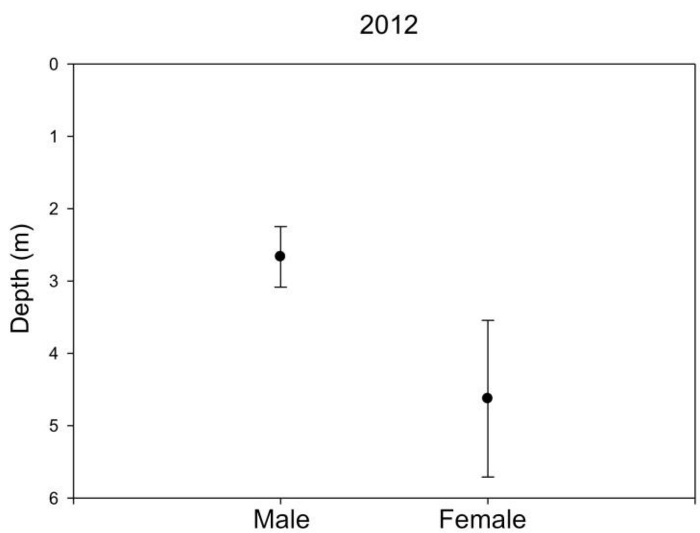
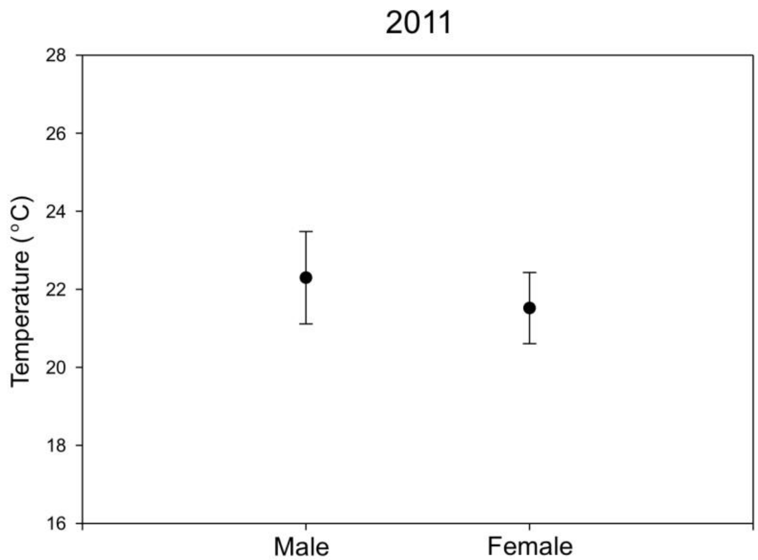


Figure 14: Comparison of mean depth used by the average male and female Northern pike in Tadenac Bay during a) 2011 and b) 2012. The average depth for males was 1.93m ± SE 0.17, n = 27, whereas females were found at depths of 2.89m ± SE 0.46 n = 9. In 2012 the difference between the two was not statistically significant but both sexes were found to use even deeper habitat.

a)



b)

