Assessing nutrient status and distribution of algal growth along a gradient of cottage development in 10 sheltered embayments in eastern Georgian Bay

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For submission to:

Environment and Climate Change Canada

Funded by:

Lake Simcoe / South-eastern Georgian Bay Clean-up Fund (LSGBCUF)

April 2016

INTRODUCTION

Lake Huron, particularly Georgian Bay, has been assessed as being ultra oligotrophic, and since the late 1990s, there has been a downward trend towards decreased levels of phosphorus and nitrogen concentrations in the pelagic zone (Dove and Chapra 2015). In the nearshore zone, however, especially in some of the sheltered embayments along the eastern shore of Georgian Bay, the water quality is variable; many sites still have low nutrients and algal biomass (Diep et al. 2009), but others have recurring episodes of hypolimnetic oxygen depletion and suspected internal phosphorus loading that are both symptomatic of impaired water quality that one encounters in eutrophic lakes (Schiefer et al. 2006). In some years, occurrence of nuisance algal blooms has also been reported (e.g. Sturgeon Bay and South Bay; Schiefer et al. 2006; Chiandet and Sherman 2014), and more recently cottagers have also complained about increased growth of benthic macroalgae. Such development of water-quality impairment could be attributed to a number of factors, including low water levels (Chow-Fraser, unpub. data), anthropogenic disturbances from increased cottage development and the lack of adequate water exchange with greater Georgian Bay.

The demand for cottages and other recreational facilities in eastern Georgian Bay has grown dramatically over the past century (Georgian Bay Township, 2014). Coastal development in this region consists primarily of cottages, resorts and marinas, all of which contribute primary nutrients to their surrounding waters via septic system effluent. Traditionally, these waste water systems are effective at treating incoming sewage; however, the Precambrian Shield region is characterized by thin soil structures and fractured bedrock (Dillon et al. 1994; Joy 2013) that prevent septic systems from functioning properly. As a result, in the Precambrian Shield region, septic systems have been identified as the largest source of anthropogenic nutrient loading (Dillon et al., 1994; Robertson et al., 1998).

The dominant geological feature in eastern Georgian Bay is the Precambrian Shield, which consists primarily of erosion-resistant bedrock. This bedrock has been shaped through past glaciations (Mcarthy and McAndrews, 2012) to create a variable coastline with many finger-like sheltered embayments. These embayments are unique coastal systems that are linked to Georgian Bay through narrow connecting channels. This can result in limited flushing and mixing patterns that would otherwise be common in more exposed bays. Since limited mixing occurs between embayment waters and the oligotrophic waters of Georgian Bay, much of the external nutrient load entering these systems tends to stay within the embayment. This phenomenon results in sheltered embayments behaving more like inland lakes than like traditional coastal embayments. The significance of this is that when these systems experience nutrient loading from anthropogenic disturbance, they are more susceptible to developing symptoms of cultural eutrophication than the more exposed coastal areas of Georgian Bay or Lake Huron (Wells and Sealock, 2009).

STUDY APPROACH

To better understand the factors that have led to water-quality impairment in these sheltered embayments, we propose to examine the interactions among basin morphometry, anthropogenic disturbance and landscape features and their effects on external and internal phosphorus loading and overall water chemistry. We will use a comparative approach to evaluate the importance of these variables on the water quality of 10 sheltered embayments that vary according to degree of cottage and road development, that range from very shallow to very deep basins, and that experience different degrees of mixing with waters of Georgian Bay (see Figure 1; Table 1). We will also use information from an inland lake (Blackstone Lake), which will serve as a reference site since most of the information in the literature pertain to lakes which are closed systems rather than embayments, which are open systems.

The information we collected included seasonal variation in nutrients (phosphorus and nitrogen), physico-chemical characteristics, chlorophyll-a pigments and estimates of coloured dissolved organic matter, and dissolved oxygen. Indices of basin morphometry were also collected and used to create an index to quantify the degree of water exchange between the embayments and the waters of greater Georgian Bay. We also estimated the level of human development in each embayment so that we could test the applicability of the Lakeshore Capacity Model (LCM; Ministries of Ontario 2010) for predicting nutrient status in the 10 sheltered embayments. The LCM was originally designed for use in inland lakes and not for coastal regions. Provincial agencies in Ontario calibrated the LCM using lakes located on the Precambrian Shield (Dillon et al. 1994; Paterson et al, 2006), and has used it extensively to provide guidance to managers regarding development of lakeshore property (Paterson et al, 2006).

Information we collected in this study will be prepared as part of the M.Sc. thesis of Mr. Stuart Campbell (expected to defend in December 2016), with two main chapters. The overarching objective of his thesis is to evaluate and identify tools that environmental managers can use to ensure the sustainable development of the coastal zone surrounding sheltered embayments in eastern Georgian Bay. Many of the tools that are currently used (e.g. mass balance nutrient models, quantification of oxygen deficits, Lakeshore Capacity Model) have been designed for application on large, thermally stratified inland lakes (Charlton, 1980; Paterson, 2006). Since sheltered embayments generally have shallow basin morphometry and are hydrologically connected to Georgian Bay, these tools might not be appropriate for use in these systems. Through his thesis, we will identify the primary determinants of the trophic status of sheltered embayments. We hope that this information will equip environmental managers with the appropriate tools to guide future development of eastern Georgian Bay in a sustainable manner.

<u>What's in this report</u>

In this final report to Environment Canada, we will provide a summary of the raw data that have been collected, along with an evaluation of the suitability of the Lakeshore Capacity Model (LCM), and an Anthro-Geomorphic Model (AGM) that we developed to predict summer mean [TP] in embayments. Please note that we have minimized redundant sampling effort by coordinating our sampling programs over the past 3 years with scientists from Environment Canada. Therefore, we are sharing data for some of the sites so that we have data from multiple years. Although our report will show gaps for some of our sites, similar data from our collaborators are available to fill these gaps. We will also attach the final report produced by Michigan Technical University in Ann Arbor, who was sub-contracted to assess changes in temperature and development of submersed aquatic vegetation (including macroalgae in the nearshore zone).

METHODS

Water quality sampling and processing

We chose to sample at the deepest spot in each embayment (see **Table 1**), because we wanted to measure the rate and spatial extent of hypolimnetic oxygen depletion; water in shallow areas usually do not undergo thermal stratification. The bathymetric maps based on coarse digital data provided by National Oceanic Atmospheric Administration and analyzed in GIS by our lab are presented in Appendix 1. Where possible, we sampled each embayment/lake on a monthly basis from May to September in a single year between 2012 to 2015. Jointly with partners in Environment Canada, we have data for multiple years for at least North Bay, South Bay, and Tadenac Bay. Unfortunately, we are unable to meet with our partners at Environment Canada before we submitted this report, and therefore cannot indicate all of the embayments for which we will have data for multiple seasons.

The sampling regime for this project was designed to capture seasonal variation in concentrations of nutrients and algal pigments (chlorophyll) during three periods: spring overturn, summer stratification and fall overturn. Except for a few cases, we were unable to sample during the spring overturn due to safety concerns (e.g. temperatures warmed too rapidly in some years). For Longuissa Bay, we were unable to sample in May because this was a replacement site for another that proved too difficult to sample after May.

On each sampling occasion, we obtained physico-chemical information from surface to about 1 m above the sediment surface, except for lakes deeper than 25 m (e.g. Blackstone Lake). A YSI 6920 V2 sonde was calibrated prior to each sampling week and used to measure temperature (°C), conductivity ($\mu S\ cm^{-1}$), dissolved oxygen (mg/L), % saturation, pH and turbidity (NTU). We also used a Van Dorn sampler to collect water at the midpoint of the epilimnion (Epi.), metalimnion (Meta) and hypolimnion (Hypo) for determination of concentrations of total phosphorus (TP; µg/L), soluble reactive phosphorus (SRP; µg/L), total ammonia nitrogen (TAN; mg/L), total nitrate nitrogen (TNN; mg/L), total nitrogen (TN; mg/L) and chlorophyll-a (CHL; µg/L). The euphotic zone in each bay was also determined with a light meter by taking readings from surface to a depth where 1% of sub-surface irradiance was measured. An integrated sample was taken with a tubing that was dropped vertically through the euphotic zone (referred to as the "integrated sample" (INT)). A Turner Designs C3 Submersible Fluorometer was also used to measure changes in algal pigments (CHL *a*) and CDOM throughout the euphotic zone on each visit.

We used Onset HOBO U26 loggers to continuously monitor dissolved oxygen concentrations and temperatures at the long-term monitoring stations from the first sampling trip (May in most cases) until the last sampling trip at each of our sheltered embayments. The loggers were deployed about 2 m above the sediment surface. In some of the embayments, however, we did not adequately secure the loggers in place and lost the unit and data. For units that functioned properly throughout the deployment period, DO and Temp were recorded hourly and used to determine the extent of the anoxic period in the embayment.

Once collected, all water samples were stored on icepacks in a cooler until they could be processed or placed immediately in a freezer for storage until they can be processed back at McMaster University. TURB readings were measured in triplicate with a HACH™ 2199Q turbidimeter, and a BOD bottle was filled with HACH™ chemicals and analyzed for DO according to the Winkler method to confirm accuracy of YSI values. TAN was analysed on-site after collection with a portable HACH™ Colorimeter. Water for CHL was also filtered in the field, after which filters were frozen and stored for processing at McMaster University. Samples for SRP were first filtered, and then the samples for SRP, TP, TNN and TN were frozen and transported back to McMaster University.

Unless otherwise indicated, all analyses were performed in triplicate for each variable. TP concentrations were determined with the molybdenum blue method (Murphy & Riley, 1962) following potassium persulfate digestion in an autoclave for 50 minutes (120°C, 15 psi). Absorbance values were read with a Genesys 10 UV Spectrophotometer and final phosphorus concentrations were calculated with a standard curve. TN and TNN samples were also processed in the laboratory and read in a DR 2800 Spectrophotometer following the HACH™ TNT 826 and cadmium reduction methods, respectively. A HACH™ DR 850 colorimeter was used to read TAN and TNN readings according to HACH methods; all readings for TAN were performed in the field with freshly collected samples. Known aliquots of water was filtered through GC filters (0.45 μm) and subsequently used to calculate concentrations CHL. Filters for CHL determination were folded, then wrapped in aluminum foil and placed in a freezer until they were processed. CHL filters were extracted in 90% reagent grade acetone in a freezer over a 24 h period. Following extraction, samples were acidified with hydrochloric acid (0.1 N), and fluorescence was read with a Turners Design Trilogy Fluorometer.

Basin morphometry

Bathymetric data were obtained from the North American Oceanic and Atmospheric Administration's Great Lakes Environmental Research laboratory webpage and the Provincial Digital Elevation Model for the province of Ontario was obtained from the Ministry of Natural Resources and Forestry through scholar's geoportal. These data were then imported into ArcGIS 10 to create a medium-scale digital elevation model (DEM) for eastern Georgian Bay. Bathymetric information collected in-situ with a Lowrance Elite-7 HDI fish finder to produce site specific DEMs where data were not available. All data were imported into ArcGIS to create a site-specific DEM (approximately 10-m accuracy). These DEMs were then used to calculate morphometric parameters for each site as shown in **Table 2**. All of the bathymetric maps for each site can be found in **Appendix 1.**

Anthropogenic stressors

To quantify the extent of human development along the shoreline, we calculated the number of buildings and docks per shoreline length for each of the embayments. To do this, we imported high resolution IKONOS satellite imagery acquired in 2002, 2003 and 2008 depending on the site, into Arc GIS 10. All residential or recreational structures (e.g. cottages, trailers, marinas, docks) within a 300-m buffer of the shoreline were enumerated. The Lakeshore Capacity Assessment Handbook states that 100 percent loading of nutrients should be assumed within 300 m of the shoreline on the Canadian Shield where soils are thin or absent (Ministries of Ontario, 2010). In addition to this, 2015 Google Earth™ imagery was used to update the database. The total number of buildings or docks was then divided by the embayment perimeter to calculate Building density and Cottage density per shoreline length. Another anthropogenic stressor we included in this study was Road density. To calculate this, we created 2-km buffers around the embayment perimeter and then used the Provincial Road Network layer to calculate road length per unit area ($m \bullet ha^{-1}$).

Degree of Mixing with Georgian Bay

We determined the degree of mixing using two methods. First, we determined it based on the difference in specific conductance of Georgian Bay water compared with specific conductance of water in the embayment. A YSI 6920 v2 Sonde and a 650 MDS Multi-Parameter Display System were used to monitor COND (µS/cm) from the mid epilimnion at regular intervals starting from the back of each embayment, through their respective connecting channels and out into Georgian Bay. Data collection ceased as COND measurements into Georgian Bay became consistent, indicating that there was no more mixing between the waters of the embayment and the waters of Georgian Bay. The difference between the Georgian Bay conductivity measurement and the conductivity measurement from the back of the embayment (Δ (delta) conductivity) were then used as a proxy to describe the degree of mixing with Georgian Bay.

Secondly, we used an **Index of Resistance to Mixing** (IRM) based on morphometric parameters that are believed to contribute to the lack of water exchange with Georgian Bay proper.

Equation 1: Index of Resistance to Mixing = $$\sqrt[2]{\left[\frac{P}{L}\right] * \text{Least Cost Pathway}}$$

Where P is the lake perimeter (m) and L is the maximum length (m). Least Cost Pathway represents the line of least resistance connecting the point at which maximum length intersects maximum breadth in the embayment, and the narrowest point in the channel that connects with Georgian Bay. We calculated this using the Least Cost Pathway tool in ArcGIS 10. A low value means that the water bodies should mix well and a high value means that the water bodies are prevented from mixing together.

Index of trophic status

To characterize the trophic status of each site, we consulted Carlson's (1977) Trophic State Index (TSI) that uses seasonal mean values of [TP], [CHL-a] and Secchi depths to generate TSI scores (TSI(TP); TSI(CHL-a) and TSI(Secchi), respectively). Although each of these parameters can be used independently to indicate trophic status for a water body, Carlson recommended that TSI(CHL-a) be used because it is a direct measure of primary productivity. Regardless of the parameter used, however, water bodies with TSI values falling below 40 were classified as oligotrophic, and those over 50 were classified as eutrophic; all intermediate values were classified as mesotrophic. Since eutrophic systems frequently exhibit symptoms of water-quality impairment such as algal blooms and anoxia (Wetzel 1983), agencies should ensure that the TSI scores for water bodies in their jurisdiction do not exceed 50.

Another approach to measure lake productivity is to quantify the rate of hypolimnetic oxygen depletion. One of the most common methods to measure such depletion is expressing it as the Areal Hypolimnetic Oxygen Depletion rate (AHOD) (Lasenby, 1975; Walker, 1979; Cornett and Rigler, 1979; Cornett and Rigler, 1980). AHOD is the amount of oxygen respired in the hypolimnion during a known period of time, expressed on an areal basis in $mg/m^2/day^{-1}$. Although this method is useful when comparing AHOD rates in the same lake over time (Matthews and Effler, 2006), it has major limitations when lakes of different depths are compared (Lasenby, 1975). For instance, lakes with a thick hypolimnion may be classified as eutrophic based solely on their morphometry (Cornett and Rigler, 1980; Charlton, 1980).

Lakeshore Capacity Model

The Lakeshore Capacity Model (LCM) is a mass-balance model created by the province of Ontario (Ministries of Ontario, 2010) to estimate total external P load that could be used to predict summer mean [TP] in lakes. This information can subsequently be used to calculate TSI to determine the trophic status of the lakes in question. The LCM is designed to separate natural inputs of phosphorus from anthropogenic inputs in order to model background, current and proposed capacity scenarios. The Lakeshore Capacity Assessment Handbook (Ministries of Ontario, 2010), which is the guiding document for this model, warns that this model might not be suitable for water bodies that are shallow (mean depth <5 m), have anoxic hypolimnion (and therefore experience internal P loading) or have tea-stained waters (i.e. with high dissolved organic carbon). To overcome the problem associated with hypolimnetic anoxia, Gartner Lee (2008) calculated the internal P load from sediments and added it to the external load in order to obtain a [TP] that approximated the measured [TP] concentration in Sturgeon Bay. This is one option that we can adopt in this study. Due to the large size and complexity of catchments for two of our 10 embayments (Musquash and Woods Bay), we were only able to use the LCM for 8 embayments. Fortunately, these embayments included Sturgeon Lake, the embayment with highest building density, and Tadenac Bay, the embayment with lowest building density. Therefore, the LCM was tested on the entire range of conditions that we are likely to encounter in eastern Georgian Bay.

Anthro-geomorphic Model

Because of limitations of the LCM (time-consuming computations, scarcity or absence of certain types of data, requirement of digital land cover data, possibility of requiring internal P load data), we developed our own model, called the Anthro-geomorphic model (AGM), which only requires two variables, Building density and the IRM score, both of which are relatively easy to calculate with satellite imagery provided by Google Earth™. The AGM can be used to predict the mean summer TP concentration in embayments without the need to determine either external or internal P loads to the embayments.

RESULTS AND DISCUSSION

Physico-chemical Properties

All of our sites became thermally stratified throughout the summer period, except for Woods Bay, which was probably too shallow to become thermally stratified (see **Figures 2a to 2l**). Despite our efforts to sample the spring overturn event, we were only able to capture this during 2012 in South Bay and North Bay, when spring arrived early and we were able to deploy our boat safely during late April. At all other sites, we initiated sampling after the surface layer of water had begun to stratify. Without exception, thermal stratification was well established by the time we visited our embayments during July. The depth of the thermocline throughout the stratification season varied among embayments, with some having a relatively shallow thermocline (e.g. Cognashene Lake, North Bay Inner) and others having a deep thermocline (e.g. Longuissa Bay, Musquash Bay). In spite of this, each embayment experienced a deepening of the thermocline as the season progressed, a common feature of dimictic water bodies in N. America. Our last sampling trip to each site was made in September, except for Blackstone Lake, which we visited in early November. This was the only lake that we sampled after fall overturn had occurred. Therefore, we deduce that overturn likely occurs in late October for all of our embayments.

Epilimnetic waters of most stratified lakes remain well oxygenated throughout the season; in the hypolimnion, however, decomposition of organic matter can dramatically decrease the dissolved oxygen (DO) levels between spring and fall overturn, especially if the water body is productive. Therefore, a straight-line vertical DO profile signifies that the lake is oligotrophic, whereas a curved line signifies that it is mesotrophic or eutrophic. In this comparative study, we used two water bodies to serve as references. Blackstone Lake, a deep (58.5 m maximum depth) oligotrophic inland lake, supports both cold-water and cool-water fisheries and has a relatively low number of cottages (Chow-Fraser 2006; Schiefer 2008). It is located very close to the eastern shore of Georgian Bay and belongs to the larger watershed of the Moon River that eventually flows into Georgian Bay. Tadenac Bay is also considered to be in reference condition, because it receives minimal human impact currently and has been for over a century. It is known to support a productive fishery of northern pike, largemouth bass and smallmouth bass. Even though it is relatively shallow (mean depth < 8m), it has one deep basin that has a maximum depth below 25 m.

When we compare the DO depth profiles of Tadenac Bay (**Figure 2j**) and Blackstone Lake (**Figure 2a**), we can readily see that both of these reference systems had orthograde profiles and more importantly water below the thermocline did not drop below 4 mg/L (threshold for fish; hypoxia) until we reached a depth of 20m. By comparison, in all of the other embayments, hypoxic conditions developed at very shallow depths just below the thermocline (see other panels in **Figure 2**). We also assembled seasonal DO data to explore the rate of DO depletion in the hypolimnion of each embayment (**Figure 3**). Immediately following spring overturn, DO levels were uniformly above 6 mg/L at all sites, and in some cases, they were at supersaturated levels. Without exception, DO concentrations declined as the season progressed, but the depletion rates and extent of depletion varied among sites. For example, DO levels in Blackstone Lake were high throughout the entire growing season, and those in Musquash and Woods Bay did not decline below 6 mg/L. At the other extreme, DO in Deep Bay, Cognashene Lake, Sturgeon Bay, North Bay and South Bay raced to reach anoxic levels, with both Deep Bay and Sturgeon Bay measuring below 1 mg/L by the beginning of July. This group of five embayments had anoxic conditions in the hypoliminon throughout the months of July, August and September. The remaining three embayments (Tadenac Bay, Twelve Mile Bay and Longuissa Bay) had intermediate conditions, reaching 2-3 mg/L only after August.

Trophic State Index

This section will focus on using seasonal mean total phosphorus and chlorophyll-a concentrations collected from all three strata of the lake/embayment (i.e. epilimnion, metaliminon and hypolimnion) to calculate Carlson's (1997) TSI score for each embayment (**Table 3**). Based on the TSI(TP)) scores for Twelve Mile Bay, Deep Bay, North Bay, South Bay and Sturgeon Bay, we classified these as mesotrophic while all the others were classified as oligotrophic. Using the TSI (CHL-a), we obtained a slightly different set of scores, with only Blackstone Lake being oligotrophic, and both South Bay and Sturgeon Bay as eutrophic while all other embayments were classified as mesotrophic. The oligotrophic character of Blackstone Lake was upheld by both TSI scores, while Tadenac Bay was classified as both mesotrophic and oligotrophic; hence, it could be described as being meso-oligotrophic. The meso-eutrophic character of South Bay and Sturgeon Bay is consistent with the DO vertical profiles reported in **Figures 2h** and **Figure 2i**, respectively. Though not reported in this report, we measured soluble reactive phosphorus (SRP) concentrations at all strata in each embayment, and can confirm that during the stratified period, coincident with development of anoxic conditions, SRP levels were relatively high in Twelve Mile Bay, Deep Bay, North Bay and Sturgeon Bay. These symptoms further reinforce the classification of this group of bays as being mesotrophic or eutrophic.

When we calculated AHOD for all of the embayments, we found that regardless of the extent of anoxic development, sites with deep basins had larger oxygen deficits than sites with shallow basins. Furthermore, when AHOD values were regressed against maximum depth, we found a positive non-linear relationship (spline fit with r^2=0.80; **Figure 4**) with our reference sites being classified as eutrophic (>250 mg/m^2/day^{-1}; Wetzel 1983). The same relationship has been reported by Muller et al. (2012). Therefore, AHOD (or derivative such as VHOD) should not be used to compare the trophic status across lakes that have diverse morphometric characteristics.

Development along the lakeshore

To quantify the increased anthropogenic impact on water quality of the embaymetns, we calculated Building density (# buildings per shoreline length) (**Table 4**). Embayments with the highest level of anthropogenic disturbance were Twelve Mile Bay, Deep Bay, North Bay, South Bay and Sturgeon Bay. This is not surprising as many of these sites are located near town centers and are all accessible by public road networks. The embayments with the lowest building densities were Tadenac Bay, Longuissa Bay and Musquash Bay. These sites had very low levels of cottage development and are only accessible by water. Woods Bay and Cognashene Lake can be described as having intermediate levels of anthropogenic disturbance.

Index of Resistance to Mixing (IRM)

The sheltered embayments in this study tend to be connected to Georgian Bay through narrow channels. As a result, these embayments are relatively isolated from the hydrological and limnological processes that occur in Georgian Bay proper. This isolation can result in poor water circulation with the oligotrophic waters of Georgian Bay and may contribute to the problems with water-quality impairment such as oxygen depletion and build-up of nutrients. The geology of Georgian Bay is dominated by two features, the Precambrian Shield in the east, which consists primarily of granite and the Niagara Escarpment on the west, which consists primarily of limestone. Limestone is a more erodible sedimentary rock and therefore contributes high levels of dissolved ions to the open waters of Georgian Bay, and as a result, high conductivity readings. Conversely, the granitic bedrock of the Precambrian Shield is less erodible and therefore contributes less dissolved ions into its watersheds, resulting in lower conductivity readings. We therefore proposed to use the difference between the embayment conductivity measurements and that of Georgian Bay to provide a simple measure of the degree of water exchange between the water bodies (see Methods).

Delta conductivity (μS/cm) values varied from low of 20 in Twelve Mile Bay, which is much more riverine than the other embayments, to a high value exceeding 80 μS/cm in North Bay and Sturgeon Bay. There were some inconsistencies for remainder of the embayments, however, that prevented us from using Δ Conductivity as an independent measure of water mixing between the embayment and Georgian Bay. A case in point is South Bay, which had a relatively low Δ Conductivity, even though it is located quite far from the open waters of South Bay. One reason for this is because South Bay is located at one of the outflows of the Severn River, and several sections of the Severn River drainage basin are situated over limestone bedrock. The high levels of dissolved ions in the river discharge may explain why South Bay has a relatively low Δ conductivity value compared with nearby North Bay. Since the water chemistry in each embayment is influenced by a number of variables including, land use, hydrology as well as geomorphology, we decided not to use Δ Conductivity to indicate degree of mixing. Instead, we developed the Index of Resistance to Mixing (IRM; Equation 1 in Methods) that only reflects the distance between the sampling location and the shortest pathway to open waters of Georgian Bay, and is not influenced by watershed geology.

Factors affecting nutrient status in embayments

We have assumed that the degree of anthropogenic disturbance along the shoreline (e.g. building density) has a negative impact on water quality in the embayment. We do not know, however, how to apportion the disturbance among the various sources, which include buildings, docks and roads. Therefore, we wanted to investigate how TP is influenced by each of the factors. We found that Building density (**Figure 5a**; r^2 = 0.73, P=0.0008), Road density (2 km buffer; **Figure 5b**; r^2 = 0.73, P=0.0008) and Dock density (**Figure 5c;** r^2 = 0.59, P = 0.0087) were all significant predictors of mean summer [TP], but Dock density explained the least amount of variation. An additional factor that is likely contributing to high nutrient concentrations is the degree to which water in a bay is exchanged with the oligotrophic waters of Georgian Bay. We would expect embayments with a low IRM score (low resistance to mixing) to have lower [TP] concentrations compared with those with high IRM scores (high resistance to mixing) because of the difference in dilution rates. Similar to the pattern in Δ conductivity values, the lowest and highest scores were still associated with Twelve Mile Bay and Sturgeon Bay, respectively (see **Table 4**). When we regressed the seasonal mean TP values against the IRM scores, we also obtained a significant positive relationship (**Figure 5d;** r^2 = 0.40, P = 0.0365), albeit this relationship was not as strong as that between TP and Building or Road density.

Multivariate predictive model: The Anthro-Geomorphic Model

We wanted to find the best multivariate model to predict TP since mean summer TP concentrations were significantly related to three anthropogenic and one geomorphic factors (**Figure 5a to d**), We decided to remove Dock density as a variable because of the high correlation between Building and Dock densities. We also removed Road density because it was highly correlated with Building density, and they both explained the same amount of variation. We kept Building density as a variable because nutrients are more directly affected by the buildings along the lake shore than by the number of roads. When we regressed [TP] against Building density and IRM, we obtained the following regression equation (after first confirming that there was no significant interaction between the two independent variables):

Equation 2: Mean Summer TP = 836.39*Building density + 0.030*IRM + 4.323

r^2=0.86; n=10; P=0.0004

This regression model was very strong, explaining 86% of the total variation in TP values. The bonus was that the variables were very easy to derive compared with those in the LCM. We will refer to this as the Anthro-Geomorphic Model (AGM), and will use it to predict mean summer [TP] to compare with the Lakeshore Capacity Model.

Estimate of internal loading

As discussed previously, loss of hypolimnetic oxygen can facilitate the release of primary nutrients from the sediments through internal loading (Nurnberg, 2003). Given that many of the embayments had anoxic hypolimnia, we had to find an efficient way to calculate internal P load for the Lakeshore Capacity Model. Since most of the methods used to quantify oxygen depletion have been developed for use in large deep lakes that develop strong thermal stratification, we had to first evaluate different methods for quantifying oxygen depletion to choose the best method for sheltered embayments. It is difficult to visualize rates of oxygen depletion using only DO depth profiles such as those presented in **Figure 2**. Instead, we can use isopleths that integrate depth and temporal dimensions into the same graphical presentation to visualize the anoxic zone. In **Figure 6**, we have assembled all temperature isopleths for each embayment. These panels are arranged in ascending order of human disturbance, with Tadenac Bay at the top left corner and Sturgeon Bay at the bottom right. It is easy to see that Longuissa and Woods Bay are too shallow to stratify, whereas Tadenac, Cognashene, Deep Bay and North Bay are clearly well stratified. All else being equal, deep and well-stratified embayments are expected to be more vulnerable to oxygen depletion than are shallow, weakly stratified or non-stratified systems.

The DO isopleth (**Figure 7**) and %DO saturation isopleth (accounting for the solubility of oxygen at different temperatures; **Figure 8**) show the undesirable development of anoxia in all of the embayments except Tadenac Bay, Musquash Bay and Woods Bay. The true oligotrophic nature of Tadenac is confirmed by the DO and %DO saturation isopleths. It was surprising to see depleted DO near the bottom of Longuissa Bay, beginning in mid July, which was accompanied by high concentrations of total ammonia nitrogen and total nitrate nitrogen (not shown here). Given the low number of cottages in the area, and the low IRM score, more studies should be conducted to ascertain the source of these nutrients and why there is development of anoxia.

Nurnberg (1987) developed the Anoxic Factor (AF), which quantifies the extent and duration of anoxia in lakes and is expressed as a single number so that it could be compared among lakes. The AF is a ratio that represents the number of days in a season that the surface area of a lake is overlain with anoxic sediments. When AF calculations for the embayments were regressed against Building density, we found a significant positive relationship (**Figure 9;** $r^2=0.56$, $P = 0.012$), which suggests to us that AF can be used to quantify internal P loading from anoxic sediments in our embayments (e.g. Nurnberg, 2008).

<u>Mass balance models: The Lakeshore Capacity Model</u>

Although we applied the LCM to 8 of the embayments, we will only show intermediate results for Tadenac Bay and Sturgeon Bay since these span the range in rate and extent of hypolimnetic oxygen depletion within our dataset. We did not see evidence of anoxia in Tadenac Bay, nor did we measure enhanced levels of soluble reactive phosphorus in the hypolimnion, which is symptomatic of internal loading. We did, however, see evidence of internal P loading in Sturgeon Bay and know from other reports (e.g. Gartner Lee 2008) that internal P loading is a significant source of phosphorus in that bay. We should point out that to truly test the applicability of the LCM, we require information on the total number of seasonal, extended seasonal and permanent residences in these embayments. Unfortunately, such information cannot be provided from the townships and we do not have the means to obtain such information ourselves. Therefore, we followed the recommendations presented in the Lakeshore Capacity Assessment Handbook (Ministries of Ontario, 2010) and classified buildings with reliable year round road access "extended seasonal", whereas buildings with no reliable year round road access were classified as "seasonal".

We calculated a total external TP load into Sturgeon Bay that was approximately 2.32 times greater than that into Tadenac Bay (**Table 5)**, but that is not surprising considering that the surface area of Sturgeon was also 2.53 times larger than that of Tadenac (see **Table 2**). As expected, the anthropogenic input for Sturgeon was much greater than that for Tadenac (about 2 orders of magnitude higher). What was perhaps surprising was the large input of phosphorus from upstream lakes, which accounted for 29% of the total external load; the counterpart for Tadenac Bay was only 16%. Based solely on the external load, the LCM would have predicted 13.23 μg/L of TP. Since the measured TP value was 18.57 (for both basins in Sturgeon Bay), this would have produced an unacceptably high underestimate of 29% (The LCM Handbook indicated that a deviation of >20% was unacceptable; Ministries of Ontario 2010). By adding in the internal load of 344.50 kg, calculated based on the AF (Nurnberg 1987), we obtained a predicted TP concentration of 17.57, which is only a 6% underestimate, and within the margin of error for acceptance. In the case of Tadenac Bay, we assumed there would be no internal loading since no anoxic conditions developed during the growing season. The predicted mean value of 7.06 μg/L for the ice-free season was very close to the measured concentration of 8.25 μg/L, which was an underestimate of about 17%, but still within the margin of error for acceptance (Ministries of Ontario 2010).

Comparison of predicted [TP] from LCM and AGM

The relationship between [TP] predicted by the LCM (no internal load) and measured [TP] for the 8 embayments is plotted in **Figure 10a**. For comparison, we also plotted the [TP] predicted by the LCM + AF (both external and internal loads) and measured [TP] (**Figure 10b**; see Table 6). This comparison shows clearly how inclusion of internal load improves the [TP] predictions for our embayments, and supports our recommendation to include internal loading estimates when using the LCM. For remainder of the report, we will only discuss LCM + AF for embayments that exhibited anoxia during the sampling period. We determined the % deviations of predicted [TP] from measured concentrations (blue bars in **Figure 11**). The deviations associated with LCM were generally larger than those associated with the AGM model (red bars in **Figure 11*).*** Using 20% as the recommended threshold for acceptance, we found that half of the values predicted by LCM+AF exceeded the threshold, while only 3 of the AGM values exceeded the threshold. Therefore, the AGM performed better than the LCM, even when internal loading data were included. AGM had the additional benefit of being less labour-intensive to compute and requiring more easily derived data compared to the LCM.

