Severn Sound

Environmental Association

Report on Water Quality from 2010 - 2012 in the Honey Harbour Area of Georgian Bay

March 2014

Report on Water Quality from 2010 - 2012 in the Honey Harbour Area of Georgian Bay

Prepared by Aisha Chiandet and Keith Sherman
Severn Sound Environmental Association

for the

Township of Georgian Bay

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FOREWORD

This document reports on technical investigations conducted by SSEA in the Honey Harbour area from 2010 to 2012 for the Township of Georgian Bay. The monitoring surveys were part of the Severn Sound Environmental Association Open Water Monitoring Program.

The report received technical review prior to its publication. This does not necessarily signify that the contents reflect the views and policies of the Corporation of the Township of Georgian Bay or the Ontario Ministry of the Environment. Mention of trade names or commercial products does not necessarily constitute endorsement or recommendation for use.

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Severn Sound Environmental Association
67 Fourth Street
Midland, Ontario, L4R 3S9
Phone: (705) 527-5166

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Acknowledgement is also extended to Dr. Todd Howell, Dr. Jim Rusak, Judi Brouse and Don Evans for their assistance and helpful comments.

Paula Madill, SSEA Sampling Technologist, coordinated the open water field work for the survey and conducted most of the sampling with assistance from SSEA summer staff. Lex McPhail, SSEA Applications Specialist, provided mapping support and assisted with GIS data analyses for this report.

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EXECUTIVE SUMMARY

The objectives of the SSEA monitoring program in the Honey Harbour area include:

1. Identify seasonal and annual trends in water quality, specifically with respect to phosphorus, nitrogen, water clarity, and chlorophyll *a*;
2. Describe temperature and dissolved oxygen profiles for North Bay, South Bay and Honey Harbour, including patterns in metalimnetic and hypolimnetic oxygen depletion
3. Identify trends in biovolume of major phytoplankton groups and of specific taxonomic groups of interest such as *Chrysosphaerella*, *Peridinium*, *Microcystis*, and other blue-green algae. Describe patterns of change in community composition;
4. Identify trends in zooplankton biomass, density, and richness; Describe patterns of change in community composition; and
5. Relate changes in water quality, phytoplankton and zooplankton community composition with other factors affecting the quality of the bays.

The SSEA Honey Harbour monitoring program is accomplished through partnership with the Township of Georgian Bay, the District Municipality of Muskoka and the Ontario Ministry of the Environment (MOE), and is coordinated with the SSEA open water monitoring program in Severn Sound and with other monitoring carried out through Georgian Bay Forever. Monitoring results are shared with the Township, the District, and the MOE. The District uses the nutrient results and temperature/oxygen profiles on their website. Results from water quality monitoring and other SSEA work in the area from past surveys is included in reports and publications from SSEA and in university research studies.

SUMMARY OF FINDINGS

Trophic Indicators

Trophic indicators typically used to assess the status of Severn Sound have been measured in the euphotic zone of three Honey Harbour area stations over the last 20 years (Station NB, in upper North Bay; SB, in South Bay north of Cow Island; and HH, off Royal Island in Honey Harbour). A reference station (M5) has also been sampled from 2003 to 2012 to compare a deep open water station with the deep basin of NB. Based on these indicators, the trophic status of upper North Bay is considered moderately enriched or mesotrophic, the status of South Bay is considered enriched or eutrophic, and the Honey Harbour area is considered moderately enriched.

Rooted Aquatic Plants in the Nearshore of Honey Harbour

Rooted aquatic plants “lock up” nutrients in their tissues during the growing season, denying these nutrients to the phytoplankton. This process is extremely important to the quality of these bays, especially South Bay which has a shallower basin and a larger amount of littoral zone to support these plants. Destruction of the rooted plant beds or an imbalance in nutrient loading could give phytoplankton a competitive nutrient advantage and promote shading out of rooted aquatic plants, resulting in nuisance growths of algae where rooted plants had once thrived. A healthy balanced ecosystem in these bays includes healthy growths of rooted aquatic plants.

Thermal Stratification and Oxygen Depletion

The deeper bays, including upper North Bay and South Bay, experience an annual cycle of thermal stratification where in spring the water column has a uniform cold temperature after ice out, a period called spring turnover. As the spring progresses to early summer, the surface waters warm, inducing a thermal stratification that persists through the summer and into the fall. The layering results in a mixed warm upper layer (the epilimnion), a zone of rapid temperature decline (the metalimnion or the thermocline) and a zone of colder water beneath (the hypolimnion). As the late fall approaches, the surface waters cool until they reach a temperature similar to the bottom waters. At this time the entire water column becomes mixed, a period called fall turnover. Depending on how stable the thermal stratification becomes and the depth and shape of the bay, the thermocline acts as a “lid”, sealing off the hypolimnion. The oxygen present in the hypolimnion in spring is depleted by decomposition processes over the course of the season. The thermocline in upper North Bay is a much more effective barrier to mixing than that of South Bay. North Bay also experiences a decline in oxygen concentration within the thermocline. Monitoring has shown that oxygen conditions in the hypolimnion of North Bay and South Bay have not changed over the period of record. Honey Harbour area is too shallow to experience thermal stratification and the deep open waters of Severn Sound are exposed to winds and currents so that thermal stratification lasts only days at a time.

Water Clarity

Water clarity as measured by Secchi disk visibility (SDV) over the 2010-2012 sampling period has been relatively uniform between all three Honey Harbour stations ranging from 2.6 to 3.4 m and 3.3 to 4.1 m at M5. Station M5 has been improving in recent years while values at all three Honey Harbour stations are lower compared to historical values.

Total Phosphorus (TP)

Mean TP euphotic zone concentrations met the RAP target of 15 µg/L at all stations from 2010 to 2012. TP concentrations at NB and SB were not shown to be significantly different from each other, but were significantly greater than concentrations at HH and M5, which in turn were not significantly different from each other. The high degree of sheltering in North and South Bay isolates the more nutrient enriched waters from the more dilute open waters of Severn Sound, while the waters at Honey Harbour are subject to greater mixing with the open waters.

No seasonal trend in TP was found at the four stations monitored during 2010 to 2012, indicating that TP in the euphotic zone was not being enriched or depleted through the summer season. During mid-July for each of 2010, 2011 and 2012, TP in the bottom waters (1 m off bottom) at NB increased compared to concentrations in euphotic zone composites. The timing of this increase coincided with bottom water oxygen depletion (to less than 1 mg/L). Phosphorus was apparently being released from the sediments due to the oxygen depleted conditions next to the sediments, causing internal loading of phosphorus to the hypolimnion.

During 2011, there was an increase in TP concentration through the water column at fall turnover, when phosphorus-rich bottom waters mixed with the upper waters, compared to the TP concentration during spring turnover of the same year. The increase in phosphorus mass represented by this difference represents approximately 10-20% of the external phosphorus load to upper North Bay at fall turnover 2011. A reduction in TP occurred from fall turnover of 2011 to spring turnover in 2012. There was an almost equal loss of P over the winter of 2011/12, accounting for approximately 16% of the external loads by spring turnover in 2012. Processes contributing to this loss are unknown at this time. The added phosphorus mass in the water column at fall turnover may settle to the lakebed during winter.

As in North Bay, South Bay, bottom water TP increased compared to concentrations in the euphotic zone, except where the hypolimnion was thinned by low water levels as in the fall of 2012, which probably caused increased exchange with upper waters.

Nitrogen

Total nitrate (nitrate+nitrite) concentrations in the euphotic zone was highest following the spring freshet at all stations, dropping quickly and then rising again with increased precipitation and runoff in the fall. Total ammonium (ammonium+ammonia) concentrations were more variable at NB and SB compared to HH and M5, and values were less than 80 µg/L at all stations. Euphotic zone concentrations of unionized ammonia (the toxic portion of total ammonium) were low and well below the MOE objective of 20 µg/L.

The values of total nitrogen at stations NB and SB are in the same range as historical concentrations, while values at HH and M5 are lower than historical concentrations.

Sulphate and Sulphide

Comparison of euphotic zone and bottom water sulphate concentrations, collected during 2012, showed that the reduction of sulphate to hydrogen sulphide (H_2S) occurred in the bottom waters at NB starting approximately a month after the onset of anoxia, but the reduction did not occur in the bottom waters of SB. No “rotten egg” odour that would indicate the presence of H_2S was observed on August 21 when bottom water sulfate dropped to 5.9 mg/L at SB. There was a strong smell of H_2S at NB beginning

September 9, corresponding to sulphate concentration of 5.0 mg/L. The odour of H_2S in the bottom water sample had disappeared at NB by Nov 15.

Metals

Generally, metal concentrations in samples from the four stations over the period 2010-2012 were low or below analytical detection. A small percentage of aluminum and copper samples exceeded the Provincial Water Quality Objectives. Iron in the bottom waters of North Bay and South Bay exceeded the aesthetic objective for iron, often after the onset of anoxic conditions.

From 2010-2012, total iron concentrations (includes soluble and insoluble forms) increased in the bottom waters compared to the euphotic zone at NB and SB as anoxia set in.

Phytoplankton

An understanding of the relationship between trophic indicators and the phytoplankton community is one of the most important aspects of water quality monitoring and surveillance for management and planning purposes. Several classes of algae make up the total biovolume of phytoplankton in the water column of the Honey Harbour area. Many of these groups or classes have members that can cause harmful algal “blooms” or heavy growths that can be a health concern or impair the use of the water for drinking or recreation. The total biovolume is controlled largely by the phosphorus concentration in the euphotic zone. Specific classes of algae, such as the blue-green algae, respond to additional factors such as temperature and wind conditions, which can result in growths that lead to harmful or nuisance conditions even where phosphorus concentrations are low.

Total phytoplankton biovolume from 1998 to 2012 have fluctuated from year to year at the three Honey Harbour stations but have not increased significantly. Total phytoplankton biovolumes are generally higher at the Honey Harbour stations than they are at the open water station.

The phytoplankton community has changed during the period from 1998-2012. In North Bay, the chrysophyte *Chrysosphaerella* and the dinophyte *Peridinium* have dominated the phytoplankton community in recent years. The proportion of *Chrysosphaerella* in particular have increased since 2008, reaching peaks greater than 80% of the total biovolume from 2009-2012. Vertical distribution measurements of phytoplankton pigments show that these and other species are selecting specific depths just above and within the thermocline in North Bay. By contrast with North Bay, blue-green algae dominate the phytoplankton community in South Bay during late summer, with peaks reaching 70% of the total biovolume. The blue-green algae *Anabaena* has become more dominant in South Bay in recent years.

Despite the need for concern and vigilance over the ecosystem changes noted, the water quality status of the area is not changing appreciable, and provides quality that does not impair recreational uses of the community. Due to their relative isolation, upper North Bay and South Bay should be considered sensitive as compared with the area of Honey Harbour that is more exposed to exchange with the open waters.

RECOMMENDATIONS

Based on the above findings, the following recommendations are made:

1. Continue monitoring the three stations in the Honey Harbour area during 2014.
2. Continued monitoring of the vertical distribution of nutrients, metals and phytoplankton biovolume in North Bay should be included in the study design.
3. Provide seasonal analysis of the phytoplankton community in South Bay for 2014.
4. Continue to coordinate efforts of various researchers working in the area to maximize the benefits of the monitoring program.
5. Develop a long-term rationale for indicators and monitoring protocols that take into account Great Lakes and global stressors influencing the Honey Harbour area. Include the following questions:
    - Why are blue-green algae blooms not more common in Severn Sound, including Honey Harbour?
    - Why do chrysophytes and dinophytes dominate in North Bay?
    - Why is clarity (SDV) worsening in Severn Sound, including Honey Harbour?
    - Why is TP declining or holding steady while total phytoplankton biovolume is fluctuating?
    - What form of phosphorus should be used as a trophic indicator? How can this be related to historical trends?
    - Why do nitrate concentrations start off higher in the spring and drop to near or below detection by early summer?
    - What factors influence nutrient conditions in the nearshore? Examine the impact of physical characteristics of the nearshore, runoff, Dreissenid mussels (zebra and quagga), shoreline alteration, water level fluctuations, and pollution sources.
    - Why has zooplankton biomass decreased since 2009 at all four stations monitored? Is this a regional phenomenon?
    - What are the dominant submerged rooted aquatic plants in North and South Bay? Has there been a change in plant communities?

INTRODUCTION

Good water quality is one of Georgian Bay's greatest assets. However, human activities can jeopardize this water quality if land use planning and responsible water recreation are not made priorities among governing agencies and residents in the area. The Honey Harbour area receives heavy recreational use. The area is sensitive to human activities, and will continue to be vulnerable if impacts are not minimized.

The SSEA Honey Harbour monitoring program is accomplished through partnership with the Township of Georgian Bay, the District Municipality of Muskoka and the Ontario Ministry of the Environment, and is coordinated with the SSEA open water monitoring program in Severn Sound and with other monitoring carried out through Georgian Bay Forever. Monitoring results are shared with the Township, the District, and the MOE. The District uses the nutrient results and temperature/oxygen profiles on their website. Results from water quality monitoring and other SSEA work in the area from past surveys is included in reports and publications from SSEA and in research studies.

This report follows a previous report on the open water quality of the Honey Harbour area up to 2009, and summarizes monitoring results for the 2010 to 2012 field seasons.

STUDY AREA

The Honey Harbour area of Georgian Bay is comprised of igneous granite and meta-sedimentary gneisses of the Precambrian Shield, and is located just north of the transition between the Shield and the sedimentary rock overlain by glacial deposits to the south (SSRAP 1989, Bajc 1994; **Figure 1**). Soils in the Honey Harbour area are thin to non-existent, leaving areas of exposed bedrock. Numerous wetlands and small streams flow to the deeply cut, isolated bays that make up the shoreline. North Bay (upper basin) is a deep (approximately 20 m), isolated bay with very restricted water circulation and minimal water inflow from the surrounding watershed (**Figure 2** and **Figure 3**). South Bay has greater water circulation than North Bay, although it is still relatively isolated, and is also shallower at approximately 10 m. In addition to the immediate watershed of the bay it also receives flow from the Severn River system via the Baxter Lake dam. Honey Harbour is also shallow (approximately 9 m) and has the greatest amount of circulation with Georgian Bay and Severn Sound.

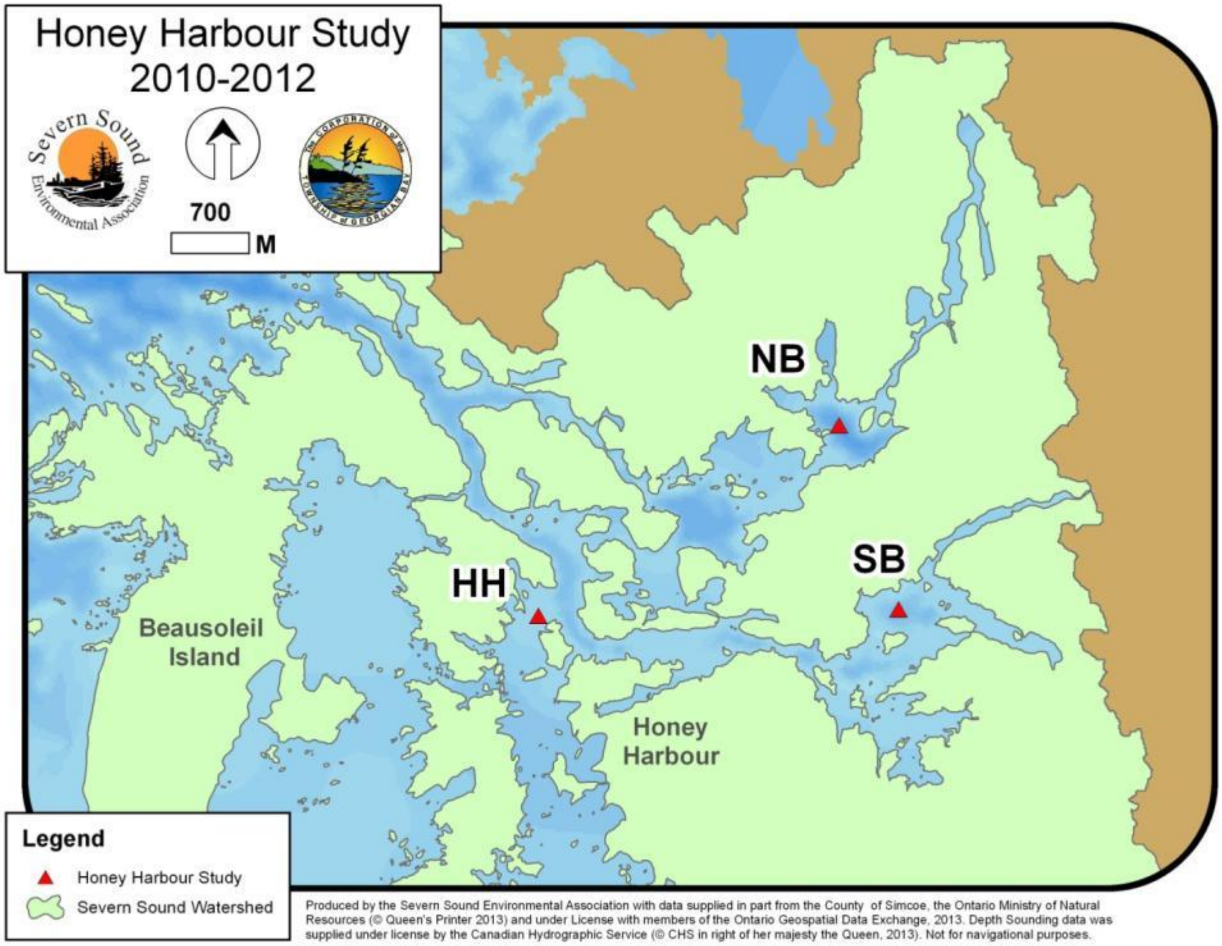

Figure 1. The Honey Harbour area of Georgian Bay and sites sampled in this study. Darker shades of blue indicate deeper waters. Note: All water depths are based on a Chart Datum of 176.1 M above sea level.

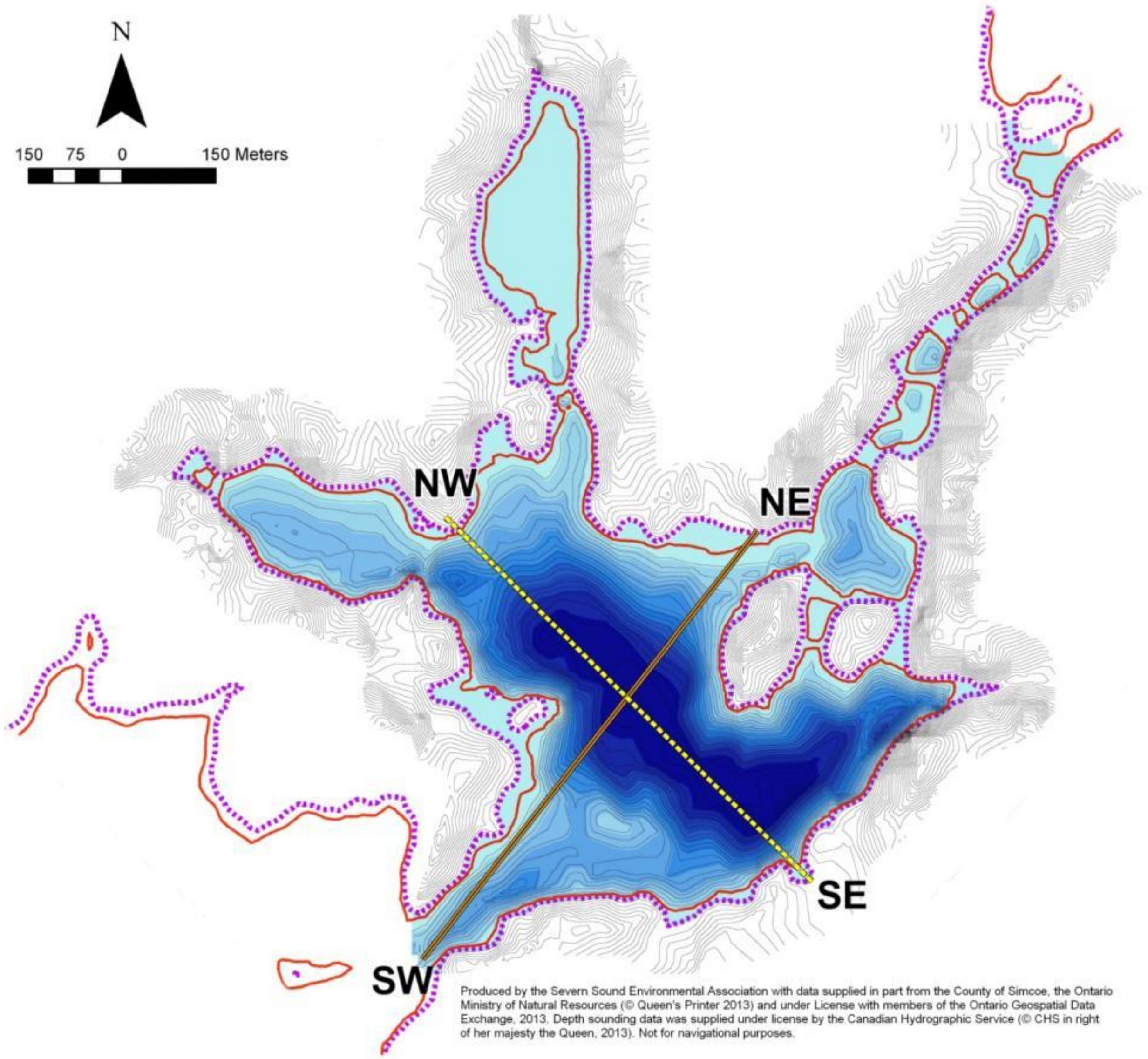

Figure 2. Bathymetry map of upper North Bay showing transects used to graph the basin profile shown in Figure 3. 1 m contours are shown. Note: All water depths are based on a Chart Datum of 176.1 M above sea level.

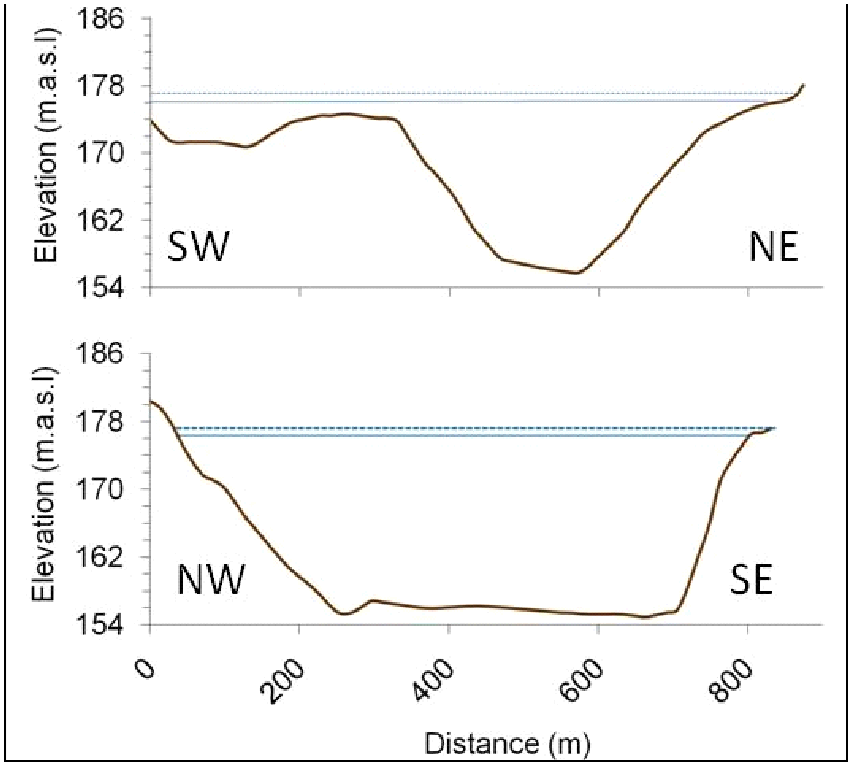

Figure 3. Transects of upper North Bay in South-West to North-East (upper panel) and North-West to South-East (lower panel) orientations. The solid and dashed blue lines indicate the water surface under high and low water levels, respectively.

The littoral zone of a lake extends from the shoreline out to the greatest depth that receives sunlight from the surface to the lake bottom. The physical characteristics of this zone play an important role in determining how much rooted aquatic plant growth can be supported, and thus how much oxygen is produced by aquatic plants that can then be circulated in the upper waters of the entire bay. In North Bay, 31% of the volume of the bay is within the littoral zone, here defined as depths less than 3 m (**Figure 4**). Decreases in water levels can bring some areas of suitable substrate and seed bank material (seeds, buds and fragments) that are normally deeper than sufficient light penetration into the light where additional rooted plant area is established. However, much of the lake bottom substrate in the littoral zone is granite bedrock, which supports minimal plant growth. The shape of the basin in upper North Bay becomes quite steep, resulting in less potential for extending rooted plant growth.

