November-2016

GB Synthesis Report: Update on Honey Harbour & Tadenac Bay Projects

PROJECT 1: Characterizing current and historical oxygen dynamics in coastal embayments of south eastern Georgian Bay [Dave Snider, Veronique Hiriart-Baer, Jacqui Milne, and Dave Depew]

PROJECT 2: Direct input of phosphorus from groundwater discharge to Honey Harbour and Tadenac Bay (control bay): septic systems and other sources [Dave Snider, Jim Roy, and John Spoelstra]

N.B. The above-mentioned projects were both led by Dave Snider. To avoid duplication, one status report is being prepared to cover both projects.

Project 1: Purpose and Objectives

The purpose of this project was to investigate the causes and consequences of dissolved oxygen (DO) depletion in coastal embayments of South Eastern Georgian Bay (SEGB); two impacted embayments (North Bay and South Bay, Honey Harbour, ON) and one unimpacted embayment (Tadenac Bay, MacTier, ON). Samples were collected to assess contemporary water quality conditions, and paleolimnological tools were used to reconstruct historical DO conditions over the last 100+ years. Three objectives were identified for this project:

(i) characterize the temporal evolution of DO depletion and phosphorus (P) concentrations in the water columns of North and South Bays, Honey Harbour, and Tadenac Bay;
(ii) characterize the sources of organic matter that lead to oxygen depletion in the hypolimnion of these waters;
(iii) determine the paleo-redox conditions (historical changes in DO) in these embayments using sediment cores and biological and geochemical indicators.

Project 1: Key Findings

(P1.i.i) HYPOLIMNETIC OXYGEN DECLINE ACROSS ALL THREE EMBAYMENTS

Five areas within the study sites became thermally stratified each summer/fall and developed hypolimnia depleted in DO. The timing, strength, and duration of hypoxia was different for each basin. The DO deficit in the unimpacted site (Tadenac Bay) was less severe, but initial DO concentrations in this embayment was always higher than in the other basins (Fig. 1).

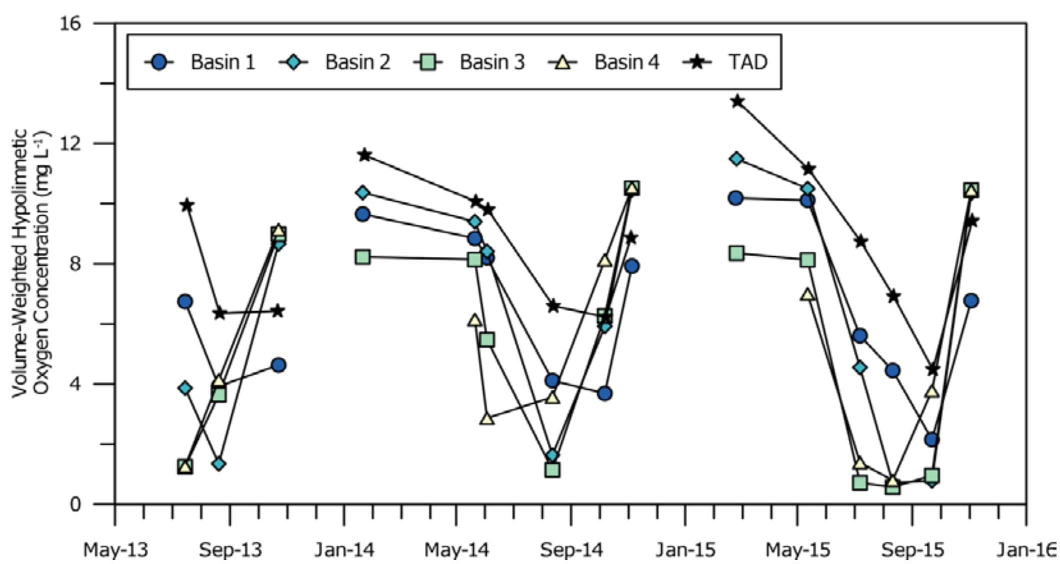


Figure 1. Volume-weighted oxygen concentrations in the hypolimnia of Basins 1-2 (North Bay), Basins 3-4 (South Bay), and Tadenac Bay (TAD).