Additional dependent variables

We have provided isopleths of our sites for additional water chemistry variables in this report. These include isopleths of pH (**Figure 12**), chlorophyll-a (**Figure 13**), CDOM

(**Figure 14**). We do not have a complete set of chlorophyll-a and CDOM isopleths for all of our sites, but we anticipate obtaining these from our collaborators at Environment Canada. We have also presented isopleths of all variables separately for each embayment in **Figure 15a to 15l** inclusive.

GENERAL CONCLUSION

In this study, we have demonstrated that the nutrient status in sheltered embayments is significantly influenced by anthropogenic stress such as cottage and dock density, and road density, as well as the basin morphometry that controls the vulnerability of the embayment to development of anoxia when the embayment becomes enriched with nutrients. We also found that there was a statistically significant relationship between nutrient status and the Index of Resistance to Mixing, which is a measure of the degree of water exchange between the embayment and Georgian Bay. Independently, building density explained 73% while IRM explained 40% of the variation in mean summer TP concentration. In a multiple regression analysis, we found that both independent variables together explained 86% of the total variation. The demand for cottages and other recreational facilities in eastern Georgian Bay will likely continue to grow. By understanding how morphometric, anthropogenic and landscape factors interact to influence nutrient loading and hypolimnetic oxygen depletion, we will be able to identify the correct tools to manage these unique coastal ecosystems. We hope that the information provided in this project will help guide future development of sheltered embayments in a sustainable manner.

ACKNOWLEDGEMENTS

This project was funded by Environment Canada through the Lake Simcoe Southeastern Georgian Bay Cleanup Fund, and student stipends through the Work Study program of McMaster University. We are also grateful to in-kind support from volunteers of Sierra Club Canada and the Georgian Bay Association. In particular, we thank Mary Muter, Jean DeMarco, Andy and Barb Metelka, as well as Paul and Judi Percheson for allowing us to use their cottages and boats throughout the summers of 2012 to 2015. We are grateful to Dr. Arthur Zastepa for use of field data to calibrate our Turners C3. Many undergraduate and graduate students participated in sampling from 2012 to 2015, and they are too numerous to name here. You were all fabulous!

LITERATURE CITED

Carlson, R. E. (1977). A Trophic State Index for Lakes. *Limnology and Oceanography*. 22: 361-369.

Charlton, M. N. (1980). Hypolimnion Oxygen Consumption in Lakes: Discussion of Productivity and Morphometry Effects. *Canadian Journal of Fisheries Aquatic Science*, 37: 1531-1539.

Chiandet, A., & Sherman, K. (2014). *Report on Water Quality from 2010 - 2012 in the Honey Harbour Area of Georgian Bay*. Severn Sound Environmental Association. Unpub. report. Accessed April 2016. http://www.severnsound.ca/Shared%20Documents/Reports/SSEA_HH_2010_to_2012_WQ_Report_20140404FINAL.pdf

Chow-Fraser (2005). Survey of the water quality and aquatic community of wetlands in Blackstone Lake. Unpub. report. Accessed April 2016. http://www.blackstonelakeassn.ca/info/2005_McMaster_Study_of_Blackstone_Lake.pdf

Cornett, J. R., & Rigler, F. H. (1979). Hypolimnetic Oxygen Deficits: Their Prediction and Interpretation. *Science*. 205, 580-581.

Cornett, R. J., & Rigler, F. H. (1980). The Areal Hypolimnetic Oxygen Deficit: An Empirical Test of the Model. *Limnology and Oceanography*. 25(4), 672-679.

Diep, N., Somers, K., & Vandermeer, L. (2009). *Eastern Georgian Bay Stewardship Workshop: Water Quality in Ontario: Georgian Bay Perspective*. Accessed April 2016. http://www.georgianbaystewardship.ca/pdf/n_diep-moe.pdf

Dillon, P., Scheider, W., & Jeffries, R. (1994). Lakeshore Capacity Study: Part 1 - Test of Effects of Shoreline Development on the Trophic Status of Lakes. *Lake and Reservoir Management*. 8: 121-129.

Dove, A. and Chapra, S. 2015. Long-term Trends of Nutrients and Trophic Response Variables for the Great Lakes. *Limnol. Oceanogr*. 60: 696-721.

Georgian Bay Township Community Profile. (2014). Township of Georgian Bay. Unpub. report. February 2014. Accessed April 2016. https://georgianbay.civicweb.net/document/116628/Georgian%20Bay%20Community%20Profile.pdf?handle=6CA69F5F375846408D951684E11C5CF5

Gartner Lee Ltd. 2008. Evaluation of Remedial Strategies for the Reduction of Algal Biomass in Sturgeon Bay: Phase 2 – Supporting Technical Studies. Prepared for the Township of Archipelago. June. Accessed April 2016. http://www.thearchipelago.on.ca/images/environment/Remediation%20Options%20(Gartner%20Lee)-Phase%202.pdf

Gunn, J.R., Steedman, J. and Ryder, R. eds (2004). *Boreal Shield Watersheds: Lake Trout Ecosystems in a Changing Environment*. New York: Lewis Publishers, Boca Raton, Florida.

Joy, D. (2013). *Contamination of Ground and Surface Water from Onsite Systems*. University of Guelph. Presentation. Accessed April 2016. http://www.aowma.com/files/Doug-Joy-ground-and-surface-water-contamination-from-onsite1.pdf

Lasenby, D. C. (1975). Development of Oxygen Deficits in 14 Southern Ontario Lakes. *Limnology and Oceanography*. 20: 993-999.

Mathews, D. A., & Effler, S. W. (2006). Long-term Changes in the Areal Hypolimnetic Oxygen Deficit (AHOD) of Onodaga Lake: Evidence of Sediment Feedback. *Limnology and Oceanography*. 51: 702-714.

McCarthy, F., & McAndrews, J. (2012). Early Holocence Drought in the Laurentian Great Lakes Basin Caused Hydrologic Closure of Georgian Bay. *Journal of Paleolimnology*. 47: 411-428.

Ministries of Ontario (Ministry of Environment, Ministry of Natural Resources and Ministry of Municipal Affairs and Housing). 2010. *Lakeshore Capacity Assessment Handbook.* Government of Ontario. Queen's Printer for Ontario, 47 pp + Appendices.

Muller, B., Bryant, L., Matzinger, A., & Wuest, A. (2012). Hypolimnetic Oxygen Depletion in Eutrophic Lakes. *Environmental Science and Technology*. 46: 9964-9971.

Nurgberg, G. K. (1994). Phosphorus Release from Anoxic Sediments: What we know and how we can deal with it. *Associacion Espanola de Limnologia*, 10(1).

Nurnberg, G. K. (1995). Quantifying Anoxia in Lakes. *Limnology and Oceanography*. 40: 1100-1111.

Nurnberg, G. K. (2004). Quantified Hypoxia and Anoxia in Lakes and Reservoirs. *The Scientific World Journal.* 4: 42-54.

Nurnberg, G. K. (2009). Assessing Internal Phosphorus Load - Problems to be Solved. *Lake and Reservoir Management.* 25: 419-432.

Nurnberg, G., & LaZerte, B. (2004). Modeling the Effect of Development in Internal Phosphorus in Nutrient-poor Lakes. *Water Resources Research.* 40 W01105 *doi:10.1029/2003WR002410*

Osgood, R. (1984). Who Needs Trophic State Indices? *Lake and Reservoir Management*. 1: 431-434.

Paterson, A. M., Dillon, P. J., Hutchinson, N. J., Futter, M. N., Clark, B. J., Mills, R. B., & Scheider, W. A. (n.d.). 2009. A Review of the Components, Coefficients and Technical Assumptions of Ontario's Lakeshore Capacity Model. *Lake and Reservoir Management*. 22: 7-18.

Robertson, W. D., Schniff, S. L., & Pacek, C. J. (1998). Review of Phosphate Mobility and Persistence in 10 Septic System Plums. *Groundwater*. 36*:* 1000-1010.

Schiefer, (2008). Water quality survey of Blackstone, Crane, Healey and Kapikog lakes. *Bluewater Sciences*. Unpublished report. Accessed April 2016. http://www.thearchipelago.on.ca/images/environment/water%20quality%20survey%20of%20blackstone%20crane%20healey%20and%20kapikog%20lakes%202008.pdf

Schiefer, K., Schiefer, K., & Wiancko, P. (2006). *Water Quality Monitoring Report 2006, Township of Georgian Bay*. Bluewater Biosciences Inc. Accessed April 2016. http://www.georgianbayassociation.com/Water%20Quality%20Monitoring%20Report-2006.pdf

Walker, W. W. (1979). Use of Hypolimnetic Oxygen Depletion Rate as a Trophic State Index for Lakes. *Water Resources Research*. 15: 1463-1470.

Well, M., & Sealock, L. (2009). Summer Water Circulation in Frenchmen's Bay, a Shallow Coastal Embayment Connected to Lake Ontario. *Journal of Great Lakes Research*. 35: 548-559.

Wetzel, R. G. (1983). *Limnology* (2nd ed.). Saunders College Publishing. Philadelphia 858 pp.

Table 1: List of study sites, including the reference lake which is indicated by the asterisk. Latitude and longitude correspond to the location in each embayment/lake where we collected water samples and monitored water chemistry. Blackstone Lake is a reference system for lakes. North Bay includes the inner basin only.

Site	Code	Latitude	Longitude
Blackstone Lake	BL	45.22278	-79.87613
Tadenac Bay	TD	45.05830	-79.97540
South Bay	SB	44.87635	-79.78651
North Bay	NB	44.89099	-79.79197
Cognashene Lake	CG	44.95328	-79.98950
Twelve Mile Bay	TW	45.08321	-79.94811
Deep Bay	DB	45.39490	-80.22375
Musquash Bay	MU	44.94828	-79.85066
Sturgeon Bay	ST	45.61325	-80.43147
Woods Bay	WB	45.13774	-79.98938
Longuissa Bay	LG	44.96137	-79.88864

Table 2. Summary of basin morphometry for study sites: A: area (m), V: volume (m^3), L: maximum length (m), B: breadth, Z_{mean}: mean depth (m), Z_{max}: maximum depth (m), Z_r: relative depth (m), D_L : shoreline development, D_V: volume development. * Blackstone Lake is a reference system for lakes. North Bay includes the inner basin only.

Site	A ($\bullet 10^6 m^2$)	V ($\bullet 10^6 m^3$)	L (m)	B (m)	Z_{mean} (m)	Z_{max} (m)	P ($\bullet 10^3 m$)	Z_r (m)	D_L	D_v
Blackstone Lake *	5.083	101.534	3983	1587	19.97	60.80	38.0	2.39	4.75	0.99
Tadenac Bay	1.969	15.972	3684	1239	8.11	29.10	16.5	1.84	3.33	0.84
South Bay	1.258	4.389	1403	891	3.49	15.96	14.8	1.26	3.73	0.66
North Bay	1.392	9.180	2137	907	6.59	22.74	14.9	1.71	3.56	0.87
Cognashene Lake	0.465	2.570	1416	576	5.53	16.88	10.2	2.19	4.21	0.98
Twelve Mile Bay	1.189	6.516	3823	461	5.48	13.89	16.5	1.13	4.26	1.18
Deep Bay	2.664	15.880	4390	760	5.96	19.51	24.5	1.06	4.23	0.92
Musquash Bay	2.508	40.293	3326	1398	16.06	42.86	16.7	2.40	3.92	1.12
Sturgeon Bay	4.988	22.109	2646	1346	4.43	14.51	33.1	0.58	4.18	0.92
Woods Bay	3.630	13.003	2781	1966	3.58	13.42	20.3	0.62	3.00	0.80
Longuissa Bay	0.355	1.276	1477	347	3.59	11.89	5.3	1.77	2.62	0.91

Table 3: Mean (±SE; µg/L) values for TP and CHL for each bay/lake (representing all strata and monthly values) and corresponding TSI values calculated with Carlson's (1977) formula. Interpretation of TSI scores: 0 to 40= oligotrophic; 40 to 50 = mesotrophic; >50 = eutrophic. *Blackstone Lake is a reference system for lakes. North Bay includes the inner basin only.

Site	TP (µg/L)	TP TSI	Trophic Status	Chl-a (µg/L)	Chl-a TSI	Trophic Status
Blackstone Lake*	6.56 (± 0.54)	31	Oligotrophic	1.90 (± 0.18)	37	Oligotrophic
Longuissa Bay	7.39 (± 0.70)	33	Oligotrophic	4.48 (± 0.34)	45	Mesotrophic
Musquash Bay	7.85 (± 0.94)	34	Oligotrophic	3.78 (± 0.38)	44	Mesotrophic
Tadenac Bay	8.24 (± 0.57)	35	Oligotrophic	5.15 (± 1.29)	47	Mesotrophic
Cognashene Lake	10.60 (± 0.89)	38	Oligotrophic	4.00 (± 0.68)	44	Mesotrophic
Woods Bay	11.11 (± 2.72)	39	Oligotrophic	4.04 (± 0.74)	44	Mesotrophic
Twelve Mile Bay	13.00 (± 1.11)	42	Mesotrophic	5.40 (± 0.78)	47	Mesotrophic
North Bay	14.45 (± 1.55)	43	Mesotrophic	7.01 (± 0.91)	50	Mesotrophic
Deep Bay	18.41 (± 2.32)	46	Mesotrophic	11.72 (± 3.32)	55	Mesotrophic
South Bay	18.85 (± 2.13)	47	Mesotrophic	6.66 (± 0.80)	49	Eutrophic
Sturgeon Bay	20.96 (± 4.45)	48	Mesotrophic	6.59 (± 0.97)	49	Eutrophic

Table 4: Number of buildings within a 300m buffer of the shoreline and buildings per shoreline meter. Building density = #buildings per shoreline length; Dock density= #docks per shoreline length; IRM refers to the Index of Resistance to Mixing (see Methods for calculation); Road density = length of roads per area (m/km^2) within 2-km buffer. Trophic status is based on both TSI(TP) and TSI(CHL) from Table 3. *Blackstone Lake is a reference for lakes. North Bay refer to the inner basin only.

Site Code	TP (µg/L)	# buildings	Building density	Dock density	IRM	Road density	Trophic status
TD	8.25	3	0.0002	0.0003	87.46	1.62	Oligo-mesotrophic
LG	7.39	6	0.0011	0.0011	54.04	0.00	Oligo-mesotrophic
BL	6.56	122	0.0032	--	62.87	--	Oligotrophic
MU	7.85	64	0.0038	0.0040	73.23	0.00	Oligo-mesotrophic
WB	11.11	90	0.0044	0.0091	124.96	3.78	Oligo-mesotrophic
CG	10.66	70	0.0069	0.0074	117.56	0.00	Mesotrophic
TW	13.00	126	0.0077	0.0160	57.27	7.54	Mesotrophic
DB	18.41	192	0.0078	0.0062	127.47	12.00	Mesotrophic
NB	14.45	149	0.0100	0.0116	62.87	7.55	Mesotrophic
SB	18.85	195	0.0130	0.0227	119.68	15.8	Eutrophic
ST	17.10	351	0.0106	0.0178	261.08	7.44	Eutrophic

Table 5: Data used in the Lakeshore Capacity Model (Ministries of Ontario; 2010) to predict TP concentration (µg/L) for Sturgeon Bay and Tadenac Bay (bays with the highest and lowest building densities, respectively; see Table 4). *This value assumes that there is no internal loading because of the absence of anoxic conditions in Tadenac Bay. **This ice-free TP concentration (TP_{if}) was calculated based on our seasonal mean value of 20.96 µg/L (see Table 4) for the North basin, and the ratio of 1.1287 for the north and south basins reported in Gartner Lee (i.e. 19.30 and 14.00 µg/L for the north and south basins, respectively; 2006).

	Sturgeon Bay		Tadenac Bay	
TP load components	**(kg)**	**% Total**	**(kg)**	**% Total**
Upstream inflow	233.44	20	57.06	16
Atmospheric input	94.75	8	55.31	15
All terrestrial input	243.93	21	247.93	68
Anthropogenic input	271.50	23	2.34	1
Total external load	**843.62**	**72**	**362.64**	**100**
Total internal load according to Nurnberg (1987)	**344.50**	**29**	**0***	**0***
Total TP load	**1,188.12**	**100**	**362.64**	**100.0**
Predicted TP_{if}	**17.57**		**7.06**	
Measured TP_{if}	**18.57****		**8.25**	
% Difference	**+5.7%**		**+17%**	

Table 6: Comparison of predicted vs measured mean summer [TP](µg/L) for embayments in this study. LCM(Lakeshore Capacity Model) indicates that only external P load is included; AF(Anoxic Factor) indicates that the internal P load is included; AGM (Anthro-Geomorphology Model) indicates that neither external nor internal load is included.

Site	LCM + AF	LCM	AGM	Measured
Deep Bay	22.65	13.27	14.67	18.41
Tadenac Bay	7.06	7.06	7.11	8.25
Longuissa Bay	10.58	10.58	6.86	7.39
Twelve Mile Bay	17.69	14.53	12.48	13.00
South Bay	22.76	19.27	18.79	18.85
Sturgeon Bay	17.57	13.27	21.02	17.10
North Bay	20.70	15.95	14.57	14.45
Woods Bay	--	--	11.75	11.11
Musquash Bay	--	--	9.70	7.85
Cognashene Lake	8.04	8.04	13.62	10.66

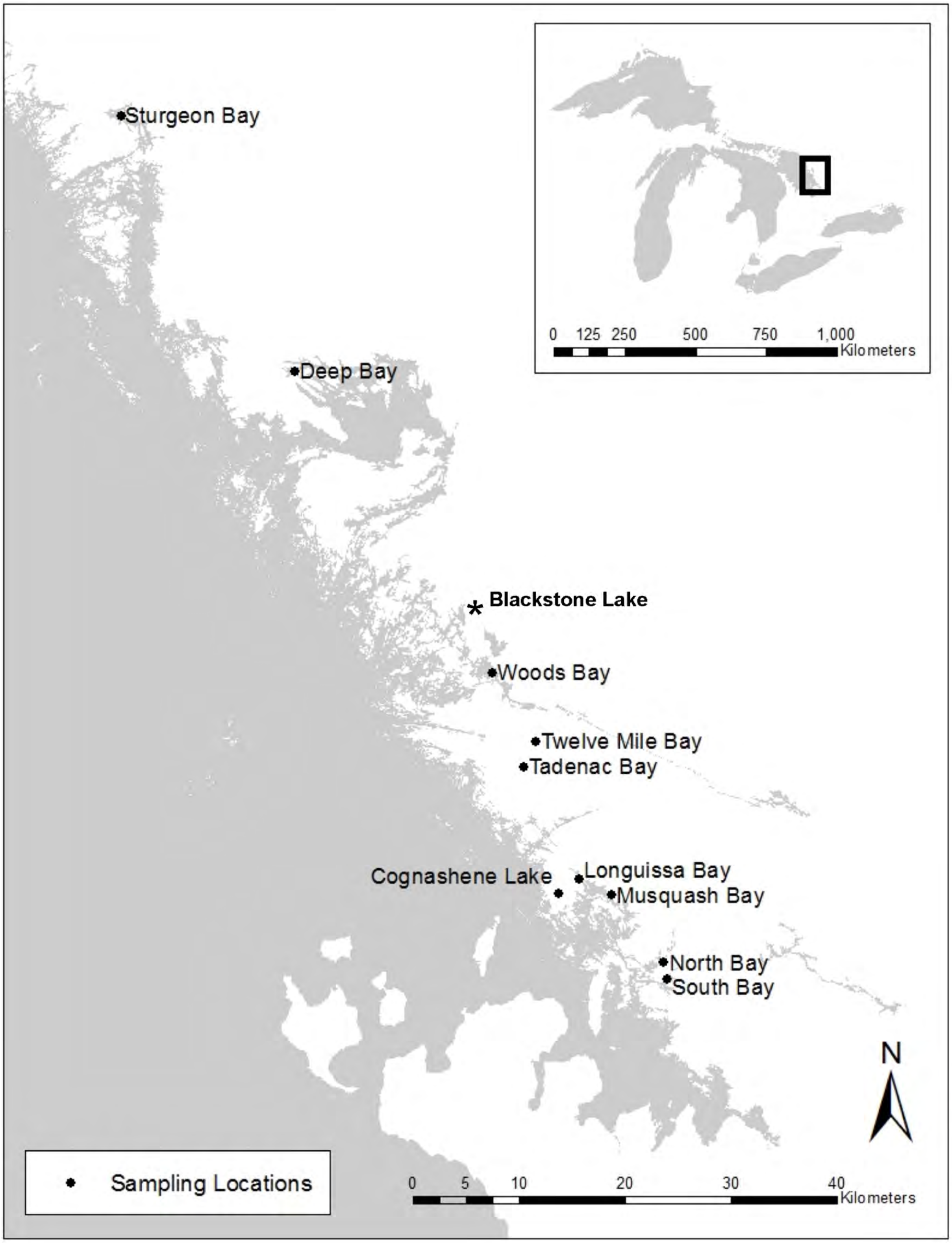


Figure 1: Location of ten sheltered embayments and the inland reference site indicated with a star.

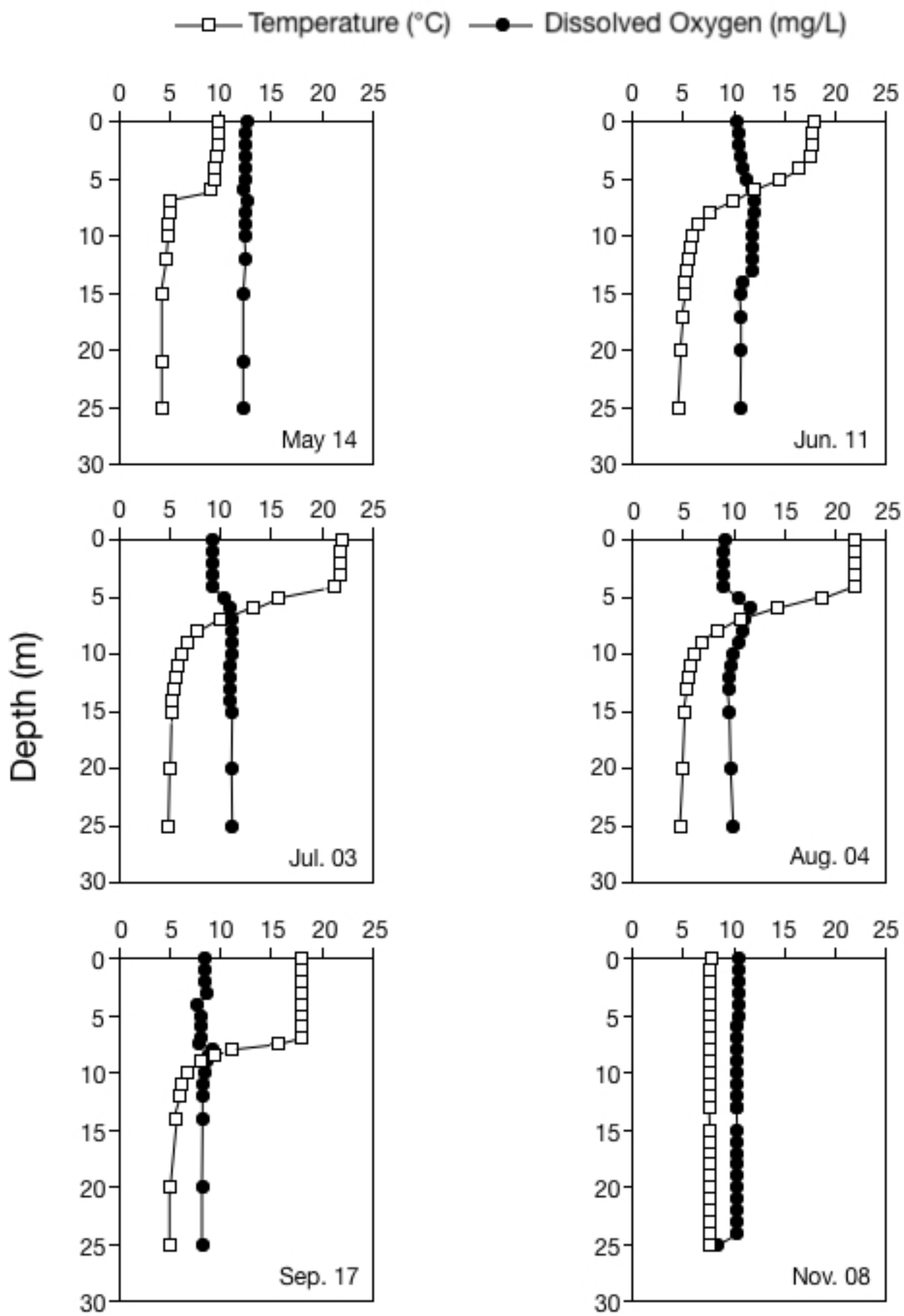


Figure 2a: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Blackstone Lake during 2013.

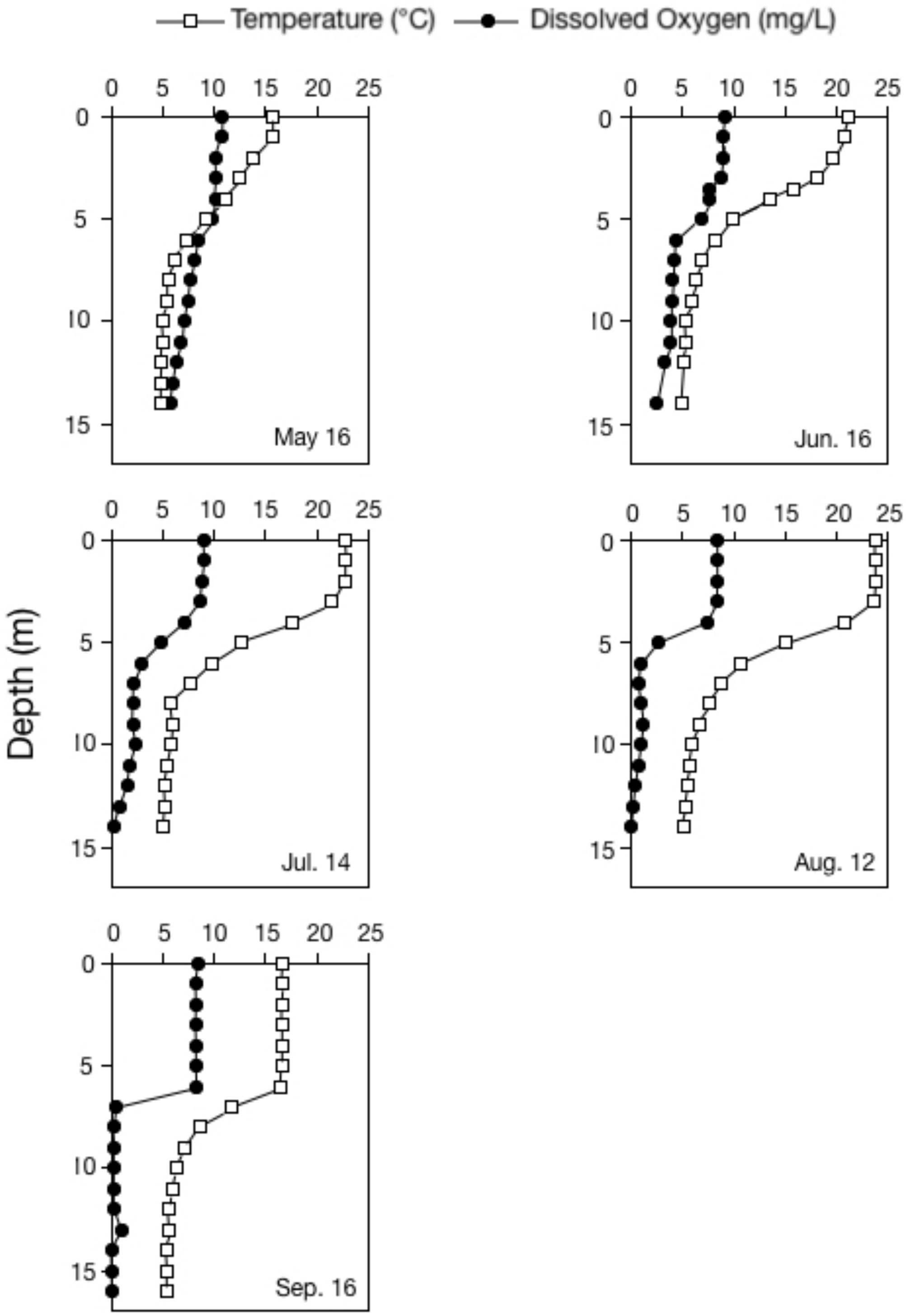


Figure 2b: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Cognashene Lake during 2014.

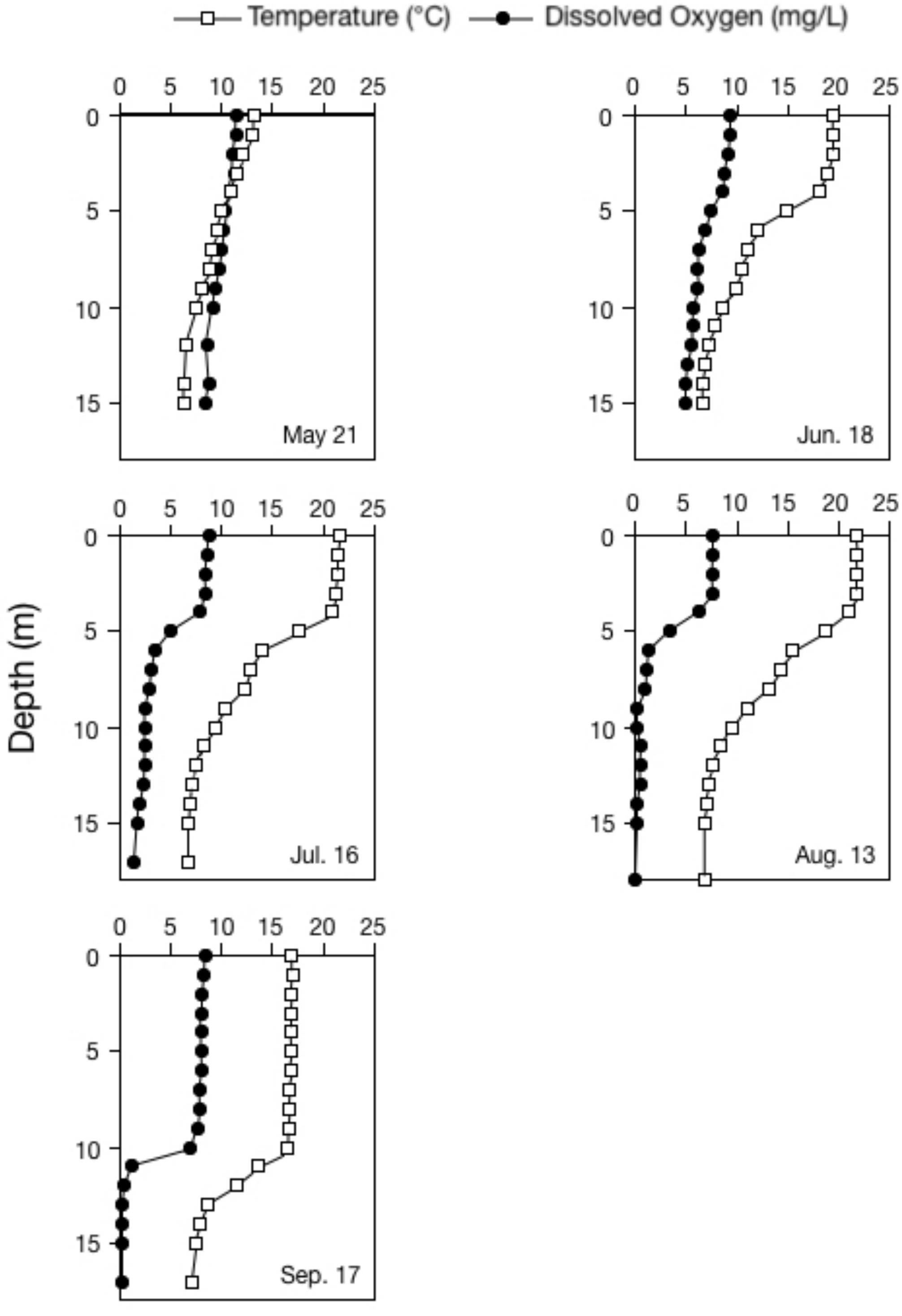


Figure 2c: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Deep Bay during 2014.