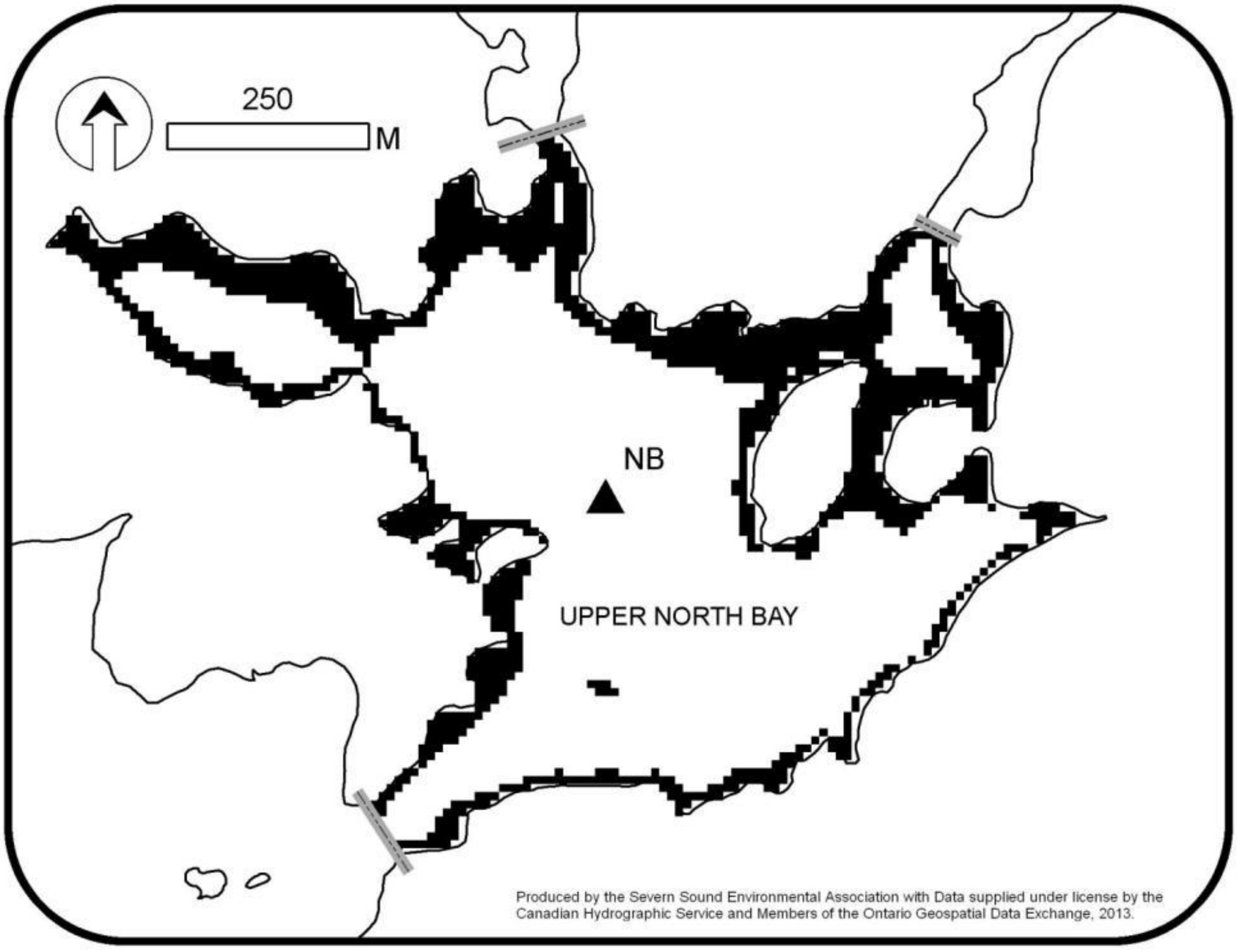

Figure 4. Map showing the area of North Bay where depth is less than 3 m. The analysis was produced using a 2-D Triangulated Irregular Network using point elevations, while the image was produced using a 10x10 m grid. The grey bars indicate the boundaries of the bay for the purpose of this analysis.

In South Bay, 64% of the volume of the bay is within the littoral zone (less than 3 m depth) (**Figure 5**). South Bay has a shallower basin with more gradual slopes to the deepest area. A greater portion of this zone is covered with soft sediments, and so there is greater coverage of aquatic plants. These plants produce oxygen during the growing season, however oxygen is consumed when they begin to die back and decompose. Decreases in water level in South Bay will expose proportionately much more suitable substrate for rooted plant growth that would otherwise not have sufficient light to support rooted aquatic plants.

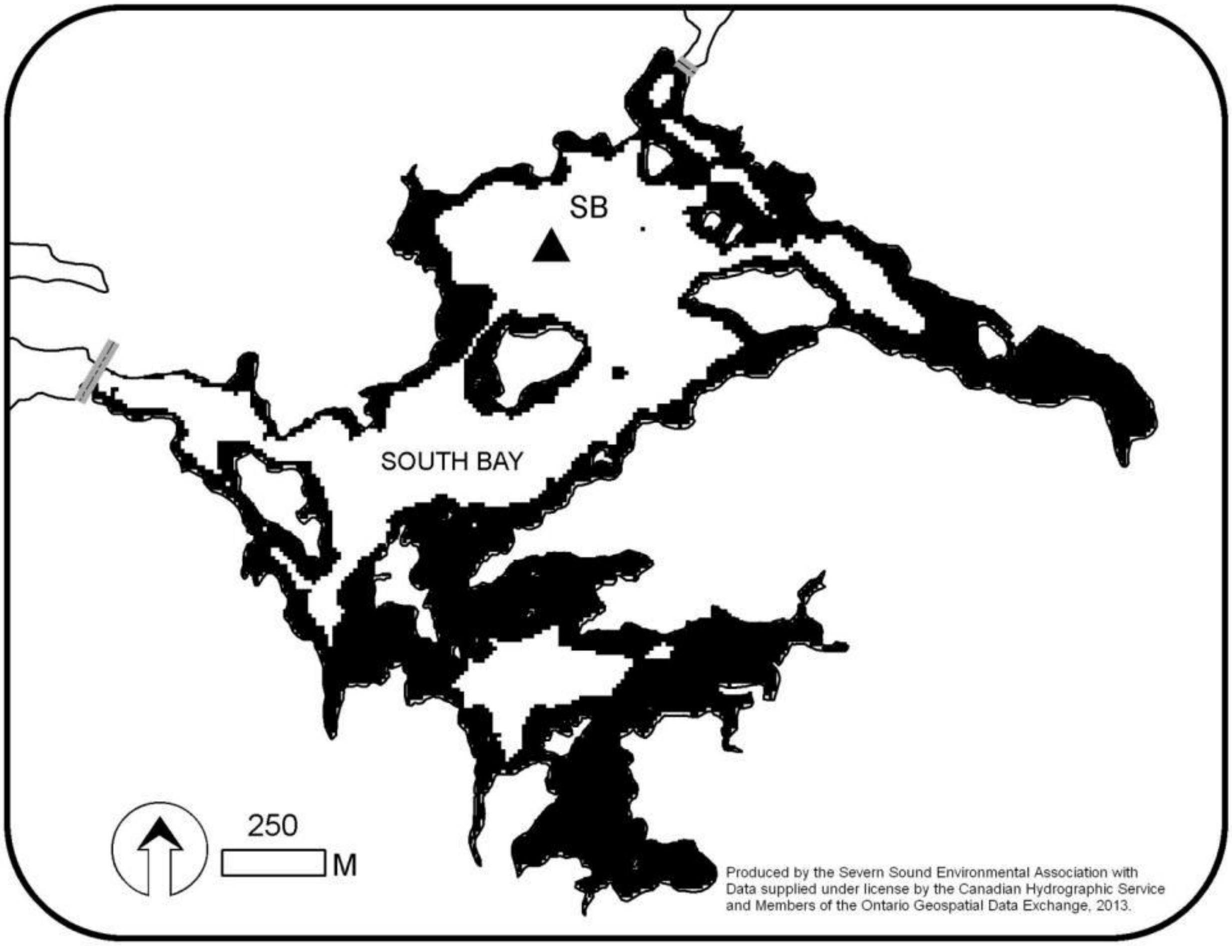

Figure 5. Map showing the area of South Bay where depth is less than 3 m. The analysis was produced using a 2-D Triangulated Irregular Network using point elevations, while the image was produced using a 10x10 m grid. The grey bars indicate the boundaries of the bay for the purpose of this analysis.

The importance of rooted aquatic plants in “locking up” nutrients in their tissues during the growing season and denying these nutrients to the phytoplankton is extremely important to the quality of these bays. Destruction of the rooted plant beds or an imbalance in nutrient loading could give phytoplankton a competitive nutrient advantage and promote shading out of rooted aquatic plants, resulting in nuisance growths of algae where rooted plants had once thrived. A healthy balanced ecosystem in these bays includes healthy growths of rooted aquatic plants.

ENVIRONMENTAL STRESSORS

Cottaging and boating are important aspects of the economy in Honey Harbour. However they are also an important potential source of environmental stress on the area. As road access increased over the past several decades, the number of seasonal and full time residences also increased dramatically. In addition to private residences, there are also marinas and campground facilities that service the large number of boaters that visit the area. Activities associated with cottaging and boating can increase the amount of nutrients (phosphorus and nitrogen) entering the bays of Honey Harbour, mainly from septic systems, detergent and fertilizer use by cottagers, and from grey and black water discharge from larger boats. Due to the varying residence times in the different bays, nutrient input from these human sources has varying effects on localized water quality. The more isolated the bay, the more vulnerable it is to both natural and cultural eutrophication. The morphometry, or shape, of some bays, such as the deep U-shape of upper North Bay, also make them prone to natural eutrophication by promoting thermal stratification and impeding bottom water circulation. Increased nutrient input from human activities has the potential to speed up this eutrophication process.

Another potential environmental stressor to the Honey Harbour area is the reduction of water levels from the relatively high levels of the 1990s to the low water phase of the last 12 years. The difference can result in a reduction in the absolute depth of the thermocline by as much as one meter, reducing the volume of the hypolimnion. The effect of this water level reduction must be taken into account in estimating the volume-weighted concentrations and the rates of change of indicators such as oxygen and phosphorus concentration.

STUDY OBJECTIVES

The Severn Sound Environmental Association (SSEA) monitors three open water stations in the Honey Harbour area for water quality and plankton communities, in addition to stations in the southern portion of Severn Sound. This report summarizes and interprets data collected by SSEA from 2010 to 2012. Our study objectives are as follows:

1. Identify seasonal and annual trends in water quality, specifically with respect to phosphorus, nitrogen, water clarity, and chlorophyll *a*;
2. Describe temperature and dissolved oxygen profiles for North Bay, South Bay and Honey Harbour, including patterns in metalimnetic and hypolimnetic oxygen depletion
3. Identify trends in biovolume of major phytoplankton groups and of specific taxonomic groups of interest such as *Chrysosphaerella*, *Peridinium*, *Microcystis*, and other blue-green algae. Describe patterns of change in community composition;
4. Identify trends in zooplankton biomass, density, and richness; Describe patterns of change in community composition; and
5. Relate changes in water quality, phytoplankton and zooplankton community composition with other factors affecting the quality of the bays.

Conclusions will include recommendations on future monitoring needs and potential for collaboration in data collection.

METHODS

OPEN WATER SAMPLING PROGRAM

Three sites were sampled in the Honey Harbour area: Honey Harbour (HH), inner/upper North Bay (NB) and South Bay (SB). Sampling locations were based on stations originally sampled by the Ministry of Environment (MOE) from 1981 to 1995, which were then taken over by SSEA in 1998 (**Figure 6**). Sampling occurred biweekly during the ice-free season, generally from May to October. SSEA station M5 was used as a reference to conditions in the deep open waters of Severn Sound.

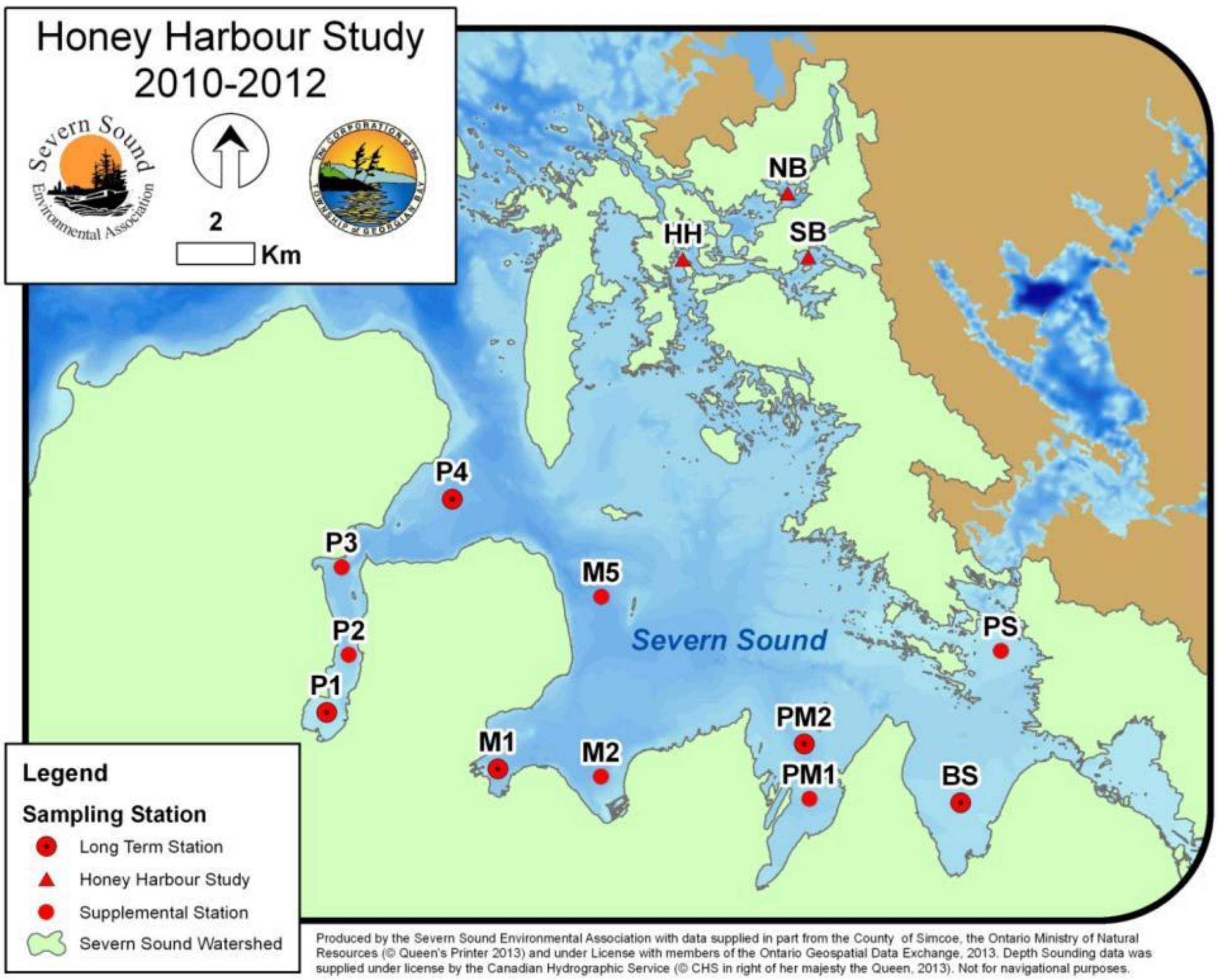

Figure 6. Open water stations monitored by SSEA. Darker shades of blue indicate deeper waters. Note: All water depths are based on a Chart Datum of 176.1 M above sea level.

FIELD SAMPLING

Temperature, conductivity, dissolved oxygen, and pH were measured with an YSI 640 multi-parameter probe at 1 m intervals beginning at the surface to 1 m off bottom. Water clarity was measured using a 20 cm Secchi disk lowered over the shaded side of the sampling vessel. The disk was used to measure total depth as well.

Water samples were collected using two 1 L bottles fitted with integrator caps and deployed to the bottom of the euphotic zone (twice the Secchi disk depth; Locke and Scott 1986). Unfiltered samples were dispensed into double rinsed PET jars, or borosilicate glass tubes in the case of phosphorus, for nutrient (nitrate+nitrite (TNO_3), ammonia+ammonium (TNH_4), total Kjeldahl nitrogen (TKN), and total phosphorus (TP)), heavy metals, chlorophyll *a*, and phytoplankton analysis. At NB and SB, samples were also taken at 1 m off bottom using a Kemmerer sampler, a device that is triggered to sample at a specific depth, rather than over a range of depths. These bottom water samples were analyzed for the same chemistry but not for chlorophyll *a* and phytoplankton. Samples for chlorophyll *a* were stored in opaque bottles and phytoplankton samples were preserved with Lugol's solution. All chemistry samples were kept on ice and shipped to the laboratory within 48 h.

From 2010-2012, a fluorometric algal pigment profiler (Fluoroprobe, bbe Moldanke) was used to obtain real time concentrations of four classes of algal pigments and apparent total chlorophyll a concentration. These classes approximately correspond to the following groups: blue-green algae, green algae, cryptophytes+some chrysophytes, and diatoms+dinoflagellates+some chrysophytes. The Fluoroprobe was used at NB and M5. At each station, the probe was lowered at a rate of approximately 2 m/s from the surface to 1 m off bottom. Water was also collected over this depth range and brought back to the lab. It was filtered using a 0.02 μm pore size ceramic filter, and used to calibrate the instrument. This was done for each station on each sampling date.

In addition to routine water sampling, additional samples were collected at discrete depths at NB and M5 in 2011 and NB only in 2012. On each visit, three discrete samples were taken, the depths of which were chosen to correspond with the peak in total chlorophyll *a* as indicated by the Fluoroprobe, along with two additional depths, evenly spaced above the hypolimnion. Samples were analyzed for total chlorophyll *a*, and preserved samples were also sent for phytoplankton analyses. Biovolume was calculated for taxa that were present in relatively large numbers, while rarer taxa were noted as present or absent.

Zooplankton samples were collected using a Wisconsin net with 80 μm mesh. The net was towed vertically from 1 m off bottom to the surface at a slow and constant rate. Samples were preserved with a buffered 4% formalin solution.

LABORATORY ANALYSES

Water samples were analyzed for all nutrient and ion parameters using standard MOE analytical methods (MOE 1974) at the MOE Dorset Lab. All phosphorus analyses were performed using low level detection methods. Chlorophyll *a* and metals analyses were performed at the MOE Rexdale lab.

Phytoplankton (i.e. algae) samples were settled at the MOE Rexdale lab and then identified to genus or species by an MOE approved private contractor. Biovolume was obtained for each taxa using standard analytical methods (Nicholls et al. 1977, Hopkins and Standke 1992), and was reported as cell volume/ unit of water volume (mm^3/m^3). For M5 and NB in 2010-2012, SB in 2011-12, and HH in 2011, each biweekly sample was counted separately (individuals). For SB in 2010 and HH 2010 and 2012, aliquots from samples taken over the entire season were combined and counted to give an annual average (pooled sample). **Table 1** indicates which samples were pooled and which were individual counts for each station over the monitoring record going back to 1998.

Table 1. For each station, the type of phytoplankton analysis is indicated, along with the dates of the first and last sample in either the pooled samples or for individual counts.

Station	Year	Type of Sample	First Sample	Last Sample
HH	1998	pooled	28-Apr-98	5-Oct-98
HH	2003	pooled	22-May-03	30-Sep-03
HH	2005	individual	3-May-05	6-Oct-05
HH	2008	pooled	6-May-08	7-Oct-08
HH	2009	pooled	5-May-09	6-Oct-09
HH	2010	pooled	4-May-10	5-Oct-10
HH	2011	individual	3-May-11	4-Oct-11
HH	2012	pooled	1-May-12	16-Oct-12
P4	1998	pooled	28-Apr-98	5-Oct-98
M5	2003	pooled	22-May-03	6-Oct-03
M5	2005	individual	3-May-05	6-Oct-05
M5	2008	individual	6-May-08	7-Oct-08
M5	2009	individual	5-May-09	10-Nov-09
M5	2010	individual	20-Apr-10	1-Nov-10
M5	2011	individual	3-May-11	1-Nov-11
M5	2012	individual	18-Apr-12	16-Oct-12
NB	1998	pooled	28-Apr-98	5-Oct-98
NB	2003	pooled	22-May-03	30-Sep-03
NB	2005	individual	3-May-05	28-Oct-05
NB	2008	individual	6-May-08	7-Oct-08
NB	2009	individual	5-May-09	10-Nov-09
NB	2010	individual	20-Apr-10	1-Nov-10
NB	2011	individual	3-May-11	24-Nov-11
NB	2012	individual	18-Apr-12	15-Nov-12
SB	1998	pooled	28-Apr-98	5-Oct-98
SB	2003	pooled	22-May-03	30-Sep-03
SB	2005	individual	3-May-05	28-Oct-05
SB	2008	individual	6-May-08	7-Oct-08
SB	2009	individual	5-May-09	10-Nov-09
SB	2010	pooled	20-Apr-10	5-Oct-10
SB	2011	individual	3-May-11	4-Oct-11
SB	2012	individual	1-May-12	16-Oct-12

Zooplankton analysis was also carried out by a private contractor for 2012 samples taken at NB, SB and M5 only. Analytical methods were consistent with MOE procedures for identification, enumeration and biomass estimation using the ZEBRA software system and the R3 counting method (Allen et al. 1994, Gemza 1995).

STATISTICAL ANALYSES

Prior to analysis, data were checked for outliers using Grubb's test. Bivariate statistical analyses included paired Student *t*-tests, linear correlations, Tukey-Kramer test and Mann-Kendall trend analyses, which were performed with either SAS JMP® 6 software (SAS Institute Inc., 2005) or Microsoft Excel 2007 (Microsoft Corporation, 2007). Analyses were considered to be significant at p values less than 0.05.

RESULTS AND DISCUSSION

TEMPERATURE AND DISSOLVED OXYGYEN

In lakes and bays with sufficient depth and sheltering, a process call thermal stratification occurs in the summer months. As the surface waters warm, a gradient of temperature forms with depth. If this gradient exceeds 1°C/m, then the upper waters no longer mix freely with the bottom waters due to the higher density of water at lower temperatures. Three layers are thus formed: the epilimnion, into which atmospheric oxygen is able to dissolve and mix, the metalimnion or thermocline, which is the zone of rapid temperature decline, and the hypolimnion or the waters beneath the thermocline (**Figure 7**). Since the hypolimnion is isolated from the atmospheric oxygen available in the epilimnion, depletion of the limited oxygen concentration can occur in relation to the oxygen demand of organic matter and decomposition processes which use the oxygen. The thermal stratification process occurs in upper North and South Bays. These are both dimictic embayments; that is in spring and fall the water column reaches a uniform temperature and is able to mix from the surface to the lake bottom. This process is called turnover. In contrast, the location sampled at station HH does not stratify. Since there is no temperature-induced barrier to mixing, atmospheric oxygen dissolved in the upper waters is able to mix into the bottom waters, preventing hypoxic conditions from developing. The location at M5 stratifies for brief periods (days) until wind-induced mixing erodes the thermal gradient.

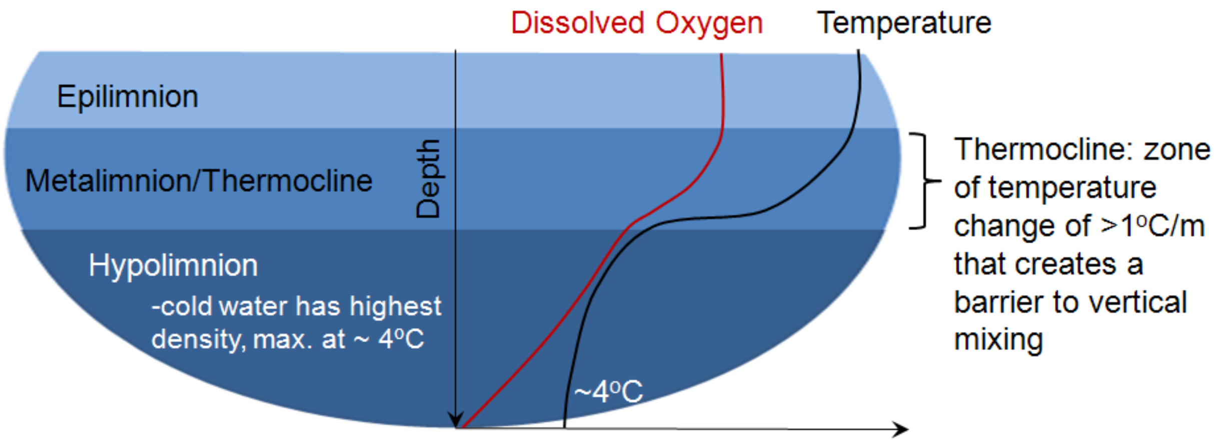

Figure 7. Diagram showing layers created by thermal stratification, and the typical pattern of temperature and oxygen decline during midsummer.

Data from 2003-2012 show that there is a high degree of consistency in the timing of onset and breakdown of stratification at North Bay (**Figure 8, left**). Spring turnover occurs early in the spring, and was only captured in 2011 and 2012. Likewise, fall turnover occurs late in the fall, and was also captured in 2011 and 2012. In 2012, the hypolimnion was the warmest it has been since monitoring began in 1981. Mean bottom water temperatures (at 1 m off bottom) were 4.8ºC in 2010, 5.6 ºC in 2011 and 6.7 ºC in 2012.

Due to the strong thermal gradients that form every summer, North Bay experiences bottom water anoxia (dissolved oxygen <1 mg/L) in a sizeable portion of the bottom waters (**Figure 8, right**). North Bay is unusual in that an oxygen depleted (DO <4 mg/L) zone or minimum also forms in the metalimnion. The potential causes of this metalimnetic oxygen minimum will be explored in later sections.

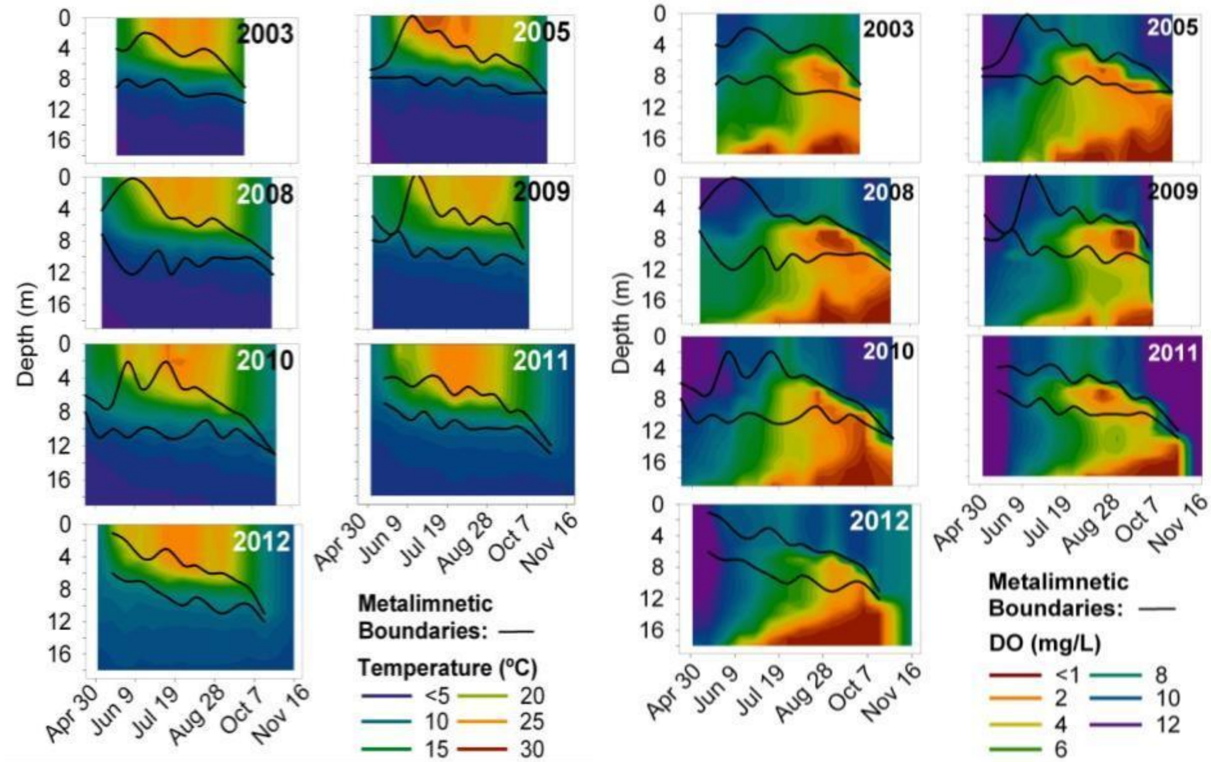

Figure 8. Isopleth graphs of temperature (left) and oxygen (right) for North Bay, 2003-2012. The black lines indicate the boundaries of the metalimnion, or thermocline.