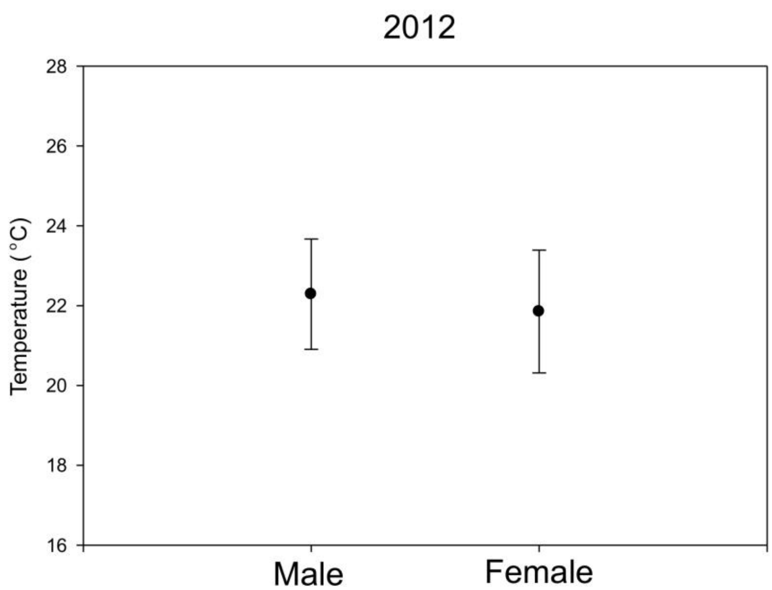
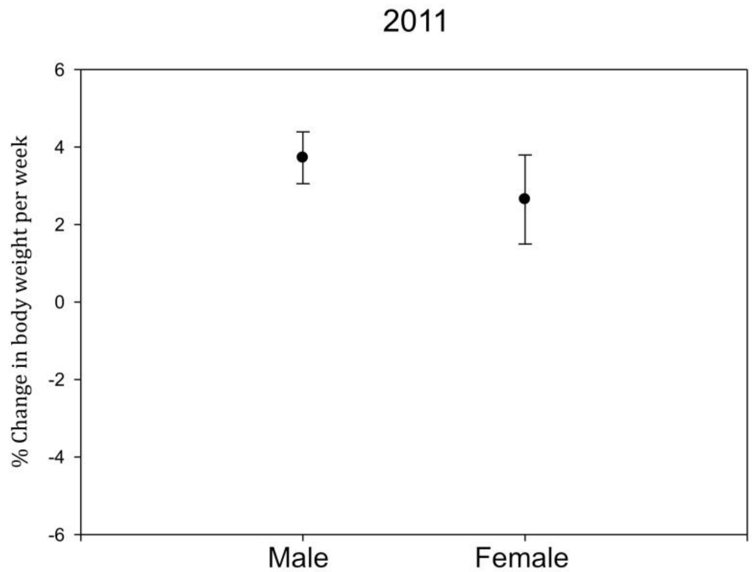


Figure 15: Comparison of water temperatures corresponding to water depths at which northern pike were found during a) 2011 and b) 2012. There were no significant differences between sexes for either year.

a)



b)

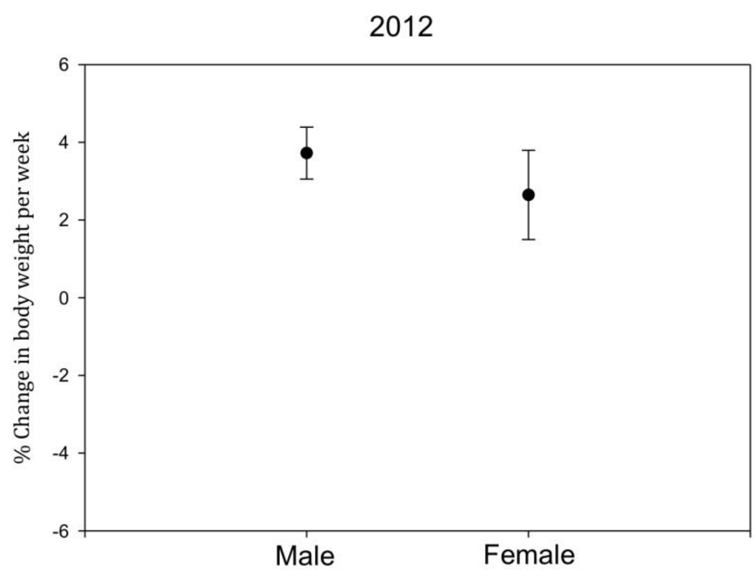


Figure 16: Estimated weekly change in percentage body weight for northern pike in Tadenac Bay during a) 2011 and b) 2012. Values are interpolated from an adjusted growth curve from Casselman's (1978) relationship between temperature and growth. There were no significant differences between males and females for either year.