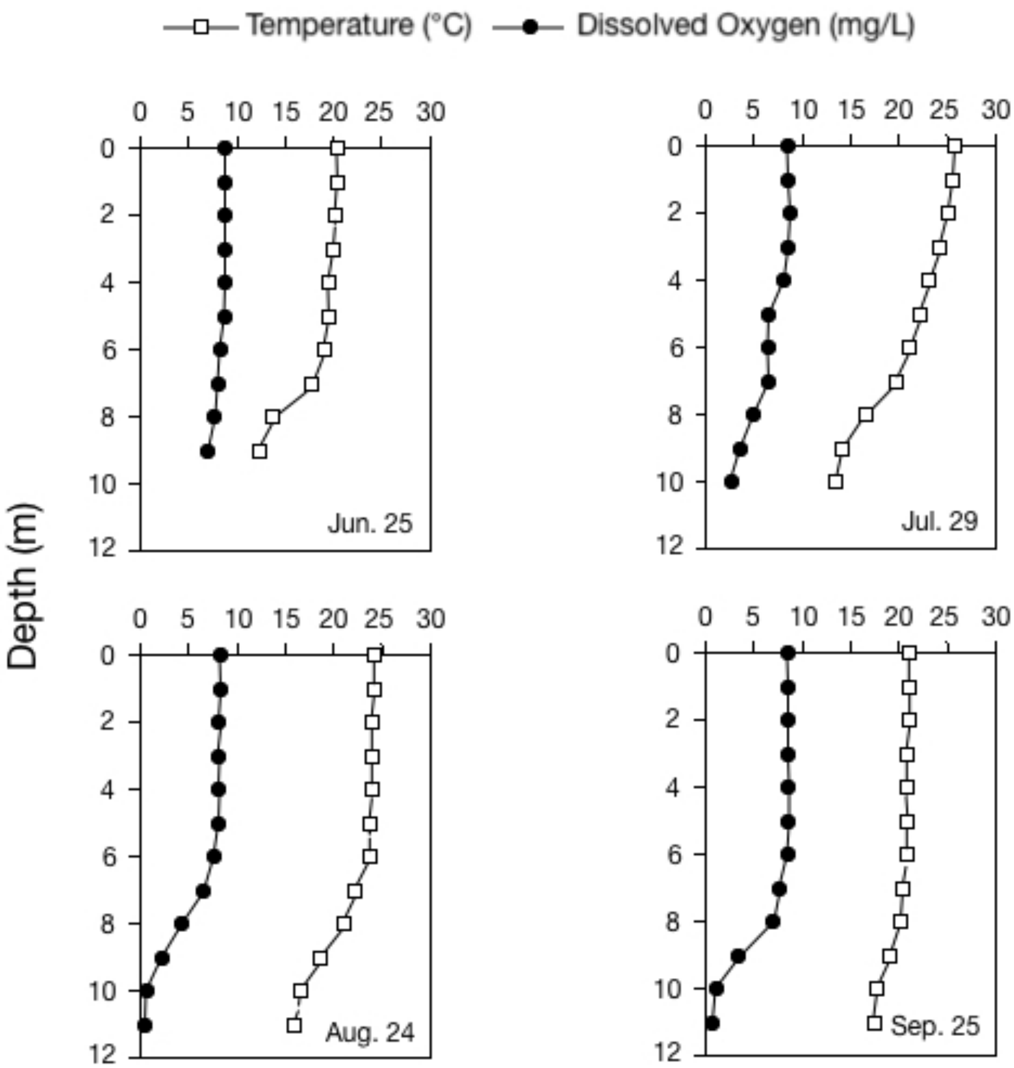


Figure 2d: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Longuissa Bay during 2015.

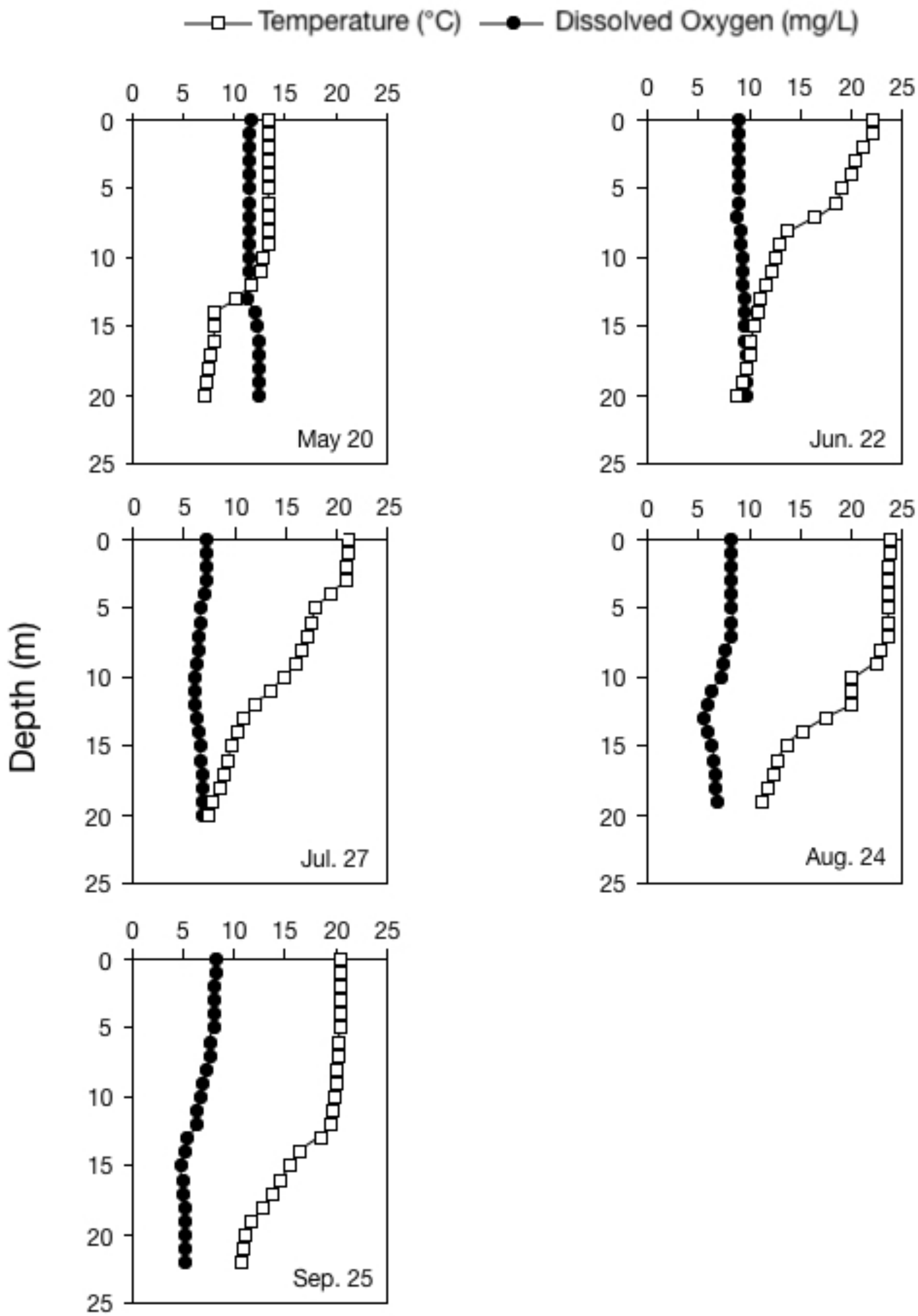


Figure 2e: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Musquash Bay during 2015.

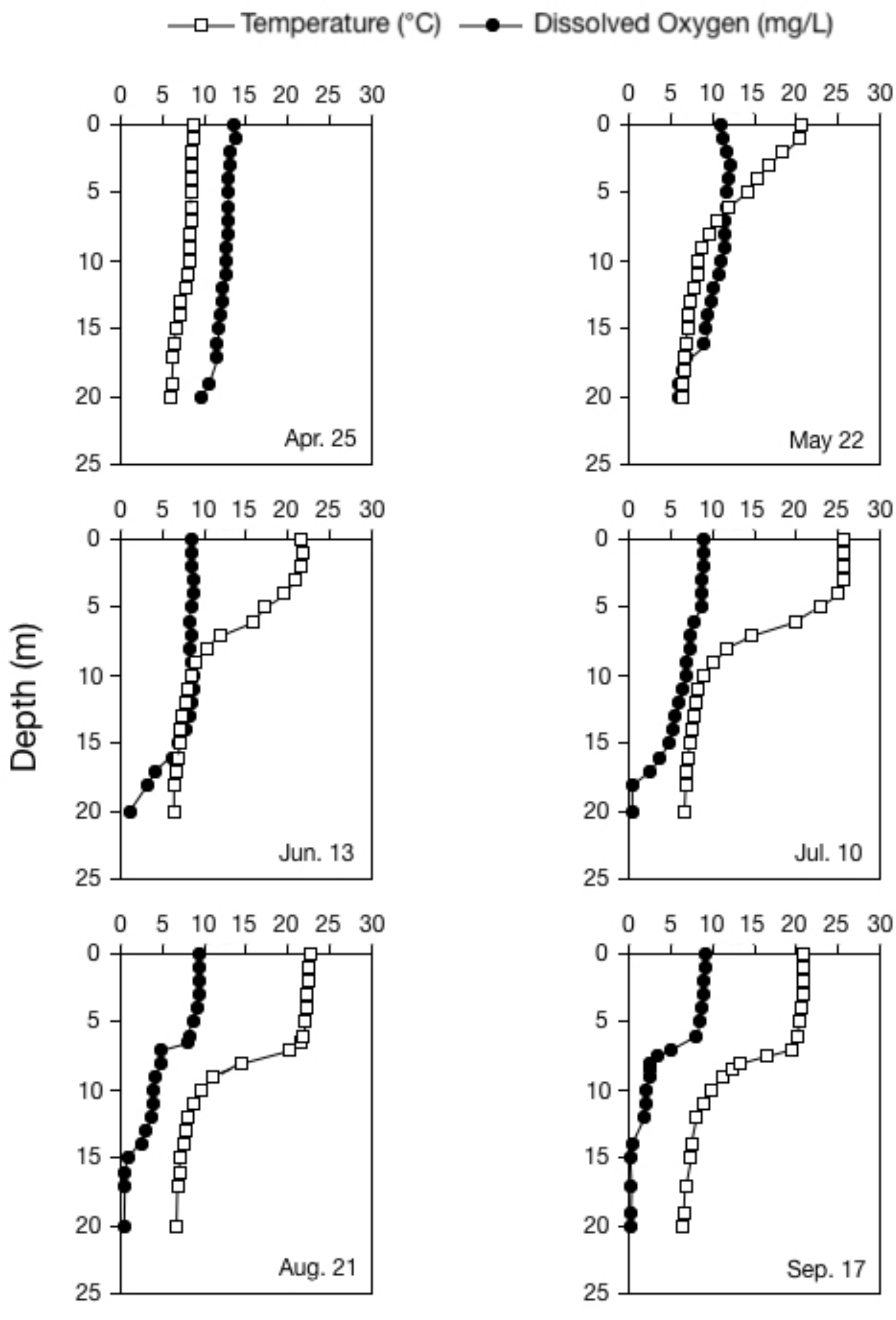


Figure 2f: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in North Bay Inner during 2012.

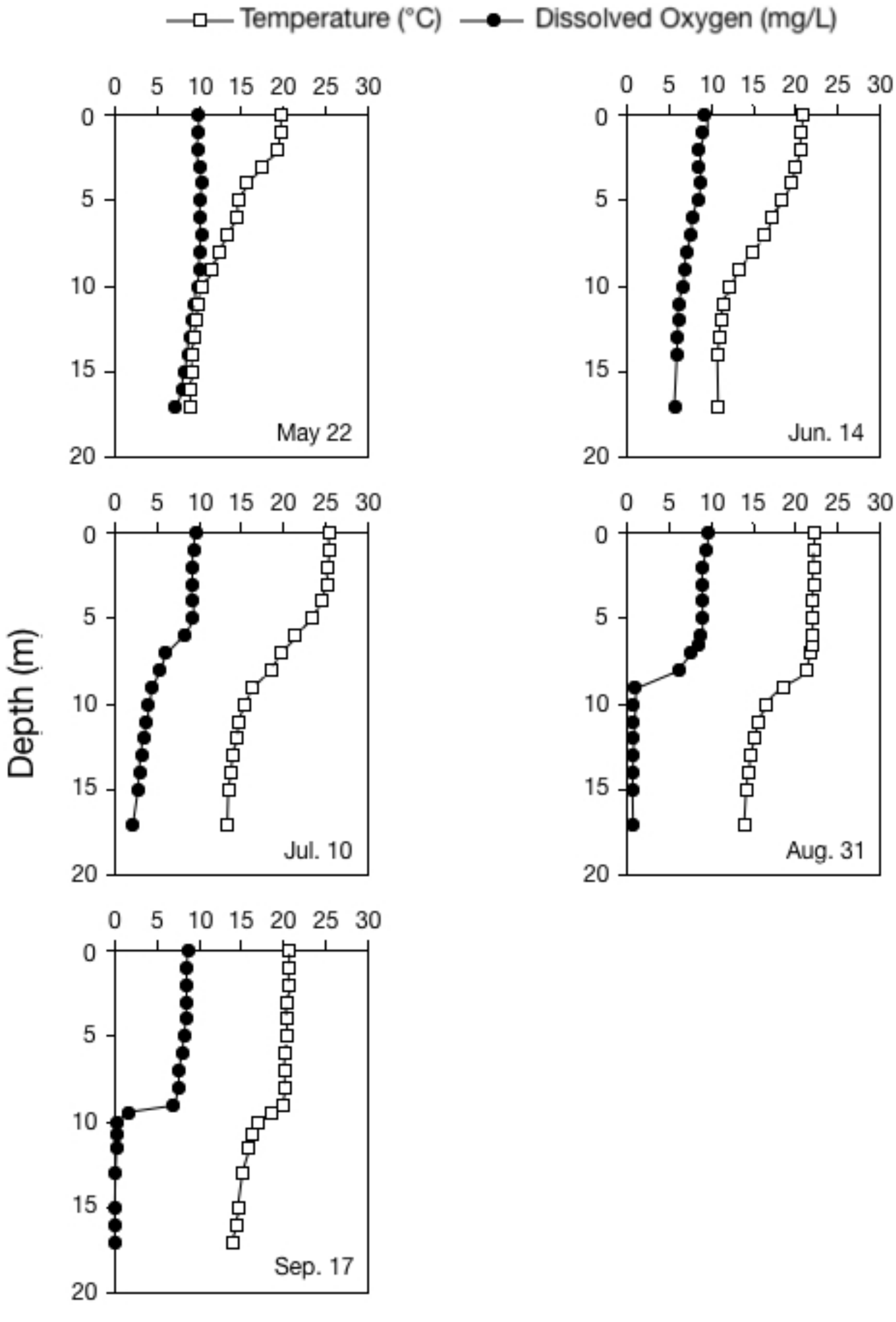


Figure 2g: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in North Bay Outer during 2012.

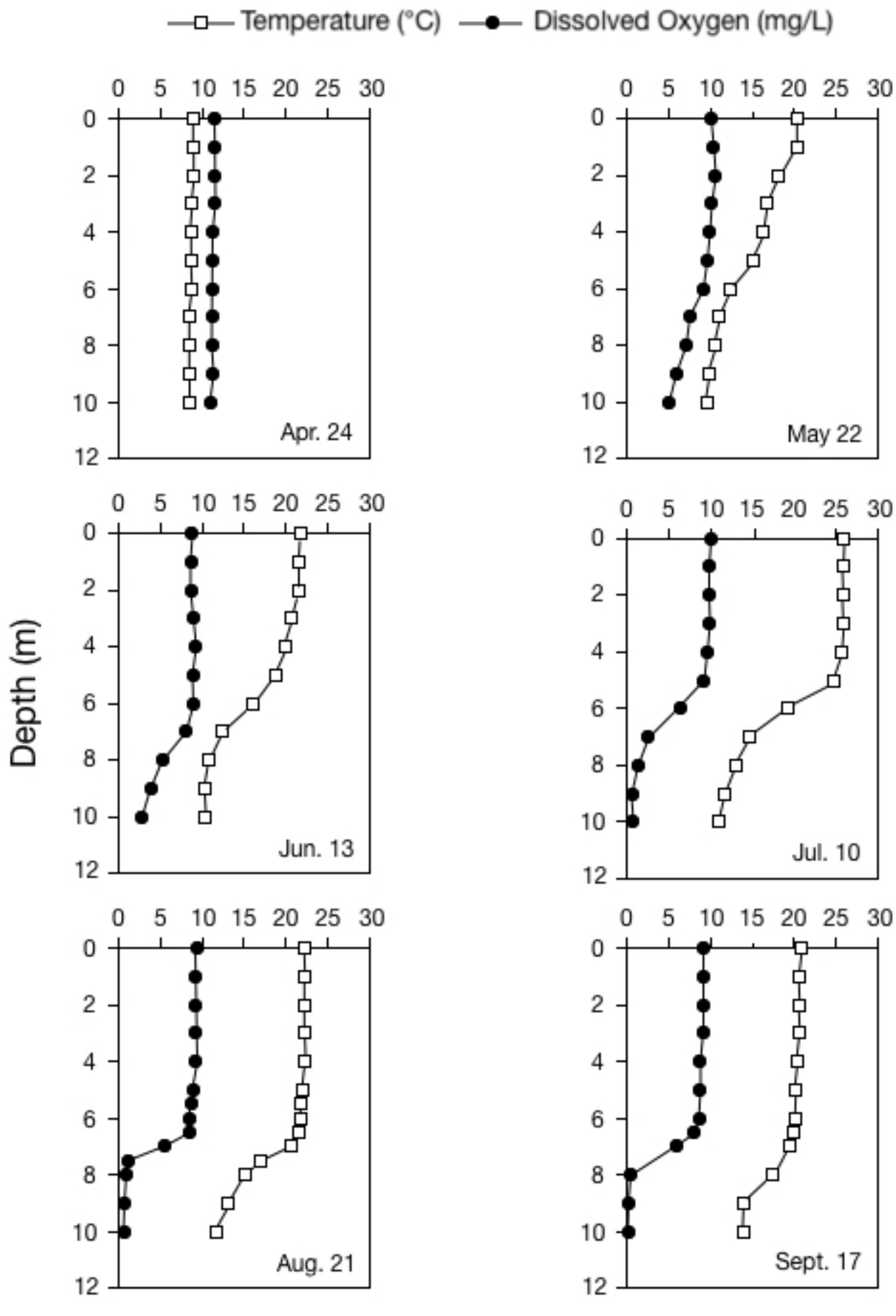


Figure 2h: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in South Bay during 2012.

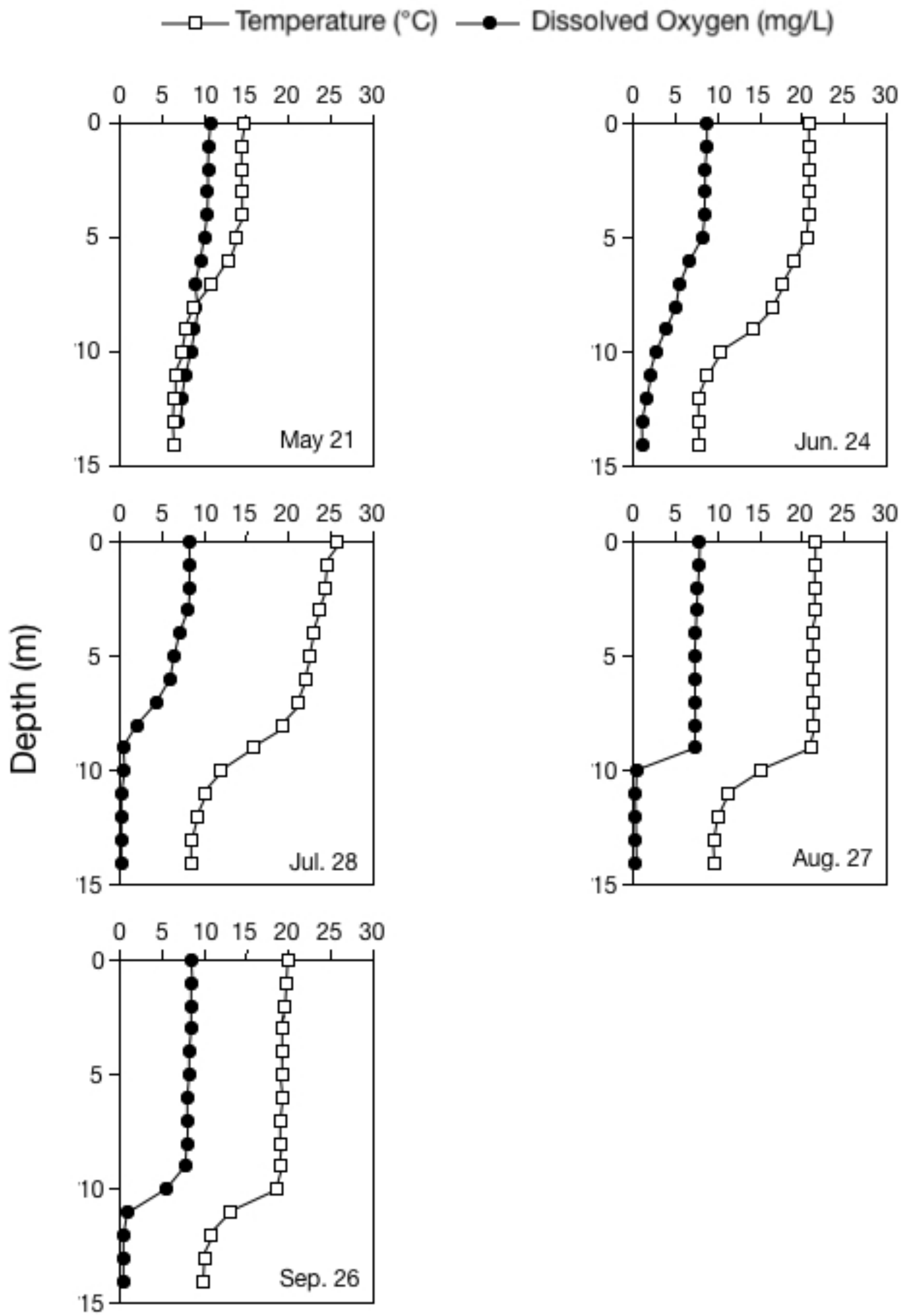


Figure 2i: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Sturgeon Bay during 2015.

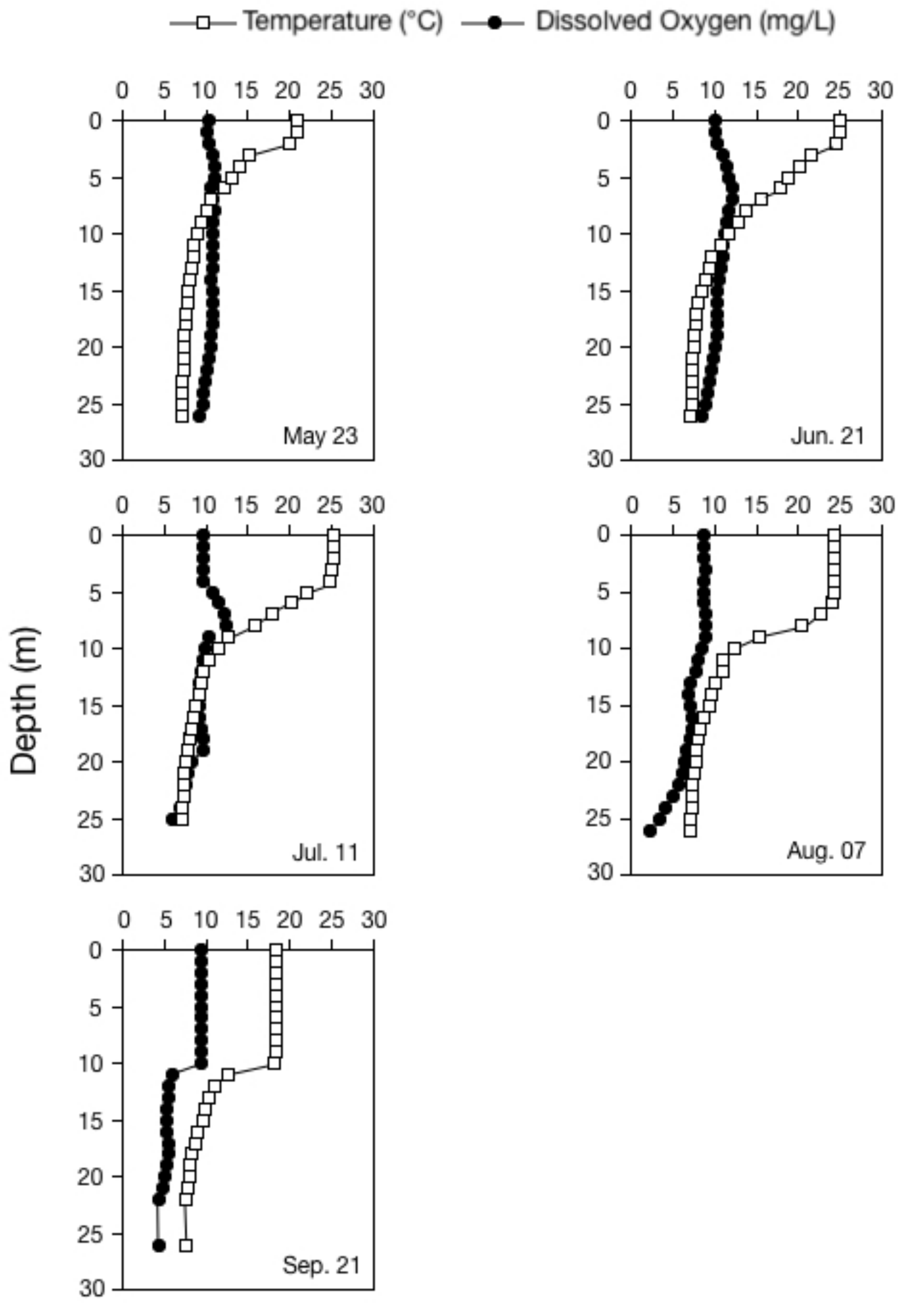


Figure 2j: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Tadenac Bay during 2012.

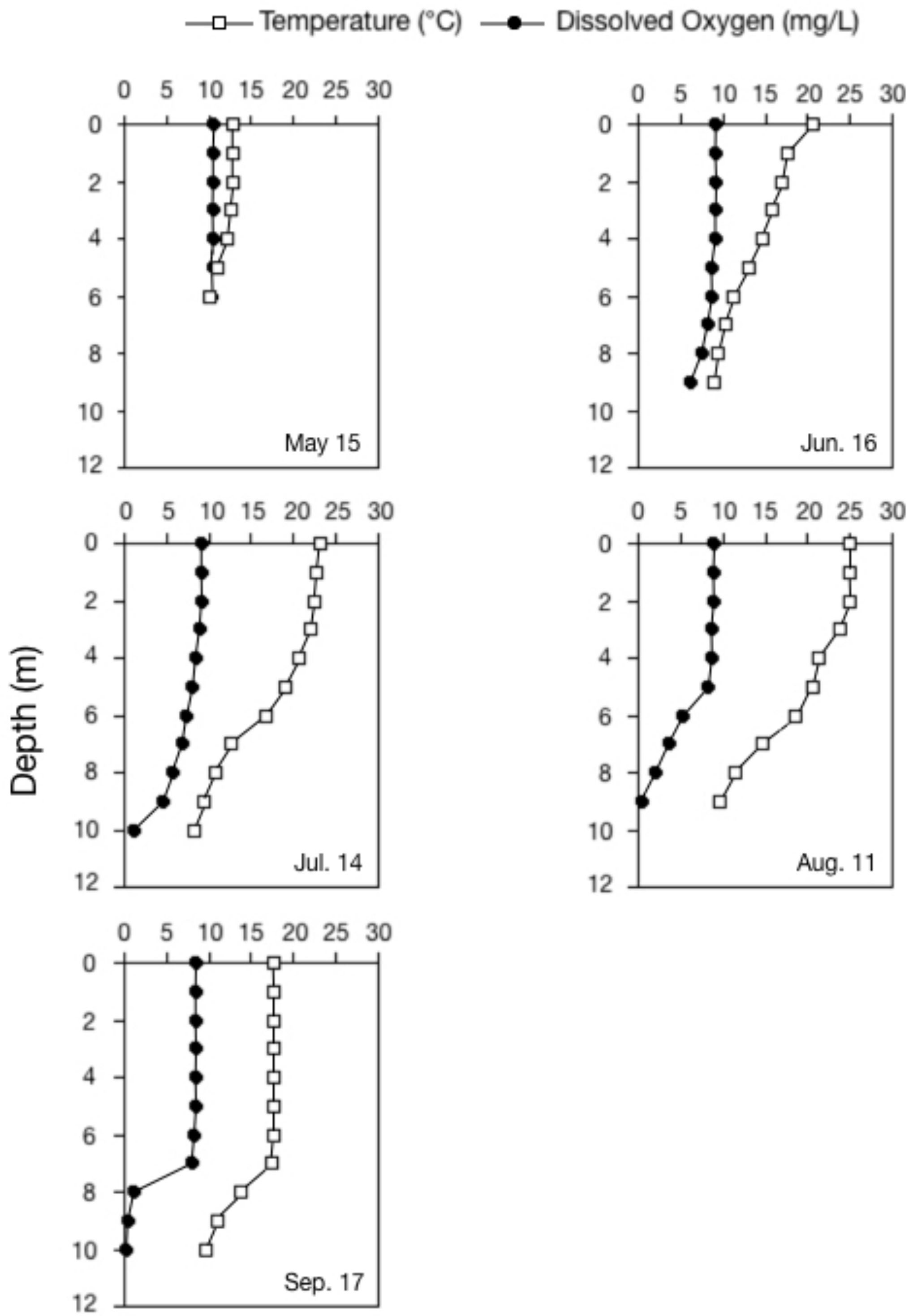


Figure 2k: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Twelve Mile Bay during 2014.

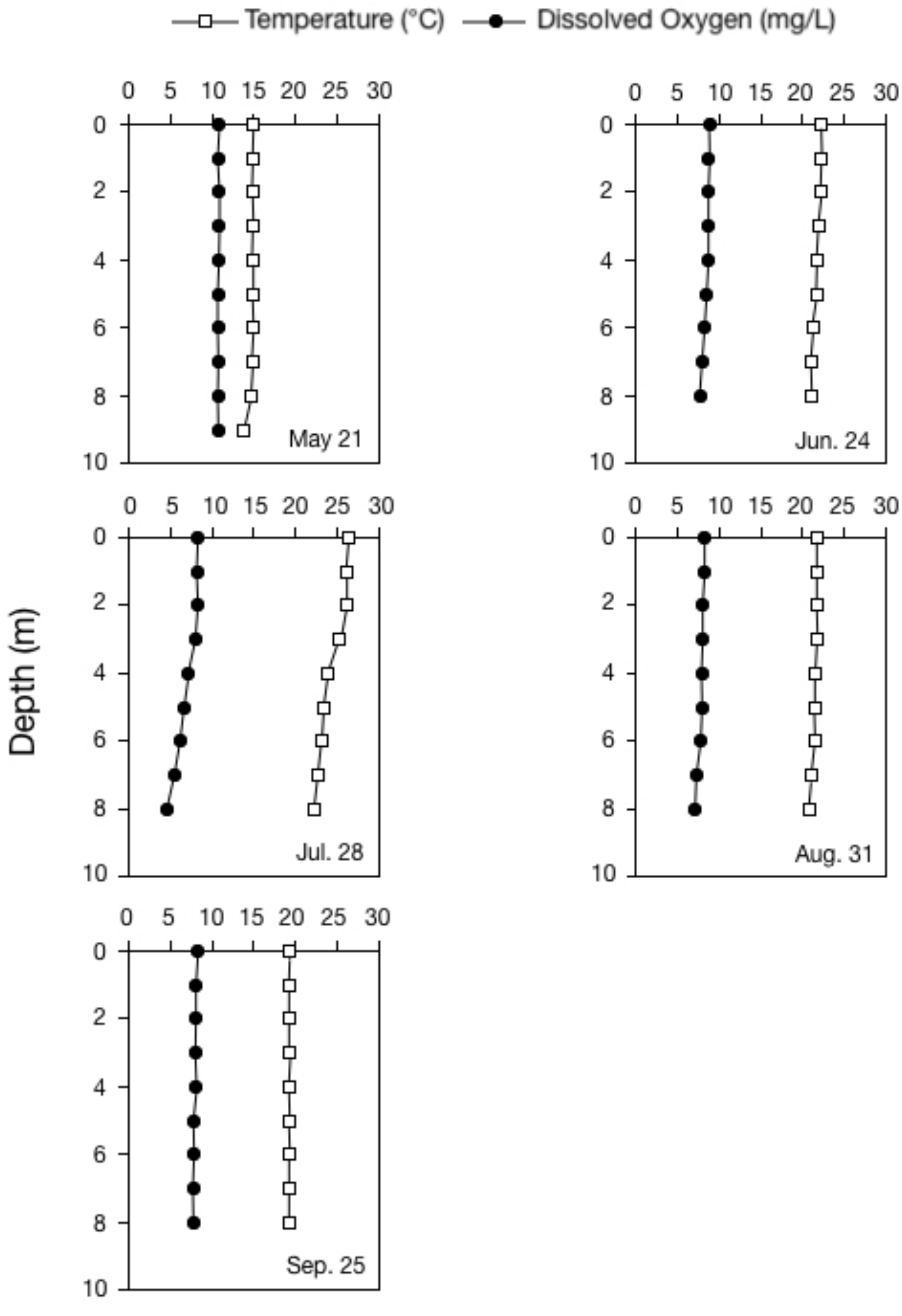


Figure 2l: Depth profiles of temperature (°C) and dissolved oxygen (mg/L) measured at the deep station in Woods Bay during 2015.