The changing volume of the hypolimnion due to water level fluctuations must be taken into account in order to compare temperature and oxygen conditions among years. Using volume-weighted hypolimnetic values, data shows that there has been no significant change in summer (late august) bottom water temperature (**Figure 9**). Likewise, there has been no significant change in summer bottom water oxygen concentration over the period of record.

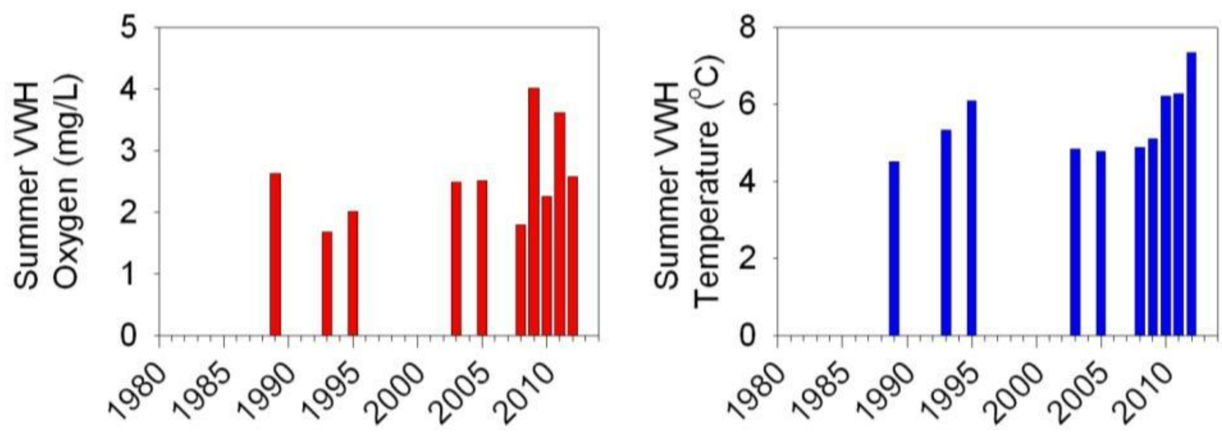

Figure 9. Trends in volume-weighted hypolimnetic oxygen and temperature at North Bay from 1989-2012. 1981 was an outlier year.

South Bay shows consistency in the timing of thermal stratification setup and breakdown, although not to the same degree as North Bay (**Figure 10, left**). Due to its shallower depth, the volume of the hypolimnion is much smaller in South Bay compared to North Bay.

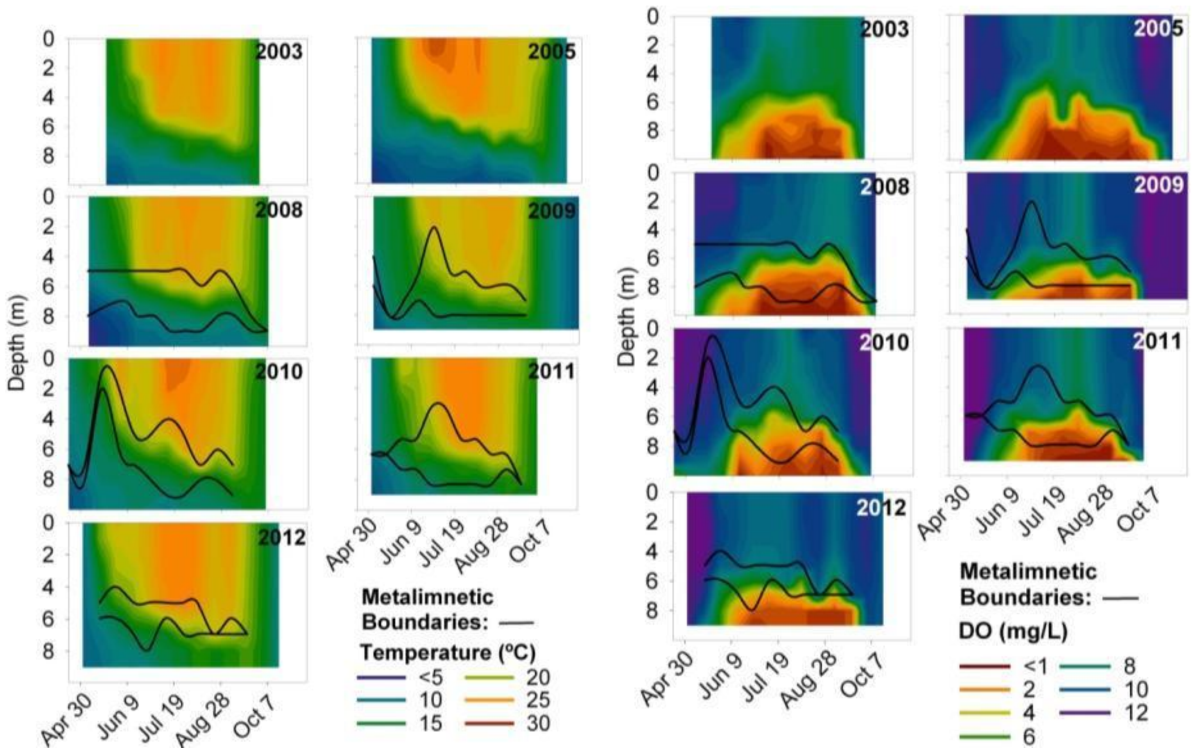

Figure 10. Isopleth graphs of temperature (left) and oxygen (right) for South Bay, 2003-2012. The black lines indicate the boundaries of the metalimnion, or thermocline.

Bottom water spring and summer temperature are closely related at NB (r^2=0.96, p<0.0001), but less so at SB (r^2=0.19, p>0.05) (**Figure 11**). At NB, 96% of the variation in summer temperature can be explained by the variation in spring temperature. The lack of a significant relationship at SB is due to the shallower depth of the basin, and greater influence of external waters through mixing with outflows of Baxter Lake.

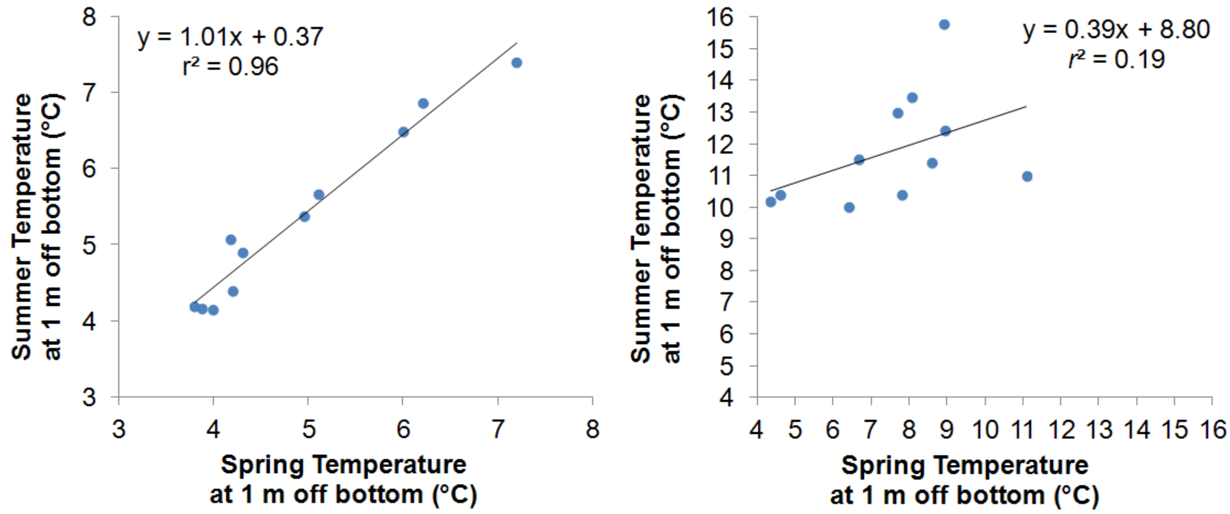

Figure 11. Relationship between spring (early May) and summer (late August) temperature at 1 m off bottom at NB (left) and SB (right).

WATER QUALITY

Lake water quality measurements that indicate trophic status, or level of nutrient enrichment, are particularly useful in studying how anthropogenic nutrient inputs affect water quality. For this study, these included TP, SDV, chlorophyll *a* and total nitrogen (TN), which is the sum of TKN and total nitrate. Annual means for each of these variables are shown in the following figures for the open waters of Severn Sound (P4 and M5) and each of the three Honey Harbour stations in order to put results from 2010-2012 into context (**Figure 12-Figure 13**). Each variable will be discussed in turn in subsequent sections.

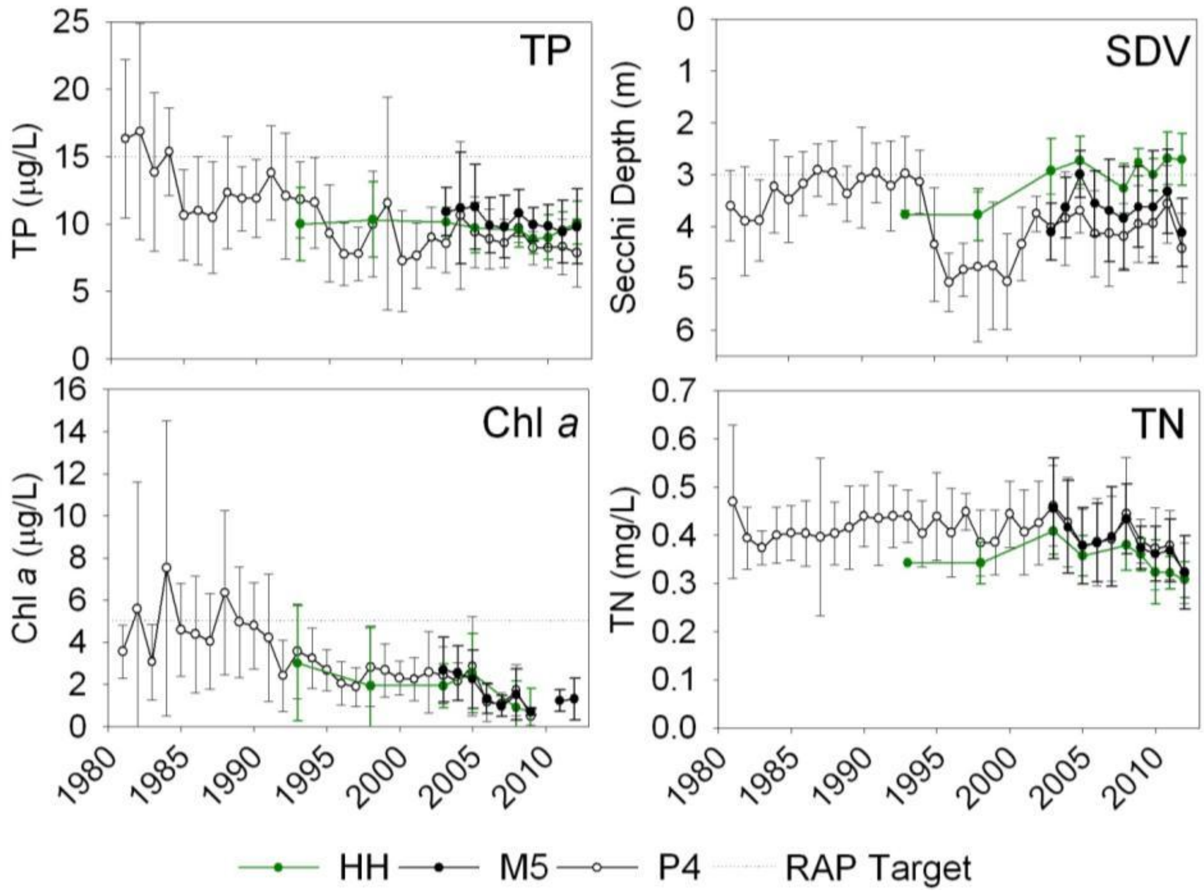

Figure 12. Annual mean values for TP, Secchi disk visibility, chlorophyll *a* and total nitrogen for Severn Sound open water stations P4 from 1981-2012 and M5 from 2003-2012, and from station HH from 1993-2012. SSRAP targets are also shown.

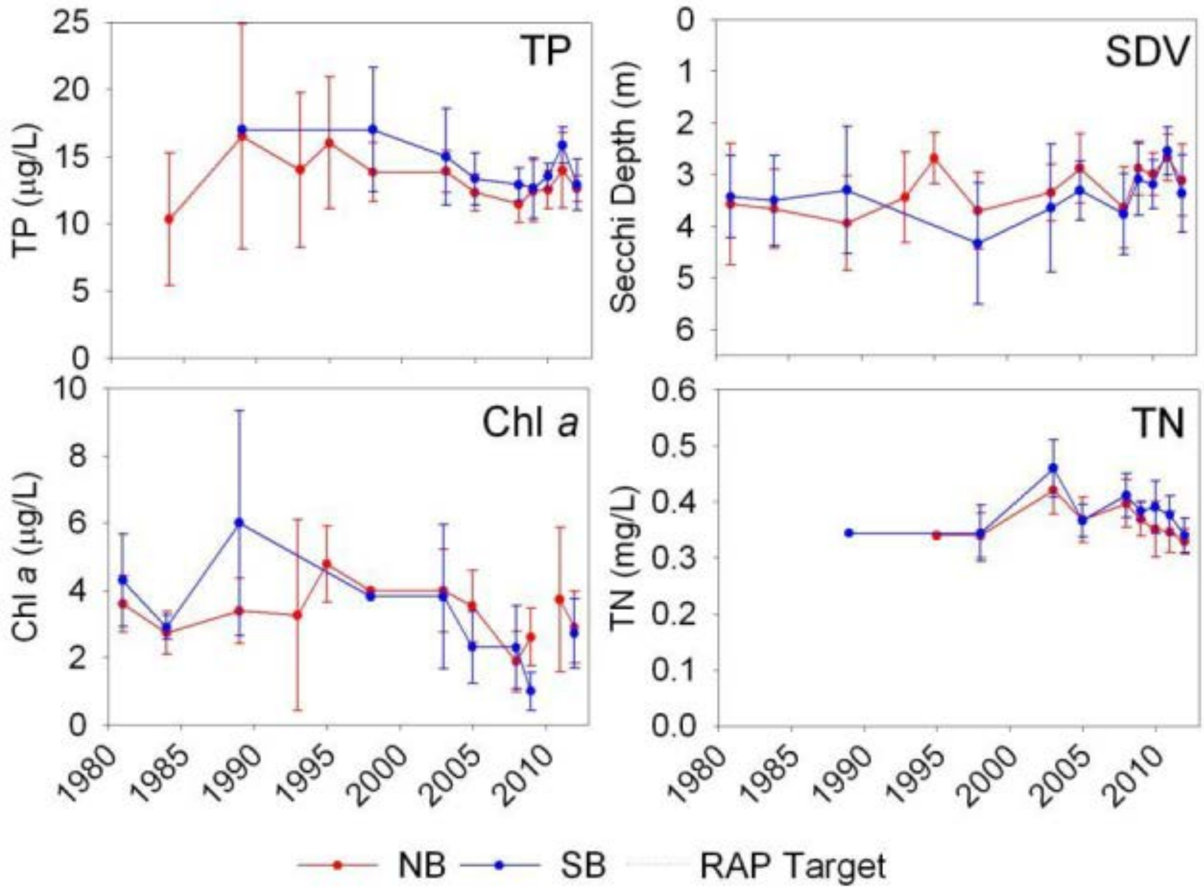

Figure 13. Annual mean values for TP, Secchi disk visibility, chlorophyll *a* and total nitrogen for NB and SB from 1981-2012. SSRAP targets are also shown.

Phosphorus

Phosphorus is essential for plant growth, and is the limiting nutrient in most freshwaters in Ontario. Total phosphorus (TP) measures both the dissolved and particulate fractions of phosphorus, the latter of which includes algae cells and small zooplankton.

Seasonal mean concentrations of TP from 2010-2012 ranged from 12.5-14 µg/L at NB, 12.9-15.8 µg/L at SB, 9.0-10.1 µg/L at HH, and 9.4-9.9 µg/L at M5. These values are generally below the RAP target of 15 µg/L, and are in the same range as historical concentrations for each station (**Figure 12-Figure 13**). On a seasonal basis, there were several patterns to note based on TP data from 2010-2012. Firstly, using a Tukey-Kramer test on biweekly pooled data across the three years, TP concentrations at NB and SB were not shown to be significantly different from each other, but were significantly greater than concentrations at HH and M5, which in turn were not significantly different from each other (**Table 2**). The high degree of sheltering in North and South Bay isolates their more nutrient rich waters from the more dilute open waters of Severn Sound, while the waters at Honey Harbour are subject to greater mixing with the open waters.

Table 2. Results from a Tukey-Kramer test for differences among stations using pooled biweekly TP data from 2010-2012. Stations not connected by the same letters are significantly different at α=0.05.

Station	Mean	Linkage	
SB	14.1	A	
NB	13.3	A	
HH	10.1		B
M5	9.7		B

Secondly, there was no seasonal trend in TP at any of the stations monitored (**Figure 14**). This indicates that TP in the euphotic zone was not being enriched or depleted through the season.

Lastly, there was a marked increase in TP at the end of the season that was observed at NB in 2011 and 2012. This corresponded to fall turnover when phosphorus-rich bottom waters mixed with the upper waters. Internal phosphorus loading in the bottom waters will be discussed below. Although fall turnover was also captured at SB from 2010-12, TP concentrations in the euphotic zone did not increase due to mixing with bottom waters like they did at NB (**Figure 14**).

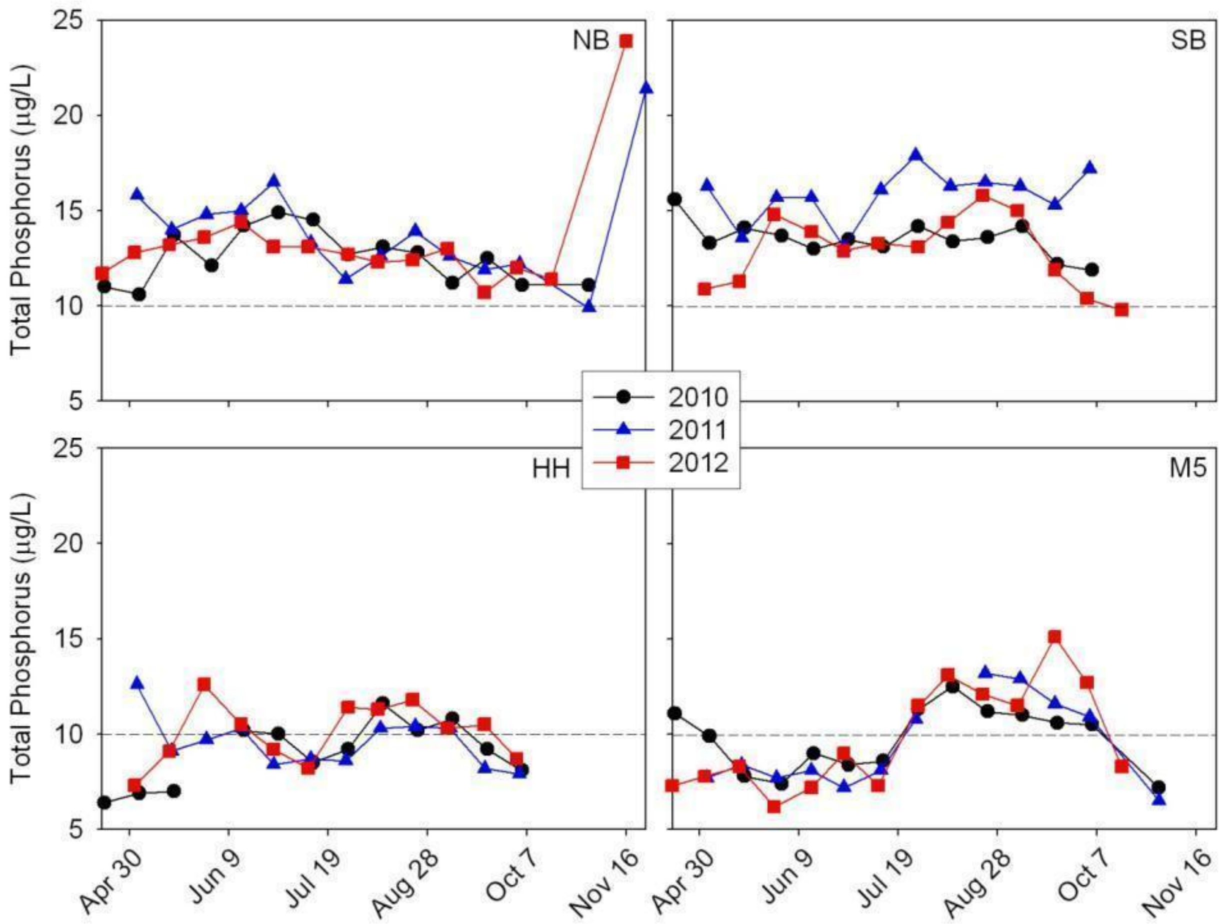

Figure 14. Seasonal TP concentrations from euphotic zone composite samples at three monitoring stations in Honey Harbour and one in the open waters of Severn Sound (M5) for 2010-12. The dashed line indicates 10 µg/L, which is the TP Provincial Water Quality Objective for preventing nuisance algal blooms.

During mid-July for each of 2010, 2011 and 2012, TP in the bottom waters (1 m off bottom) at NB began to increase dramatically compared to concentrations in euphotic zone composites (**Figure 15**). The timing of this increase coincided with bottom water oxygen depletion, specifically when DO concentration dropped below 1 mg/L, or the level considered to be anoxic. P is released from the sediments due to the reducing environment created under such conditions. Over the course of the season, the temperature in the bottom waters stayed constant, indicating a lack of mixing with the upper waters.

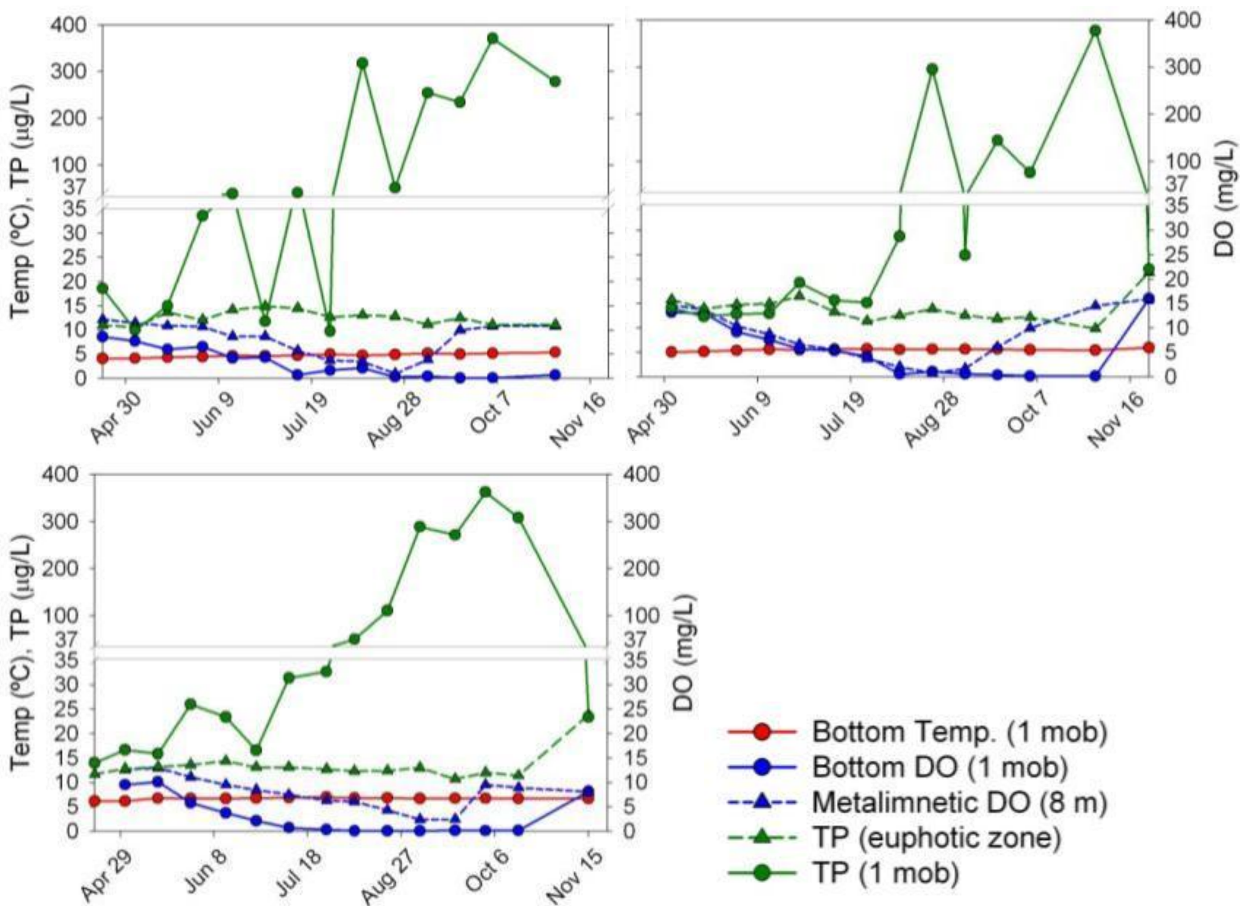

Figure 15. Temperature, dissolved oxygen and total phosphorus in the bottom waters, metalimnion and/or euphotic zone at NB in 2010 (top left), 2011 (top right) and 2012 (bottom). Note the break in the y-axis; above 37 the scale increases to increments of 100.