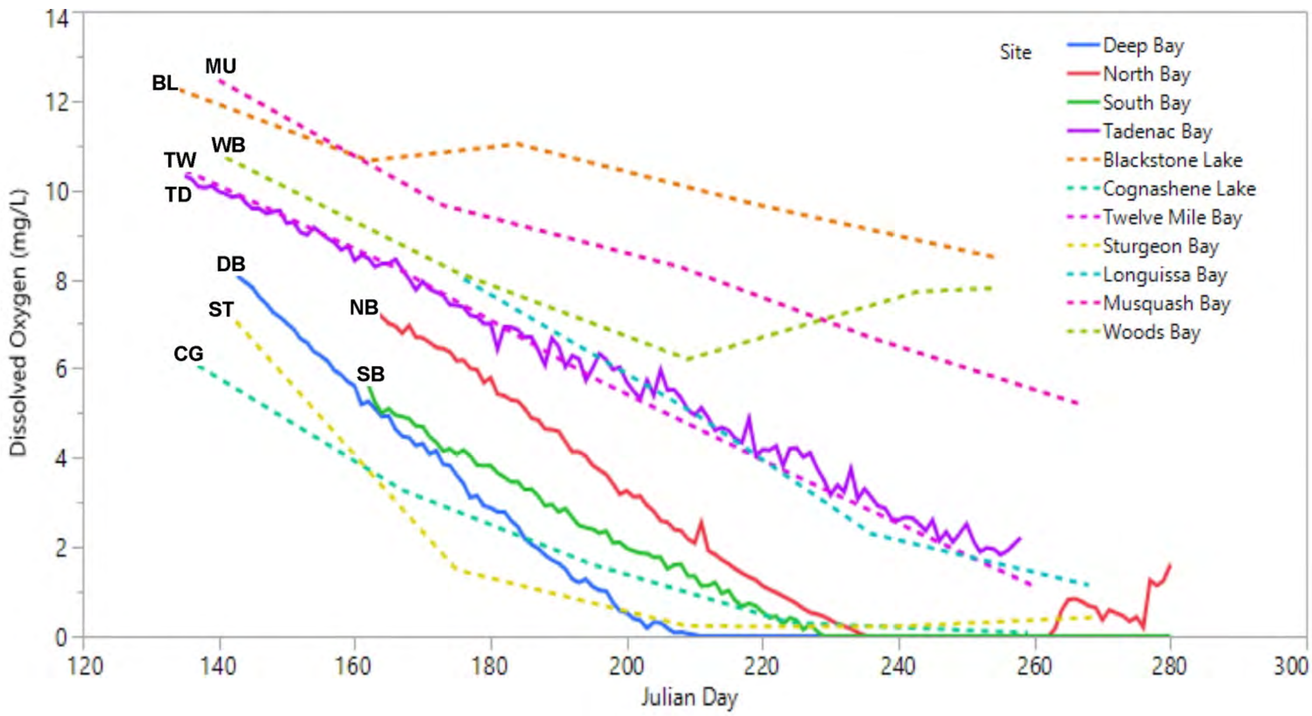


Figure 3: Changes in hypolimnetic dissolved oxygen (DO; mg/L) concentrations within each embayment at the deep station. Unbroken lines are for data collected with in-situ Onset HOBO U26-001 DO data loggers whereas dashed lines are for those collected at monthly intervals taken approximately 2 m above the sediment surface.

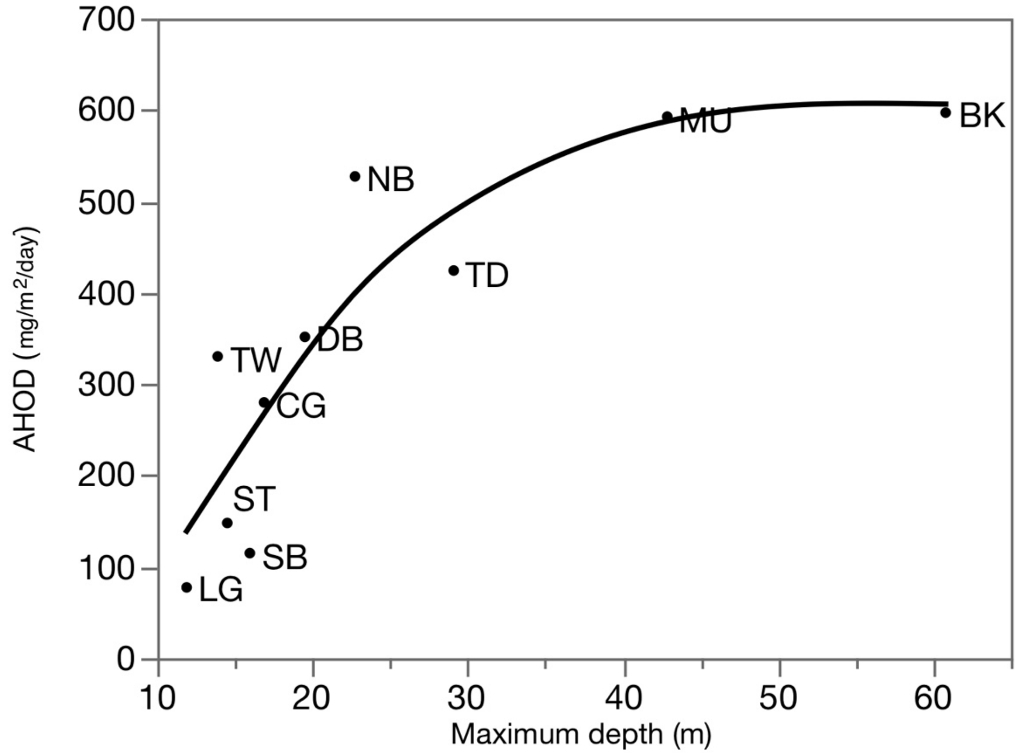


Figure 4: Relationship between relative AHOD values and maximum depth of embayment. The line is a spline fit to show the curvilinearity.

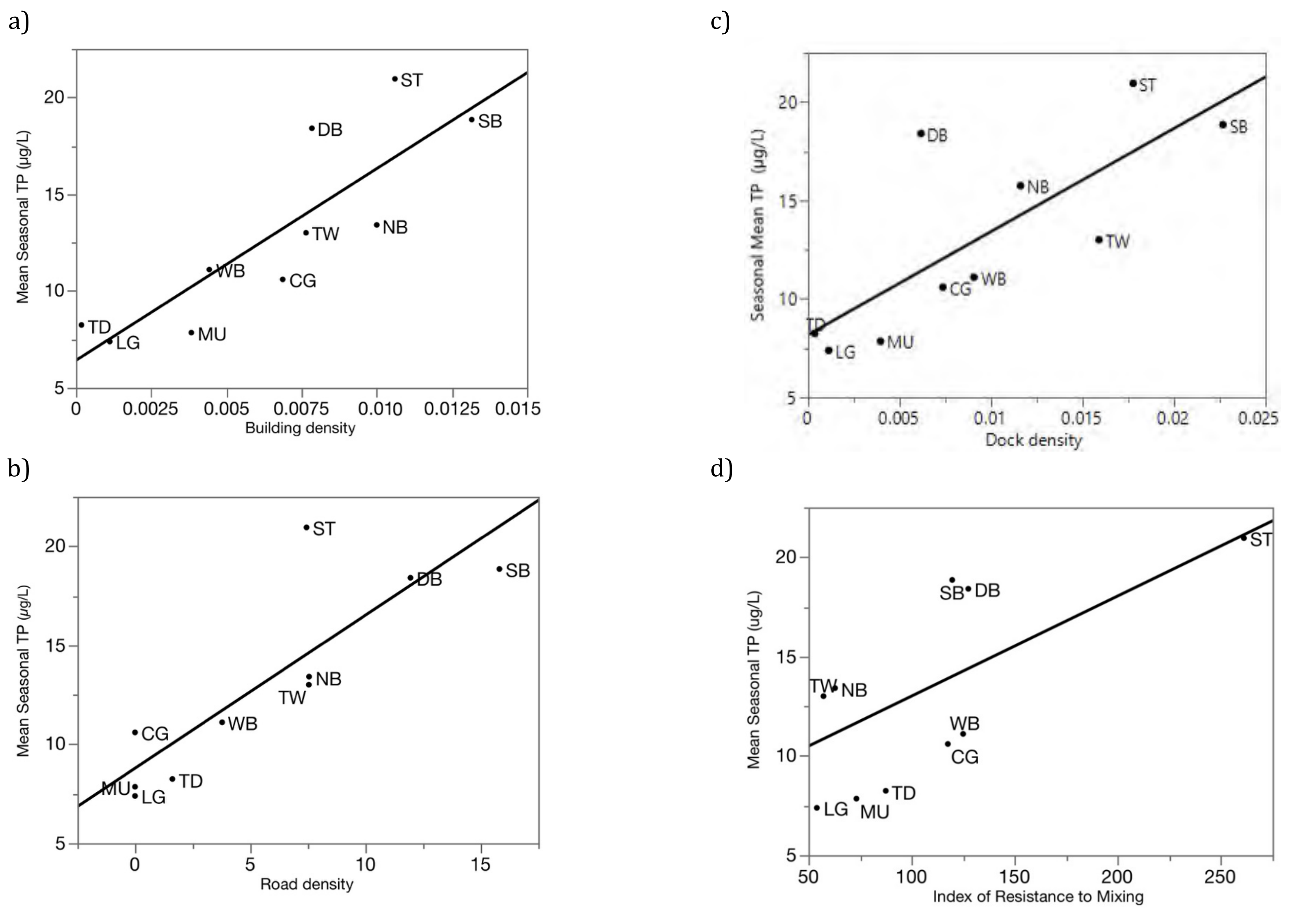


Figure 5: Regression between mean seasonal TP concentration and a) Building density (#/shoreline length) b) Road density (within 2-km buffer of shoreline; m/ha) and c) Dock density (#/shoreline length).

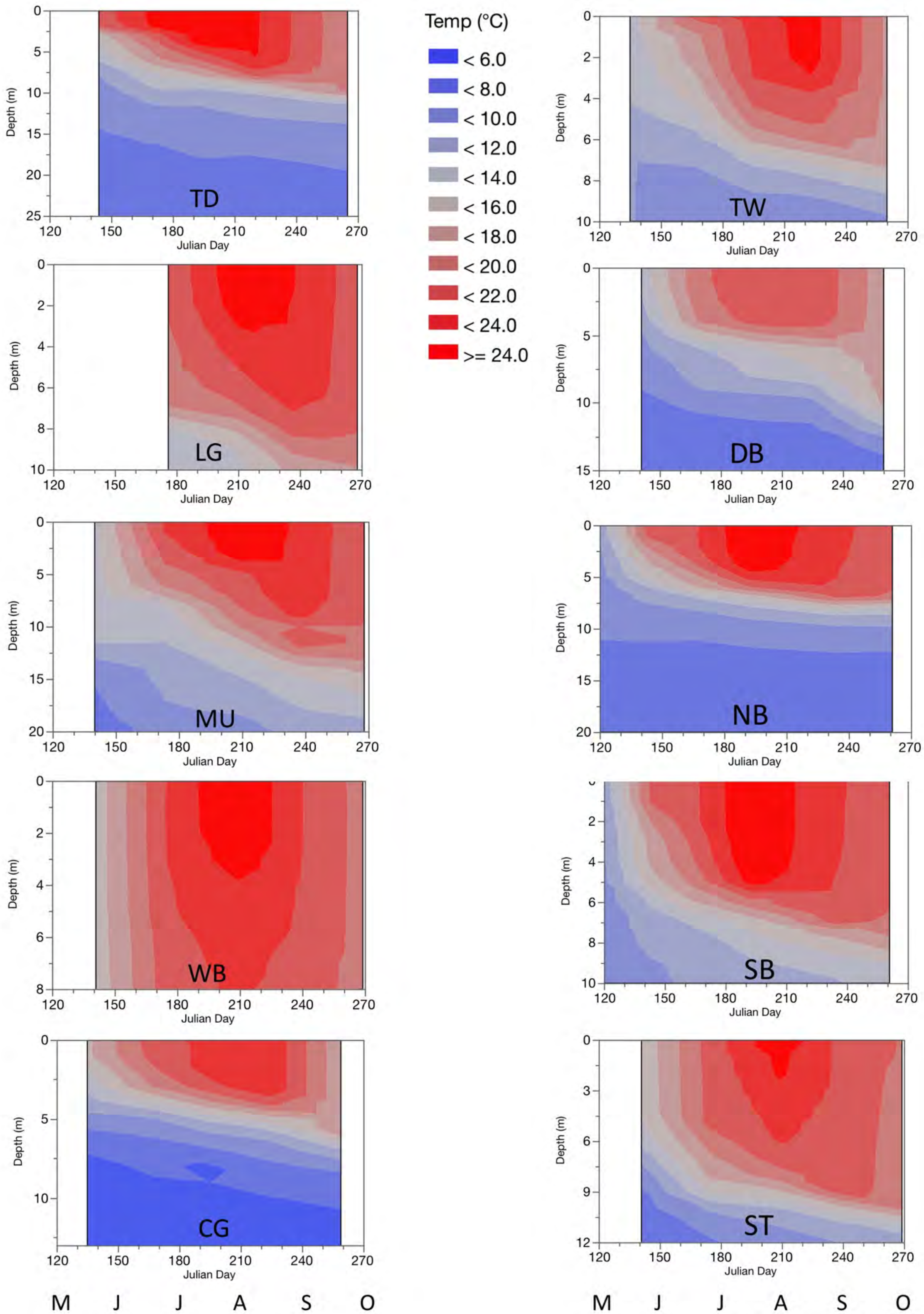


Figure 6: Temperature (TEMP) isopleths for each bay in this study. NB refers only to the inner basin of North Bay.

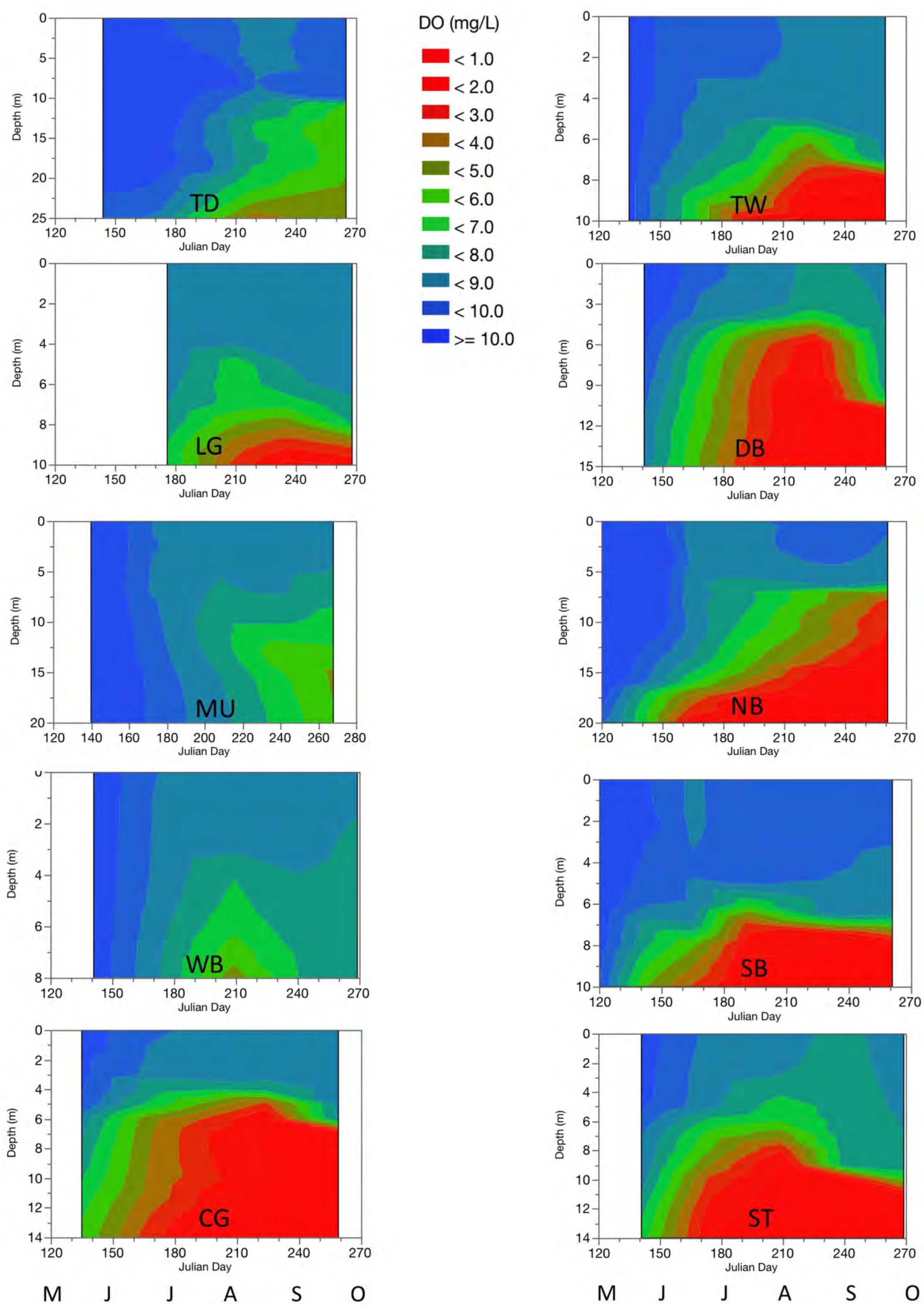


Figure 7: Dissolved oxygen (DO) isopleths for each bay in this study. NB refers only to the inner basin of North Bay.

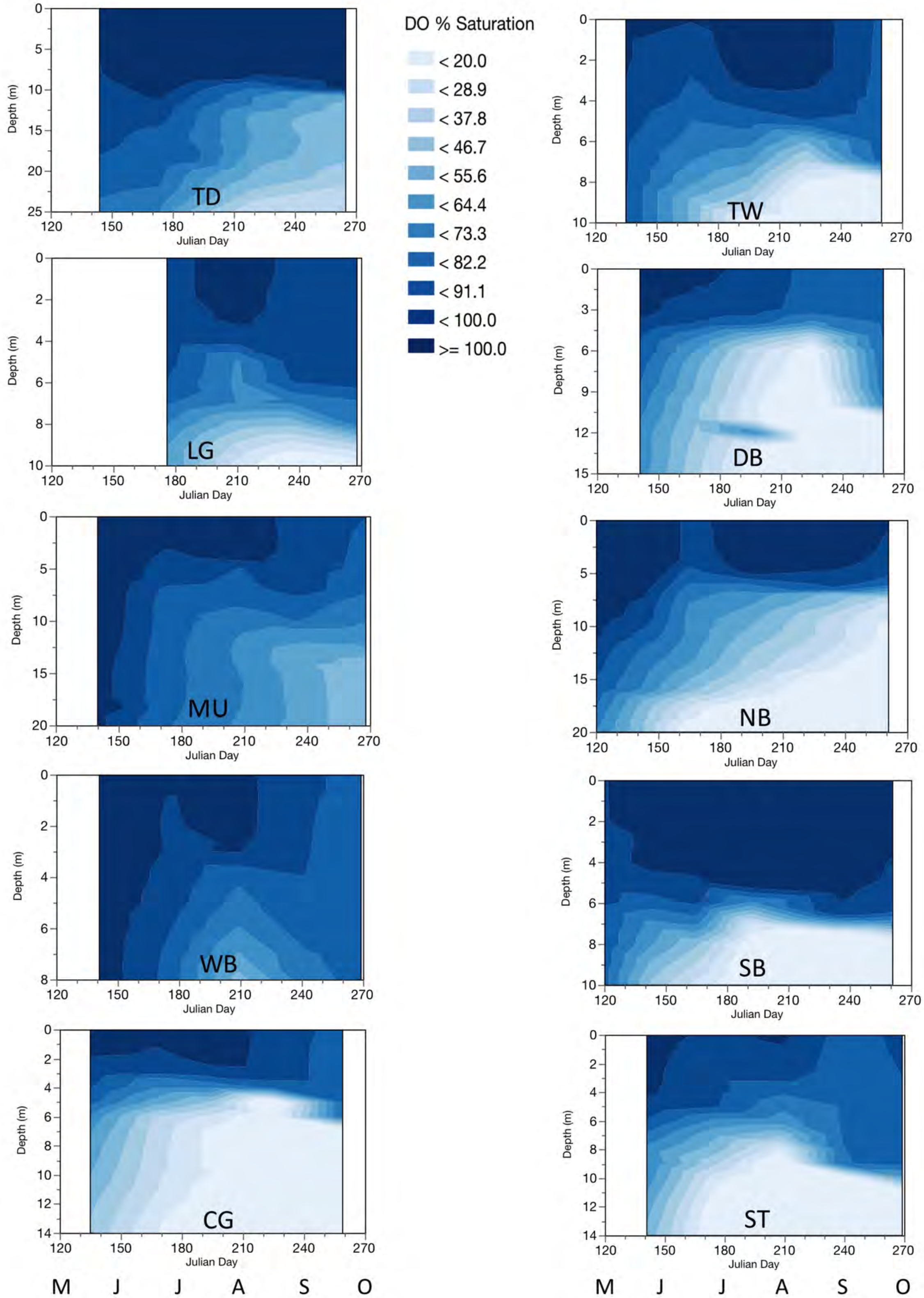


Figure 8: %Dissolved oxygen (DO) saturation isopleths for each bay in this study. NB refers only to the inner basin of North Bay.

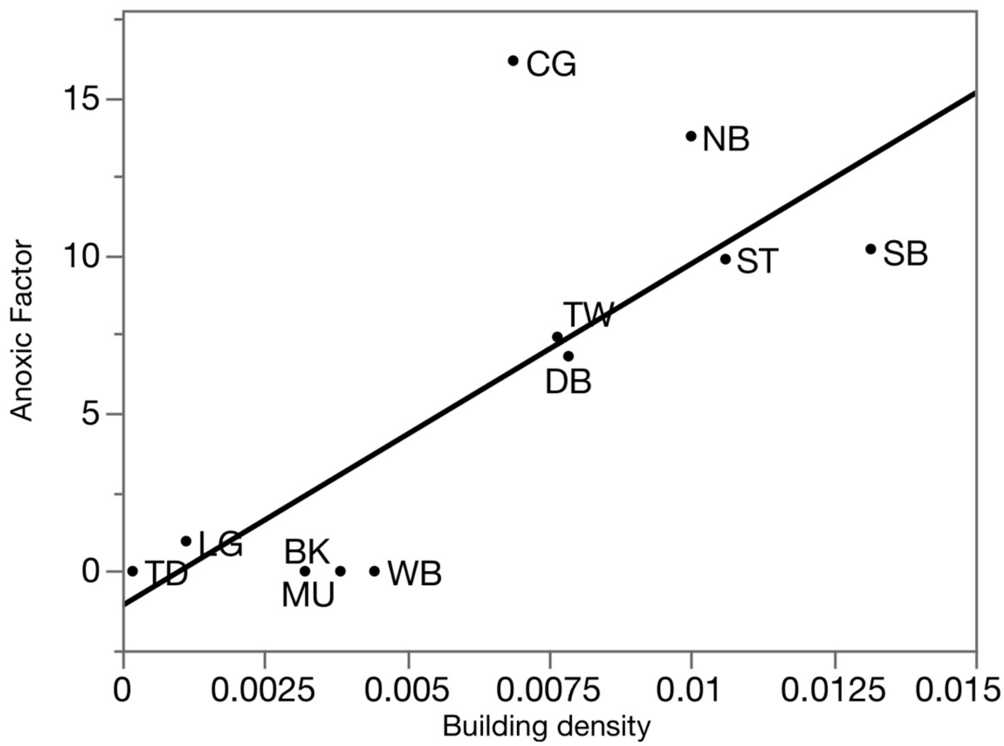
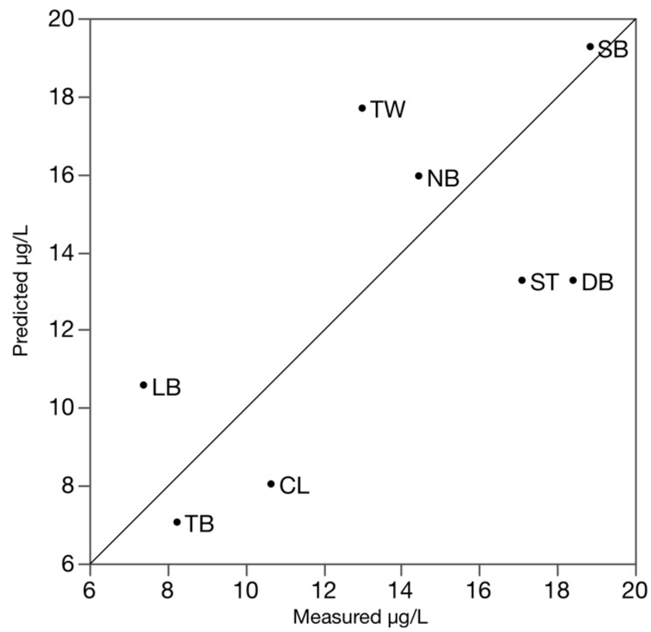


Figure 9: Regression of Anoxic Factor for each embayments against building density (#/shoreline length).

a)



b)

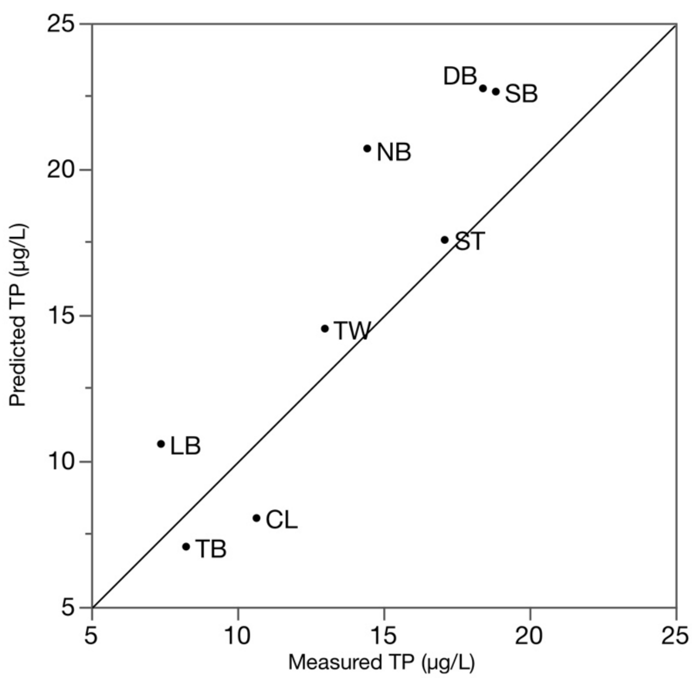
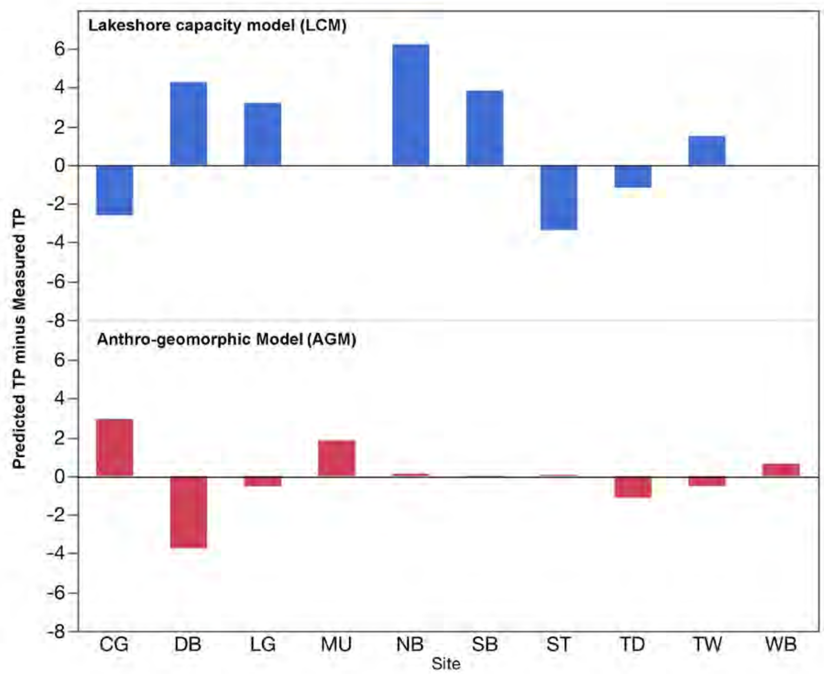


Figure 10: Comparison of predicted versus measured summer mean [TP] derived with the Lakeshore Capacity Model considering a) no internal P loading data and b) additional internal P loading data. The line of unity is indicated in both graphs.

a)



b)

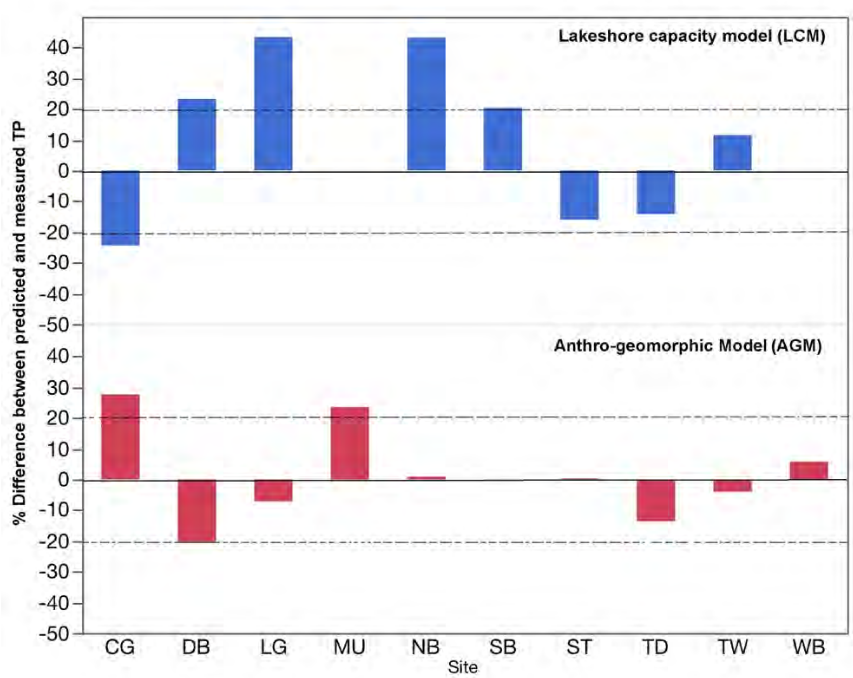


Figure 11: Amount of deviations of predicted mean summer [TP] from measured [TP] for embayments (see site codes in Table 1). Data are presented as a) raw units µg/L and b) % difference. All sites occurring above +20% and -20% are unacceptable deviations.

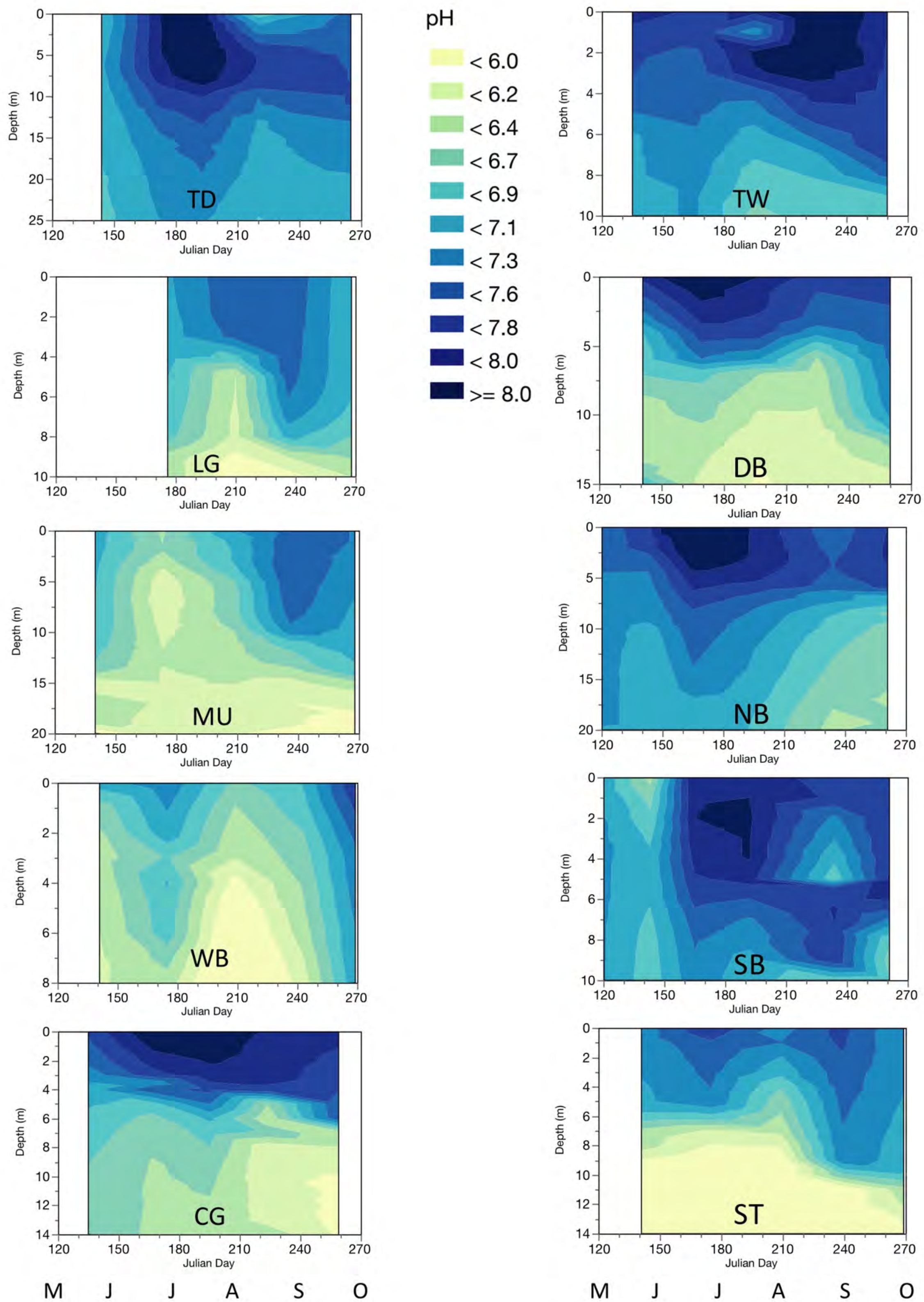


Figure 12: pH isopleths for each bay in this study. NB refers only to the inner basin of North Bay.

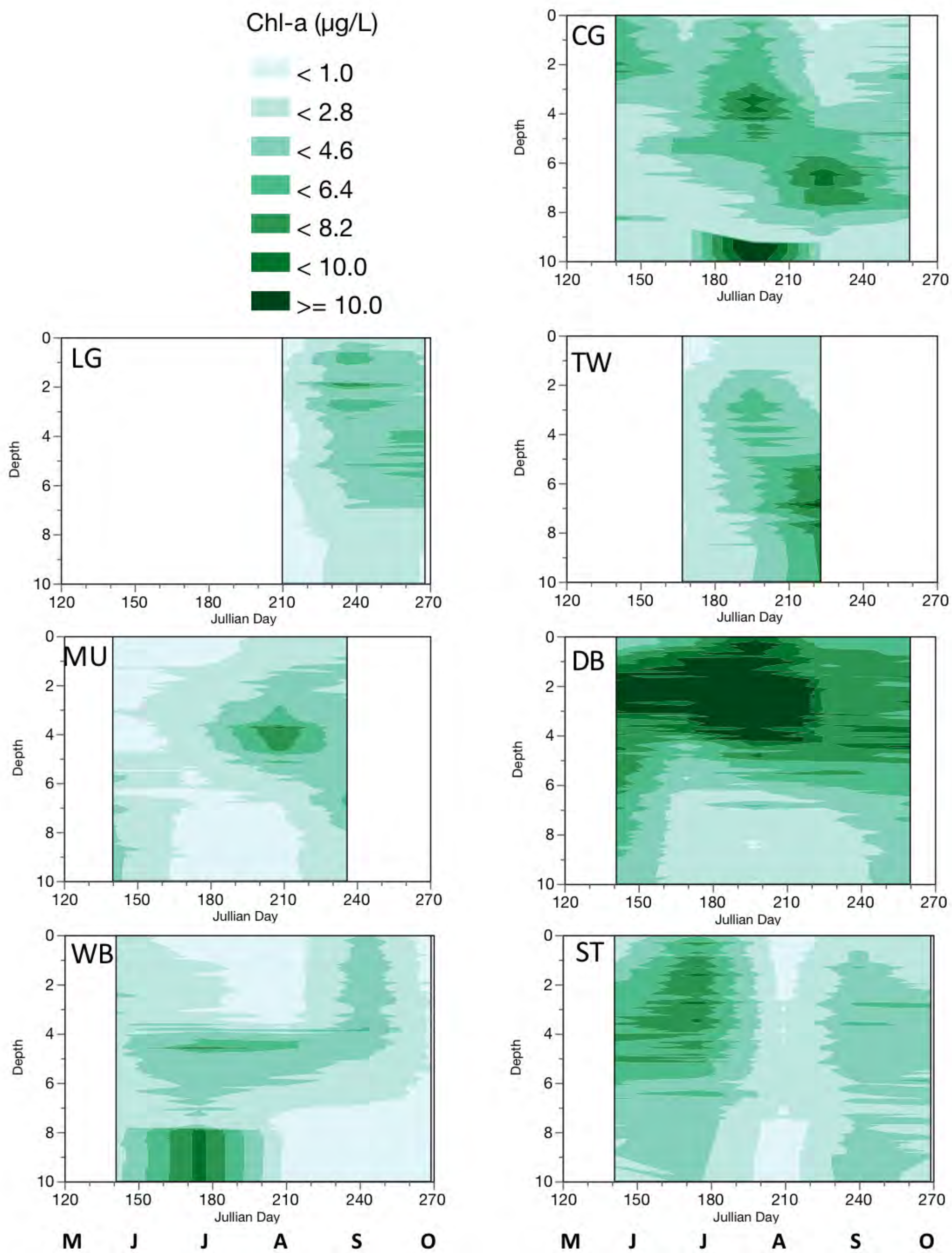


Figure 13: Chlorophyll-a (CHL-a) isopleths for six bays in this study. Data were obtained with a Turners C3 *in situ* submersible fluorometer. Corresponding data for Tadenac Bay, North Bay or South Bay are available from Environment Canada.

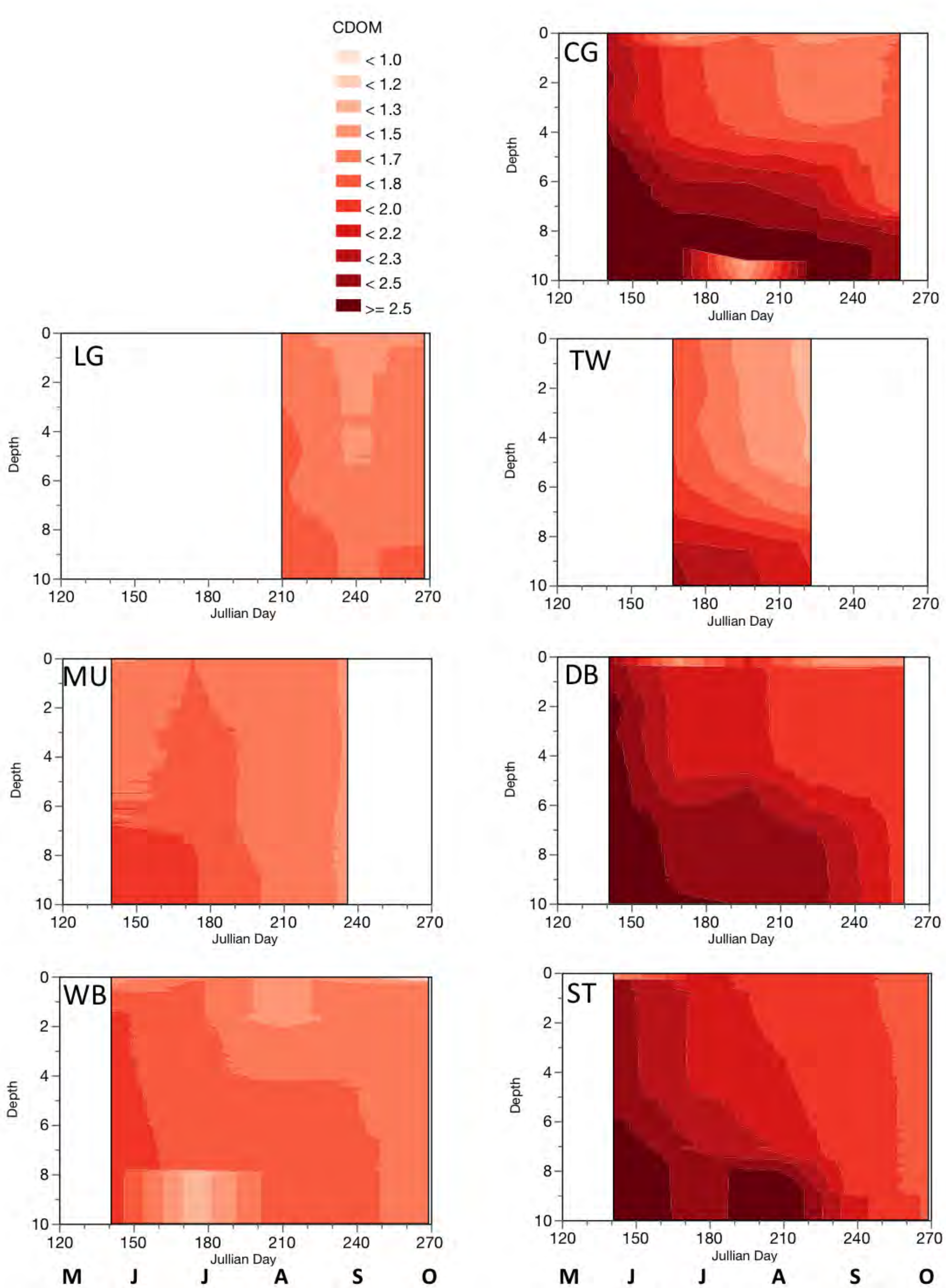


Figure 14: Coloured dissolved organic matter (CDOM) isopleth for six bays in this study. Data were obtained with a Turners C3 *in situ* submersible fluorometer. Corresponding data for Tadenac Bay, North Bay or South Bay are available from Environment Canada.

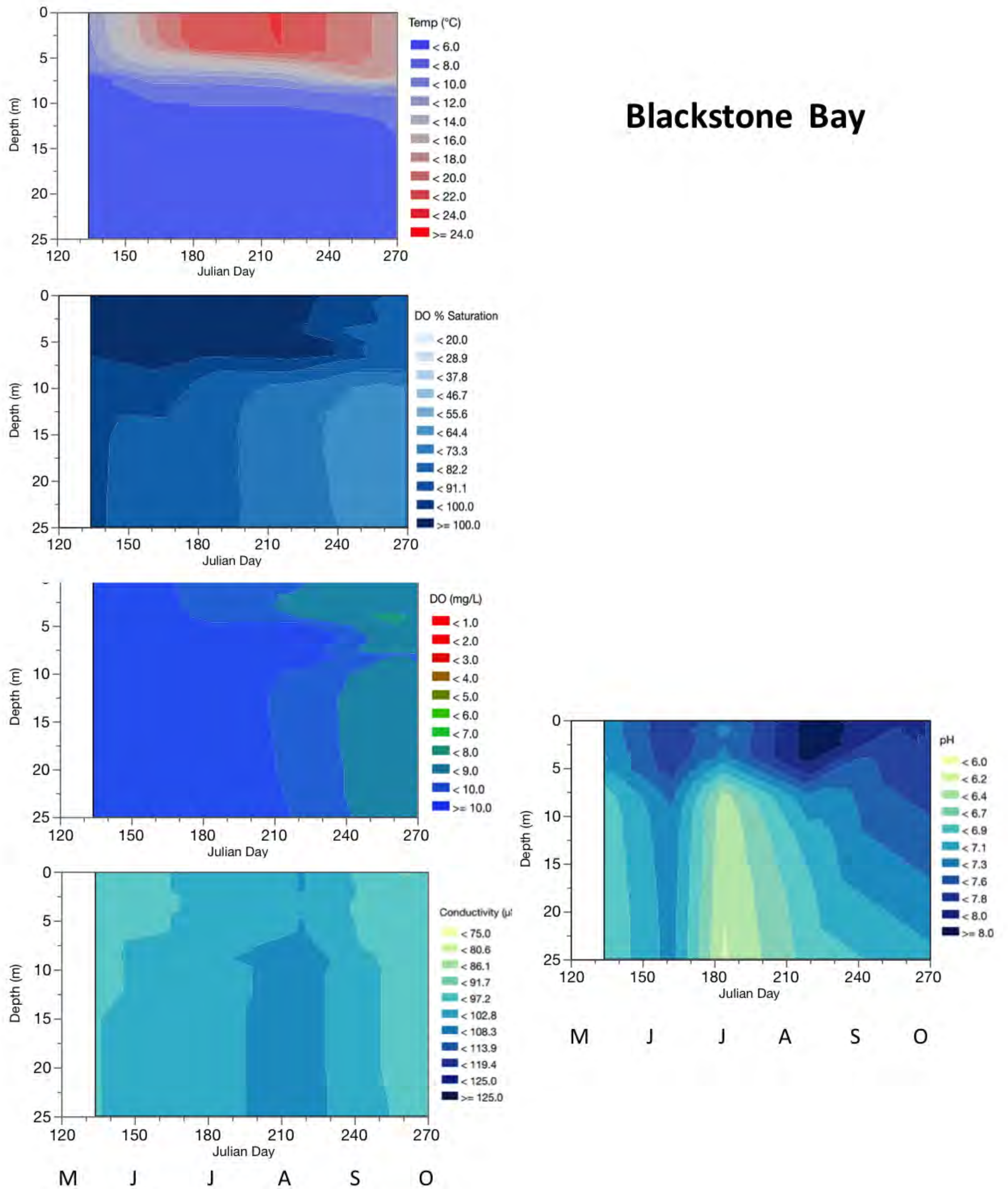


Figure 15a: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND) and pH for Blackstone Lake.

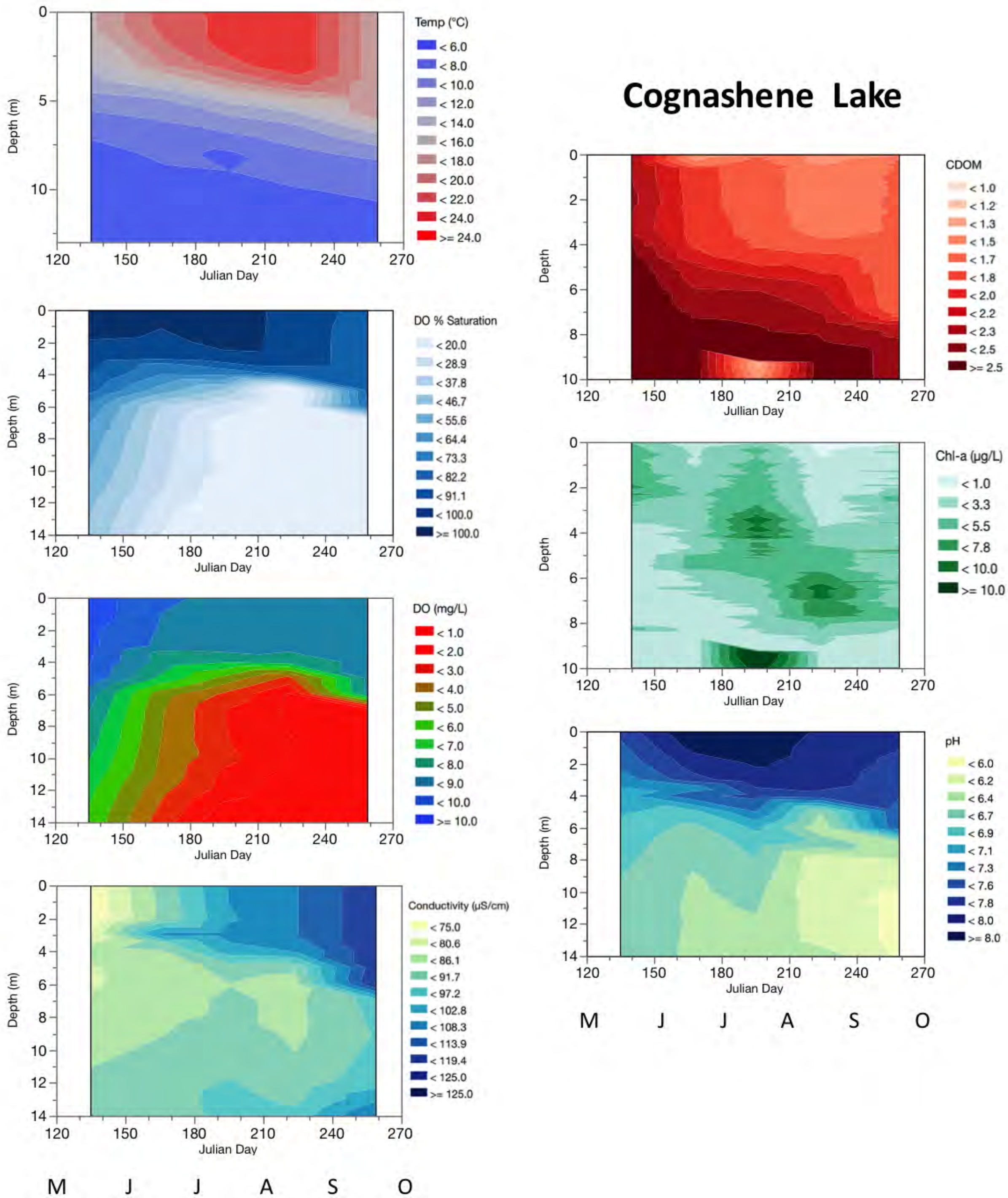


Figure 15b: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND), coloured organic matter (CDOM), chlorophyll-a (CHL-a) and conductivity (COND) for Cognashene Lake.

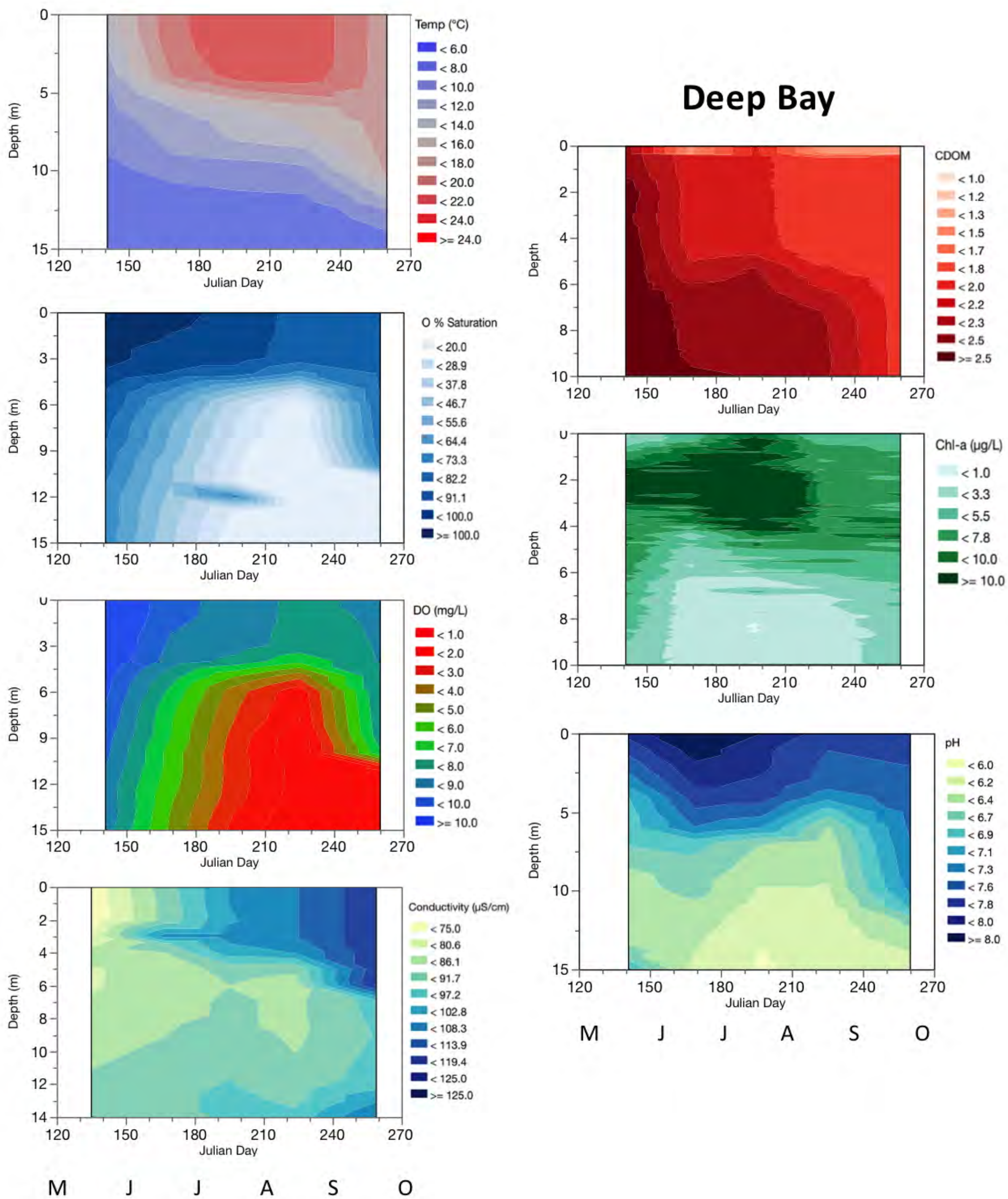


Figure 15c: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND), coloured organic matter (CDOM), chlorophyll-a (CHL-a) and conductivity (COND) for Deep Bay.

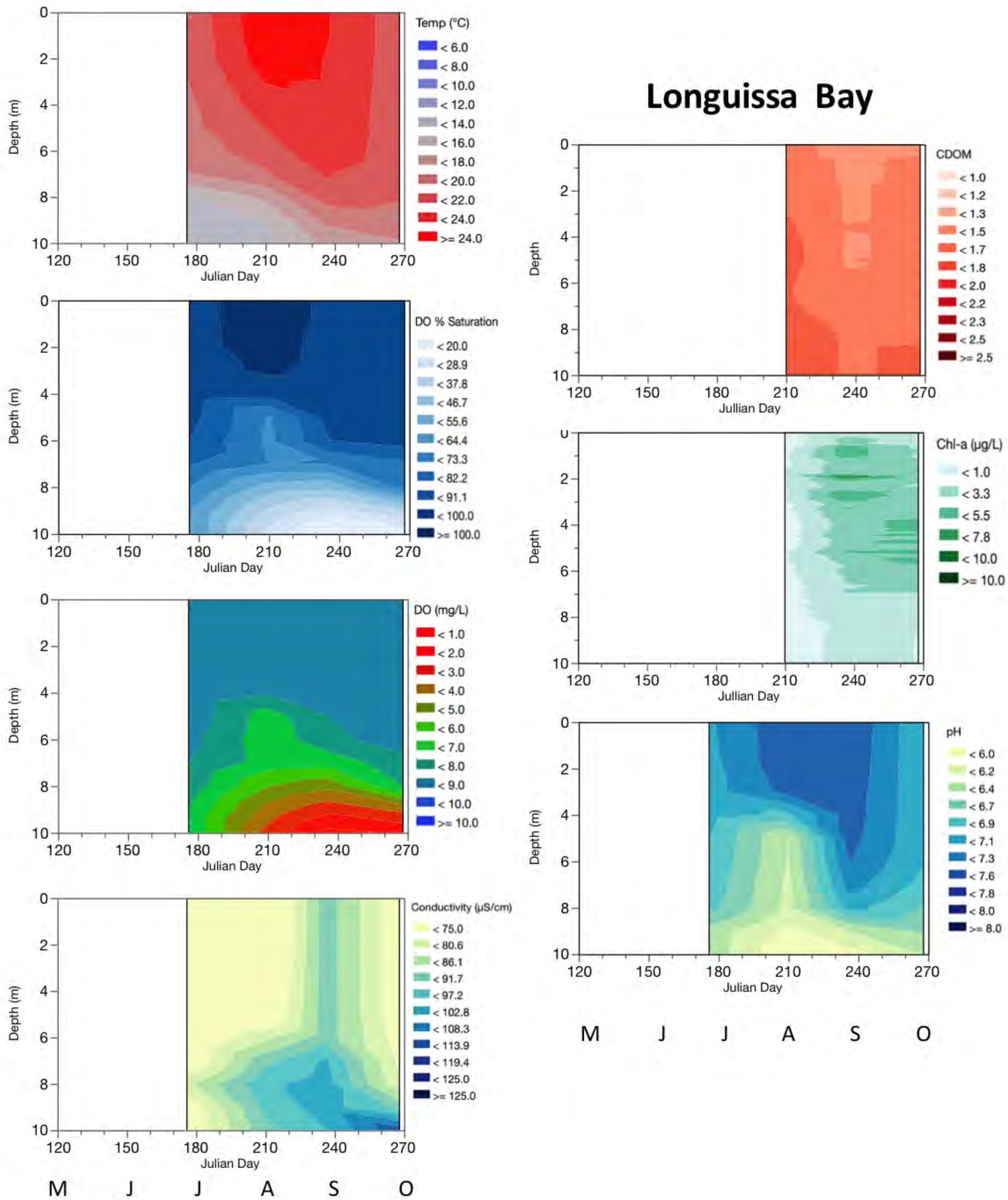


Figure 15d: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND), coloured organic matter (CDOM), chlorophyll-a (CHL-a) and conductivity (COND) for Longuissa Bay.

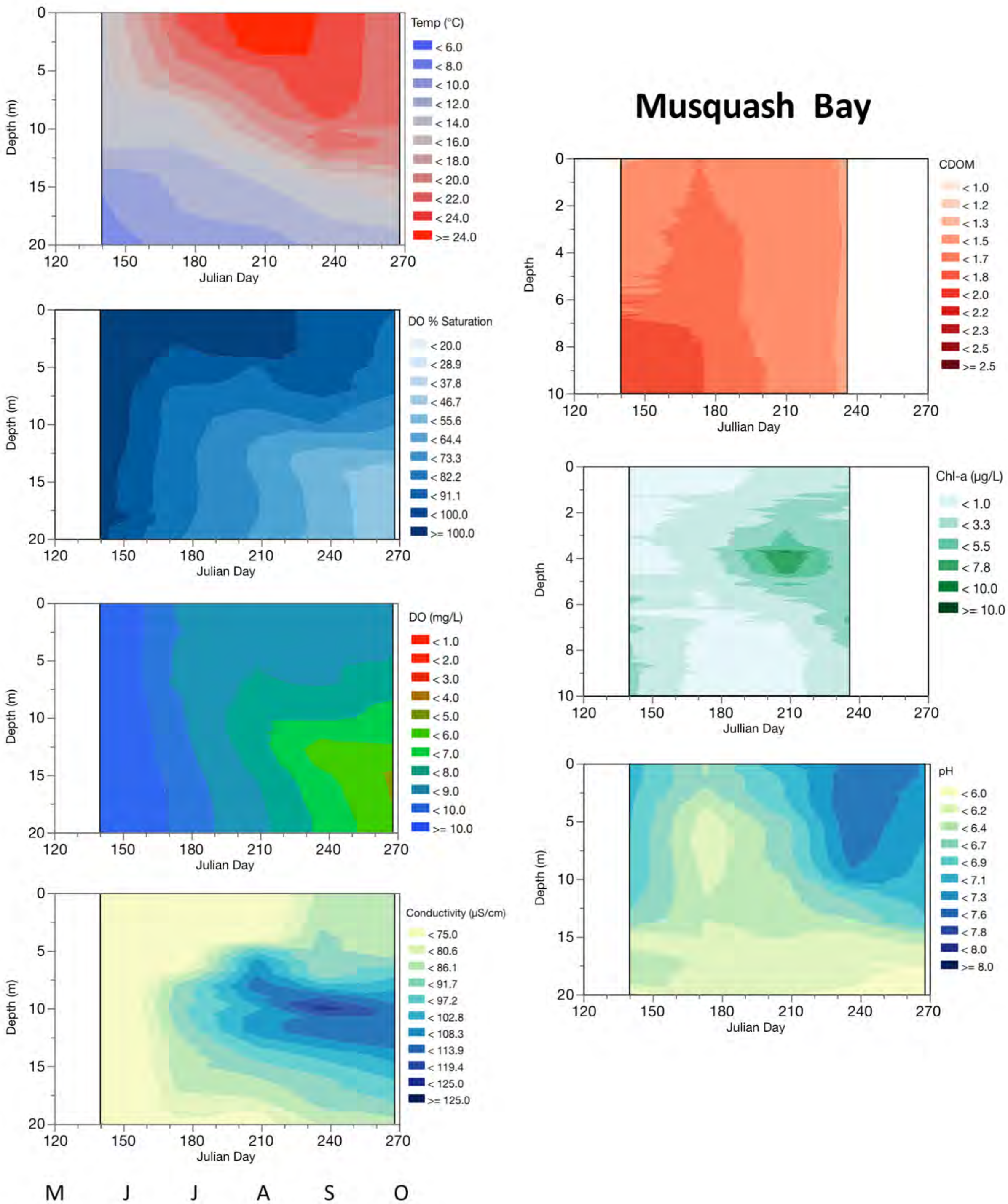


Figure 15e: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND), coloured organic matter (CDOM), chlorophyll-a (CHL-a) and conductivity (COND) for Musquash Bay.

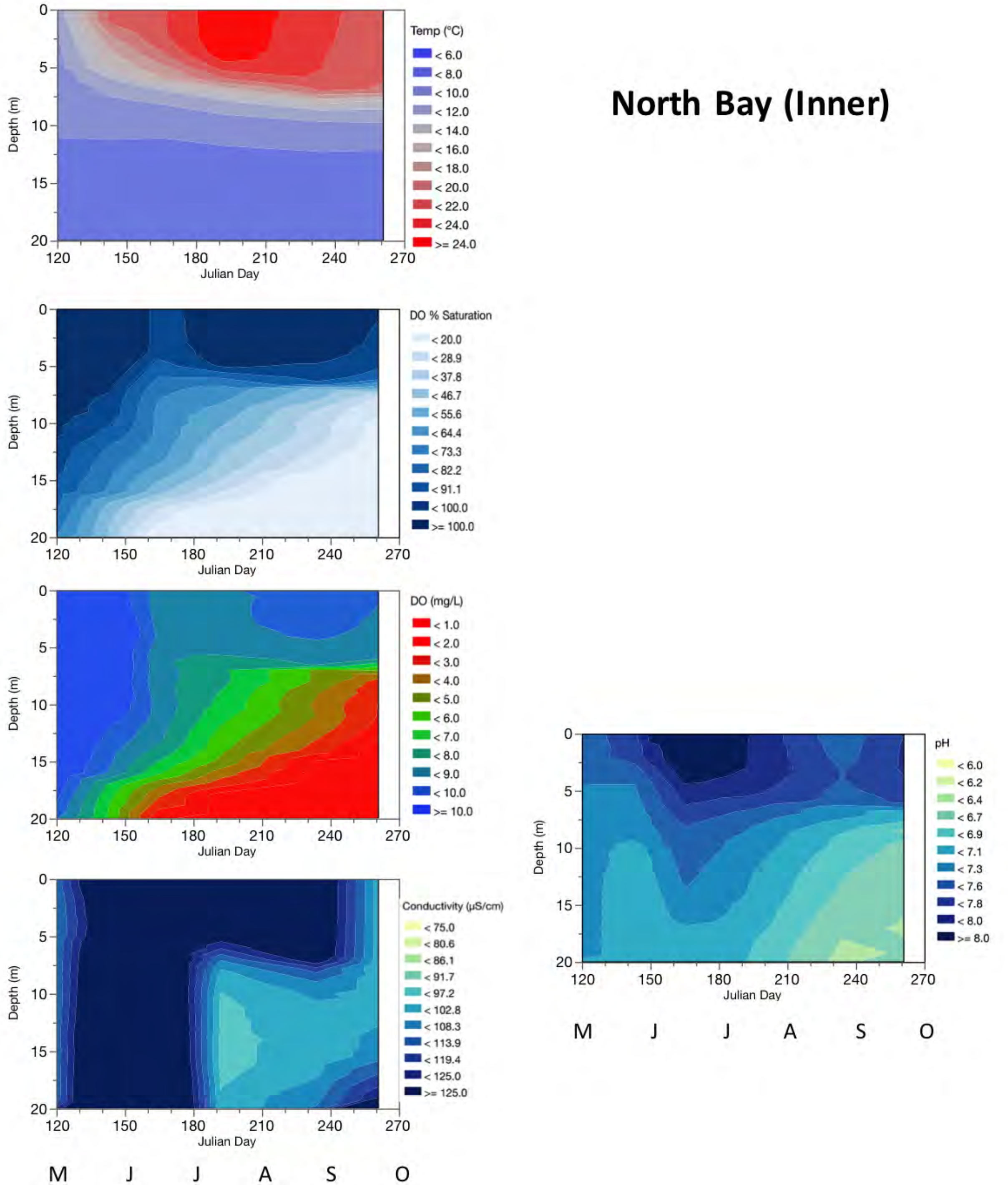


Figure 15f: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND) and pH for North Bay (Inner).