It is interesting to note in the figure above that TP concentrations following fall turnover were higher in the fall compared to spring in both 2011 and 2012. This indicates that internal loading is increasing the TP concentration in the water column. Conversely, the spring 2012 concentration was lower than the fall 2011 concentration, indicating a P loss over the winter.

Using TP data for the euphotic zone and bottom waters from these periods, it is possible to calculate the change in the concentration of TP from spring to fall, and from fall to the following spring, and to determine what TP load is represented. First, an average was taken of euphotic and bottom water TP for the first and last sampling dates, during spring and fall turnover (note temperature profiles; **Table 3**). The difference between TP in spring to fall and fall to following spring was calculated, along with the number of days in between each pair of sampling dates. These values were then used to calculate a phosphorus regeneration rate or flux. This rate was multiplied by the volume of upper North Bay ($3.5x10^6$ m^3, excluding the small arms on the north side) to obtain an internal phosphorus loading.

Table 3. TP concentrations in the euphotic zone and 1 m off bottom at NB in spring and fall of 2011 and 2012. Assuming fully mixed conditions, the average of euphotic zone and bottom water concentrations was calculated. The difference between spring to fall of the same year, and fall to spring of the following year was calculated, as was the number of days between sample dates. These later two calculations were used in calculating phosphorus regeneration rate, and in turn the regenerated P load.

Date	$TP_{Euphotic\ Zone}$ (µg/L)	$TP_{1\ m.o.b.}$ (µg/L)	TP_{Mean} (µg/L)	TP_{Diff} (µg/L)	# Days	P Regen. Rate (µg/L/d)	Regen. P Load (kg)
May 03/11	15.8	14.1	14.95				
				6.8	205	0.03	21.4
Nov 24/11	21.4	22.1	21.75				
				-8.9	146	-0.06	-30.4
Apr 18/12	11.7	14	12.85				
				10.8	211	0.05	36.6
Nov 15/12	23.9	23.4	23.65				

From the external TP supply modeling done for Muskoka District (Brouse, personal communication), the total TP supply to all of NB is approximately 360 kg TP/yr. Upper North Bay represents roughly half of the total volume and watershed, so the total external TP supply is estimated at 180 kg TP/yr. The loading from internal phosphorus regeneration from the sediment over the summer season represents approximately 10-20% of total external load to upper North Bay. There was an almost equal loss of P over the winter of 2011/12, accounting for approximately 16% of total external load. Processes contributing to this loss are unknown at this time. The added phosphorus mass in the water column at fall turnover may be settling to the bed during winter.

Due to the relative shallowness of South Bay and the smaller volume of the hypolimnion, the bottom waters are not as cold as they are in North Bay, indicating less stability through the water column. However, the thermal gradient is strong enough that bottom water anoxia occurs, generally by early July. As in North Bay, when anoxia sets in, bottom water TP increases compared to concentrations in the euphotic zone (**Figure 16**). Although the fall turnover had occurred at SB by early October in all three years, a gradient persisted between bottom water TP and euphotic zone concentrations in 2010 and 2011, but not in 2012. In 2012 TP concentrations in the bottom waters were orders of magnitude lower than in 2010 and 2011. It is possible that the very low water levels experienced in the fall of 2012 (Canadian Hydrographic Service data for Midland) allowed mixing to occur more thoroughly than in the previous years, which in turn allowed the mixing of accumulated TP into the upper waters in South Bay.

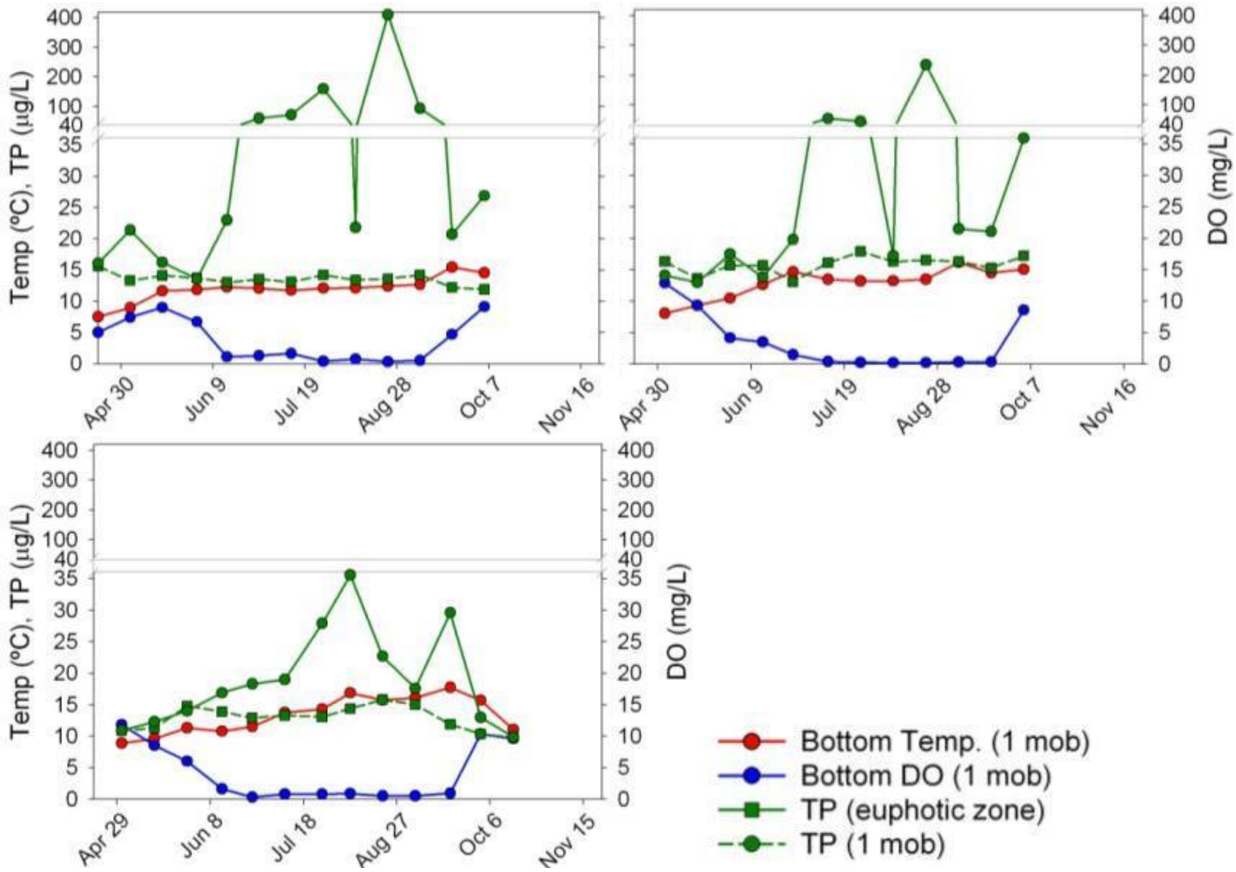

Figure 16. Temperature, dissolved oxygen and total phosphorus in the bottom waters, metalimnion and/or euphotic zone at SB in 2010 (top left), 2011 (top right) and 2012 (bottom). Note the break in the y-axis; above 40 the scale increases to increments of 100.

Water Clarity

Suspended solids in the water column, either algae or organic and inorganic sediments, as well as colour from wetland drainage can contribute to reduced water clarity. During the summer, algal blooms are generally the greatest contributor to low water clarity. Water clarity was measured as Secchi disk visibility (SDV).

From 2010 to 2013, the mean annual SDV ranged from 2.7-3.1m at NB, 2.6-3.4 m at SB, 2.7-3.0 m at HH and 3.3-4.1 m at M5. With the exception of M5, these values are lower compared to historical values for each station (**Figure 12-Figure 13**). Clarity at the Honey Harbour stations between 2010-2012 fluctuated above and below the objective set in the RAP of 3 m, and was in typical of moderately enriched conditions (**Figure 17**). On a seasonal basis, there were no distinct patterns in clarity, and no drastic reductions in clarity that can be attributed to specific algae blooms, although a clear water phase occurred briefly at NB and SB on Sept 19 2012. On this date, algal pigment profiles indicated that a bloom of several taxa occurred between 9-11 m. Algae that are able to control their buoyancy, and thus their position in the water column, may have been responsible for this bloom, and their migration to lower depths may have resulted in increased clarity in the upper waters.

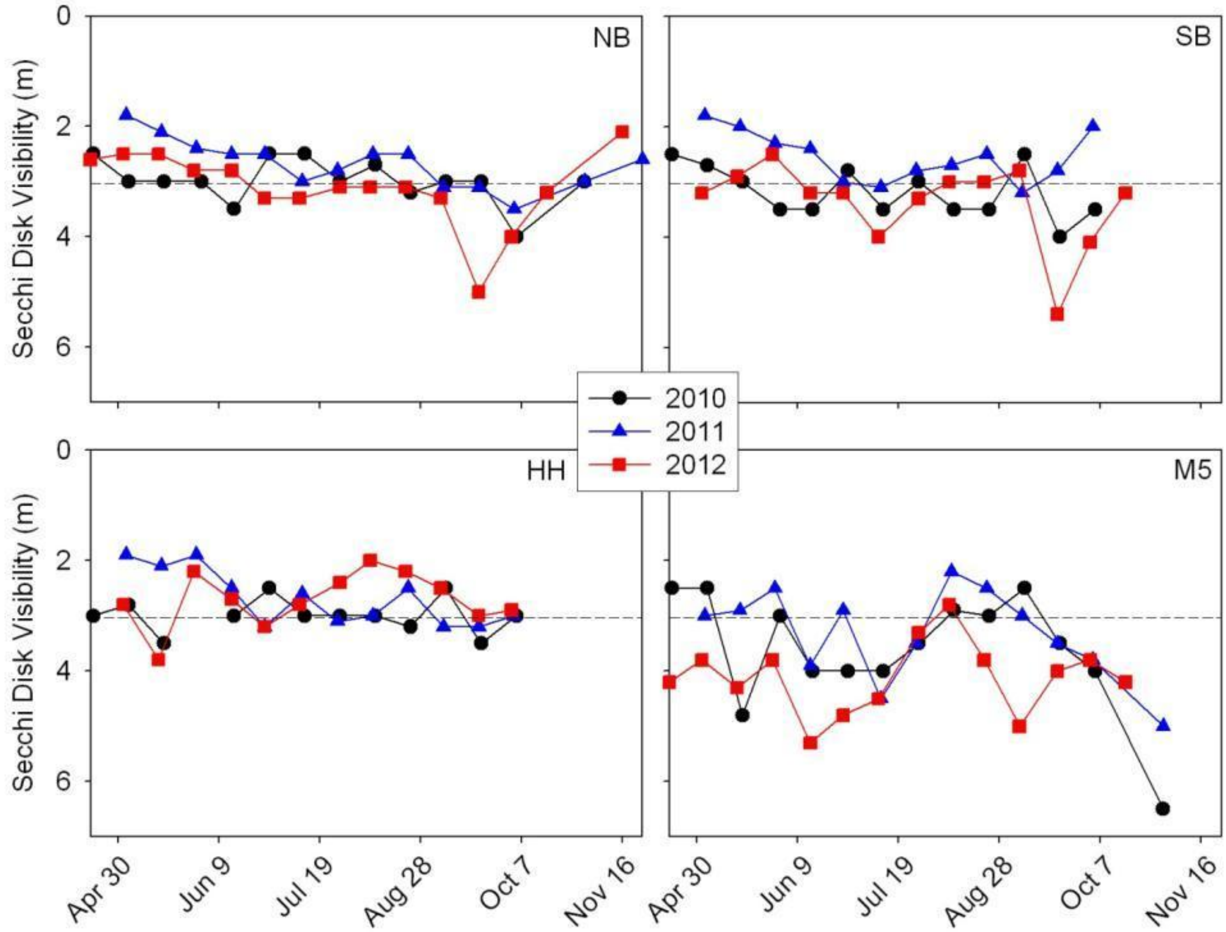

Figure 17. Seasonal SDV concentrations at three monitoring stations in Honey Harbour and one in the open waters of Severn Sound (M5) for 2010-12. The dashed line indicates 3 m, which is the Remedial Action Plan target for water clarity.

Generally, a relationship between algal biovolume and water clarity exists in many lakes. Using all data available from Severn Sound open water monitoring stations from 1969-2012, it is apparent that a negative exponential relationship exists between SDV and algal biovolume (**Figure 18**). Pooled annual means of total algal biovolume and SDV from NB, SB, and HH from 1998-2012 do not show as clear a relationship when examined on their own. This could be due to the depth at which algae proliferate, particularly in North Bay. Some of the highest densities of algae tend to proliferate below 5 m, as indicated by the location of the peak in fluorescence-inferred chlorophyll *a* profiles, and are often missed by euphotic composites. Vertical distribution of phytoplankton will be discussed in further detail in the section on phytoplankton.

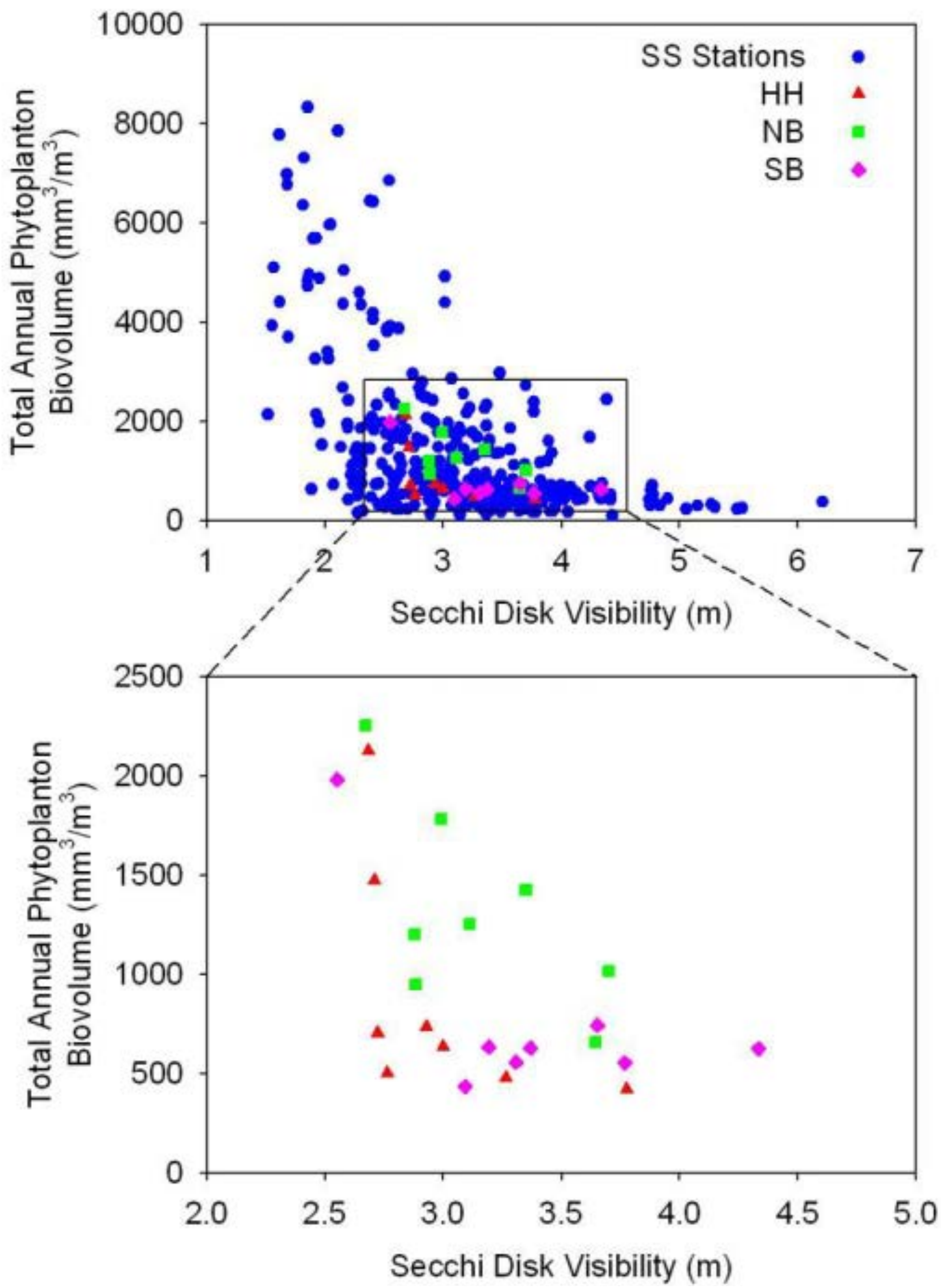

Figure 18. The top panel shows annual mean Secchi disk visibility versus total biovolume using pooled annual mean data from all Severn Sound open water monitoring stations, including NB, SB, and HH from 1969-2012. The bottom panel zooms in on data for the Honey Harbour stations.

Nitrogen

Nitrogen can be found in both organic (dissolved and particulate phases, e.g. TKN) and inorganic forms (e.g. ammonium and nitrate) and is an important nutrient for algal growth, second only to phosphorus. Ammonium and nitrate are the most biologically available forms of nitrogen.

External inputs of nitrate can come from fertilizers and sewage sources. Nitrite is quickly converted to nitrate in oxygen rich environments, and is included in the analysis of total nitrate reported by the lab (TNO_3). Seasonally, nitrate tends to be highest following the spring freshet, dropping quickly to near the detection limit of the test, and then rising again with increased precipitation and runoff in the fall. These patterns are readily seen in data from 2010-2012 from the Honey Harbour stations and the open waters of Severn Sound (**Figure 19**). In addition, concentrations were lower at NB and SB, and highest at M5. This highlights the differences in runoff quantity influencing these stations. North and South Bays are fed by relatively small, Precambrian Shield, wetland-dominated watersheds, while M5 is highly influenced by the agricultural and urbanized landscape of the southern portion of the Severn Sound watershed.

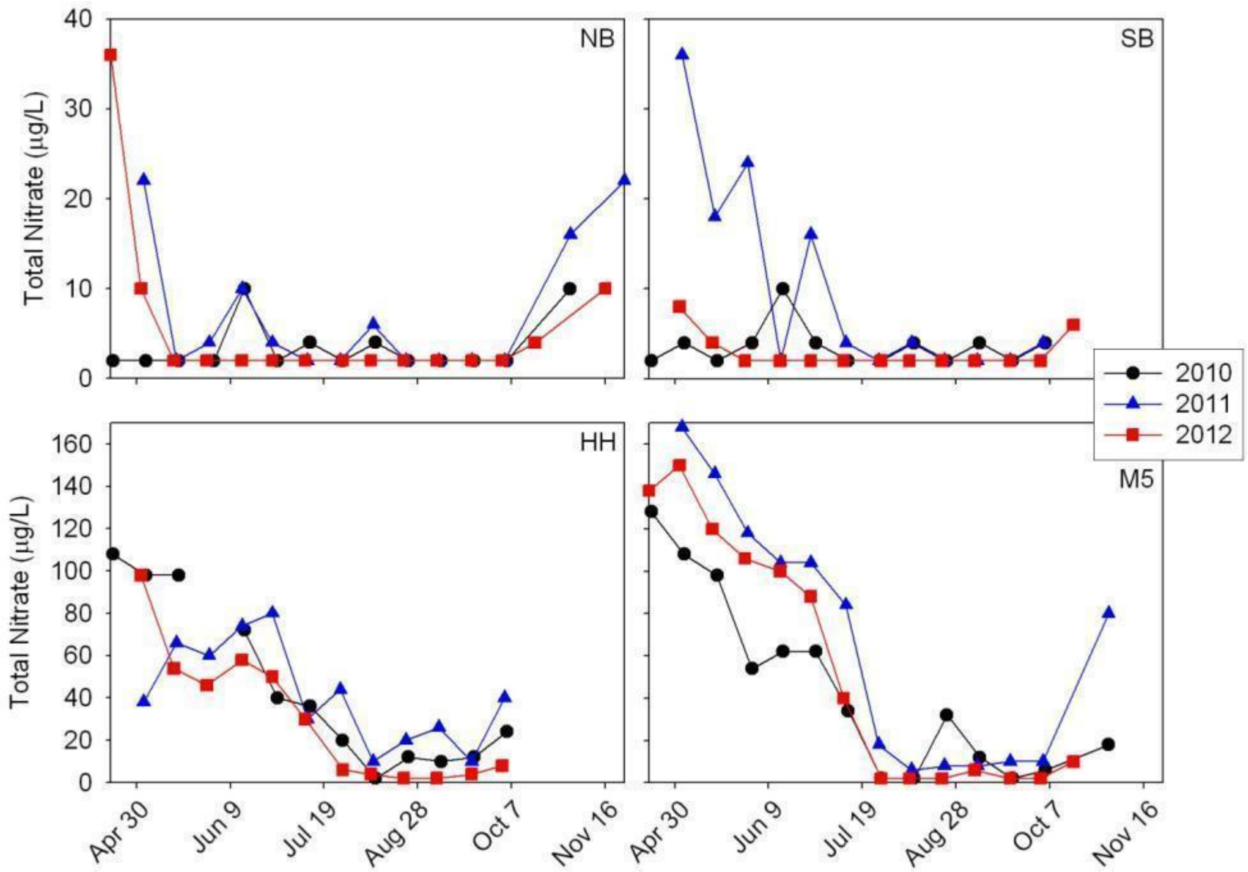

Figure 19. Seasonal total nitrate concentrations from euphotic zone composite samples at three monitoring stations in Honey Harbour and one in the open waters of Severn Sound (M5) for 2010-12. Note the different scales for the top two graphs compared to the bottom two.

As seen with TP, there are differences in total nitrate concentrations between the euphotic zone and the bottom waters. Bottom water values are generally higher than the euphotic zone for most of the seasonal sampling period at both station NB and SB compared with the seasonal fluctuation described above for the euphotic zone (**Figure 20, top**).

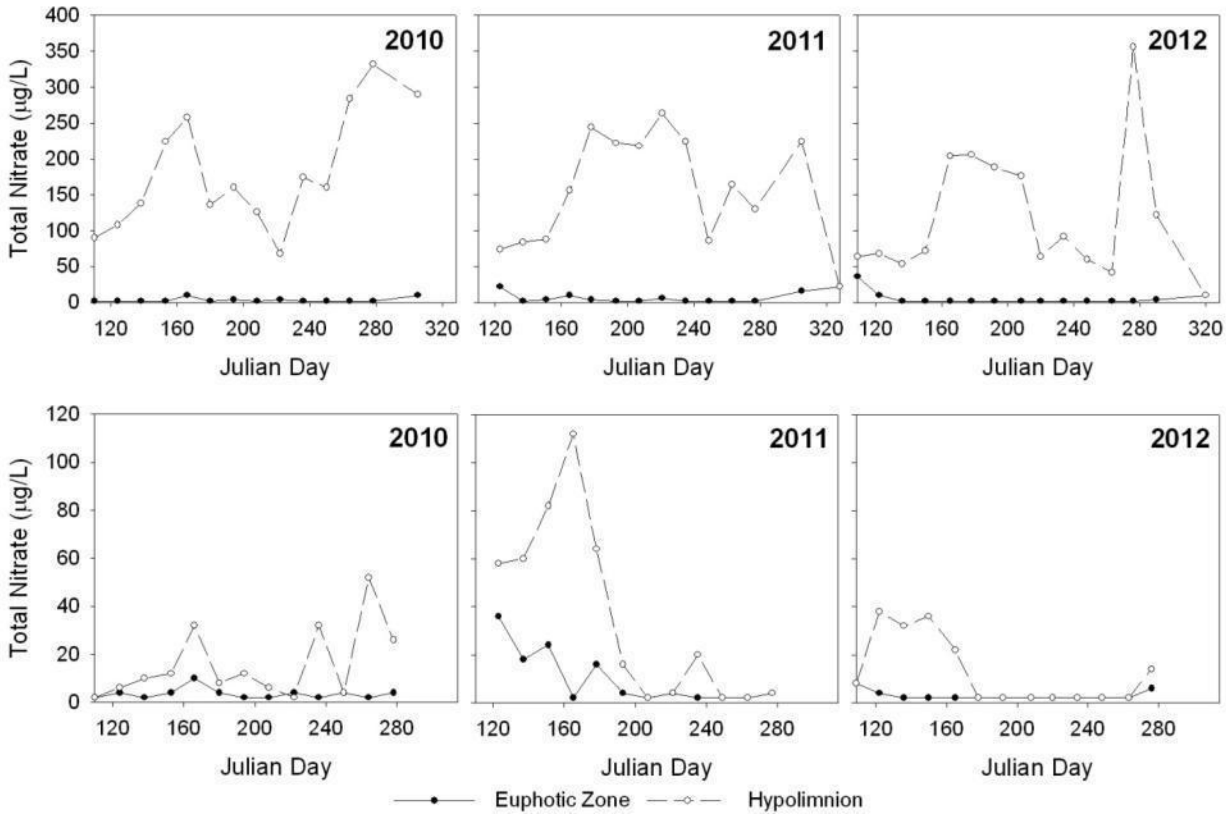

Figure 20. Total nitrate for euphotic zone and hypolimnion samples taken at NB (top) and SB (bottom) in 2010-2012.

Like nitrate, total ammonium can come from fertilizers and sewage sources. Total ammonium was highly variable, and did not show any consistent seasonal patterns from 2010-2012, aside from a mid-summer decline at NB and SB (**Figure 21**).

Concentrations were more variable at NB and SB compared to HH and M5, and values were less than 80 µg/L at all stations. Euphotic zone concentrations of unionized ammonia (the toxic portion of total ammonium) were low and well below the MOE objective of 20 µg/L.

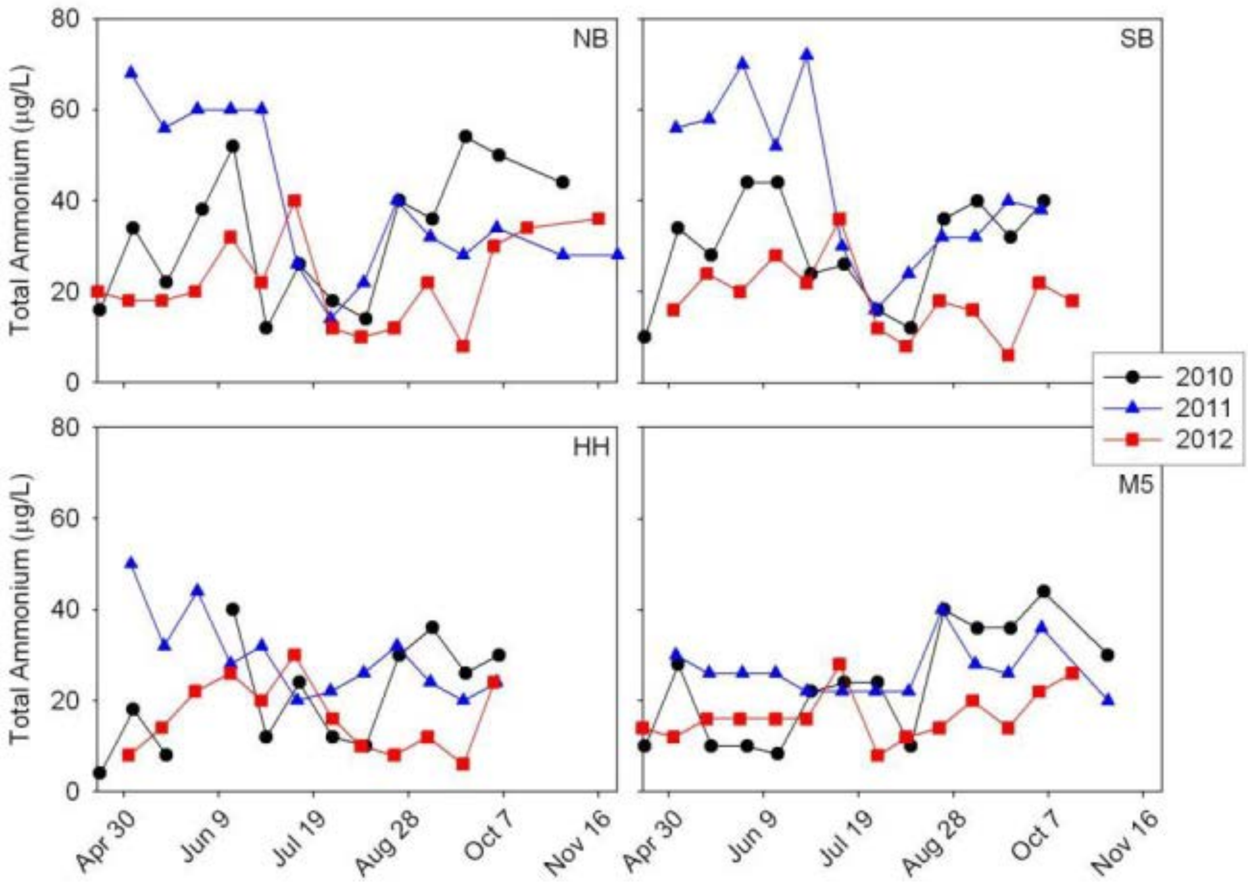

Figure 21. Seasonal total ammonium concentrations from euphotic zone composite samples at three monitoring stations in Honey Harbour and one in the open waters of Severn Sound (M5) for 2010-12.

Total ammonium concentration in the bottom waters was generally higher and more variable than in the euphotic zone at NB and SB (**Figure 22**). In 2011 at NB and 2012 at SB, concentrations were not significantly different between the two sample depths. Total ammonium concentrations in the bottom waters at both stations were much more variable compared to nitrate, however differences between euphotic zone and bottom water samples tended to be greatest later in the season after anoxia had set in.

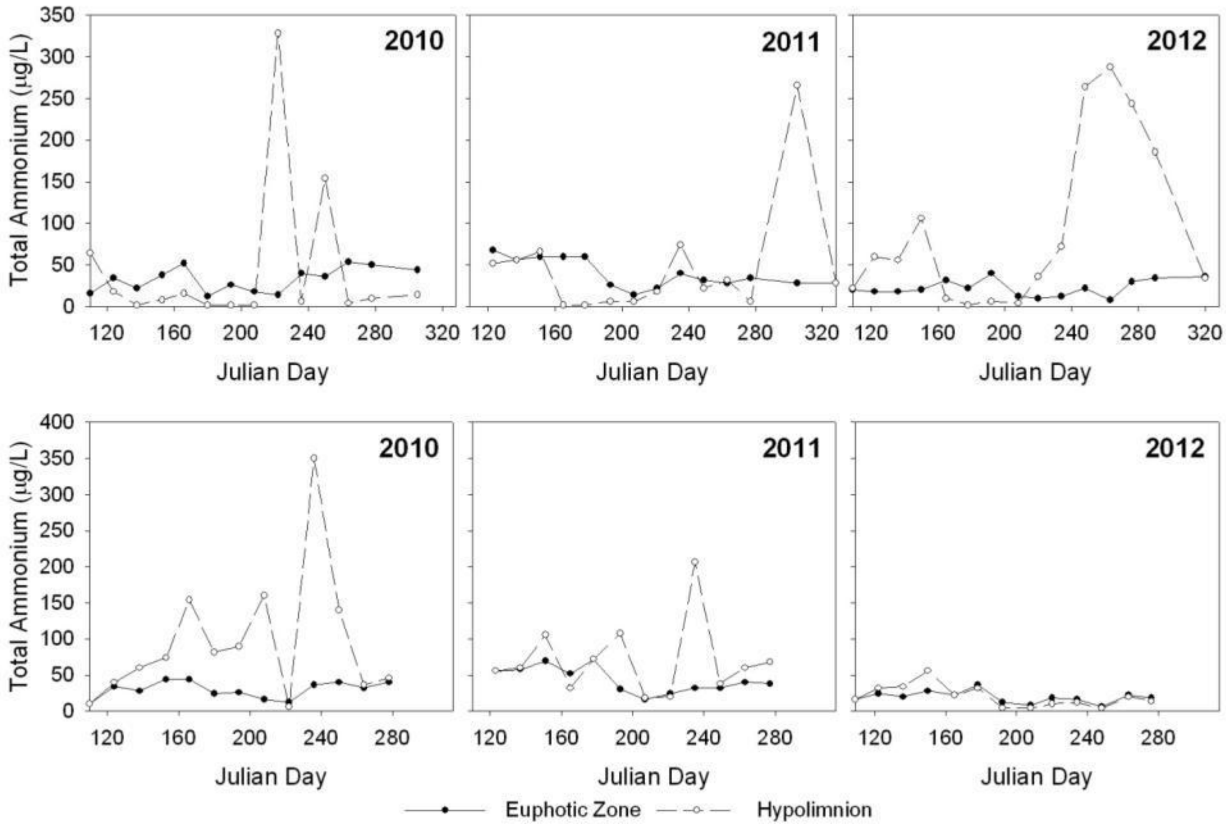

Figure 22. Total ammonium for euphotic zone and hypolimnion samples taken at NB (top) and SB (bottom) in 2010-2012.

Total nitrogen during fall turnover conditions ranged from 314-338 µg/L at NB, 320-382 µg/L at SB, 280-346 µg/L at HH and 288-322 µg/L at M5. These are considered at the low end of the range for moderately enriched lakes. The values for NB and SB are in the same range as historical concentrations, while values for HH and M5 are lower than historical concentrations (**Figure 12-Figure 13**).

Sulfate

Sulfate also undergoes chemical transformations in oxygen depleted conditions, transforming from sulfate to sulfide. As this occurs, the amount of sulfur measured as sulfate decrease as it is converted to hydrogen sulfide (H_2S) gas. This transformation can be confirmed if a "rotten egg" smell is detected for a bottom water sample. Comparison of euphotic zone and bottom water sulphate concentrations, collected during 2012, showed that sulfate depletion occurred starting approximately a month after the onset of anoxia at NB, but did not occur at SB. No smell was observed on Aug 21 when bottom water sulfate dropped to 5.9 mg/L at SB. There was a strong smell of H_2S at NB beginning Sept 9, corresponding to sulfate concentration of 5.0 mg/L. The odour of H_2S in the bottom water sample had disappeared at NB by fall turnover (Nov 15, 2012). The presence of H_2S has implications for the solubility of iron in bottom waters, which will be discussed below.

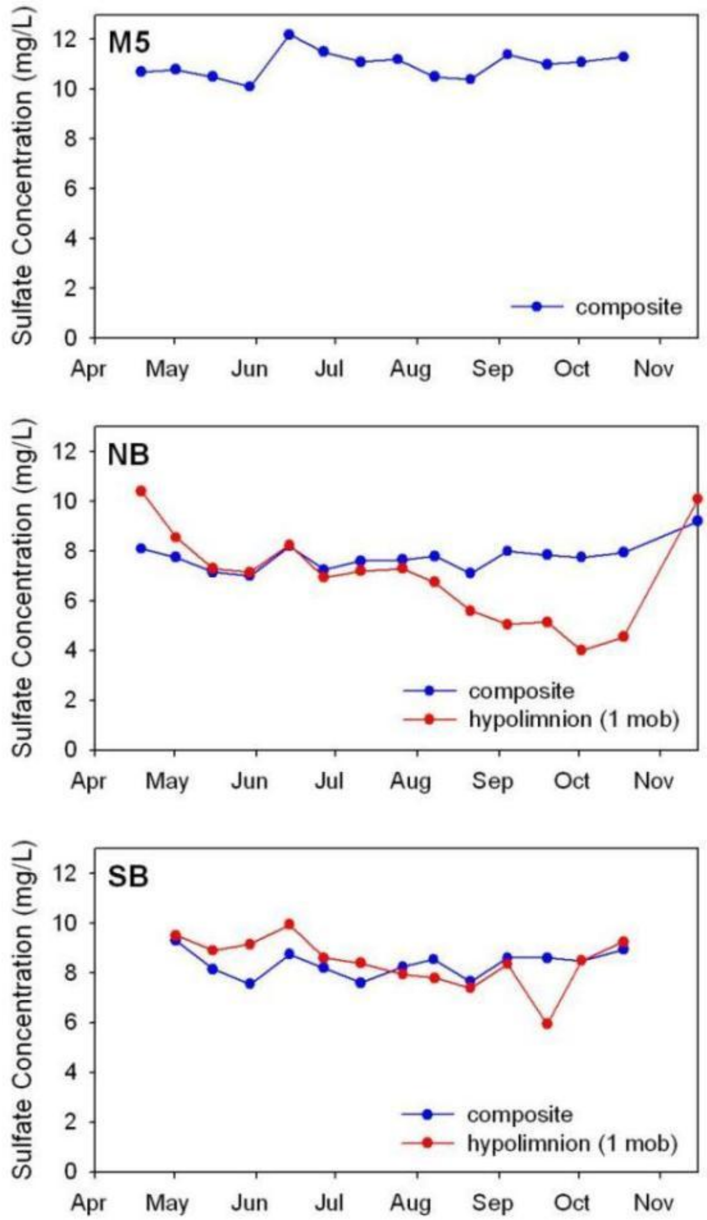

Figure 23. Sulfate concentrations at M5, NB and SB in 2012. Composite and bottom water concentrations are shown.

Metals

Heavy metals in lake water can occur due to industrial contamination, past or present, sewage and stormwater inputs, and geological weathering. Metals of particular interest in terms of human and aquatic health include arsenic, cadmium, chromium, copper, and lead. Overall, the concentrations of all measured heavy metals in the Honey Harbour area were low, and in many cases, concentrations were below the limit detectable of the test method (**Table 4**).

Table 4. Percentage of data from 2010-2012 where concentrations of metals were greater than analytical detection limits for NB, SB, HH and M5 in both euphotic zone composites and bottom water (1 m.o.b.) samples where applicable. Maximum values are also shown, reported in µg/L. Maxima were calculated using 2010-2012 data combined. Total number of samples collected for each station between 2010-2012 is shown at the bottom of the table. Metals that were not detected are indicated by n.d.

		NB				SB				HH		M5	
		% Detect		Maximum Value		% Detect		Maximum Value		% Detect	Maximum Value	% Detect	Maximum Value
Chemical Symbol	Metal Name	Euphotic Zone	1 m.o.b.	Euphotic Zone	1 m.o.b.	Euphotic Zone	1 m.o.b.	Euphotic Zone	1 m.o.b.	Euphotic Zone	Euphotic Zone	Euphotic Zone	Euphotic Zone
Ag	Silver	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al	Aluminum	100	100	34.1	46.4	100	100	49.7	85.2	100	29.6	100	175.0
As	Arsenic	62	57	0.5	2.0	73	68	0.7	3.5	48	0.5	63	0.6
Ba	Barium	100	100	18.0	34.6	100	100	25.1	29.5	100	18.5	100	28.5
B	Boron	84	89	12	12	82	87	15	15	81	11	83	14
Be	Beryllium	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cd	Cadmium	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co	Cobalt	n.d.	51	0	0.7	n.d.	35	0	0.5	n.d.	0	n.d.	0
Cr	Chromium	16	17	1.22	0.60	15	13	0.90	0.70	10	0.40	17	3.60
Cu	Copper	86	89	1.79	2.30	85	90	11.50	1.90	81	1.40	89	38.90
Fe	Iron	100	100	270	7150	97	100	127	4120	95	90	66	115
Mn	Manganese	100	100	65.8	1240.0	100	100	29.5	1140.0	100	13.5	100	14.5
Mo	Molybdenum	86	80	3.36	0.30	82	84	2.64	2.22	67	0.20	86	3.63
Ni	Nickel	19	77	0.80	1.68	12	61	0.60	0.60	24	0.50	46	2.48
Pb	Lead	n.d.	6	0	0.30	n.d.	6	0	0.30	19	0.20	n.d.	0
Sb	Antimony	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Se	Selenium	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sr	Strontium	100	100	103.0	112.0	100	100	121.0	120.0	100	91.1	100	124.0
Ti	Titanium	100	100	1.50	2.22	100	100	1.60	5.50	100	1.50	100	2.10
Tl	Thallium	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
U	Uranium	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
V	Vanadium	35	37	1.65	1.64	85	71	2.13	2.13	52	1.87	80	2.82
Zn	Zinc	73	100	3.3	4.5	82	97	5.4	3.6	100	2.0	71	3.5
	# of samples, *n*	37	35			33	31			21		35	

Of those metals that were present in detectable amounts, concentrations were generally below Provincial Water Quality Objectives (PWQOs). There were a small number of exceedances of the PWQO for aluminum in the bottom waters at SB, and in the euphotic zone at M5 (3%), as well as a small number of exceedances of the PWQO for copper in the euphotic zone at SB and M5 (3 and 6%, respectively) (**Table 5**). The PWQO for iron was often exceeded in the bottom waters at NB and SB (54 and 23%, respectively).

Table 5. Percentage of data from 2010-2012 where concentrations of metals were greater than MOE's Provincial Water Quality Objective for NB, SB, HH and M5 (values above zero are bolded in red). Data that is less than analytical detection limits are indicated by n.d.

		NB		SB		HH	M5
Chemical Symbol	PWQO (µg/L)	% Exceedance Euphotic Zone	1 m.o.b.	% Exceedance Euphotic Zone	1 m.o.b.	% Exceedance Euphotic Zone	% Exceedance Euphotic Zone
Ag	0.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al	75	0	0	0	**3**	0	**3**
As	5	0	0	0	0	0	0
Ba	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
B	200	0	0	0	0	0	0
Be	11	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cd	0.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co	0.9	0	0	0	0	0	0
Cr	1 (for hexavalent)	0	0	0	0	0	0
Cu	5	0	0	**3**	0	0	**6**
Fe	300	0	**54**	0	**23**	0	0
Mn	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mo	40	0	0	0	0	0	0
Ni	25	0	0	0	0	0	0
Pb	3	0	0	0	0	0	0
Sb	20	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Se	100	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sr	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ti	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tl	0.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
U	5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
V	6	0	0	0	0	0	0
Zn	20	0	0	0	0	0	0

Several metals undergo chemical transformations under anoxic conditions, changes which can alter their solubility in water, causing them to be released from sediments. Of particular interest is the transformation of iron in the hypolimnion. Bottom water iron dynamics have implications on internal P loading and cyanobacteria production since they have higher Fe requirements than other groups of algae (Morton & Lee, 1974; Parr & Smith, 1976; Brand, 1991). When sediments become anoxic, insoluble ferric iron (Fe^{3+}) in the form of ferric carbonate ($Fe_2(CO_3)_3$) is reduced to soluble ferrous iron. $Fe_2(CO_3)_3$ often has phosphate adsorbed to it, and when it is reduced, this phosphate is released into the waters above the sediment, thereby contributing to internal P loading. In the presence of H_2S, highly insoluble ferrous sulphide (FeS) is formed (Mackie 2001). Consistently from 2010-2012, total iron concentrations (includes soluble and insoluble forms) increased in the bottom waters compared to the euphotic zone at NB and SB as anoxia set in (**Figure 24, Figure 25,** and **Figure 26**). As seen before, when the water column becomes isothermal, euphotic zone and bottom water concentrations become equal. It is unknown at this time what portion of total iron in the bottom waters is in the insoluble form or the soluble form. It is also unknown how sharp the gradient is from the Fe-enriched bottom waters into the rest of the hypolimnion. Both of these questions have potential implications for cyanobacterial growth.

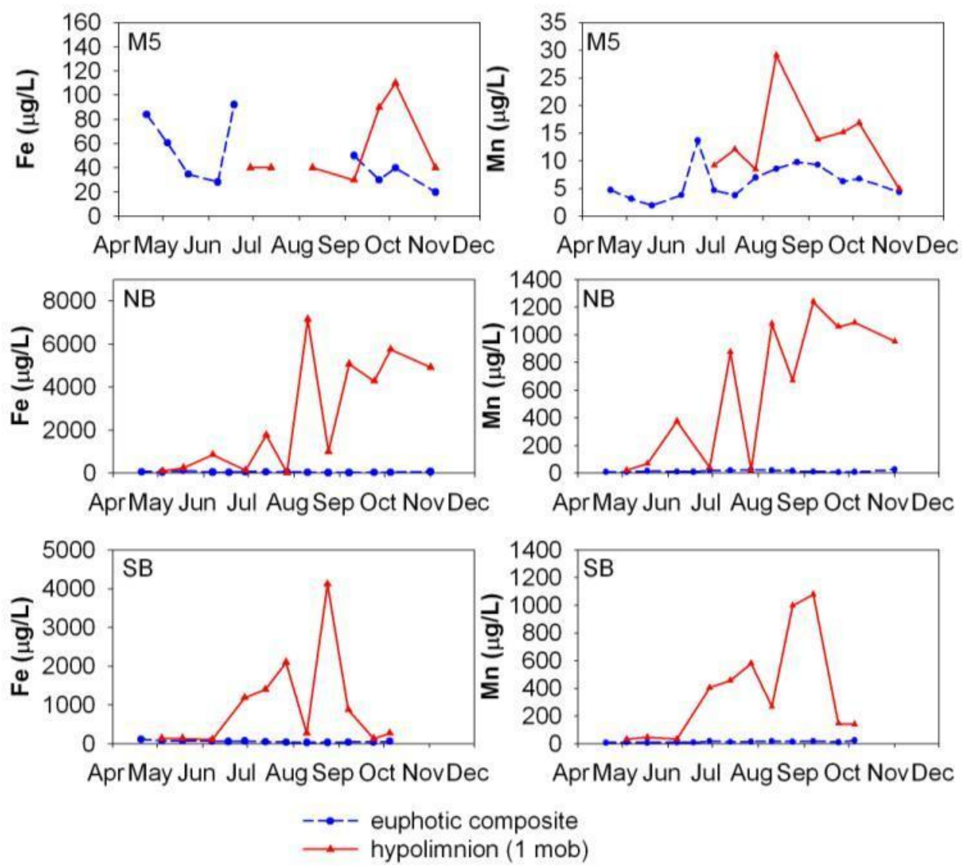

Figure 24. Iron and manganese at M5, NB and SB in 2010. Composite and bottom water concentrations are shown.

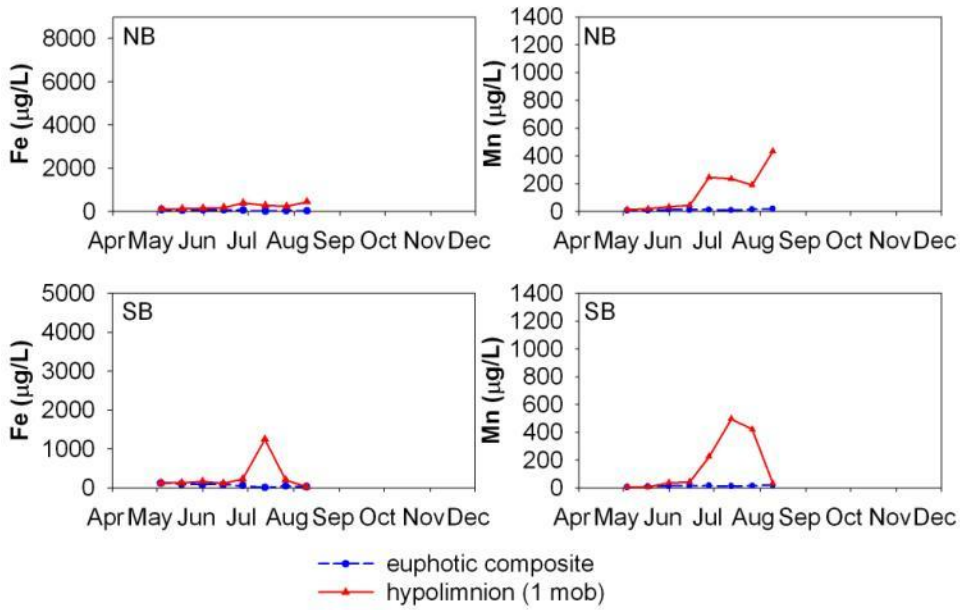

Figure 25. Iron and manganese at NB and SB in 2011. Composite and bottom water concentrations are shown. Data was unavailable beginning in mid-August.

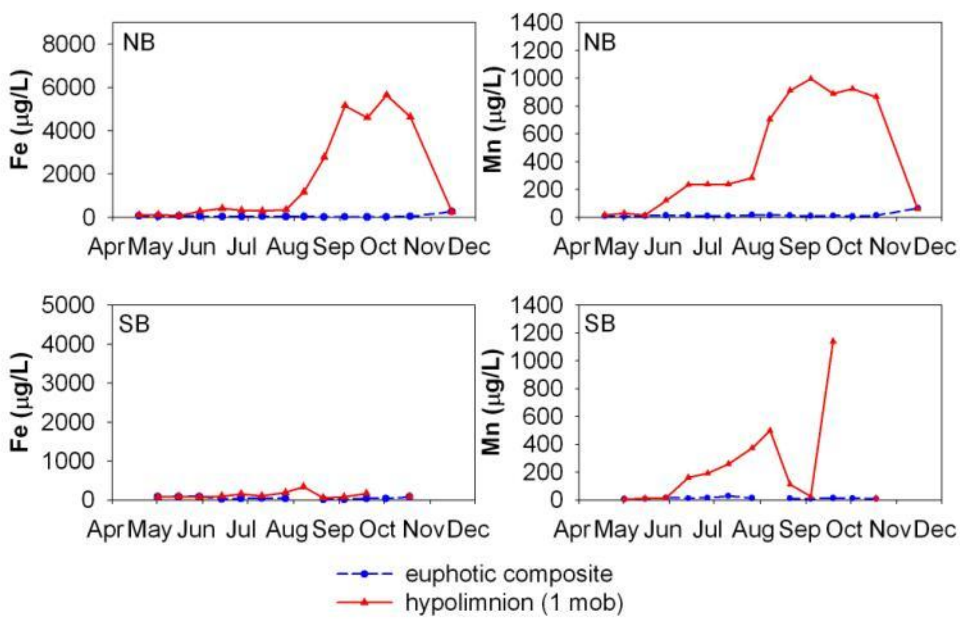

Figure 26. Iron and manganese at NB and SB in 2012. Composite and bottom water concentrations are shown. Data for SB euphotic zone and bottom waters were unavailable for Aug 7 and Oct 2, respectively.

As with TP, Fe and Mn appear to increase in the water column at NB from spring to fall turnover conditions. Out of the three years when metals data were collected, 2012 was the only year where sampling continued until fall turnover, and where metals data were available for the entire season. Results show that the average concentration throughout the water column (average of euphotic composite and bottom water discrete samples) on April 18 2012 was 95 µg/L for Fe and 14.1 µg/L for Mn. Fall turnover concentrations on Nov 15 were 265 µg/L and 63.8 µg/L for Fe and Mn, respectively. For Fe, these changes represented an increase of 2.8 times between the spring and fall. For Mn, the increase was 4.5 times. At SB, differences in Fe and Mn were much smaller. It is currently unclear whether higher concentrations observed in the fall will lead to elevated concentrations the following spring, or, like TP, concentrations of these metals will be depleted over the winter season.

PHYTOPLANKTON

Phytoplankton are tiny (usually microscopic) one-celled or colonial plants that grow suspended in the lake water column. Total biovolume (i.e. the total volume of all algae cells in a sample) is used to assess a lake's overall response to nutrient loads and concentrations, and is an accurate estimate of the total biomass of algae. It is measured in mm^3/m^3, or $mm^3/1000L$. As a conceptual aid, 1 mm^3 is the volume of a poppy seed, and $1m^3$ is roughly the size of an average kitchen range.

Several classes of algae make up the total biovolume of phytoplankton in the water column of the Honey Harbour area. Many of these groups or classes have members that can cause algal "blooms" or heavy growths that can be a health concern or impair the use of the water for drinking or recreation. The total biovolume is controlled largely by the phosphorus concentration in the euphotic zone. Specific classes of algae, such as the blue-green algae, respond to additional factors which can result in growths that lead to harmful or nuisance conditions even at low phosphorus concentrations. An understanding of the relation of the trophic indicators to the phytoplankton community is one of the most important aspects of water quality monitoring and surveillance for management and planning purposes.

A detailed breakdown of phytoplankton biovolume by a taxonomic group such as class or genus can be used to determine how populations of different members of the algae community vary through space and time.

Over the period 1998 to 2012 total biovolume of phytoplankton over the ice-free period has ranged from 700 to 2000 mm^3/m^3 at NB, 450 to 600 mm^3/m^3 at SB with one peak year of 2000 mm^3/m^3 (2011); 500 to 2000 mm^3/m^3 at HH; and 500 to 800 mm^3/m^3 at M5. Since monitoring for algae began in 1998, total biovolume at NB has fluctuated, but not increased significantly (**Figure 27**). However there have been changes in specific classes of algae. Based on Mann-Kendall trend tests there was a significant increase in chrysophytes at NB, dinophytes at SB and cryptophytes at HH. Peaks in chrysophyte biovolume occurred in 2011 at SB and HH and 2012 at HH, but there was no significant trend. Increased chrysophyte abundance has been observed in many Ontario lakes (Paterson et al 2004), and may be a response to regional drivers such a climate change, rather than changes in local conditions.