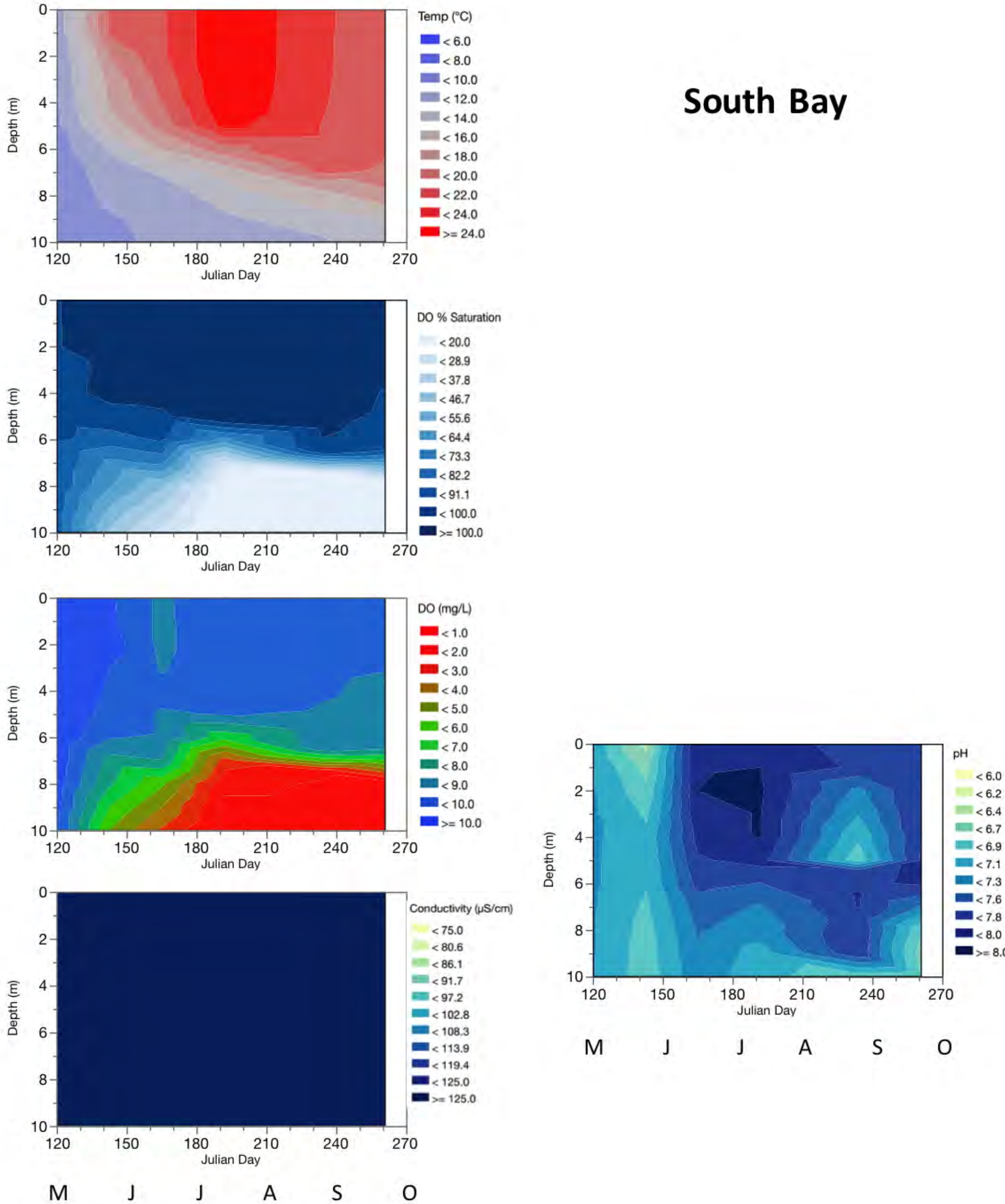


Figure 15g: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND) and pH for South Bay.

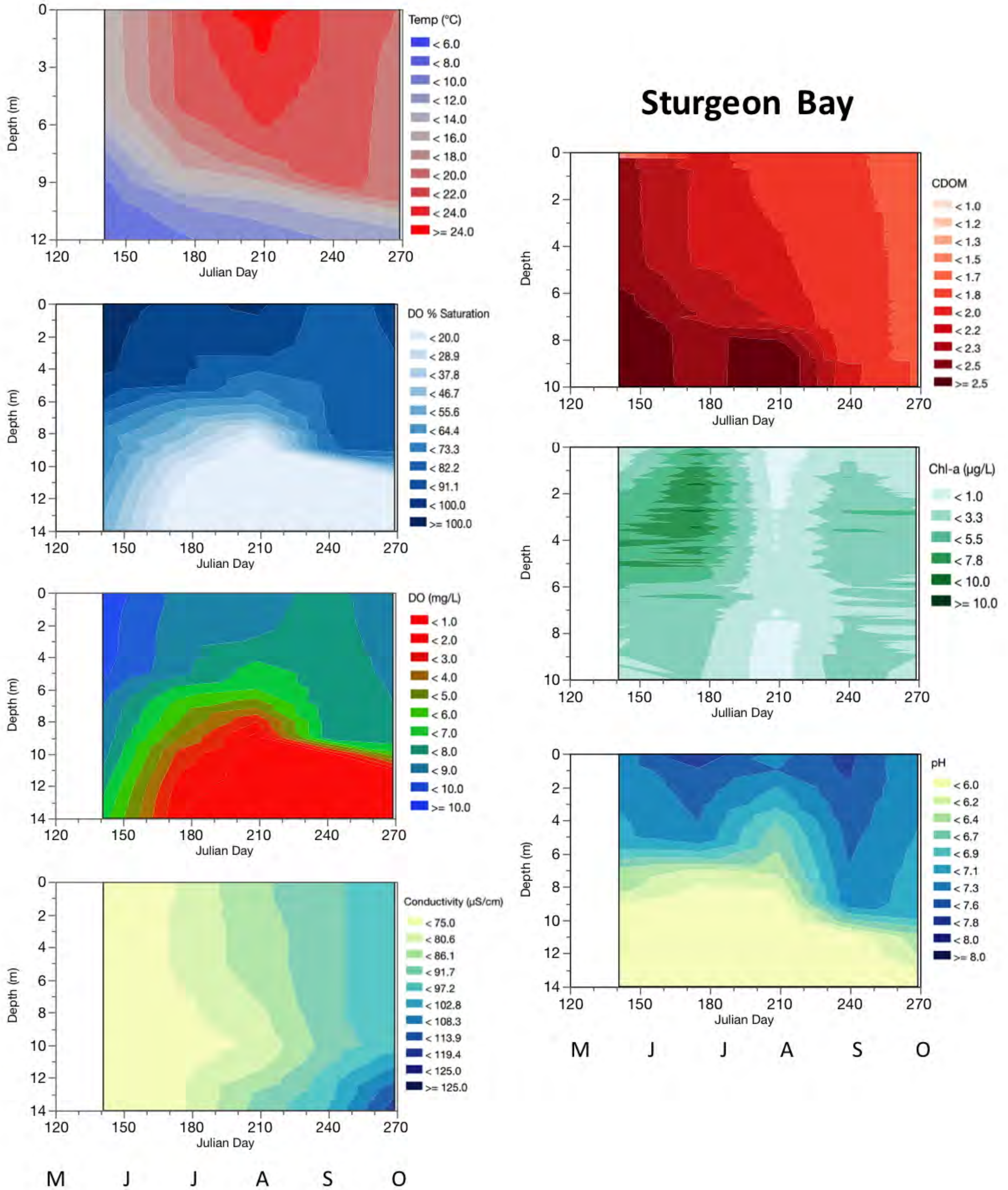


Figure 15h: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND), coloured organic matter (CDOM), chlorophyll-a (CHL-a) and conductivity (COND) for Sturgeon Bay.

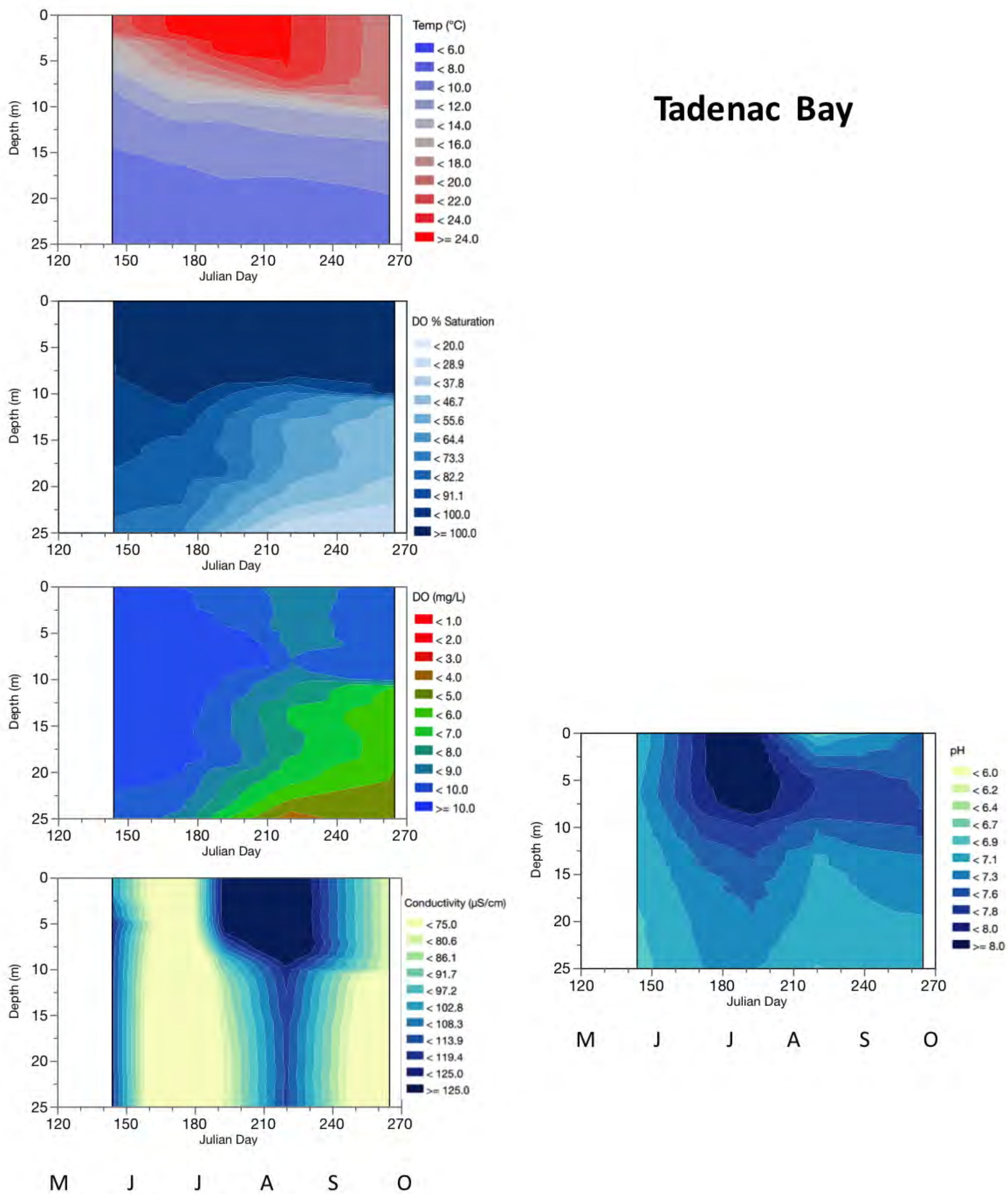


Figure 15i: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND) and pH for South Bay.

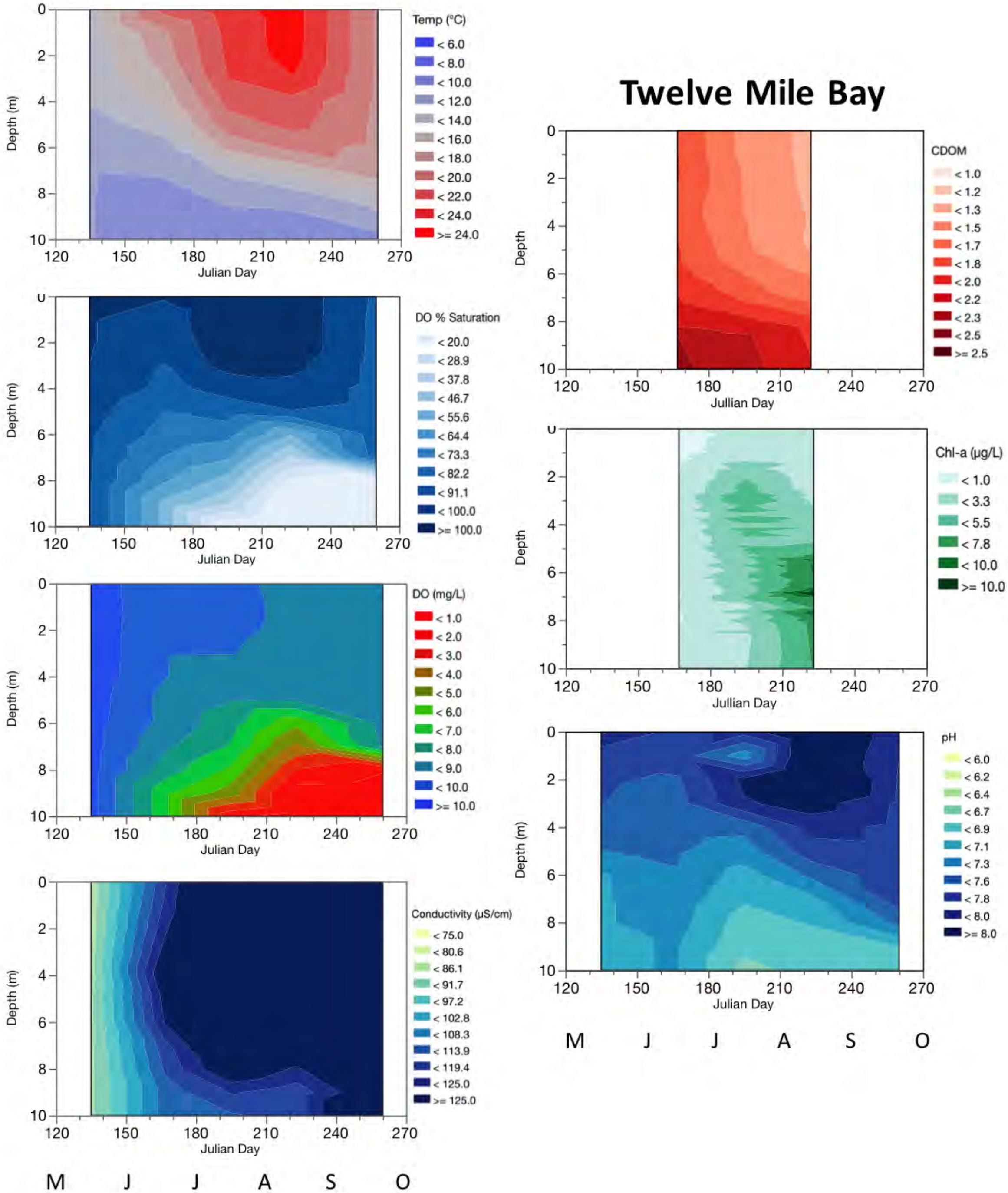


Figure 15j: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND), coloured organic matter (CDOM), chlorophyll-a (CHL-a) and conductivity (COND) for Twelve Mile Bay.

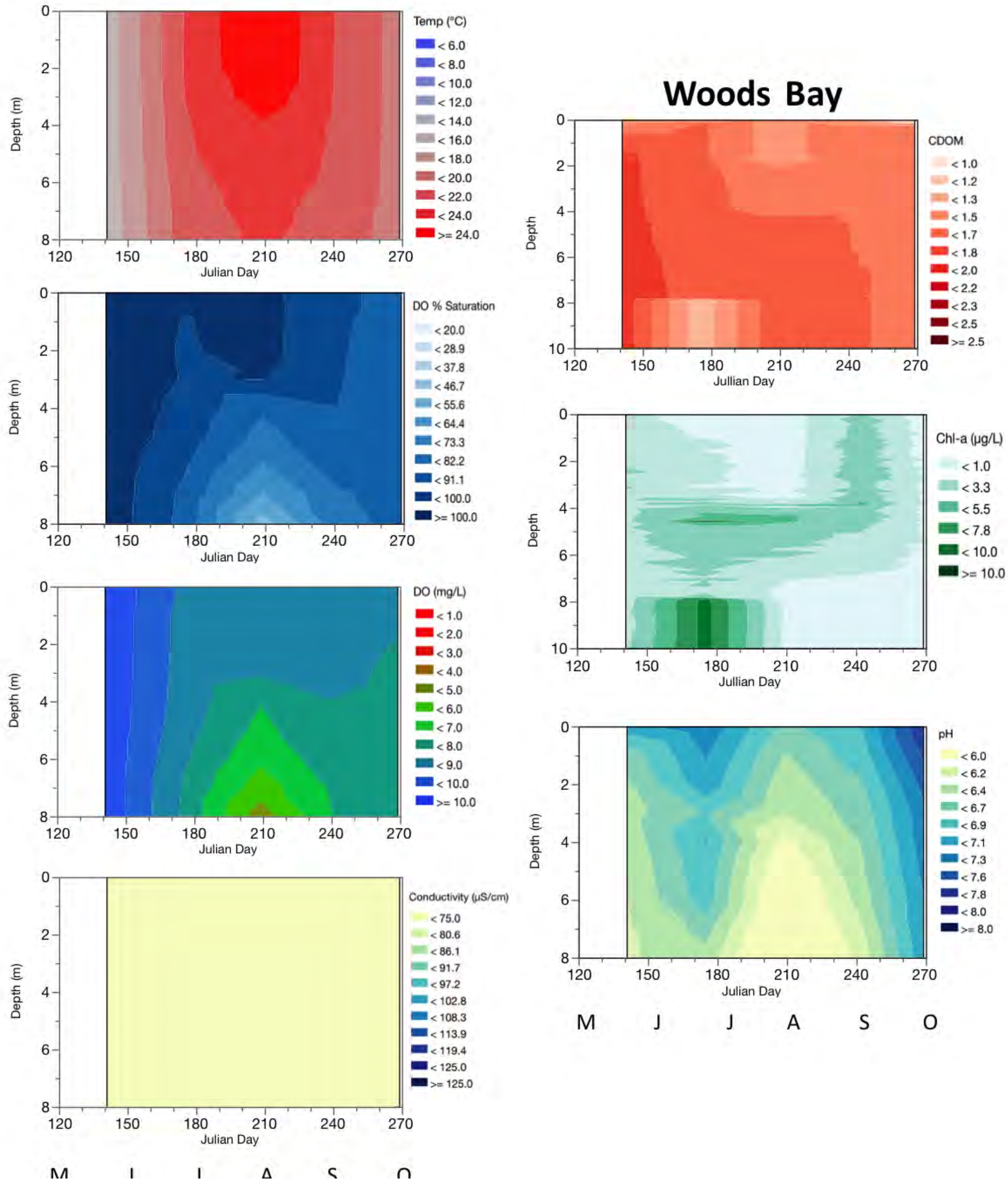
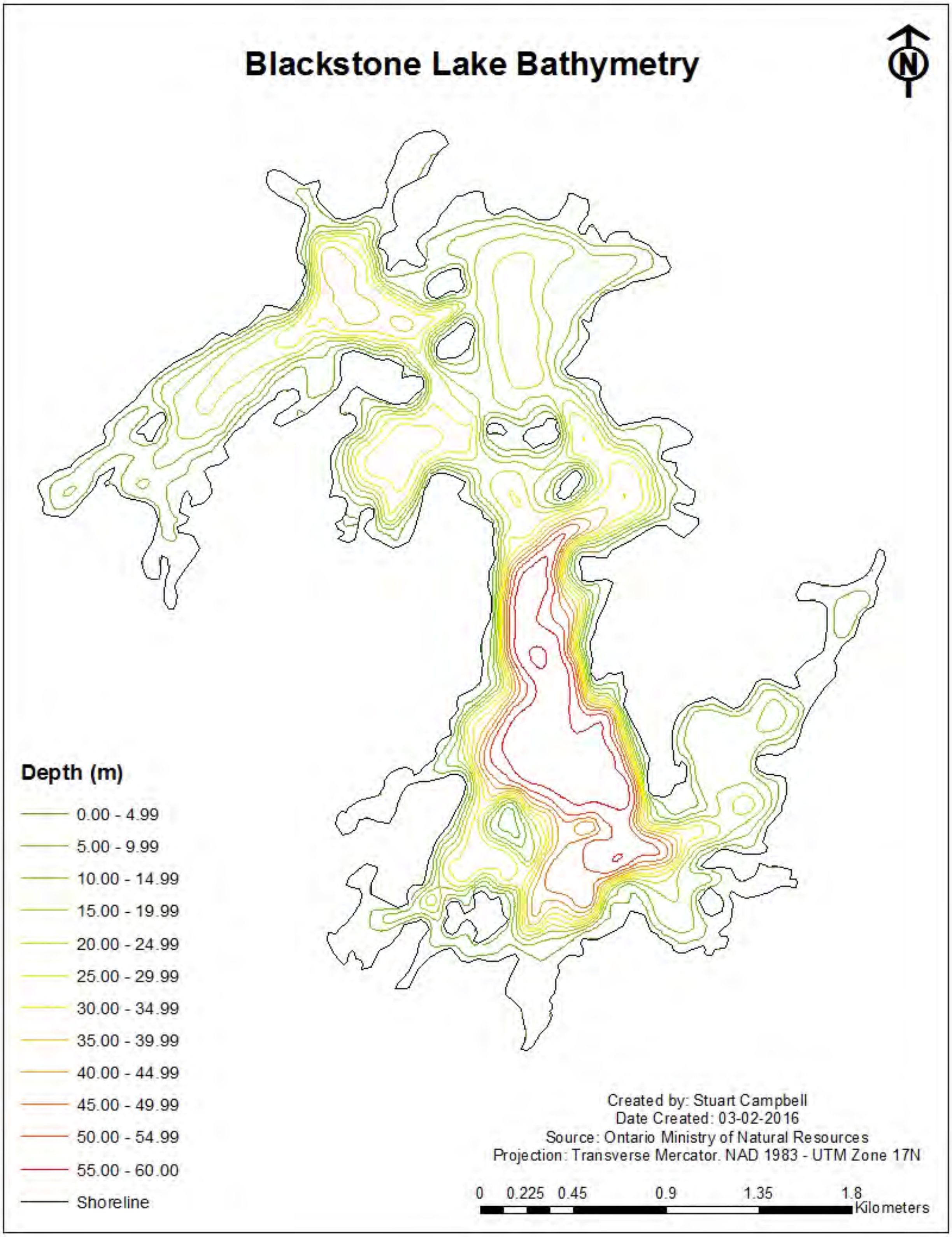


Figure 15k: Isopleths of temperature (TEMP), % dissolved oxygen (DO) saturation, dissolved oxygen (DO), and Conductivity (COND), coloured organic matter (CDOM), chlorophyll-a (CHL-a) and conductivity (COND) for Woods Bay.

Appendix 1: Bathymetric maps for each of the water bodies in this study



Bathymetry of Blackstone Lake

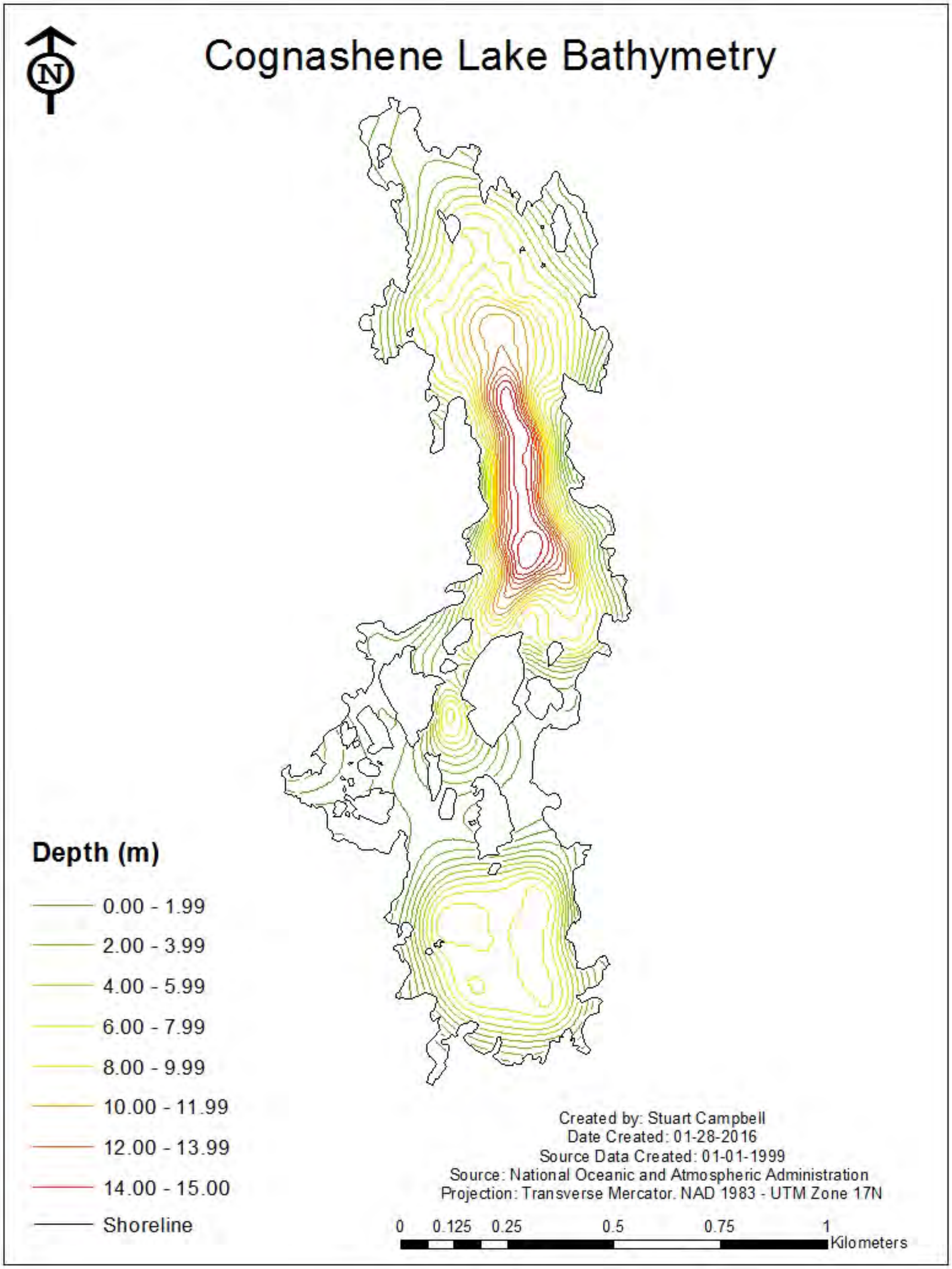
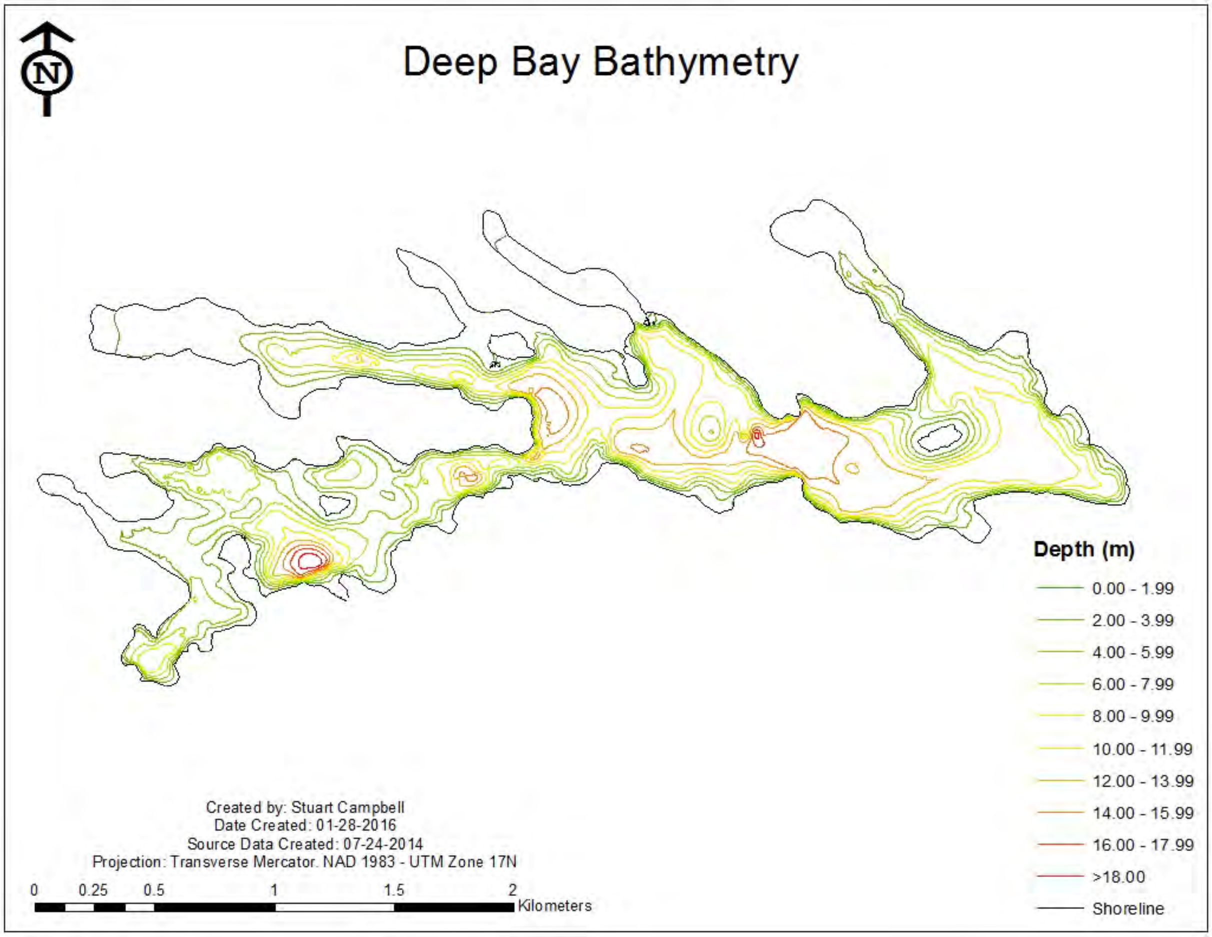
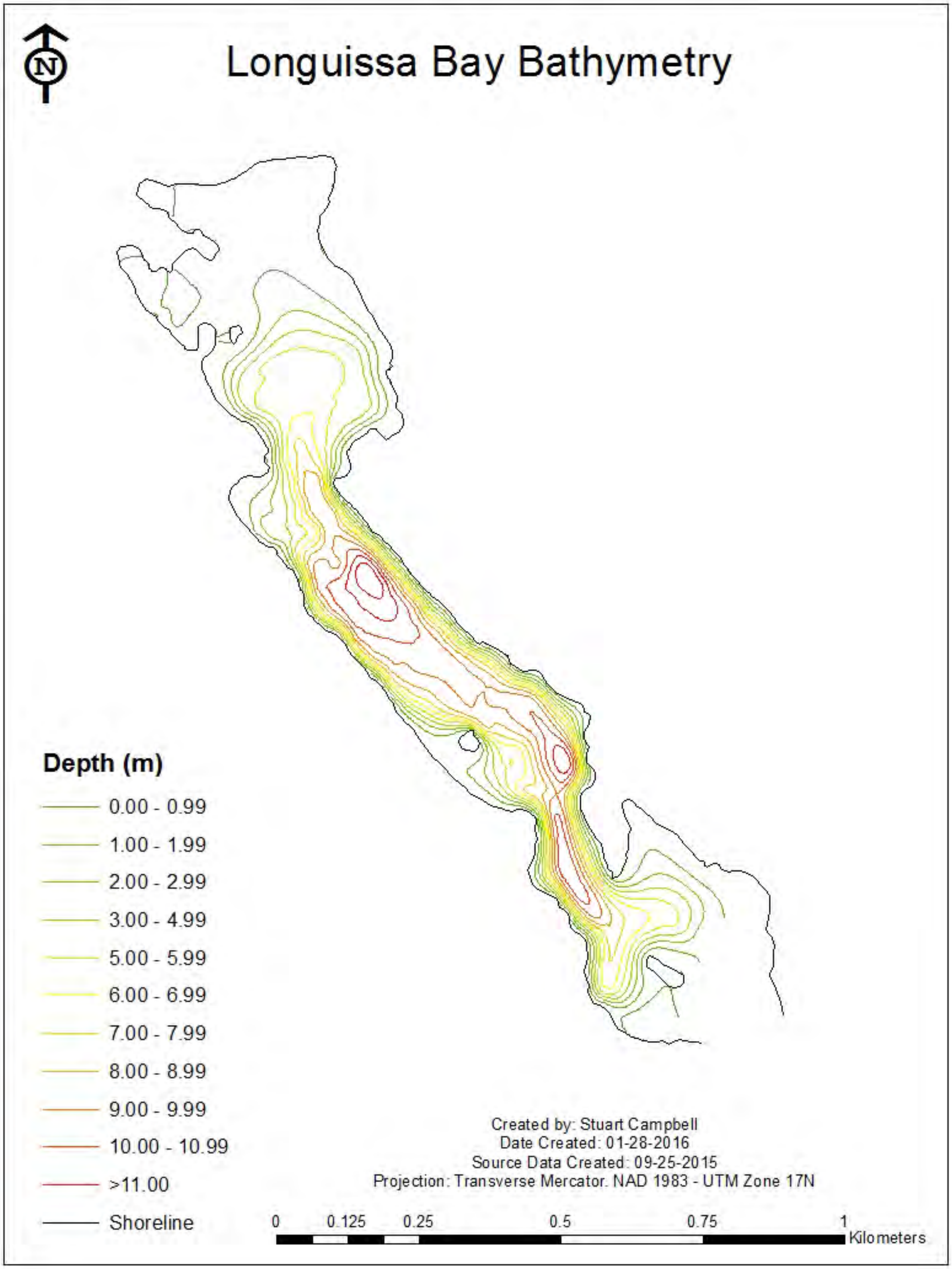