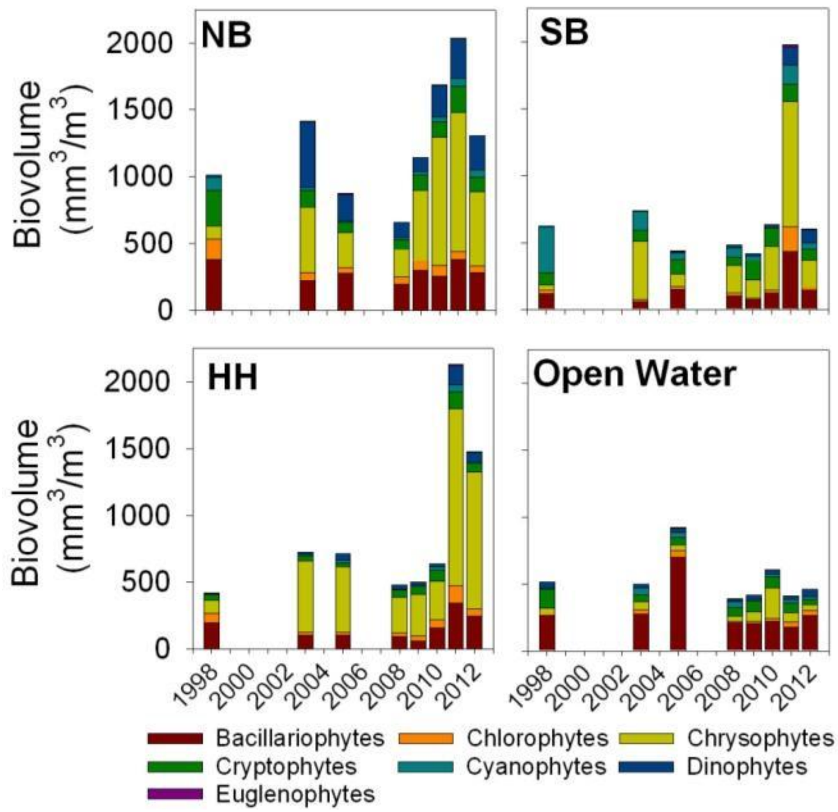

Figure 27. Total annual phytoplankton biovolume summarized by class for the three Honey Harbour station and M5 (open water) from 1998-2012.

Seasonal Dynamics

Seasonal algal biovolume data allow for a more in-depth examination of variations in biovolumes of algal groups and of specific taxa. Algal concentrations are generally higher at the Honey Harbour stations than they are at the open water station, the short-lived mid-summer population peaks in diatoms at M5 notwithstanding (**Figure 28** and **Figure 29**).

The most dominant group at NB was chrysophytes, which generally peaked in early and late summer. These peaks were dominated by *Chrysosphaerella brevispina*, which is a mixotrophic species. Mixotrophs are algae that can acquire cellular energy through photosynthesis or through ingesting small bacterial cells or particles. This gives them a competitive advantage over other types of algae in low nutrient and light conditions.

Data since 2005 show that *Chrysosphaerella spp*. (includes *C. longispina* but is mostly comprised of *C. brevispina*) reached as high as 92% of total biovolume (**Figure 30**). Since 2010, peaks have been occurring in early and late summer as opposed to a single peak. Based on inferred total chlorophyll *a* profiles (**Figure 31**) and discrete depth microscope counts (**Figure 33**), these blooms tended to occur at depth between 3-6 m.

Note that the peaks in *Chrysosphaerella* did not coincide with periods of low metalimnetic DO.

The second most dominant group at NB was dinophytes, which tended to proliferate during or after *Chrysosphaerella spp*. blooms (**Figure 28**). This group was dominated by *Peridinium wisconsinense*. This taxa is typical of the summer epilimnion of mesotrophic lakes. It has been proposed that the ratio between this species and *P. willei* can be used as an indicator of trophic status (McCarthy et al 2011), however it was not always possible to identify all *Peridinium* to species.

Data since 2005 show that *Peridinium spp*. (includes *P. willei* but is mostly comprised of *P. wisconsinense*) reached as high as 56% of total biovolume (**Figure 30**). Based on inferred total chlorophyll *a* profiles (**Figure 32**) and discrete depth microscope counts (**Figure 34**), these blooms tended to occur at depths between 7-10 m. The fact that they occupy a different location in the water column explains why they are able to proliferate at the same time as *Chrysosphaerella*.

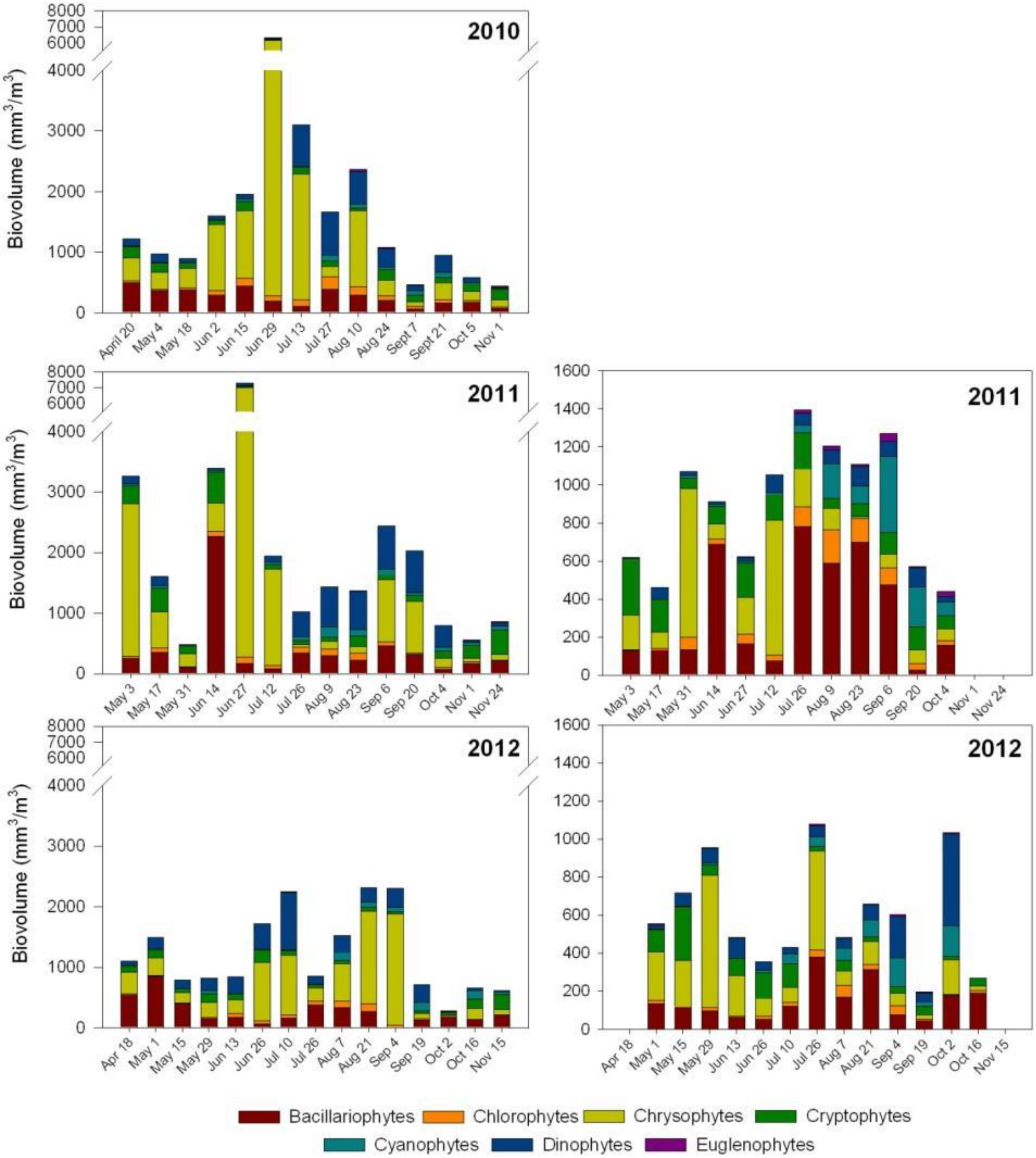

Figure 28. Seasonal phytoplankton biovolume euphotic zone composites at NB from 2010-12 (left) and SB from 2011-2012 (right). Note the break in the y-axis for NB, above which the scale changes.

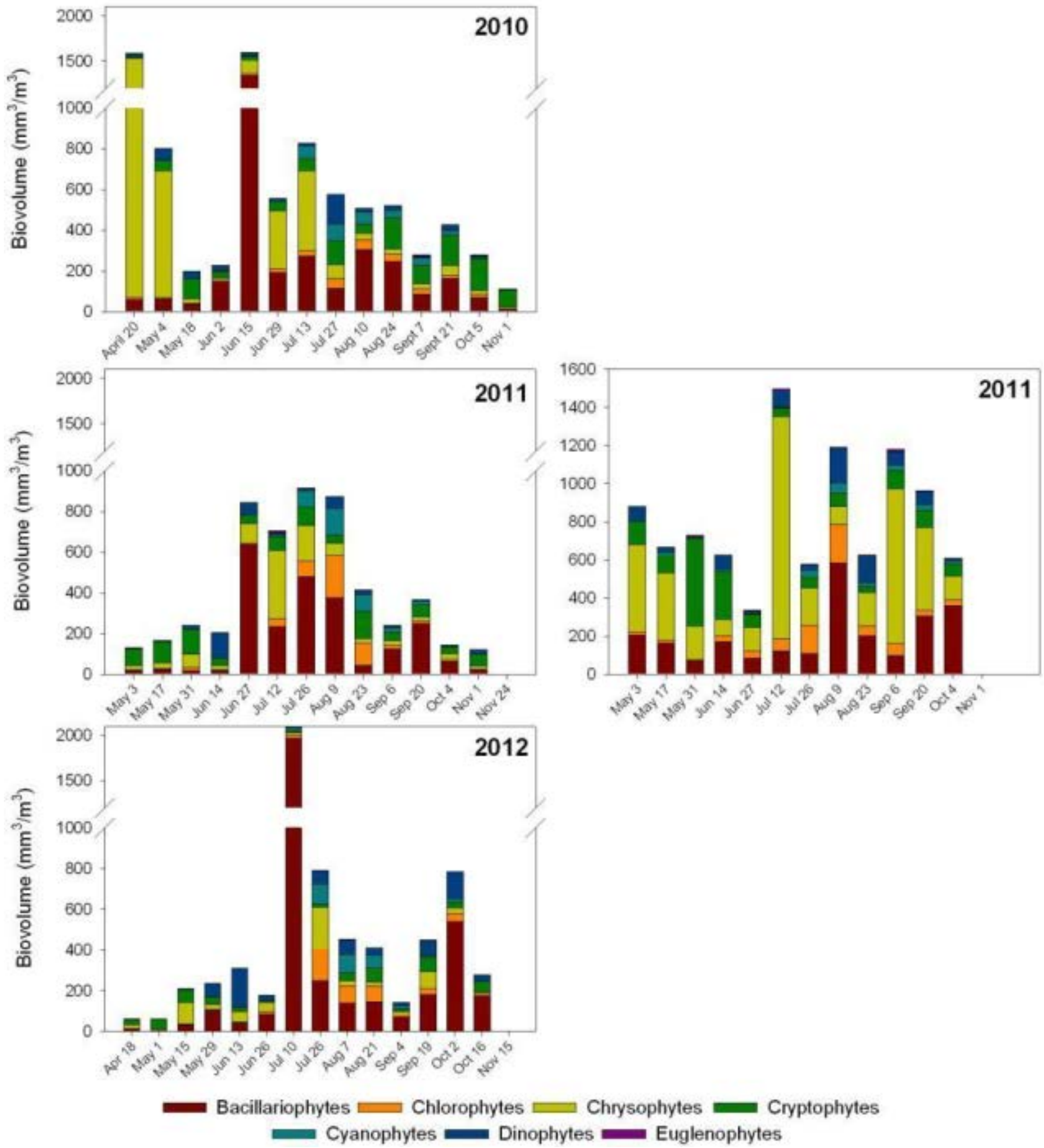

Figure 29. Seasonal phytoplankton biovolume in euphotic zone composites at M5 from 2010-2012 (left) and HH for 2011 (right).

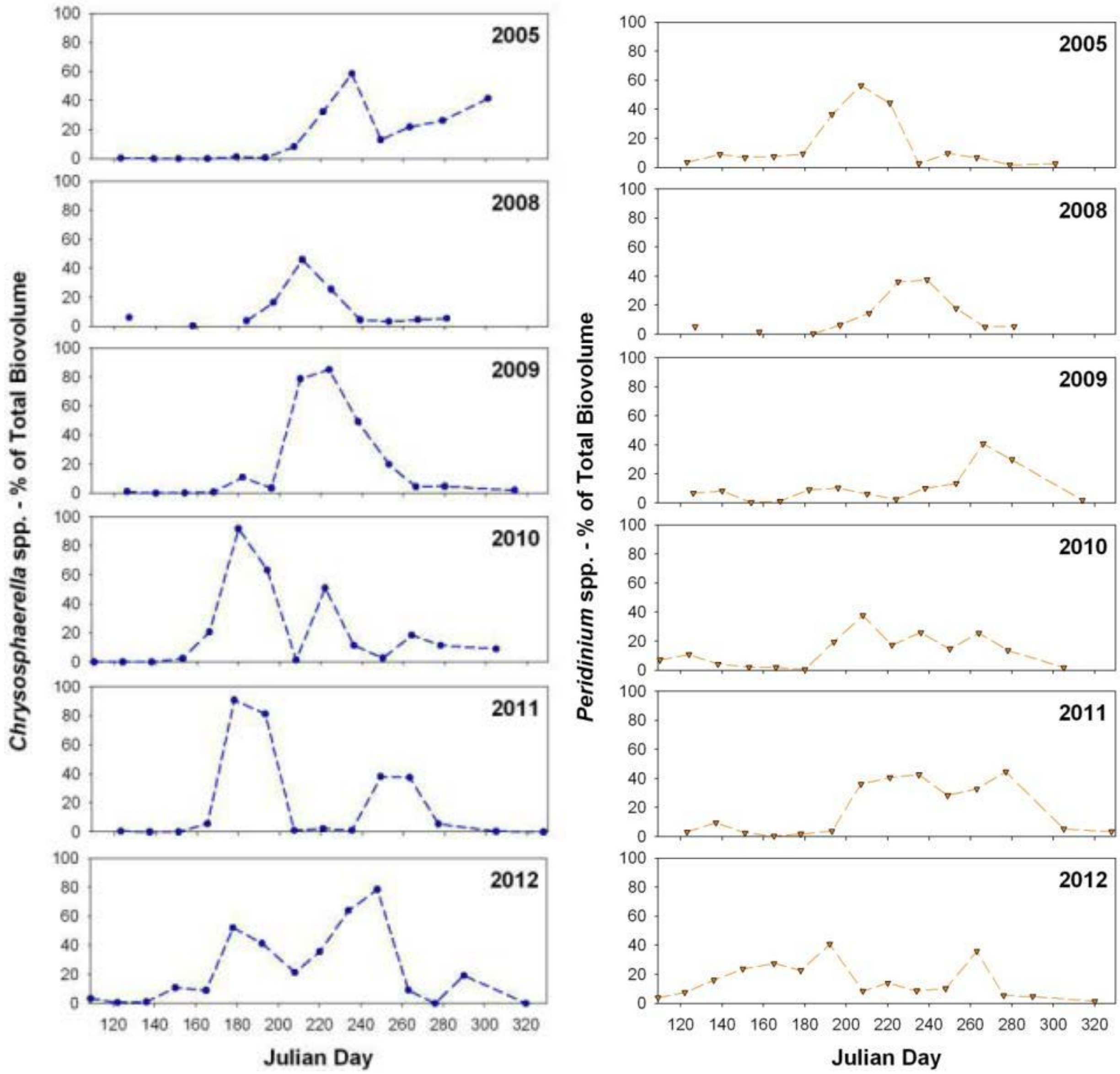

Figure 30. *Chrysosphaerella spp.* (left) and *Peridinium spp*. (right) as a percentage of total phytoplankton biovolume from 2005-2012 at NB.

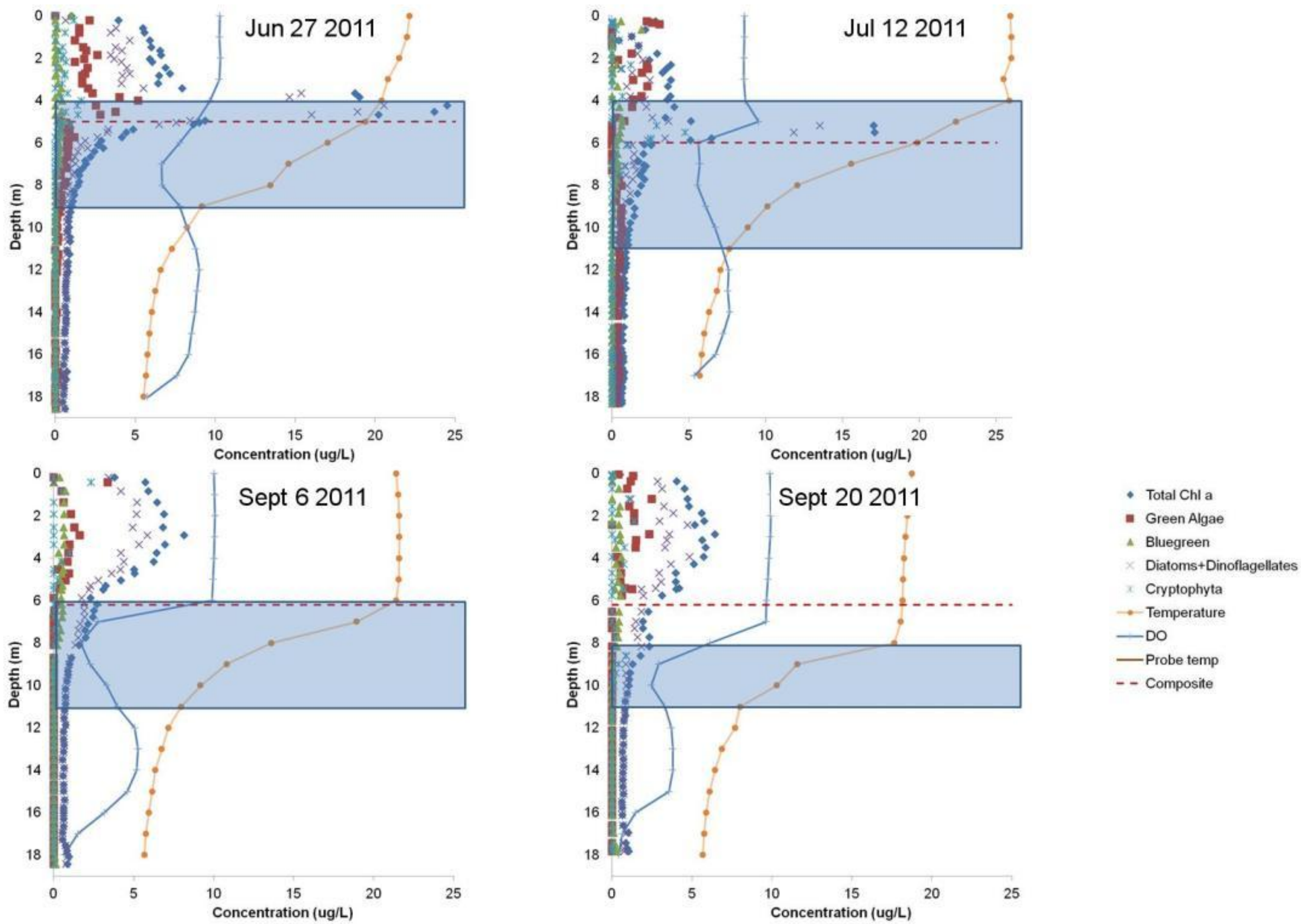

Figure 31. Pigment profiles taken using the Fluoroprobe for specific dates in 2011 at NB. Also shown is temperature and DO taken using the YSI sonde, the depth of composite samples, and the extent of the metalimnion (represented by the light blue box).

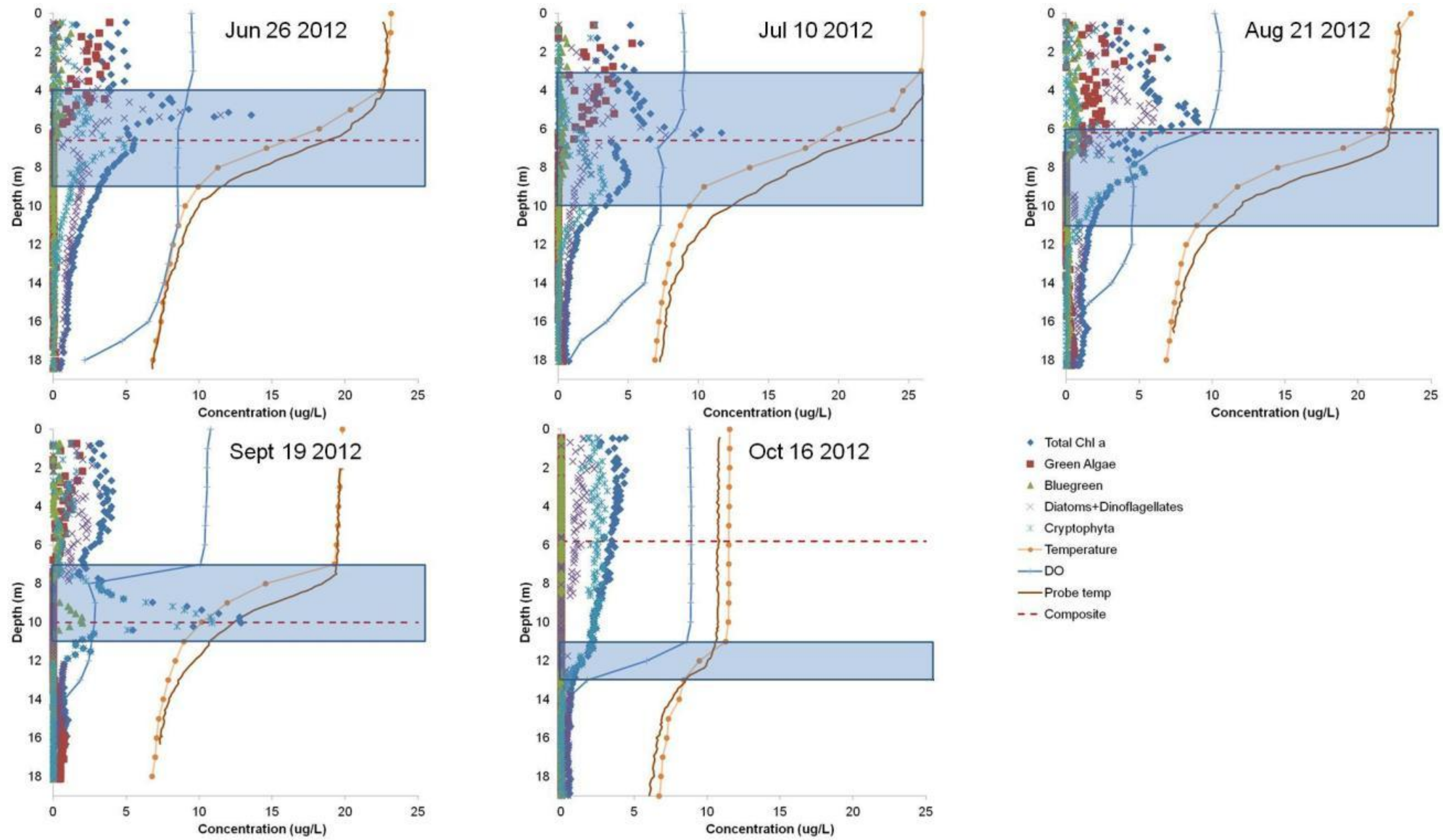

Figure 32. Pigment profiles taken using the Fluoroprobe for specific dates in 2012 at NB. Also shown is temperature and DO taken using the YSI sonde, the depth of composite samples, and the extent of the metalimnion (represented by the light blue box).

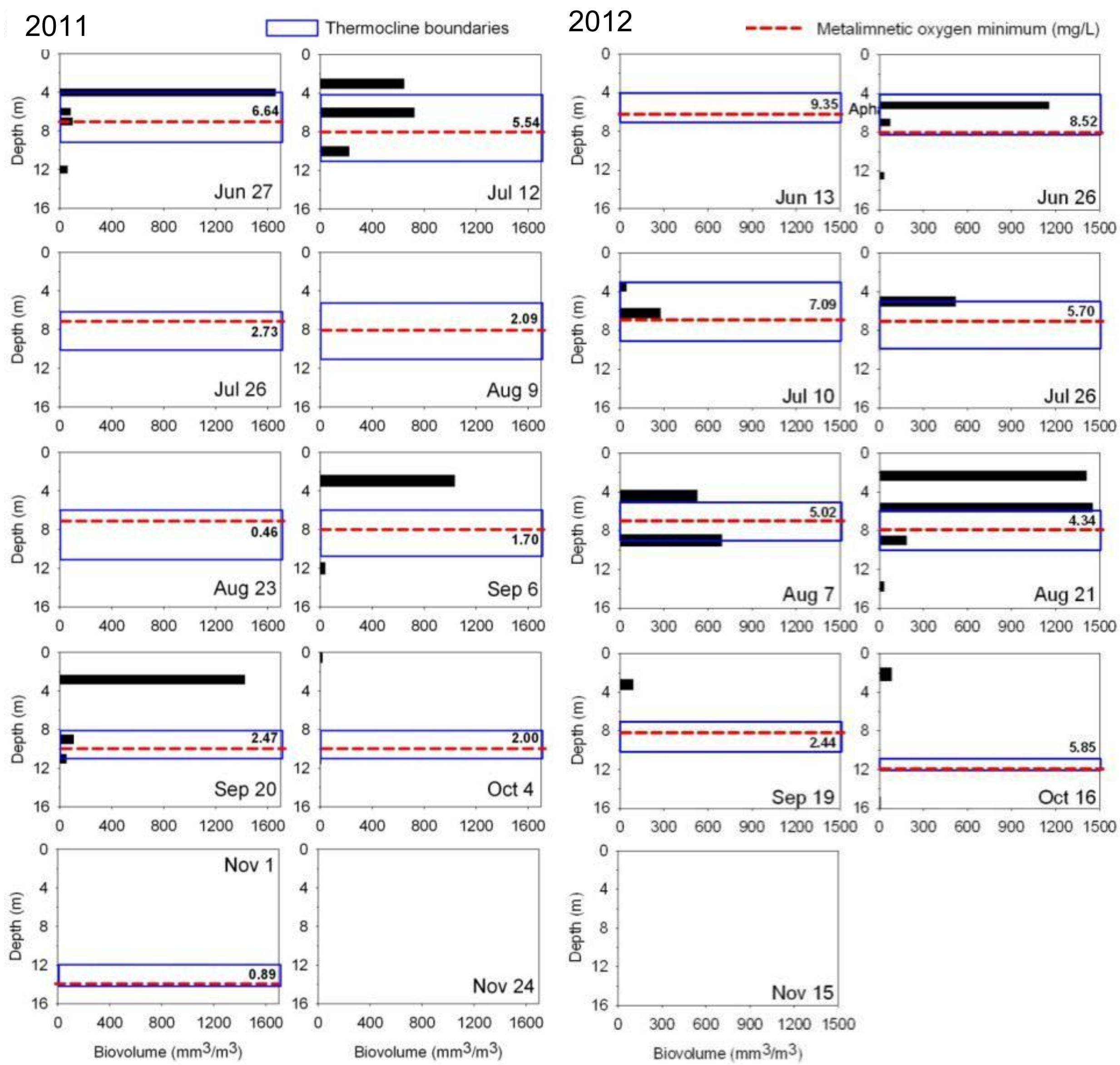

Figure 33. *Chysosphaerella spp.* biovolume based on microscope counts of samples taken at discrete depths in 2011 (left) 2012 (right) at NB. Also shown are the thermocline boundaries (blue boxes) and the depth at which the metalimnetic oxygen minimum occurred, labeled with the value of the minimum.