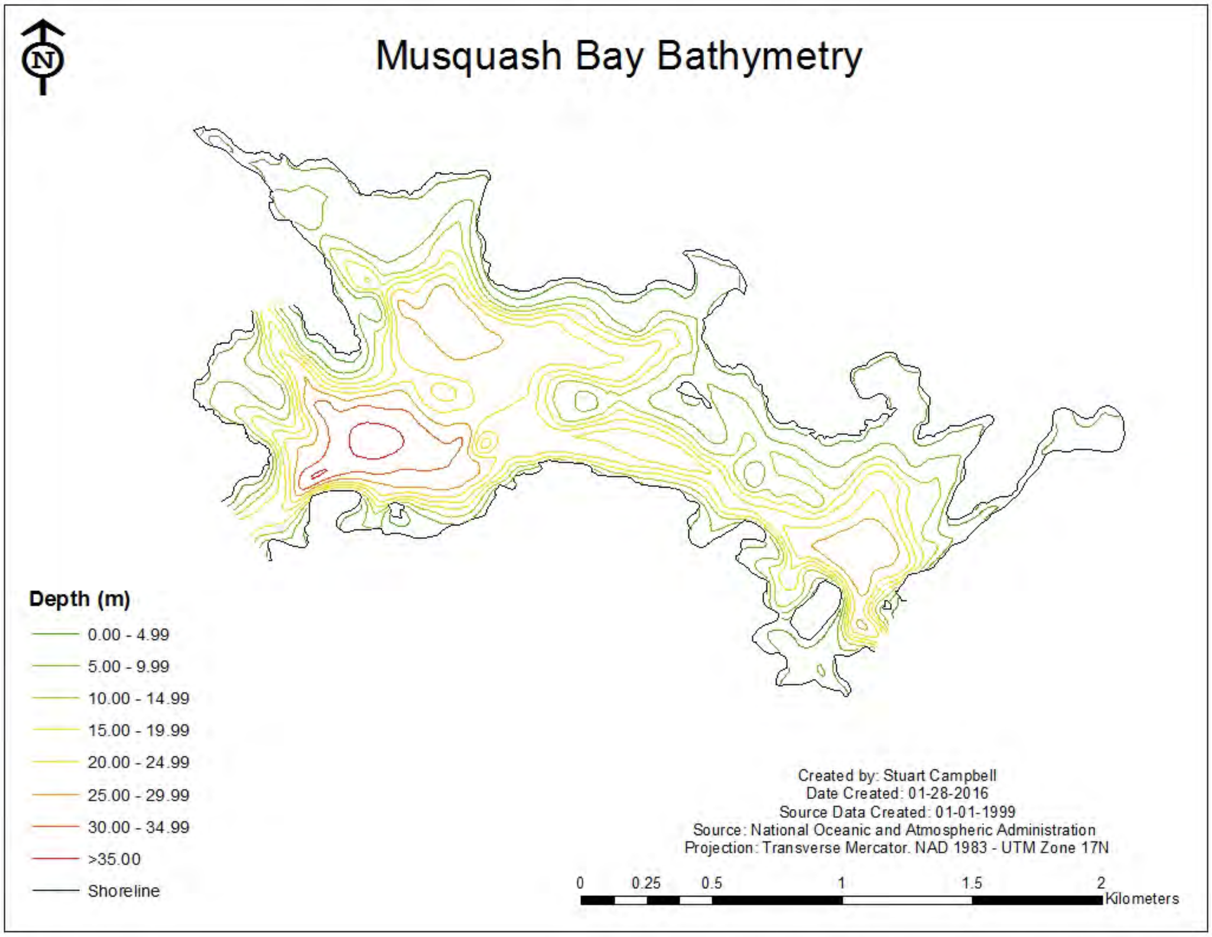
Figure: Bathymetry of Cognashene Lake



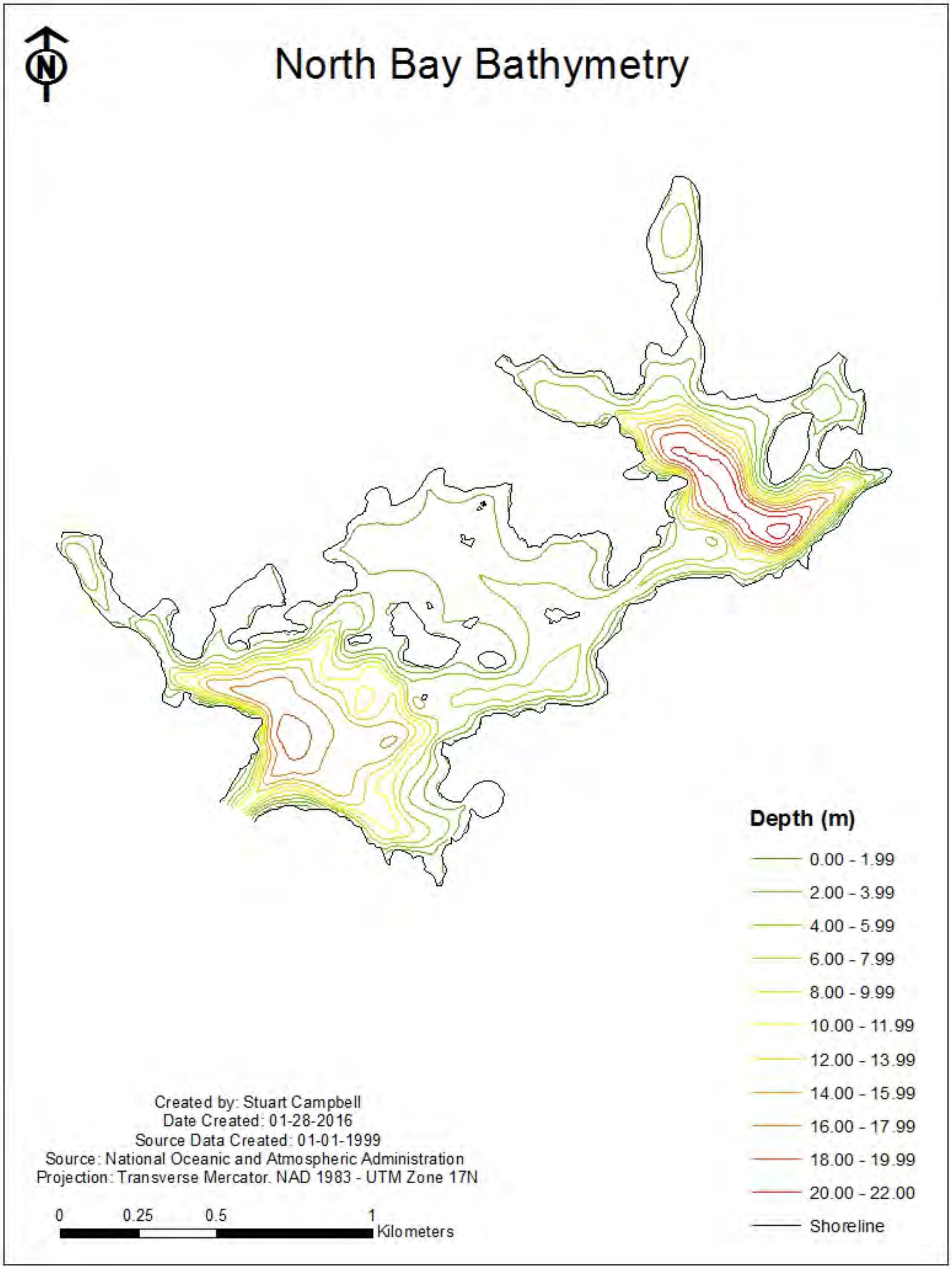
Bathymetry of Deep Bay



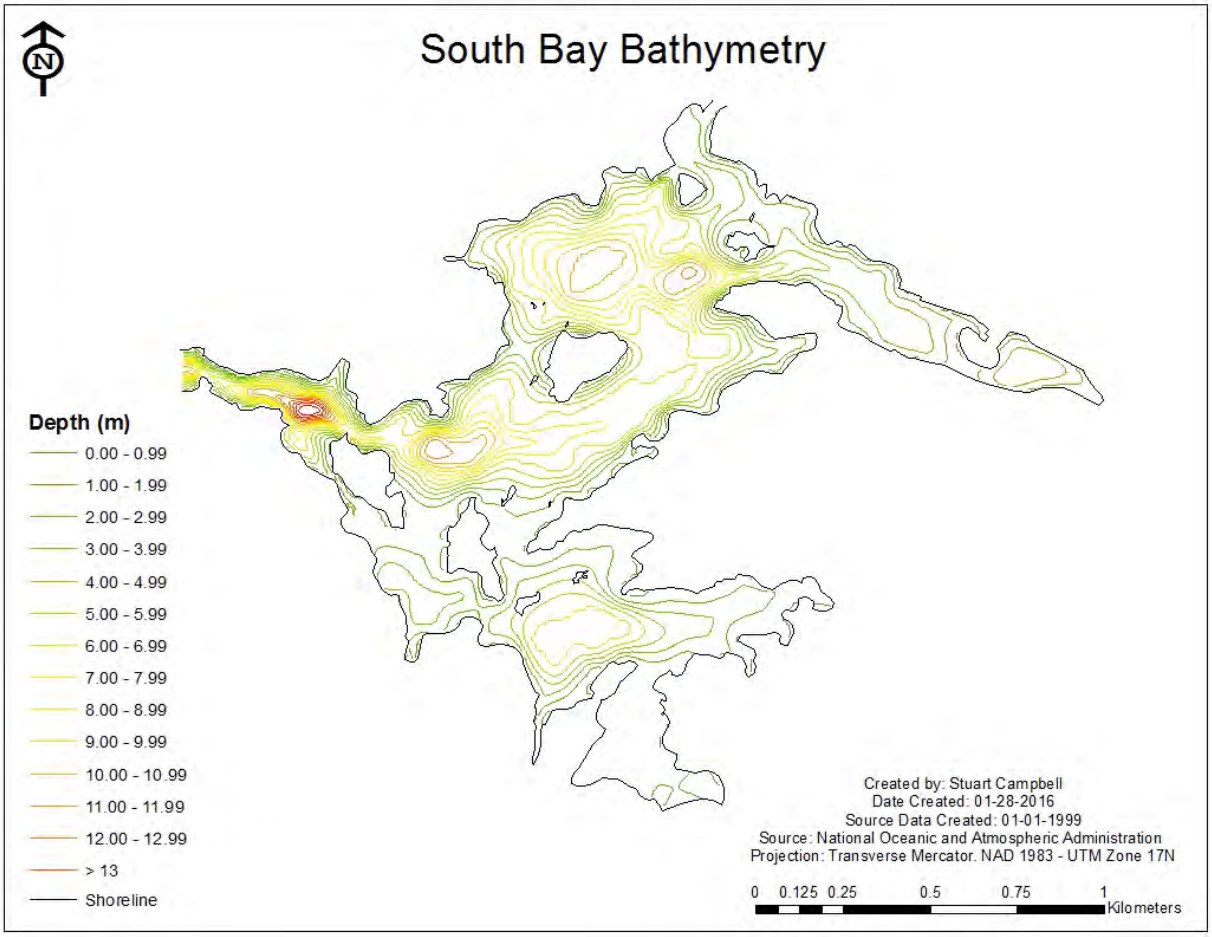
Bathymetry of Longuissa Bay



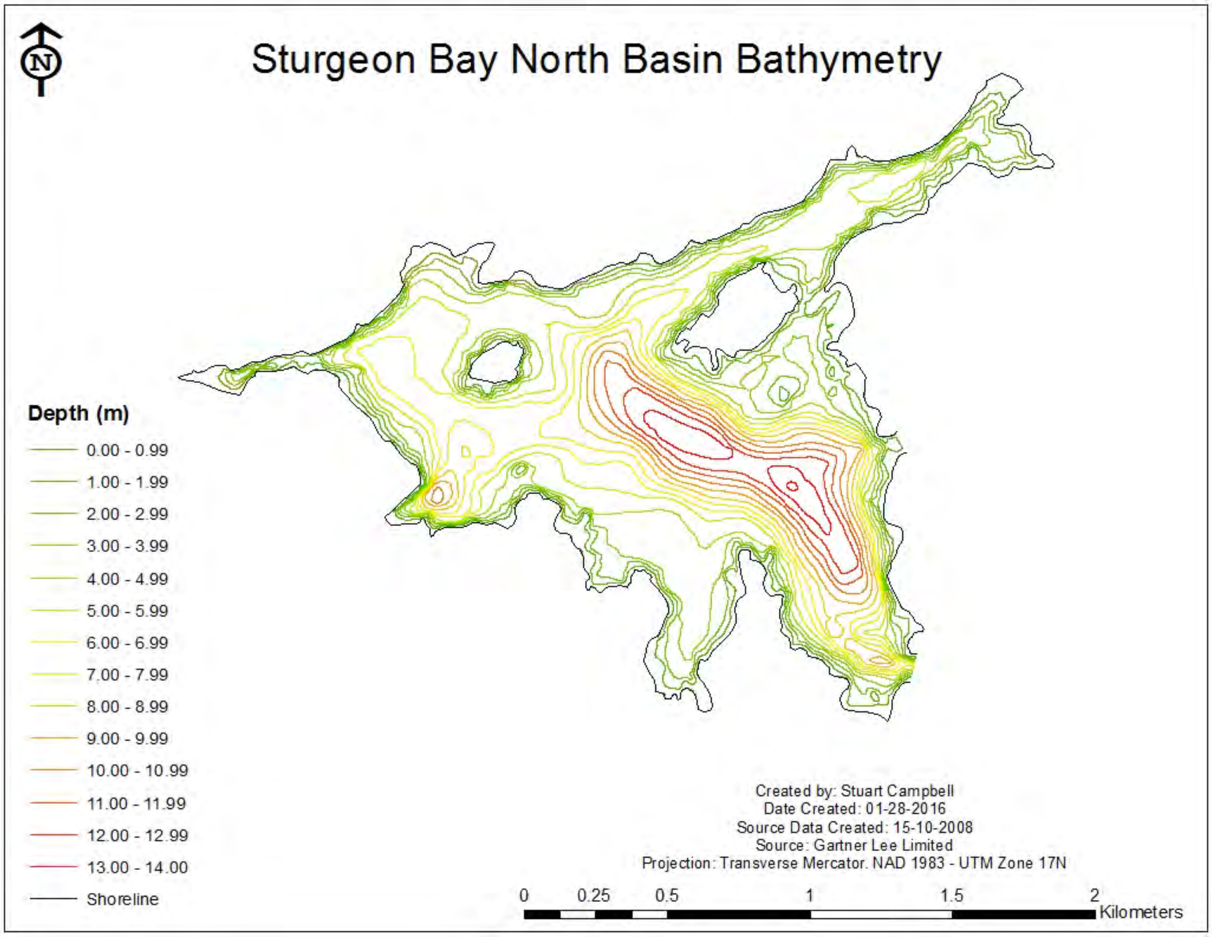
Bathymetry of Musquash Bay



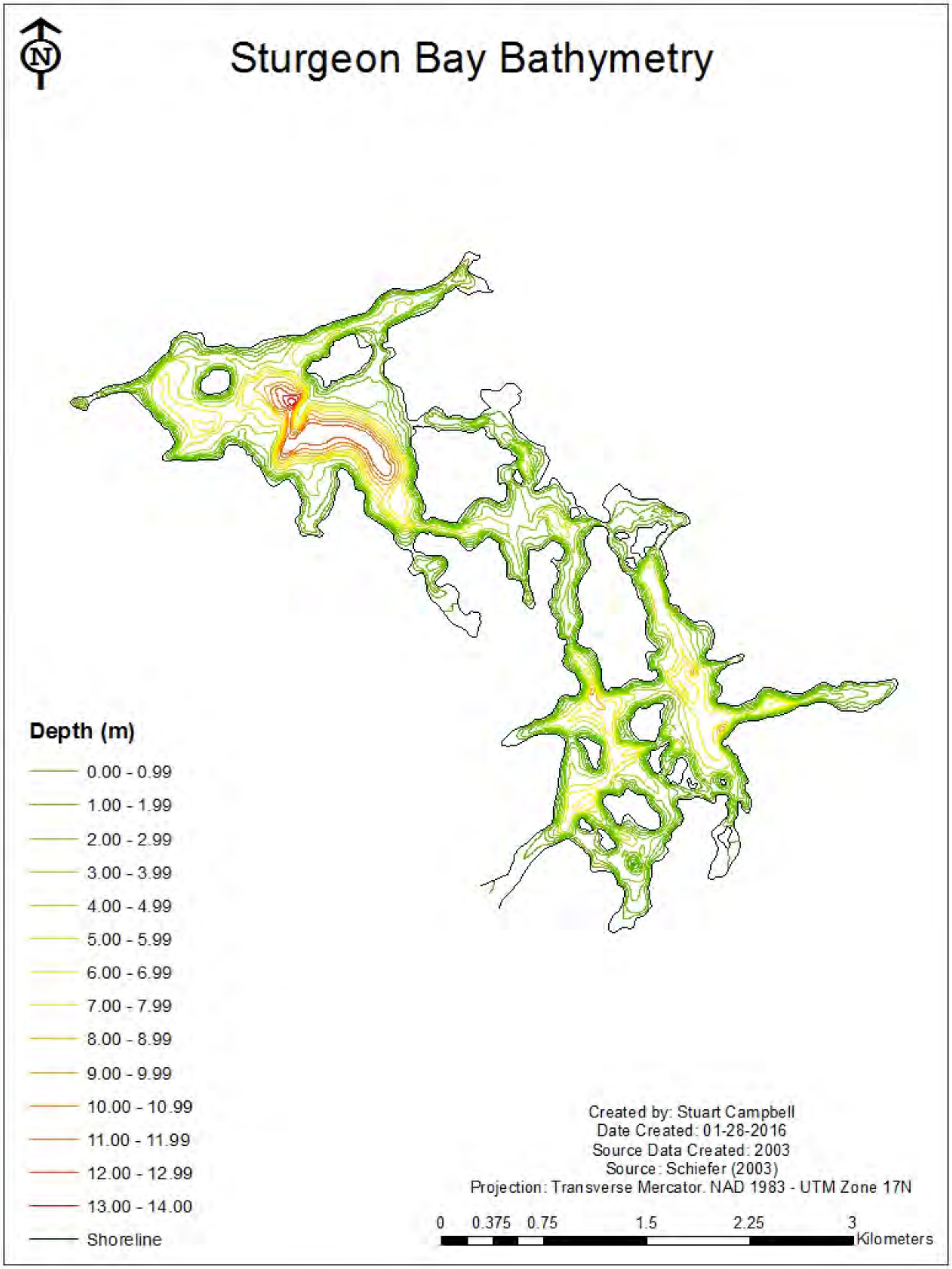
Bathymetry of North Bay



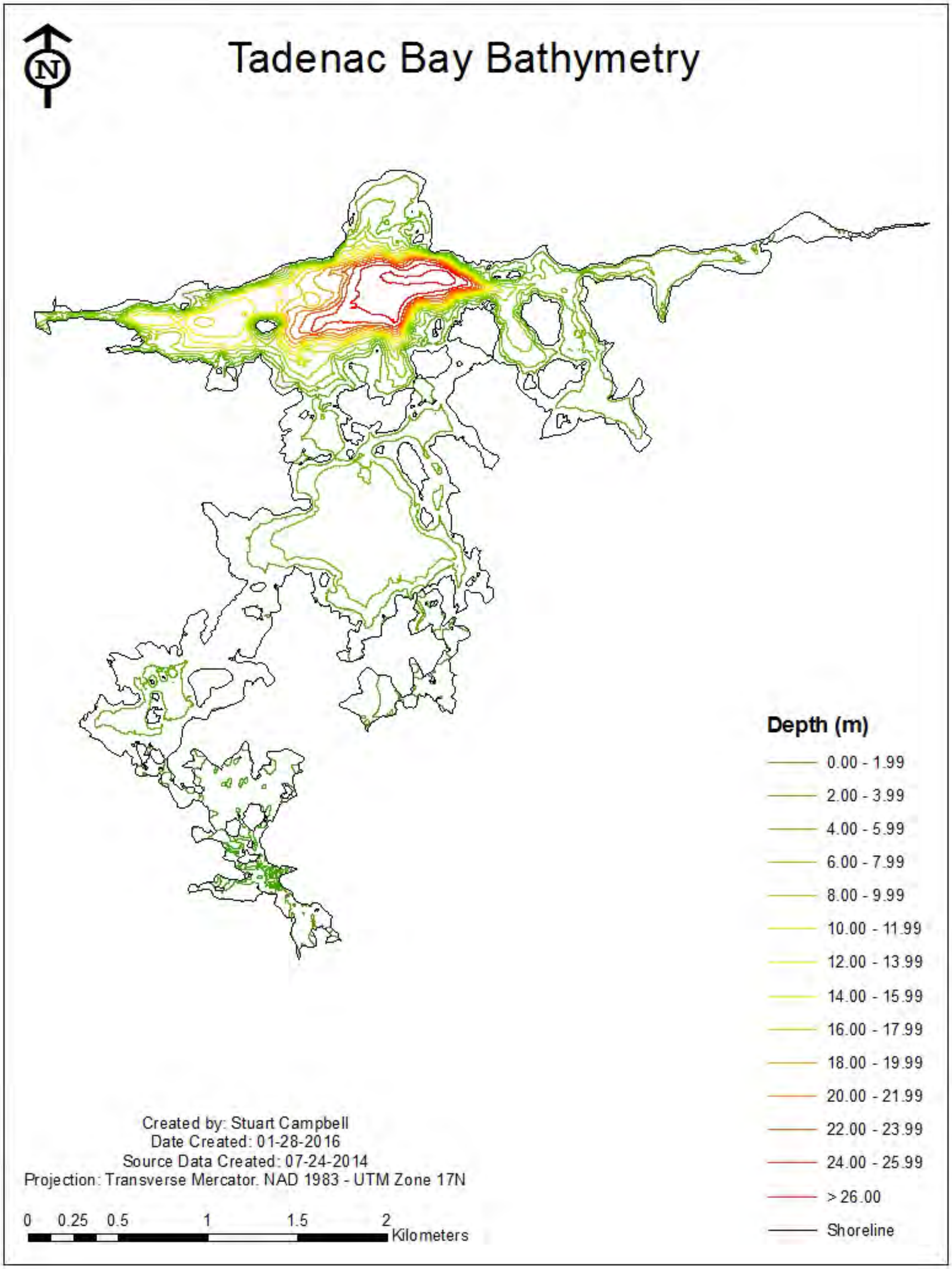
Bathymetry of South Bay.



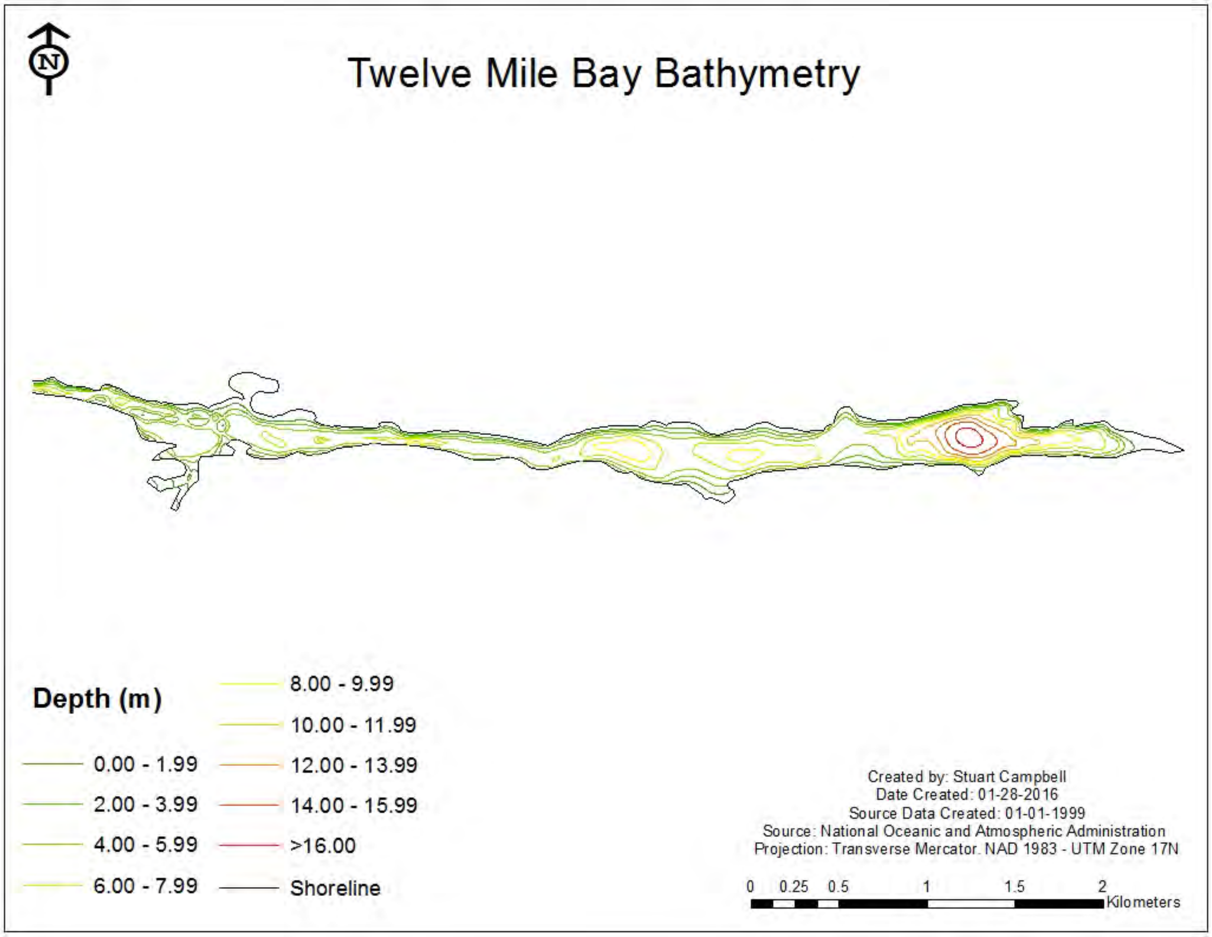
Bathymetry of Sturgeon Bay, North Basin



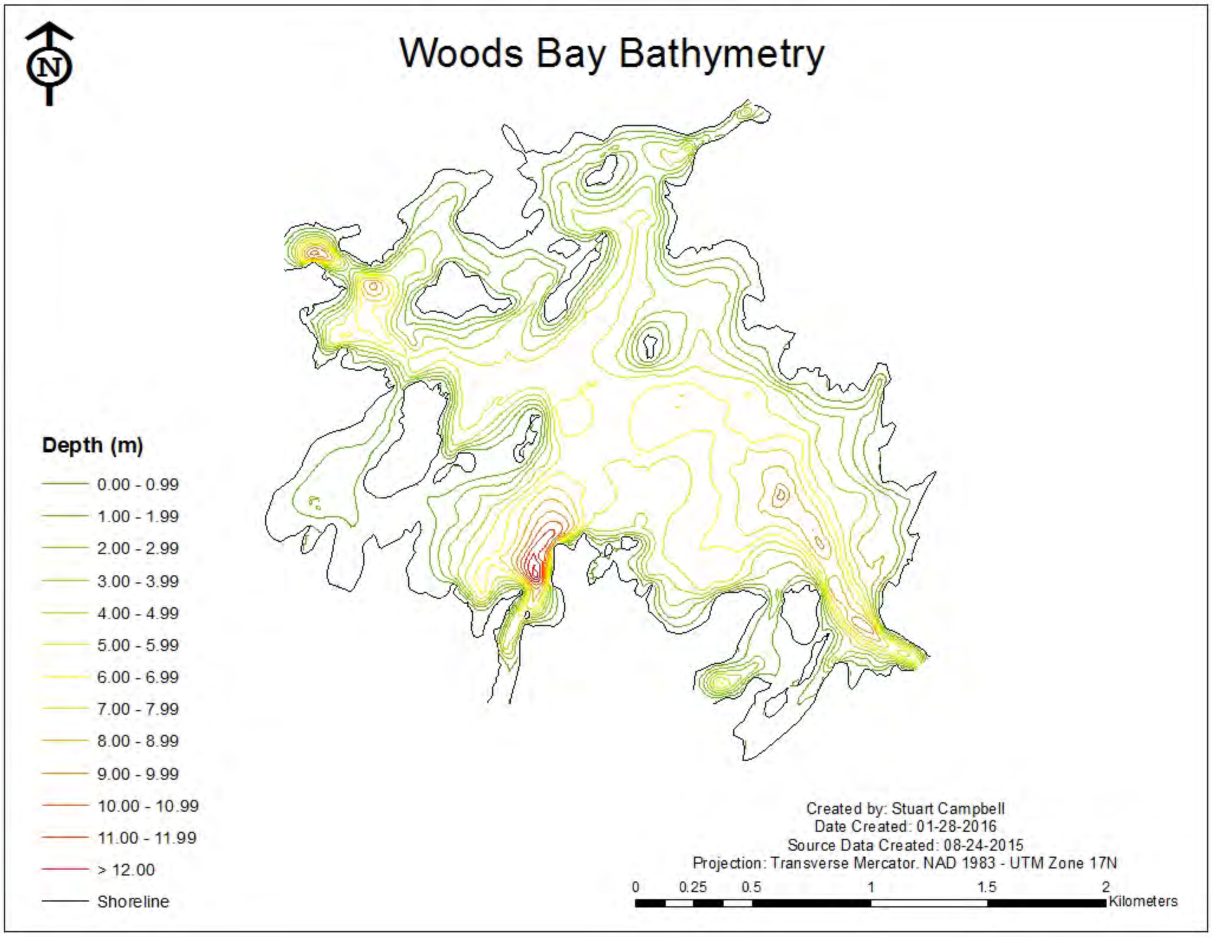
Bathymetry of Sturgeon Bay



Bathymetry of Tadenac Bay.



Bathymetry of Twelve Mile Bay.



Bathymetry of Woods Bay.