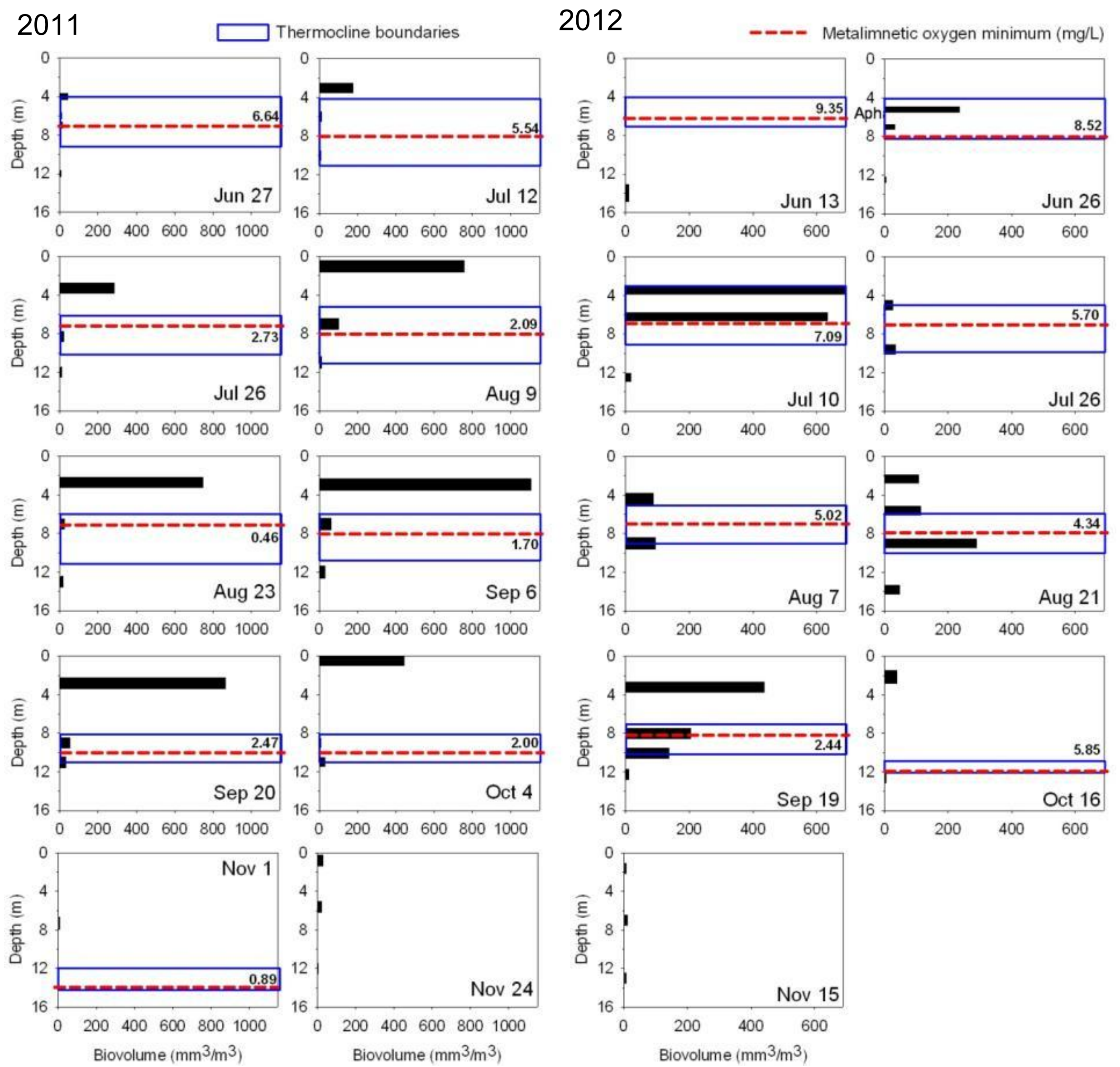

Figure 34. *Peridinium spp.* biovolume based on microscope counts of samples taken at discrete depths in 2011 (left) 2012 (right) at NB. Also shown are the thermocline boundaries (blue boxes) and the depth at which the metalimnetic oxygen minimum occurred, labeled with the value of the minimum.

Seasonal data from 2010-2012 at NB shows that cyanobacteria do not dominate at any point over the season (**Figure 29**). The only occurrence of cyanobacteria at NB that reached appreciable biovolume was a growth of *Planktothrix agardhii* in the fall of 2012, which occurred between 9-10 m (and **Figure 32**, Sept 19 panel. This species has the potential to produce microcystin, a type of toxic metabolite produced by some species of cyanobacteria under certain conditions. Even if favorable conditions existed, levels of *P. agardhii* are much lower than what would be considered a risk for drinking water.

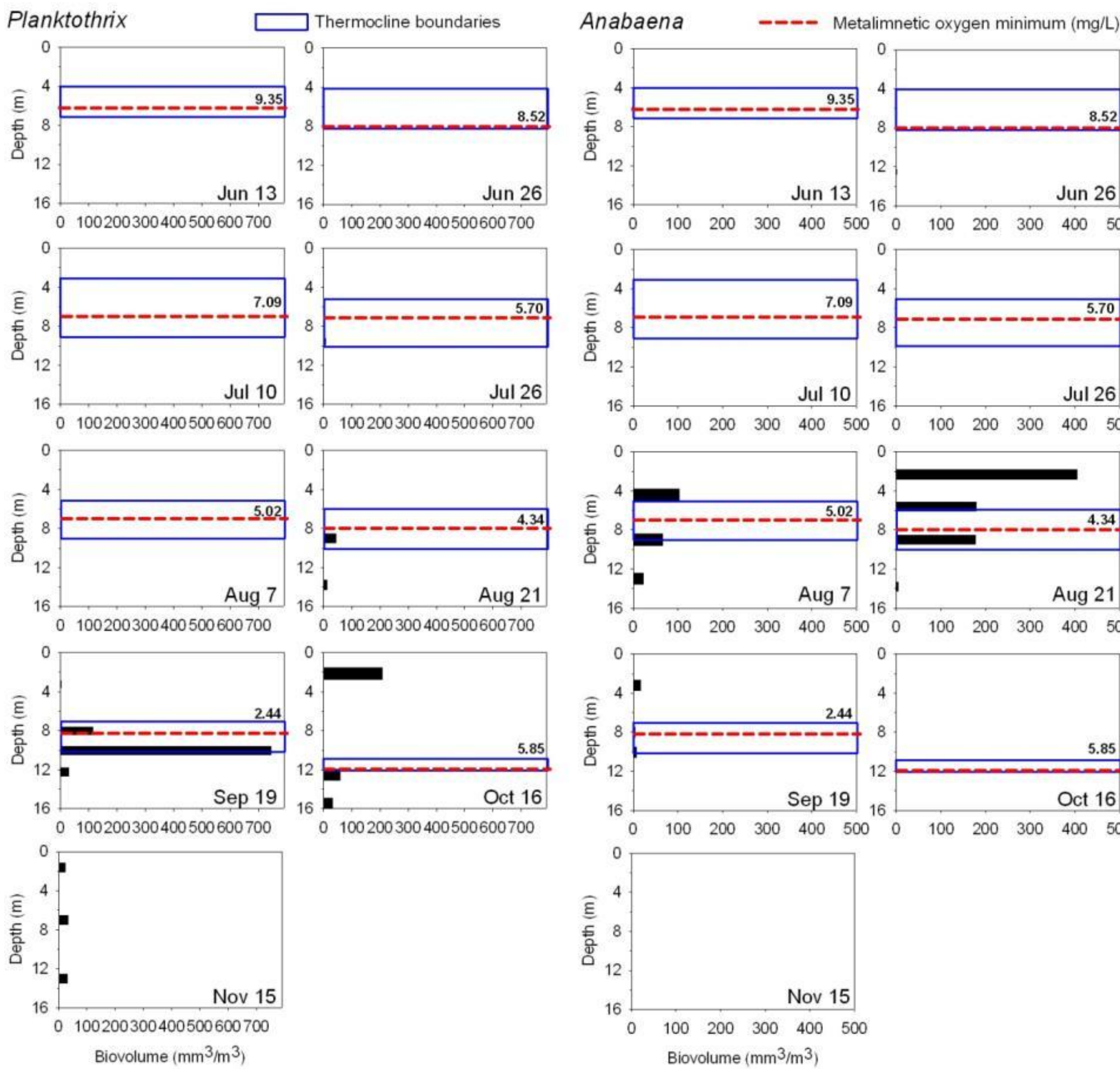

Figure 35. *Planktothrix* and *Anabaena* biovolume based on microscope counts of samples taken at discrete depths in 2012 at NB. Also shown are the thermocline boundaries (blue boxes) and the depth at which the metalimnetic oxygen minimum occurred, labeled with the value of the minimum.

By contrast with NB, total cyanophyte biovolume at SB peaked in early and late September of 2011 to the point of dominating or nearly dominating the phytoplankton community. The dominant taxa was *Anabaena*. This nitrogen-fixing cyanophyte is also capable of producing cyanotoxins such as microcystin, but like *P. agardhii* in North Bay, was present in small amounts compared to what would be considered a drinking water threat. In past years, cyanobacteria dominance has been over 70% of total biovolume for brief periods in late summer (**Figure 36**). These peaks were caused by blooms of *Planktothrix agardhii* (2005-2009). It is unclear why *P. agardhii* biovolumes dropped off in subsequent years, and in 2011 and 2012 were replaced by *Anabaena*.

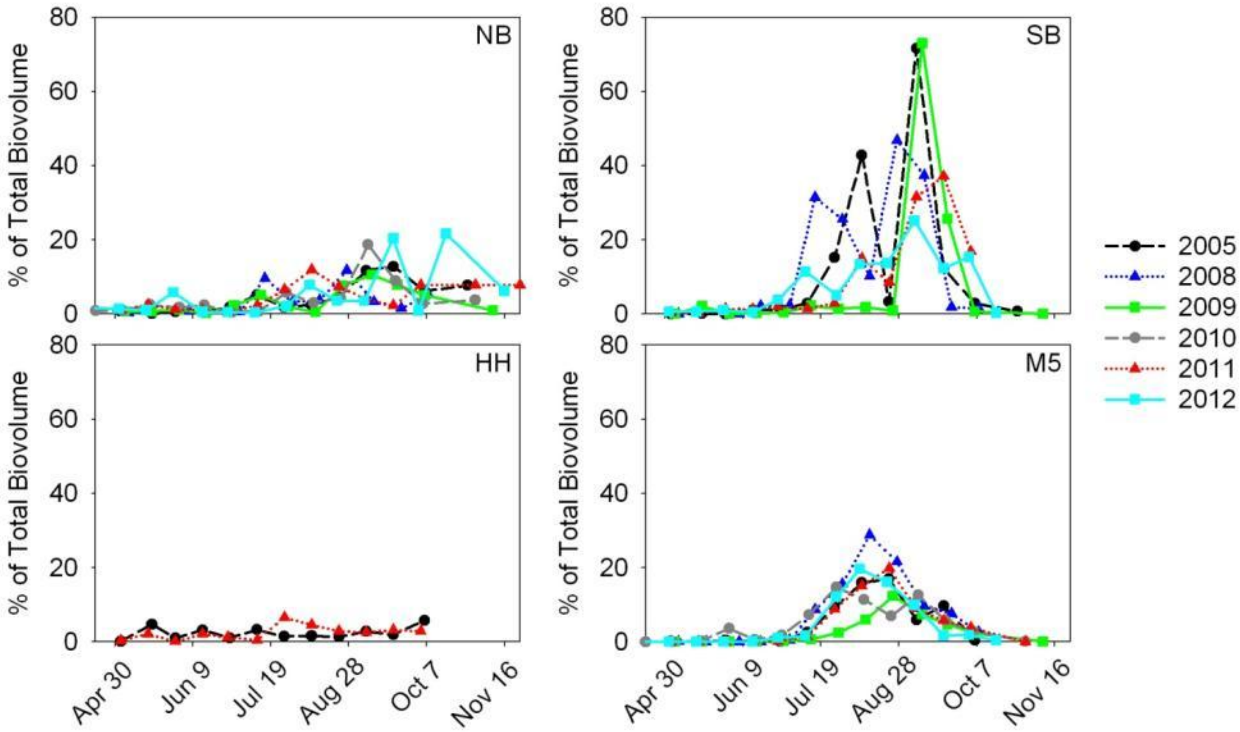

Figure 36. Total cyanobacteria biovolume expressed as a percentage of total phytoplankton biovolume for NB (upper left), SB (upper right), HH (lower left) and M5 (lower right) from 2005-2012.

Vertical Distribution of Phytoplankton

New field instrumentation has allowed for the measurement of variation in algal groups with depth in real time. The Fluoroprobe converts fluorescence measurements of four different pigment into concentrations, and each pigment roughly corresponds to a class of algae. Diatoms, dinoflagellates and chrysophytes are grouped together, and at this time cannot be distinguished. New methods in processing raw fluorescence data are being developed and may allow for greater resolution between groups.

A comparison between NB and M5 illustrates how algae are influenced by vertical mixing of the water column (**Figure 37**). At M5, mixing events redistribute algae through the water column. Diatoms are the most tolerant of this constant mixing, hence their dominance in the open waters (**Figure 29**). Once the thermocline is established at NB, algae are generally not found below the top of the hypolimnion, and thus do not inhabit the bottom waters (**Figure 38**).

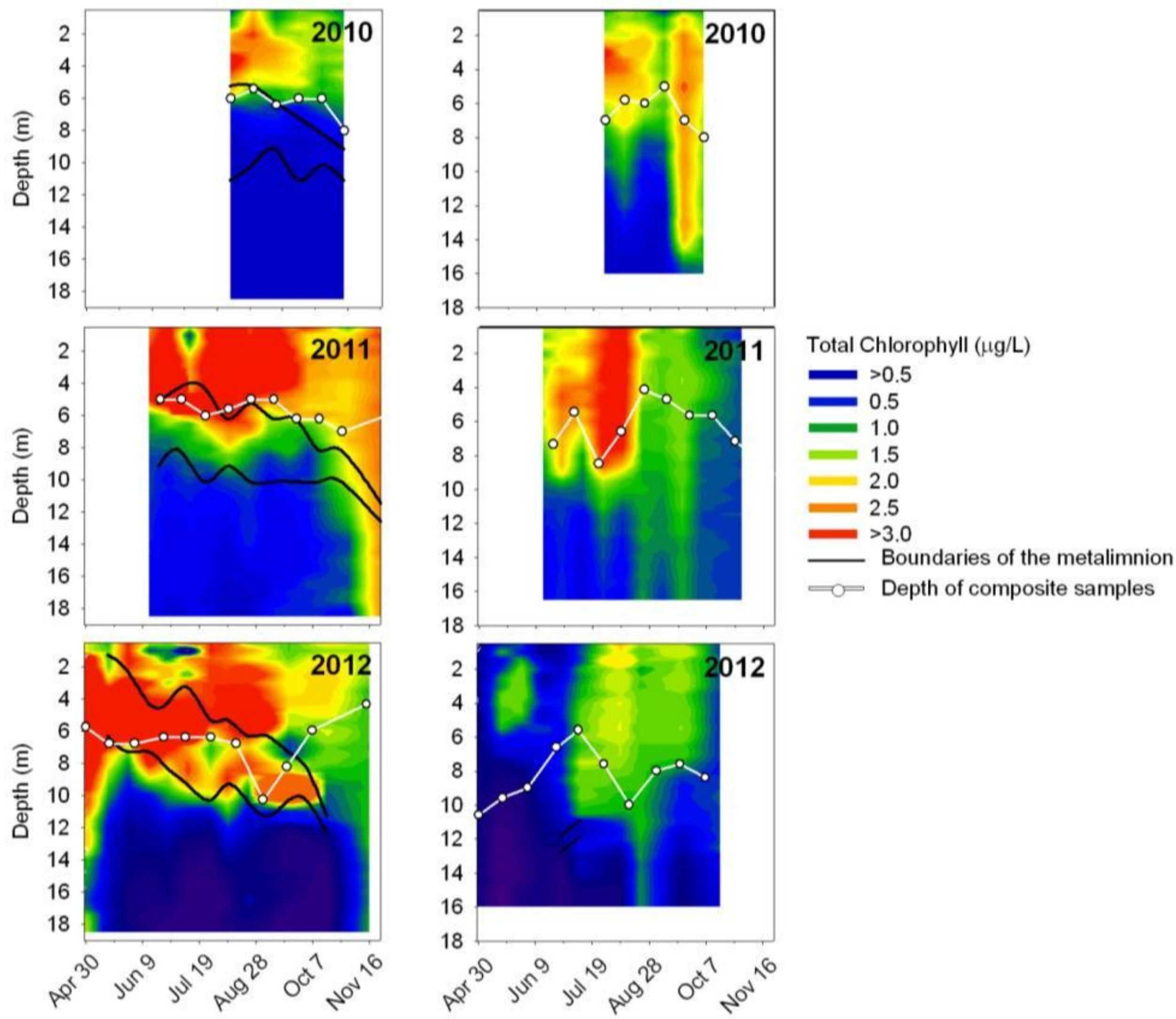

Figure 37. Pigment inferred chlorophyll *a* isopleths at NB (left) and M5 (right) from 2010-2012.

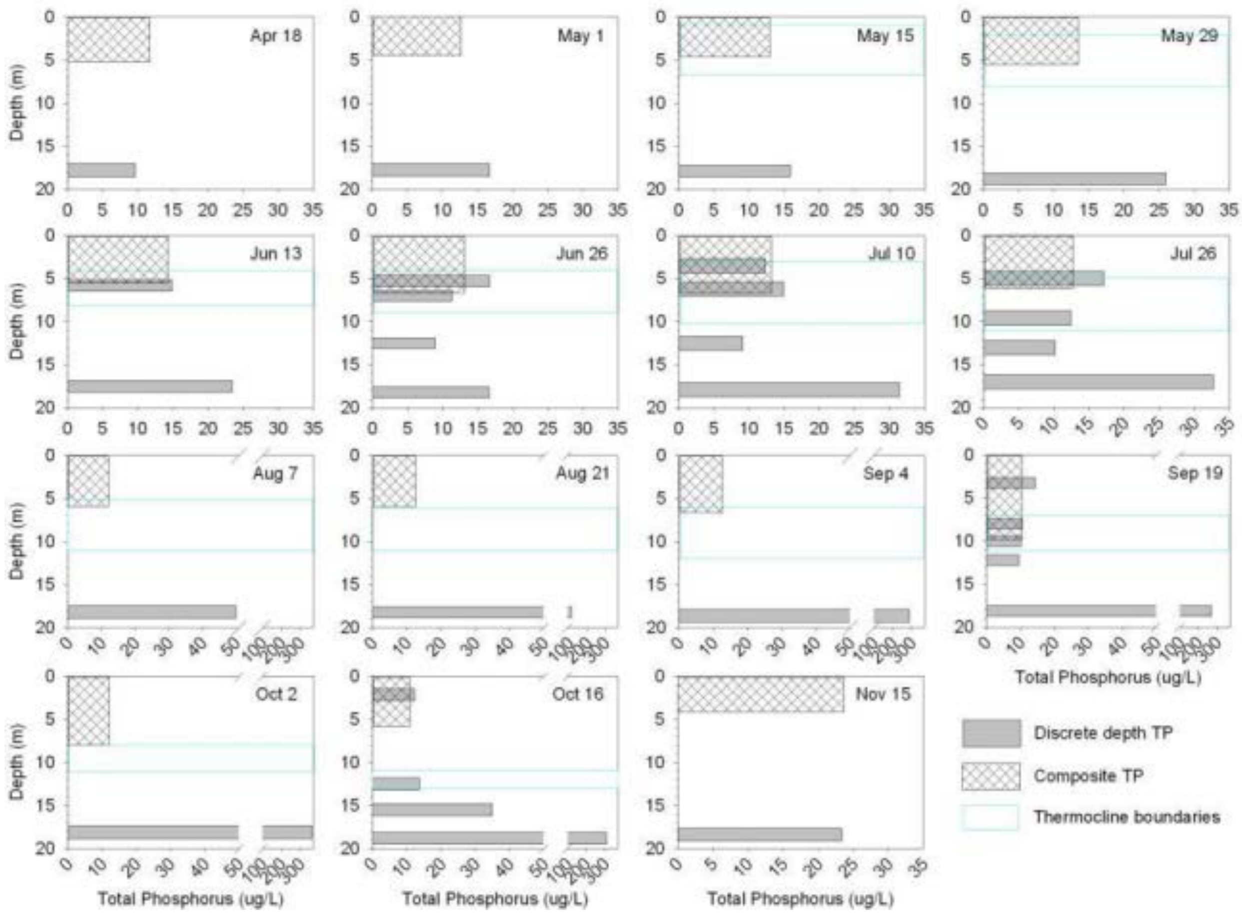

Figure 38. Total phosphorus concentrations from samples taken at discrete depths and in the euphotic zone at NB in 2012. The boundaries of the thermocline are shown in blue.

On July 12 2012, pigment profiles were taken in three locations in North Bay, one at NB and one on the northwest and southeast side of the station (**Figure 39**). Profiles show a consistent vertical distribution of cryptophytes/some chrysophytes (which includes the previously identified *Peridinium*) and diatoms/dinophytes (which includes the previously identified *Chrysosphaerella*) (**Figure 40**). However, there is a great deal more diatom/dinoflagellate pigment in the southeast corner of the basin compared to the other locations. Concentrations in the southeast corner were similar to what they were in the center of the basin two days earlier. This is likely the result of prevailing wind-driven currents. These results illustrate how spatially and temporally variable algal populations are, and how easy it is to miss peaks in algal groups.

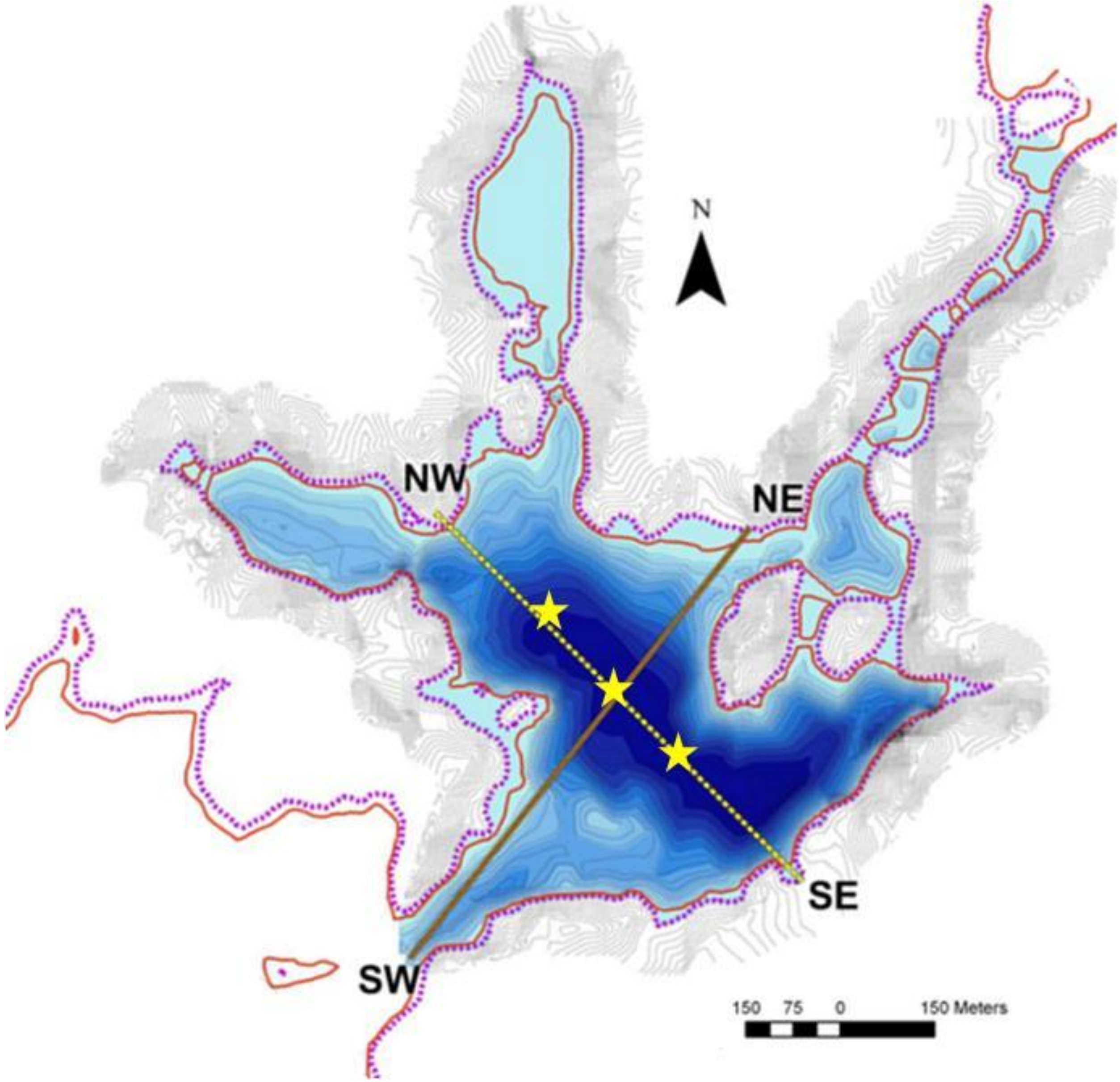

Figure 39. Fluoroprobe profile sampling points on Jul 12 2012 in North Bay.

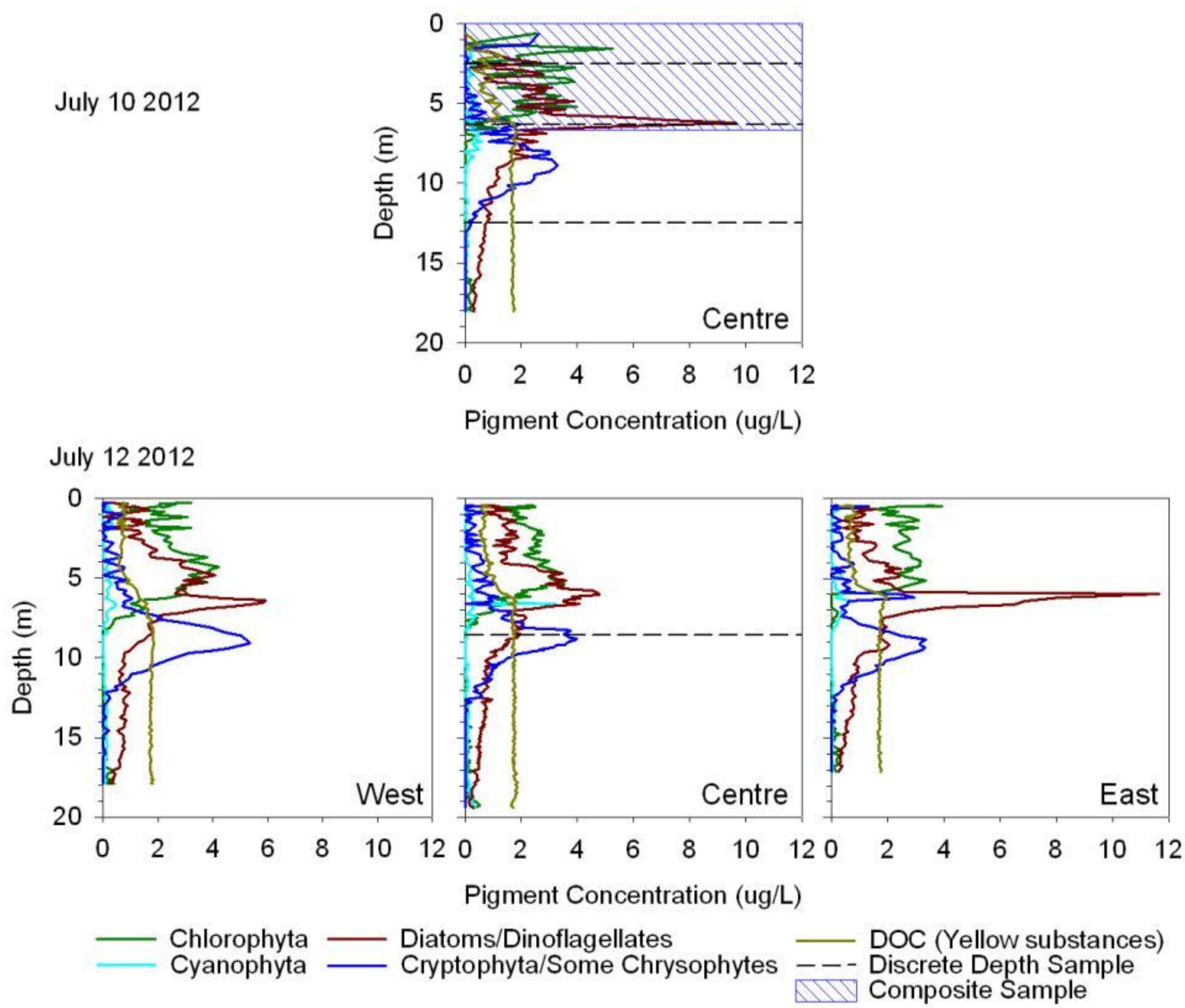

Figure 40. Vertical pigment profiles taken using the Fluoroprobe at NB (centre). The upper graph shows data from a routine sampling run on July 10 2012 while the bottom row of graphs show data taken at three points sampled along the long axis of the bay on July 12 2012.

In summary, total phytoplankton biovolume at all Honey Harbour stations has not increased over the last several years, however community composition appears to be shifting. Dominance by chrysophytes and dinophytes continues in North Bay, while the dominant cyanobacteria in South Bay appears to be shifting to *Anabaena*. Continued monitoring will determine whether this pattern continues. Re-analysis of pigment fluorescence data using new methods may shed light on additional patterns in vertical distribution of algae class.

ZOOPLANKTON

Zooplankton are small (usually <1 mm) invertebrates that live in the water column of lakes. They can be strictly herbivorous, grazing on algae, carnivorous, preying on other zooplankton or protists, or omnivorous. Some zooplankton are herbivores in their juvenile stage, and become omnivores or carnivores in their adult stage. Since zooplankton are a critical part of the aquatic foodweb, consuming large amounts of algae and acting as a food source for small fishes, it is important to know which species or genera make up the zooplankton community, in what numbers, and how those numbers change annually.

Zooplankton populations can be described in three ways, using density, biomass or richness. Density refers to the number of animals in a 1 m^3 volume. This can be expressed in absolute terms, or as a percentage of the total density, called relative density. Biomass is the mass of animals (in mg) per 1 m^3 volume, and can also be expressed in absolute or relative terms. It is useful to use both units of measurement, since zooplankton vary widely in size. For example, juvenile copepods (called nauplii or copepodids, depending on age) can be very numerous at different times over the season, but are very small, so they do not contribute a large amount of food, or biomass, to the foodweb. By contrast, the same number of the larger bodied *Daphnia* would contribute several times the amount of biomass to the foodweb. Biomass is useful in examining questions related to foodweb dynamics, while density is useful in examining questions related to population growth and reproduction.

Finally, taxa richness, or diversity, can be used to assess the resilience of a community. The more taxa (expressed at number of genera for this report) that make up a community, the more resilient it is to changes in environmental conditions and predation pressures. For example, in a diverse community, if one taxa is eliminated due to heavy predation one year, there is likely another one that occupies the same ecological niche able to take its place, thus maintaining the overall function of the community (e.g. grazing capability).

Zooplankton density, biomass and taxa richness at NB, SB and M5 were much lower from 2009-2012 compared to past years (**Figure 41**). The cause of these reductions is unknown, but could be related either to fish predation, environmental factors, or both. Reductions in zooplankton populations has implications for the biological control of the phytoplankton community, particularly among herbivorous taxa since they can consume large amounts of algae through filter feeding. Planktivorous and juvenile fish also rely on zooplankton for food, and may be impacted by reductions in zooplankton populations.

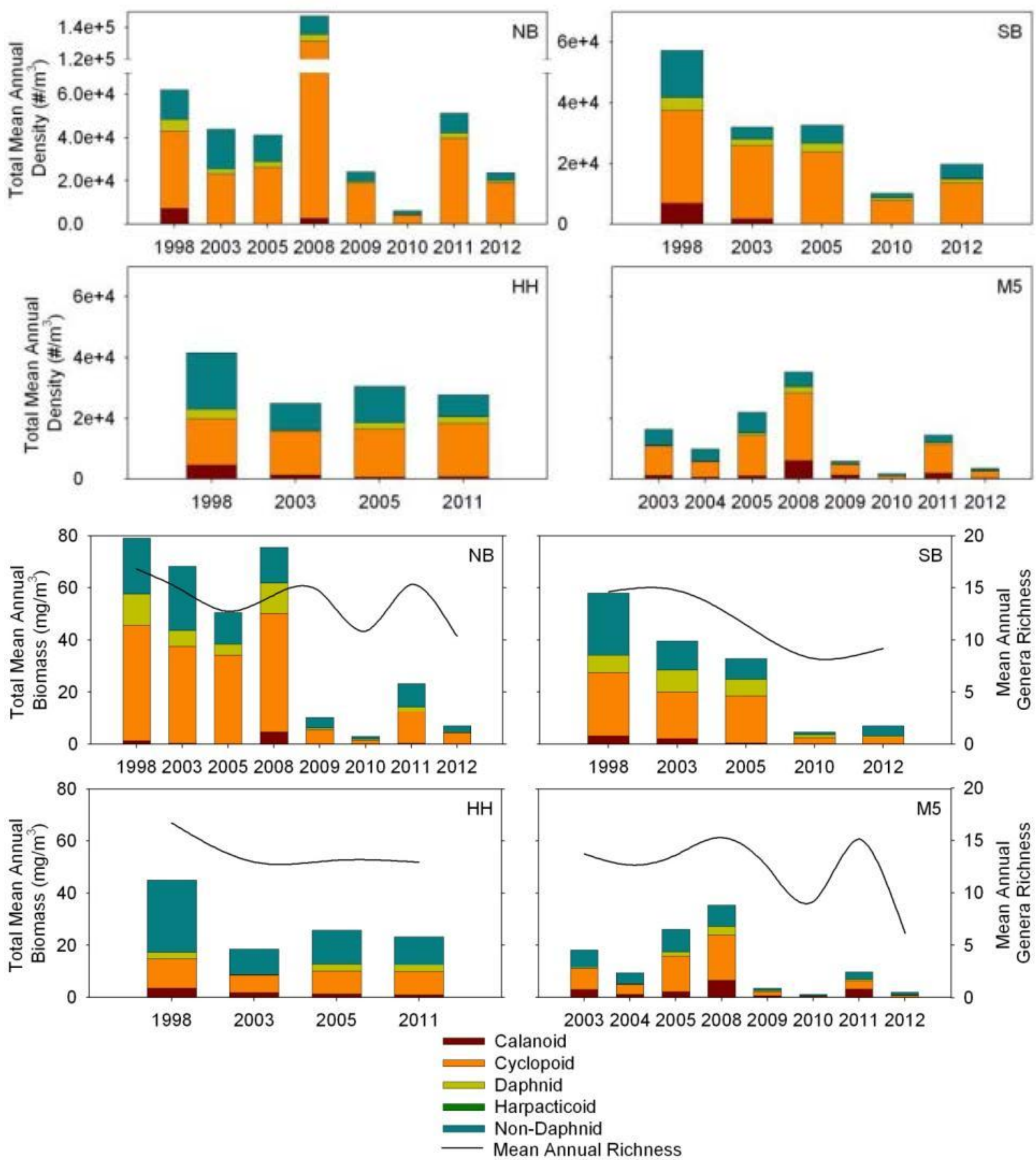

Figure 41. Zooplankton density (top) and biomass (bottom), summarized by order total for NB, SB, HH, and M5 from 1998-2012.

A type of multivariate ordination analysis called non-metric multidimensional scaling was done using zooplankton data from NB, SB, HH and M5 from 1998-2012. Results show that there is a clear separation of sites into two groups based on year, one from 1998-2008 and one from 2009-2012. Three genera were most strongly correlated with the ordination axis: *Daphnia*, a type of cladoceran, *Bosmina*, a type of non-daphnid cladoceran, and *Tropocyclops*, a type of cyclopoid copepod. Upon closer examination of density data for these taxa at NB, M5 and SB, it is clear that populations have dropped over the last four year, which coincide with the increase in dominance by *Chrysosphaerella* at NB (**Figure 42** and **Figure 44**). Whether or not these patterns are linked remains to be determined.

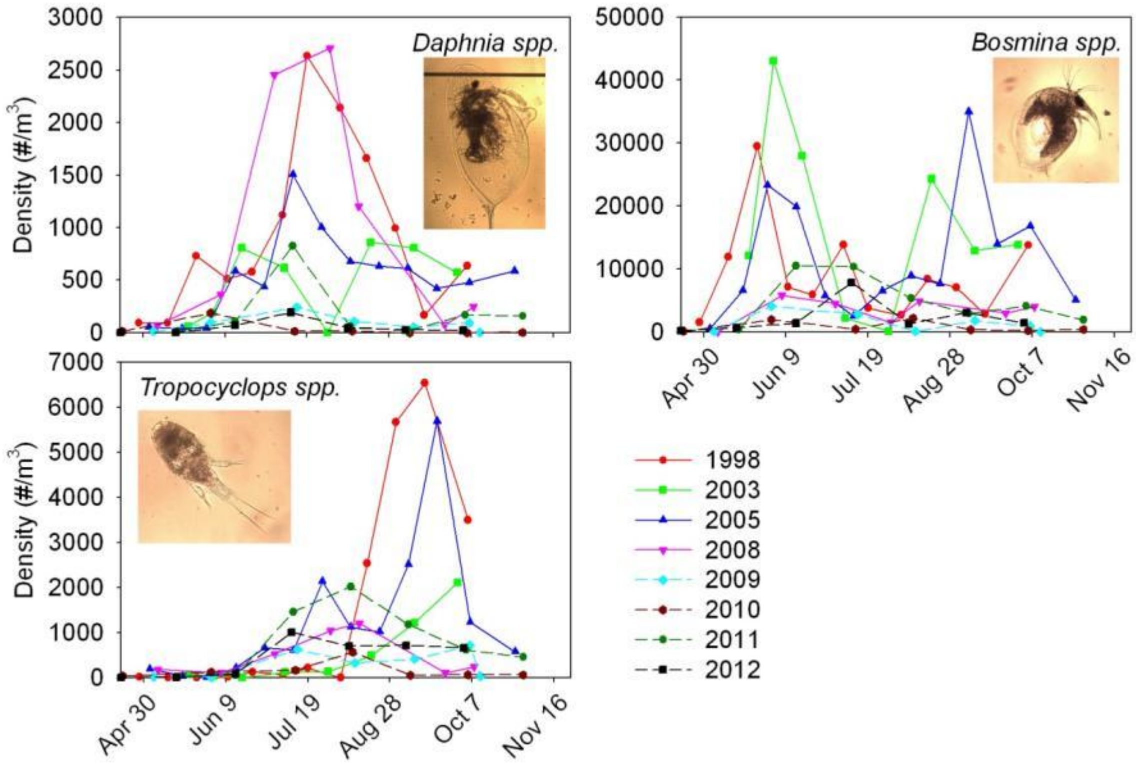

Figure 42. Seasonal density data for select zooplankton taxa at NB from 1998-2012.

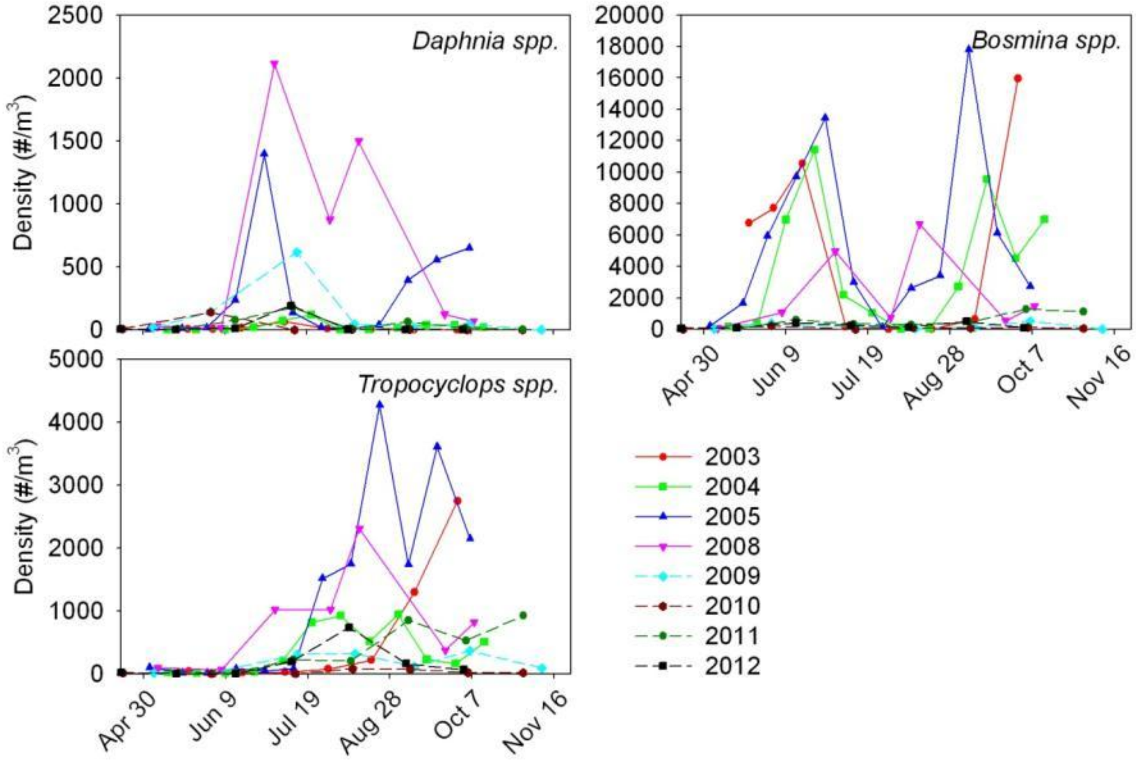

Figure 43. Seasonal density data for select zooplankton at M5 from 1998-2012.

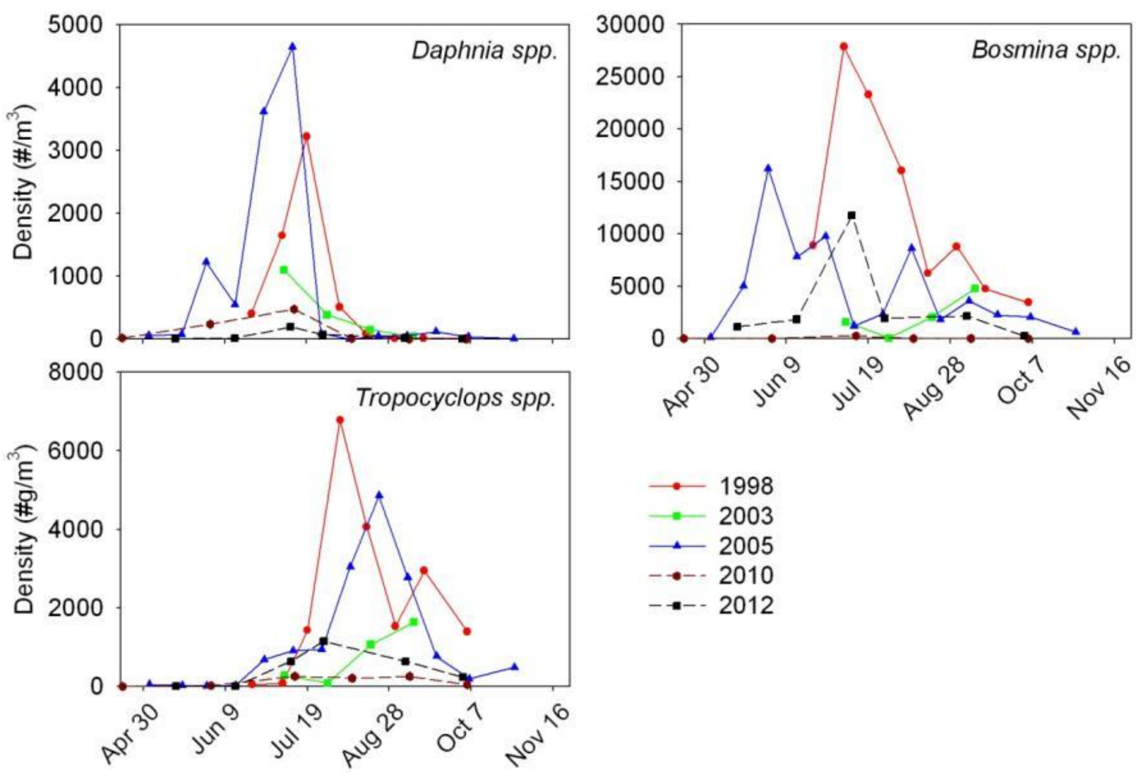

Figure 44. Seasonal density data for select zooplankton at SB from 1998-2012.

CONCLUSIONS

Based on these indicators, the trophic status of upper North Bay is considered moderately enriched, the status of South Bay is considered enriched and the Honey Harbour area is considered moderately enriched.

The very stable thermal regime in North Bay promotes the layering of phytoplankton growth and slows the sinking of organic matter within the thermocline or metalimnion of the water column. Other environmental factors such as changes in climatic variables may interact to affect the vertical distribution of phytoplankton, oxygen concentration and nutrients within the mid-depths of the water column of the bay. The oxygen regime, although fluctuating from year to year, has not changed over the period of record. Trophic status of North Bay, based on TP, oxygen depletion, phytoplankton biovolume and other chemical features is considered mesotrophic, or moderately enriched, and is not changing appreciably. Water clarity may be influenced by the vertical distribution of phytoplankton in the water column. There are subtle changes in the phytoplankton community such as the dominance of chrysophytes and dinophytes. Cyanophytes (blue-green algae) are not dominating in North Bay despite the build up of TP in the bottom waters.

In South Bay, shallower depths result in a less stable thermal regime and rapid depletion of dissolved oxygen in the hypolimnion. The bottom waters receive more exchange with the upper layers. Cyanophytes dominate the phytoplankton at during late summer each year. Again, subtle changes in phytoplankton community are occurring that require further monitoring.

The Honey Harbour station (HH) has quality more comparable to the open waters of Severn Sound due in part to an increase in exchange with these waters.

Despite the need for concern and vigilance over the ecosystem changes noted, the water quality status of the area does not appear to be changing rapidly and provides quality that does not impair recreational uses of the community. Upper North Bay and South Bay should be considered sensitive as compared with the area of Honey Harbour that is more exposed to exchange with the open waters.

RECOMMENDATIONS

Based on the above findings, the following recommendations are made:

1. Continue monitoring the three stations in the Honey Harbour area during 2014.
2. Continued monitoring of the vertical distribution of nutrients, metals and phytoplankton biovolume in North Bay should be included in the study design.
3. Provide seasonal analysis of the phytoplankton community in South Bay for 2014.

4. Continue to coordinate efforts of various researchers working in the area to maximize the benefits of the monitoring program.
5. Develop a long-term rationale for indicators and monitoring protocols that take into account Great Lakes and global stressors influencing the Honey Harbour area. Include the following questions:
   - Why are blue-green algae blooms not more common in Severn Sound, including Honey Harbour?
   - Why do chrysophytes and dinophytes dominate in North Bay?
   - Why is clarity (SDV) worsening in Severn Sound, including Honey Harbour?
   - Why is TP declining or holding steady while total phytoplankton biovolume is fluctuating?
   - What form of phosphorus should be used as a trophic indicator? How can this be related to historical trends?
   - Why do nitrate concentrations start off higher in the spring and drop to near or below detection by early summer?
   - What factors influence nutrient conditions in the nearshore? Examine the impact of physical characteristics of the nearshore, runoff, Dreissenid mussels (zebra and quagga), shoreline alteration, water level fluctuations, and pollution sources.
   - Why has zooplankton biomass decreased since 2009 at all four stations monitored? Is this a regional phenomenon?
   - What are the dominant submerged rooted aquatic plants in North and South Bay? Has there been a change in plant communities?

GLOSSARY

adsorb – not to be confused with absorb, adsorption refers to a process whereby a thin layer of molecules adhere to the outer surface of a material rather than being incorporated into that material.

chlorophyll *a* – this photosynthetic pigment is found in all phytoplankton, and can be used as a way to assess the amount of algae in a waterbody.

epilimnion – the upper water mixed layer of a thermally stratified waterbody. This layer is subject to wind mixing, and is where much of the phytoplankton production occurs. It is separated from the cooler hypolimnion by the thermocline.

euphotic zone – the zone from the surface of a lake down to where sunlight no longer penetrates. This is the productive zone of a lake.

genera – in taxonomic nomenclature, the first part of a scientific name of a species. In the example of the zebra mussel, *Dreissena polymorpha*, *Dreissena* is the genus (plural genera) name, and *polymorpha* is the species name.

Grubb's test – a statistical test used to detect outliers in a set of numbers. The test flags only one outlier in a set of values.

hypolimnion – the bottom water layer of a thermally stratified waterbody. Due to density differences between warm and cold water, the hypolimnion becomes separated from the epilimnion by the thermocline, and is not able to mix with the upper waters.

Mann-Kendall trend test – a statistical test used to detect unidirectional trends in data that does not necessarily have a normal distribution.

p – a probability value from 0-1 that answers the statistical question: If two or more populations really have the same mean overall, what is the probability that random sampling would lead to a difference between sample means as large (or larger) than what is observed? For example, a *p* value of 0.03 means there is a 3% chance of observing a difference as large as what is observed even if the two population means are identical. A *p* value is compared against a predetermined probability threshold (called α), usually of 0.05. A *p* value that is less than this threshold indicates a statistically significant test.

phytoplankton – also called algae, these are tiny unicellular plants that generally get their energy from the sun. Some can ingest other particles, including bacteria, to obtain energy. Some are also capable of movement, and can migrate to areas of higher nutrient concentration or particle density within the water column.

spring freshet – the period of intense runoff following significant snowmelt in the spring

statistically significant – this is an often misinterpreted term that refers to the outcome of a statistical test. It does not necessarily have a bearing on the real world; that is, a result that is statistically significant may not have any ecological importance, and a result that is not statistically significant may be very ecologically important. Context must be considered when interpreting this term.

taxa (plural of taxon) – refers to taxonomic groups, such as classes, genera or species

thermal stratification – a process by which a lake separates into layers based on temperature differences. Since water has the highest density at 4°C, cold water sinks to the lake bottom, and the temperature rises moving closer to the lake surface. Under calm conditions, and/or specific basin shape characteristics, three non-mixing layers may form: the epilimnion (upper layer), metalimnion (transition layer characterized by a temperature change greater than1°C) and hypolimnion (lower layer).

thermocline – also called the metalimnion, this is the middle transition layer of a thermally stratified waterbody. The thermocline is defined as the zone of temperature change of more than 1°C. This layer separates the upper epilimnion and lower hypolimnion.

***t* test** – a statistical method used to test whether there is a statistically significant difference between two groups, e.g. phosphorus data from two different sites.

Tukey-Kramer test – a statistical test that allows for comparison of means among three or more groups to determine if there are statistically significant differences, and where those differences lie. This test corrects for multiple comparisons, minimizing the family-wise error rate.

zooplankton – small, sometimes microscopic animals that live in the water column of both marine and freshwater ecosystems. Belonging to three major groups of invertebrates, they are a diverse group defined by their size rather than their taxonomic classification.

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