Satellite-based Assessment of Nutrient Status and Distribution of Algal Growth in Eastern Georgian Bay

Project Performance Report

Sub-grant of Environment Canada Grant Project 2014R00105

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March 31, 2015

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Project Summary

As part of Environment Canada grant project #2014R00105 entitled "Assessing nutrient status and distribution of algal growth along a gradient of cottage development in 10 sheltered embayments in eastern Georgian Bay" (PI Dr. Patricia Chow-Fraser of McMaster University), a research team of the Michigan Tech Research Institute (MTRI) used satellite remote sensing data to produce a suite of water characteristic and vegetation products for the study region, the eastern portion of Lake Huron's Georgian Bay.

These products include an updated submerged aquatic vegetation (SAV) distribution map derived from Landsat 8 imagery, a time series of Landsat-based SAV maps extending back to 1985, as well as monthly maps of lake surface temperature and color producing agent (CPA - chlorophyll-a, dissolved organic carbon and suspended minerals) concentrations. The overall purpose of this initiative was to summarize and synthesize environmental information on the study area that is available from existing remote sensing products developed by MTRI and to fine-tune those products for Georgian Bay conditions, as data contributions to Dr. Chow-Fraser's larger study on algal growth and nutrient status. Field data collected in southeastern Georgian Bay in July 2014 by MTRI staff were used to validate these products.

The current and historic surface temperature, CPA profiles and SAV distribution in this area are of interest both because this is a relatively pristine area of the lower Great Lakes and in view of the qualitative changes in these characteristics reported for the area. Prior to this project, the lack of monitoring and research in the study area meant that the ecological effects of recent changes including lower water levels, shifts in nutrient availability and invasions by non-native species have not been clear. The principal management concerns for the area include nutrient concentrations and related excessive benthic and planktonic algae, low dissolved oxygen concentrations (DOC) in the water column, and the loss and degradation of aquatic habitat. More environmental data are also needed to inform efforts to rehabilitate the lake trout population in Georgian Bay.

This project was undertaken with financial support from Environment Canada's 2013-2017 Lake Simcoe/South-Eastern Georgian Bay Clean-Up Fund.

Project Activities and Accomplishments

Mapping Submerged Aquatic Vegetation (SAV)

Updated SAV Map for Georgian Bay from Landsat 8

In 2013, MTRI created lake-wide maps of the distribution of nearshore SAV ca. 2010 for Lakes Michigan, Huron, Erie and Ontario (Brooks et al. 2015). Using the visible blue and green spectral bands of the Landsat Thematic Mapper (TM) sensor, MTRI applied a classification method involving a band ratio technique for water column depth correction based on methods developed by Lyzenga (1978, 1981, and Lyzenga et al. 2006). The nearshore regions of these lakes were classified as dense SAV, sparse SAV or uncolonized substrate. Based on previous surveys, most of this SAV was likely *Cladophora* algae (Shuchman et al. 2013). At the basin level, this method achieved an overall accuracy of 83%. Building on this product, here we utilized the more advanced, newer Landsat 8 sensor to create a more detailed and up-to-date 2013 growing season map of SAV for the study area (Figure 1). Landsat 8, launched in February 2013, presents several improvements over the Landsat 5 and 7 sensors, including a significantly better signal-to-noise ratio and 12-bit quantization enabling a wider range of response values to be captured. The updated, Landsat 8-based 2013 map was validated via comparison with field data on lake bottom types collected in eastern Georgian Bay by the MTRI field team in July 2014.

The updated 2013 map (Figure 1) and the original basin-wide map corresponding to ca. 2010 (Figure 2) indicate similar patterns of SAV growth. The 2013 map identifies somewhat more SAV growth on the rocky substrates offshore from Parry Sound and less vegetation around the Penetanguishene Peninsula.

Figure 1: Map of submerged aquatic vegetation (primarily benthic algae) derived from Landsat 8 imagery collected in mid-August 2013.

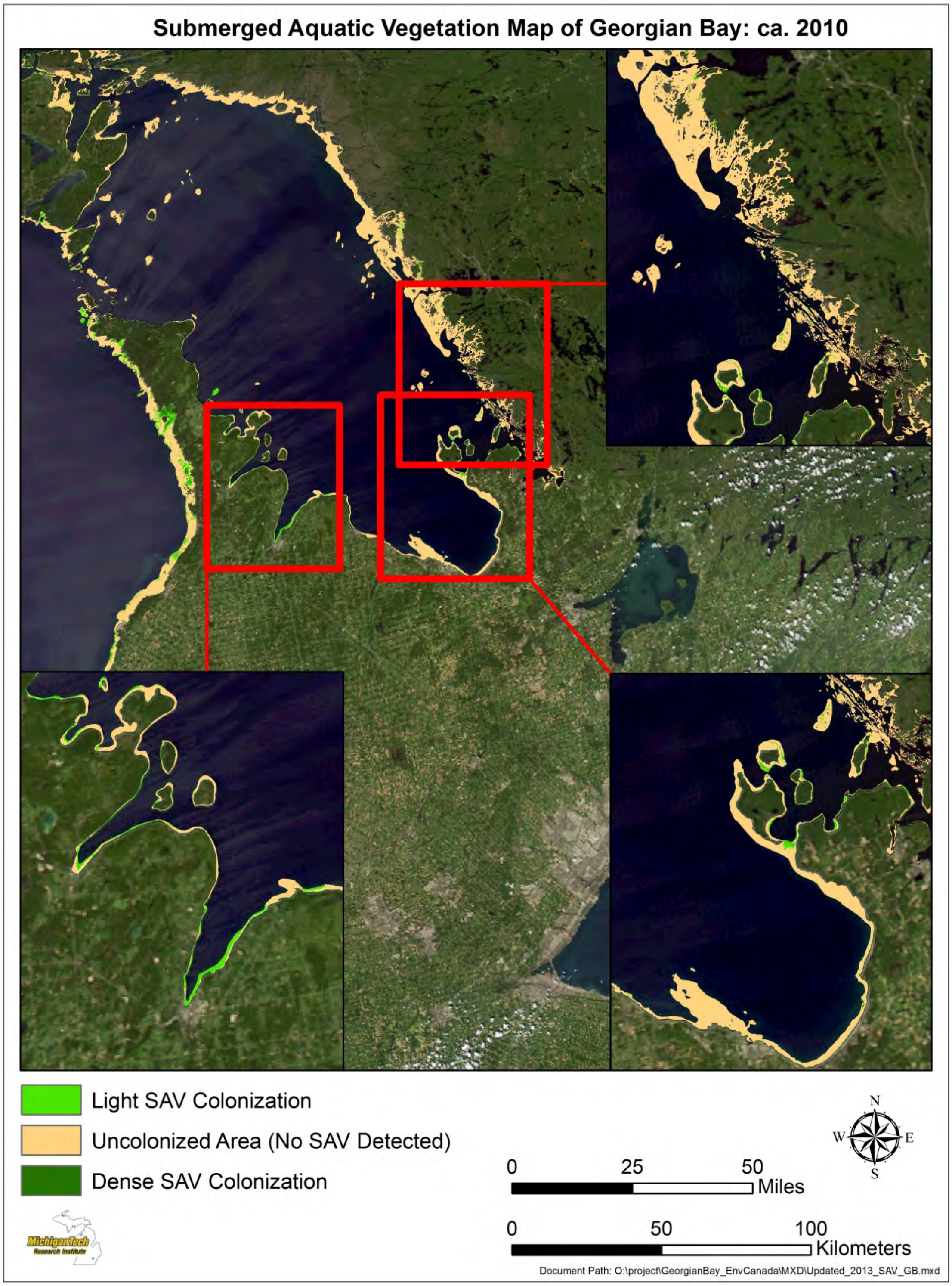

Figure 2: Original map of submerged aquatic vegetation derived from Landsat 5 imagery and corresponding to ca. 2010 described in Brooks et al. 2015.

Table 1 below compares the update to the ca. 2010 map. The bottom detection depth limit, i.e., the maximum water depth at which the lake bottom could be classified, was similar between the two maps (12.7 vs. 12.4 meters). However, because we were utilizing a shorter time series of imagery to construct the 2013 map, there were a few areas that could not be classified because the water was consistently too turbid in 2013. For this reason, the total mapped area was slightly higher for the 2010 map than for the 2013 update. In both maps, approximately 5% of pixels were classified as SAV. Based on previous field measurements of *Cladophora* density in the Great Lakes (Brooks et al. 2015), the estimated biomass of the satellite-visible nearshore SAV in Georgian Bay is between 3,000 and 6,000 metric tons (dry weight).

Table 1: Characteristics of ca. 2010 basin-wide SAV map and 2013 Landsat 8 update.

	Landsat 8, August 2013	**Landsat 5, ca. 2010**
Bottom detection depth limit (m)	12.7	12.4
Total mapped area (km^2)	1047	1167
Percent of mapped area classified as SAV	4	6
Nominal SAV biomass estimate based on 50 g DW/m^2 (metric tons)	2985	3325
Upper SAV biomass estimate based on 100 g DW/m^2 (metric tons)	5970	6650

<u>Validation of 2013 map</u>

On July 21-22, 2014, Amanda Grimm, Nate Jessee, and Zach Raymer of MTRI collected ground truth data on the distribution of submerged aquatic vegetation (SAV) in eastern Georgian Bay to validate MTRI's SAV map product. As a secondary objective, at a subset of sites, the field team used an Analytical Spectral Devices, Inc. (ASD) FieldSpec3 Spectroradiometer to acquire spectral data at the water surface and a chlorophyll fluorometer to measure chlorophyll-a concentrations. These data were collected to help evaluate and train MTRI CPA results. Finally, a Secchi disk was used to estimate water clarity at each site. The locations of the 76 visited sites offshore from Parry Sound are shown in Figure 3.

At all validation sites, the bottom substrate was observed using an underwater drop camera, and the percent cover, height and type of SAV were recorded and water clarity was estimated with a Secchi disk. Using the sampling density scheme developed by C. Brooks for Shuchman et al. 2013 and Brooks et al. 2015, based on Congalton and Green 2008, it was determined that a minimum of 50 underwater image SAV density samples were needed to produce statistically meaningful validation results. This minimum was exceeded (of the 76 visited sites, 61 were mappable with Landsat for a total of 61 map/ground truth comparisons).

At six field points, the ASD spectroradiometer was used to collect spectra at the water surface by a trained technician (Z. Raymer) and a FluoroProbe was used to estimate chl-a concentrations along the water column. The FluoroProbe was also deployed at 5 non-CPA field points. Finally, a handheld AquaFluor fluorometer, less accurate but faster than the FluoroProbe, was used to estimate surface chl concentration at 41 points.

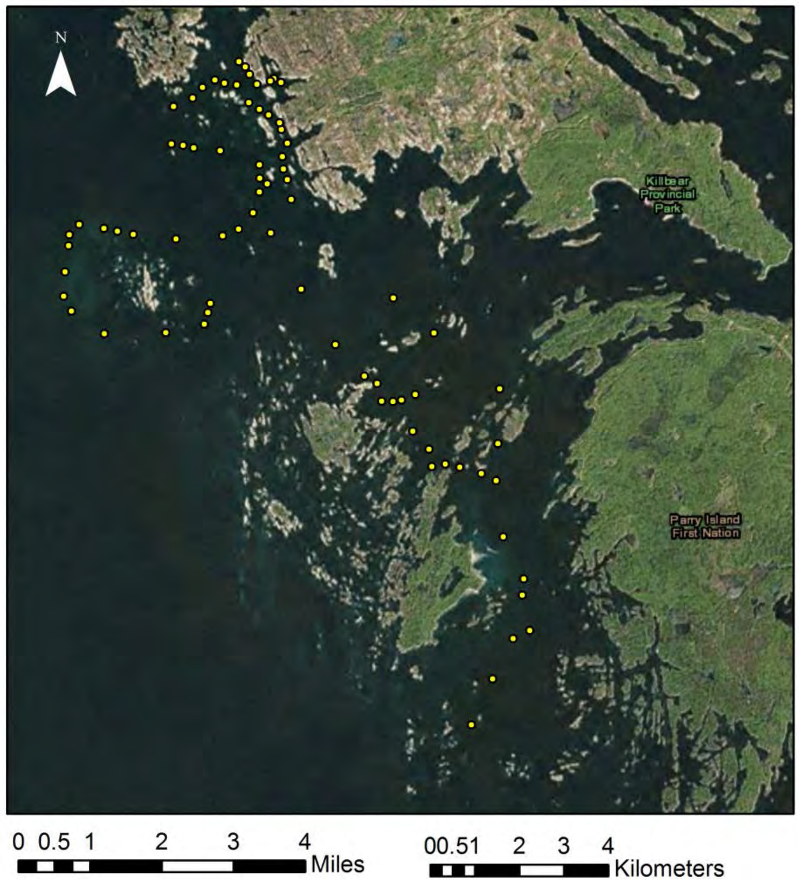

Figure 3: Locations of ground truth (water truth) points visited in July 2014.

The comparison of SAV classes derived from a 2013 Landsat 8 image to the field data collected in July 2014 resulted in an overall classification accuracy of 85% (Table 2). Both the classified map and ground truth data indicate a low amount of SAV cover in the surveyed area offshore from Parry Sound. Most bottom substrates were rocky and therefore likely to be physically suitable for SAV colonization, with lower numbers of sand/sediment sites.

Table 2: Confusion matrix of 2013 Landsat 8-based map and 2014 field data.

	Ground Truth				
Map Classes	**SAV**	**Bare Substrate**	**Row Total**	**Users Accuracy**	**Commission Error**
SAV	4	1	5	80.0%	20.0%
Bare Substrate	8	48	56	85.7%	14.3%
Column Total	12	49	61		
Producers Accuracy	33.3%	98.0%			
Omission Error	66.7%	2.0%		**Overall Accuracy:**	85%

Time series analysis

In addition to producing the updated map of present-day conditions, MTRI applied the depth correction methodology to the available archive of Landsat TM imagery to develop a time series of SAV distribution at five year intervals from the beginning of Landsat TM data collection (mid-1980s) to the present. MTRI has already created such time series for six areas spread across the four lower Great Lakes that were of interest based on extensive local SAV growth (see Brooks et al. 2015). This previous work demonstrated the capacity of the MTRI classification process to track changes in SAV extent for an area of interest over time.

Maps classified from Landsat 5 images collected in 1985, 1990, 1995, 2000, and 2005 were compared to the 2011 and 2013 Landsat-based maps. The nearshore areas that could be classified in each of the 7 maps were intersected to identify the area that was classified in all years. The percentage of this standardized area classified as SAV in each year was then compared. As Figure 4 indicates, SAV cover was higher in 1985 and 1990 (>10%) and has declined monotonically since that time. This corresponds with a similar decline observed for an area along the Bruce Peninsula in Landsat time series imagery, presented in Brooks et al. 2015.

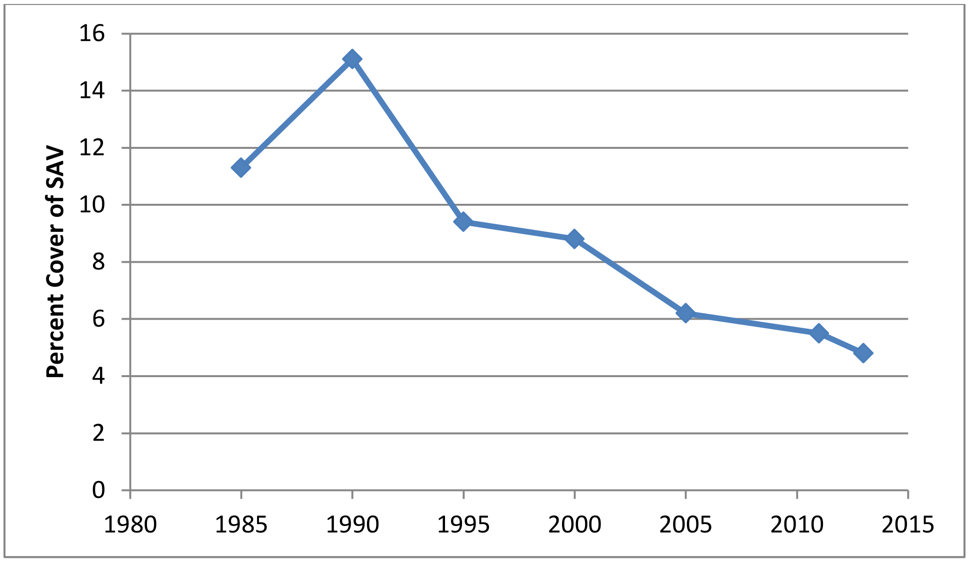

Figure 4: Change in percent cover of SAV for the nearshore areas mappable in all years of the Landsat time series.

Previous work by MTRI has documented that increasing water clarity across the Great Lakes basin can be observed in the form of an increasing satellite optical depth over time. This is also true for Georgian Bay, where satellite optical depth generally increased from the beginning to the end of the time series (Figure 5). Water clarity was particularly high in 2000, indicating that Landsat happened to capture that image under unusually good optical conditions. The Landsat optical depth for the 2013 image was not included in Figure 5 because the image was collected by a different sensor (Landsat 8) with different characteristics that enable it to detect bottom reflectance from deeper water.

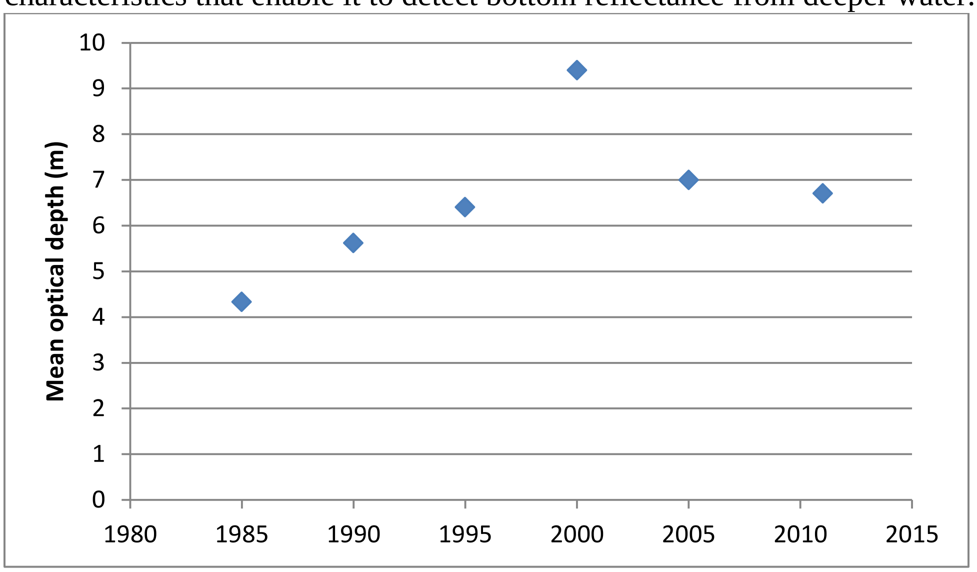

Figure 5: Change in Landsat optical depth in Georgian Bay over time.

The change in satellite optical depth described above, along with variations in the nearshore areas that could be mapped related to the locations of sediment plumes and other obstacles, resulted in high variation in the total area of nearshore lake bottom that could be mapped over the time series. In general, increasing water clarity resulted in a corresponding increase in the mappable area within the bay (Figure 6). Figure 6 emphasizes the pattern that SAV percent cover has always been low in Georgian Bay. While the percent cover has decreased overall, it was not high to begin with compared to most areas of the Great Lakes that are shown in Brooks et al. 2015.

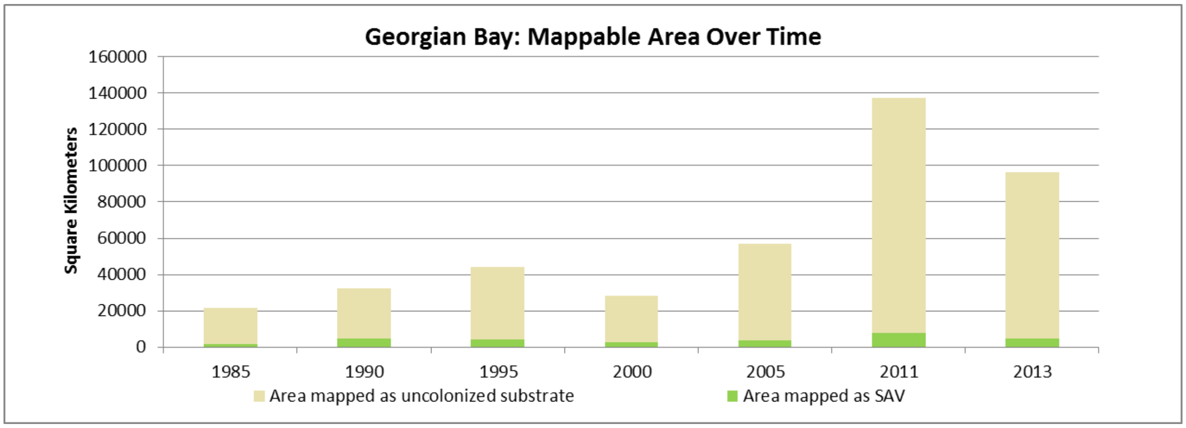

Figure 6: Areas mapped as SAV and colonized substrate in each year of the Landsat time series analysis.

Lake Surface Temperature (LST)

Satellite-derived remote sensing lake surface temperature (LST) retrievals from the MODIS Aqua satellite sensor were collected and processed by MTRI for all cloud-free dates in Georgian Bay from July 2002 through January 2013. The LST product used by MTRI is derived from the 3.7–4.2 µm wavelength range utilizing MODIS bands 20, 22, and 23. This particular LST product is collected by the MODIS sensor during the overnight pass and has proven to be more accurate than the 10–12 µm daytime collection (Brown and Minnett, 1999). These derived LST data have been acquired from the NASA OceanColor web portal, georeferenced using ENVI geospatial imagery software and mapped using ArcGIS Desktop. All cloud-free imagery from August 2002 through present day were delivered as GeoTIFF raster files for further analysis in GIS. Figure 7 is an example of an LST map generated by MTRI and delivered to Dr. Chow-Fraser.

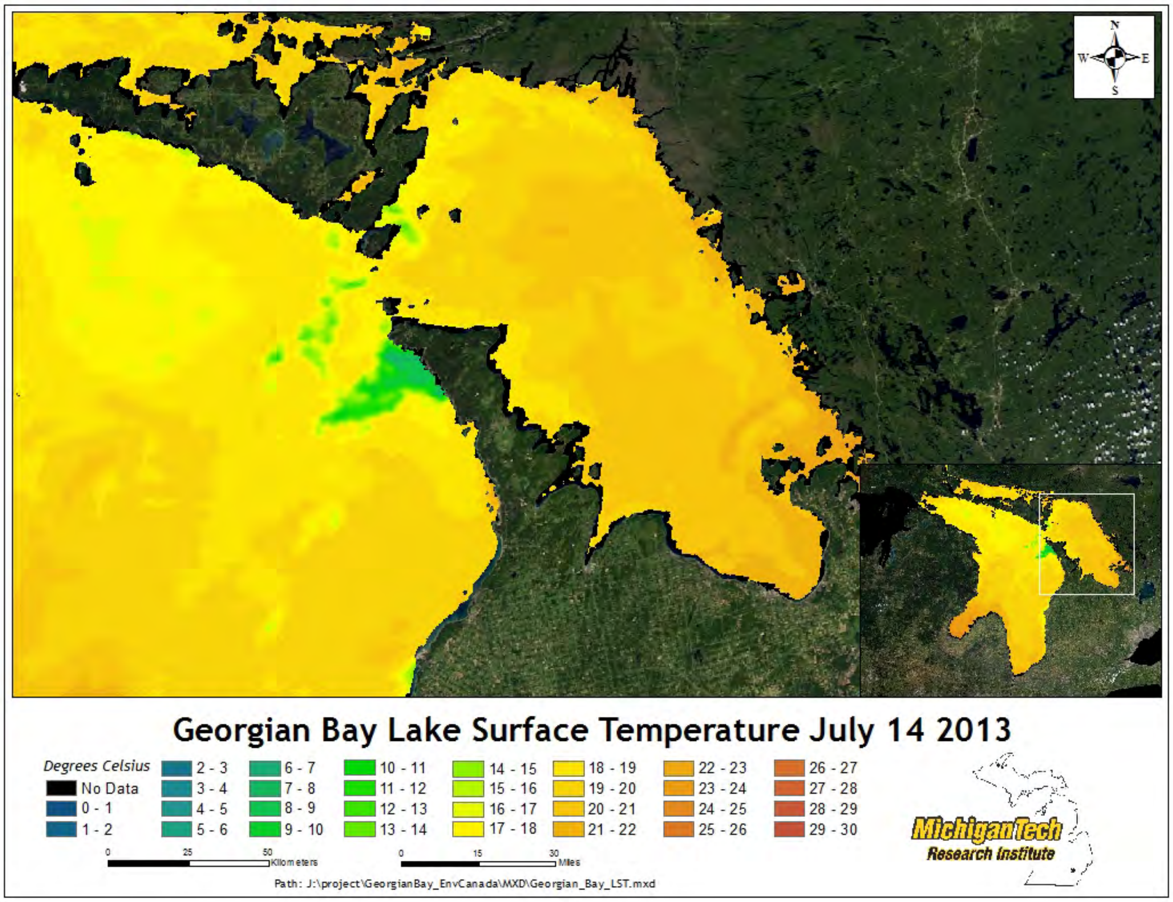

Figure 7: Example remote sensing-derived lake surface temperature map of eastern Georgian Bay on July 14, 2013.

For the LST products, a total of 460 GeoTIFF files were delivered. The following table summarizes the number of satellite scenes per year.

Table 3: Lake Surface Temperature scenes delivered by MTRI.

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Scenes	13	13	38	61	49	61	47	53	66	34	50	50

Color-Producing Agents

In addition to the lake surface temperature data, a robust satellite-derived chlorophyll (CHL), dissolved organic carbon (DOC), and suspended minerals (SM) algorithm has been developed and successfully validated for the Great Lakes (Pozdnyakov et al. 2005 and Shuchman et al. 2013), called the color producing agent algorithm (CPA-A). In particular, in situ data was collected and tested against our current algorithms allowing us to utilize a hydro-optical model tuned for Georgian Bay. This algorithm detects and estimates the concentrations of color producing agents in optically complex "Case II" waters of the Laurentian Great Lakes. This algorithm primarily utilizes imagery from the MODIS Aqua satellite sensor but is also capable of using data from the newly deployed VIIRS sensor and historical data from the MERIS and SeaWiFS sensors. Like the LST products, MTRI generated CPA maps of all five of the Laurentian Great Lakes from August 2002 through January 2013. These data were delivered as GeoTIFF files and further validated with new field data collected in Georgian Bay. The data files shared are monthly averages for all months starting in August of 2002 through January of 2013 for a total of 139 monthly averages for each CPA variable. In addition to the three CPA products, MTRI also shared the colored dissolved organic matter (CDOM) data layer, which is used to calculate DOC using a regression formula tested using in situ data. The CDOM layer corresponds to specific absorption at the 443 nm wavelength. Figure 8 is a representative example of remote sensing derived concentrations of the three CPAs and CDOM in Georgian Bay.

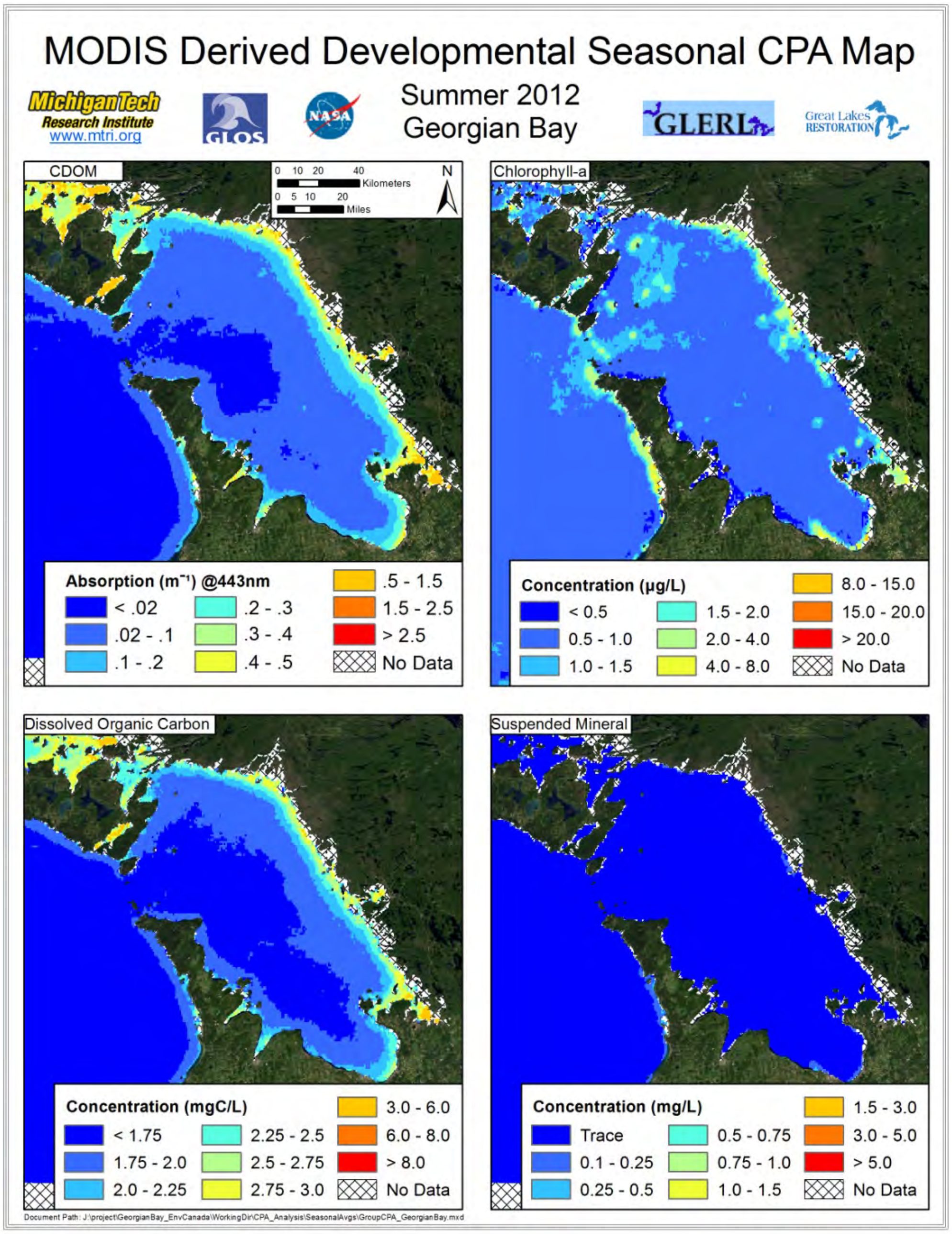

Figure 8: Example CPA outputs for Georgian Bay based on MODIS imagery averaged between June and August of 2012. The same types of satellite imagery-based mapping were produced for the 2002-2014 MODIS time period.

References

Brooks, C., Grimm, A., Shuchman, R., Sayers, M., & Jessee, N. (2015). A satellite-based multi-temporal assessment of the extent of nuisance *Cladophora* and related submerged aquatic vegetation for the Laurentian Great Lakes. *Remote Sensing of Environment* 157: 58-71.

Brown, O., Minnett, P., Evans R., Kearns E., Kilpatrick K., Kumar A., Sikorski R. and Zavody A. (1999). MODIS Infrared Sea Surface Temperature Algorithm, Algorithm Theoretical Basis Document Version 2.0. University of Miami, Miami, FL. Contract Number: NAS5-31361. Retrieved on 3/27/15 from http://modis.gsfc.nasa.gov/data/atbd/atbd_mod25.pdf

Lyzenga, D.R. (1981). Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. *International Journal of Remote Sensing 2:* 71–72.

Lyzenga, D. R., Norman P. Malinas, and Fred J. Tanis. (2006). Multispectral Bathymetry Using a Simple Physically Based Algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, Vol 44, No 44, 2251-2259.

Lyzenga, D. R. (1978). Passive remote sensing techniques for mapping water depth and bottom features. *Applied Optics*, Vol 17, 379-383.

Pozdnyakov, D., Shuchman, R., Korosov, A., Hatt, C., (2005). Operational algorithm for the retrieval of water quality in the Great Lakes. *Remote Sensing of Environment*. 97, 353-370.

Shuchman, R. A., Sayers, M. J., & Brooks, C. N. (2013). Mapping and monitoring the extent of submerged aquatic vegetation in the Laurentian Great Lakes with multi-scale satellite remote sensing. *Journal of Great Lakes Research*, 39(S1), 78-89.

Shuchman R. A., G. Leshkevich, M. J. Sayers, T. H. Johengen, C. N. Brooks, and D. Pozdnyakov. (2013). An algorithm to retrieve chlorophyll, dissolved organic carbon, and suspended minerals from Great Lakes satellite data. Special Issue on Remote Sensing of the Great Lakes and other Inland Waters. Supplement 1, *Journal of Great Lakes Research* Vol. 39(S1), 14-33.