(P1.i.ii) BASIN MORPHOMETRY IS A VERY IMPORTANT DRIVER OF OXYGEN CONSUMPTION

Smaller volume basins (Basins 3-4; Fig. 2a) went hypoxic earlier and faster than basins with larger volumes (Basins 1-2 and TAD; Fig. 2a-b). DO consumption in lakes is largely driven by organic matter decomposition. The ratio of the hypolimnetic volume (V_H) to the area of the sediment-water interface (A_{SWI}) is an excellent predictor of the rate of oxygen consumption (Fig. 3).

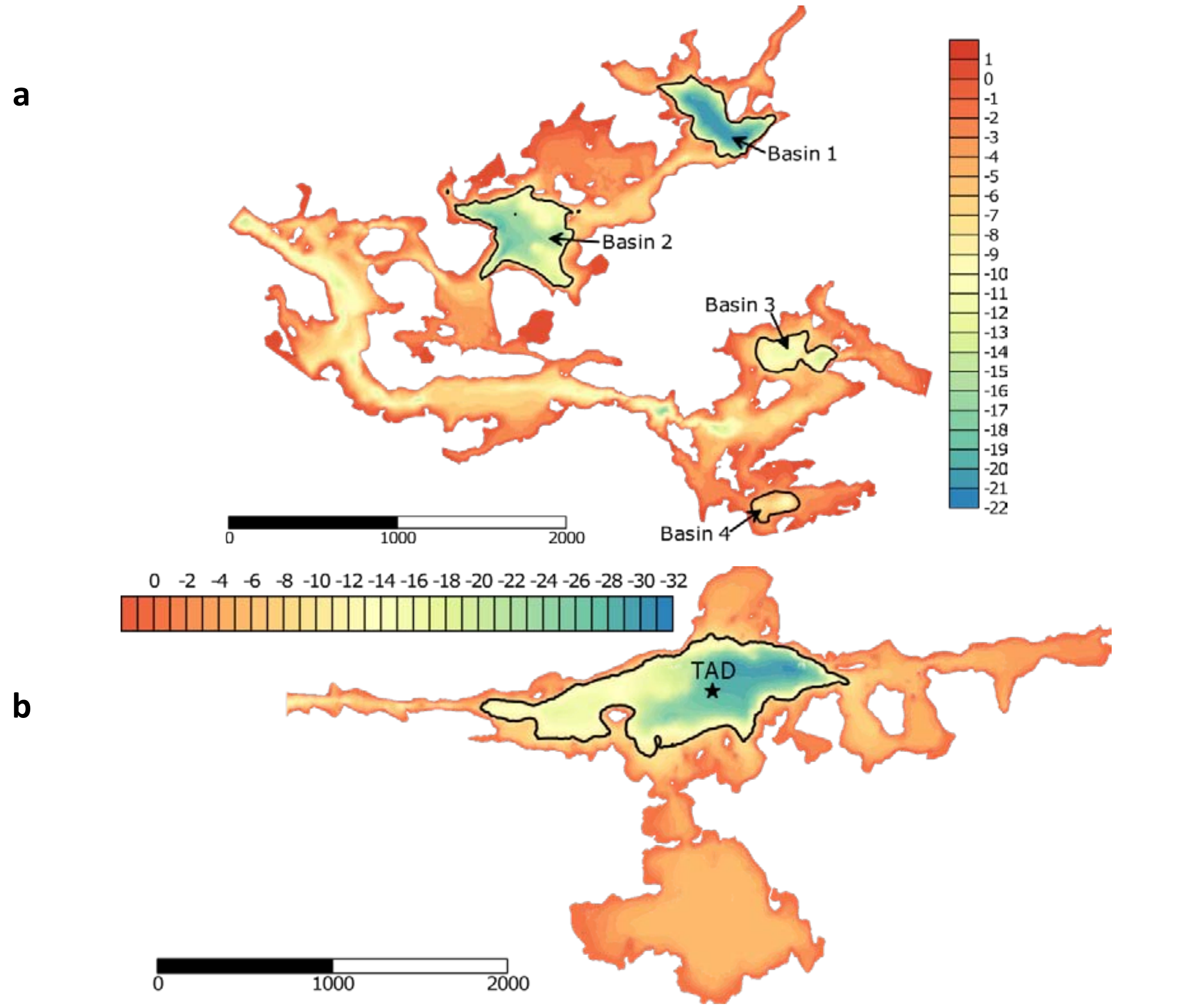


Figure 2. (a) Location and delineation of Basins 1-2 (North Bay) and Basins 3-4 (South Bay). (b) Location and delineation of the Tadenac Bay basin (TAD). Depth (in meters) below the water surface is shown using the colour gradient.

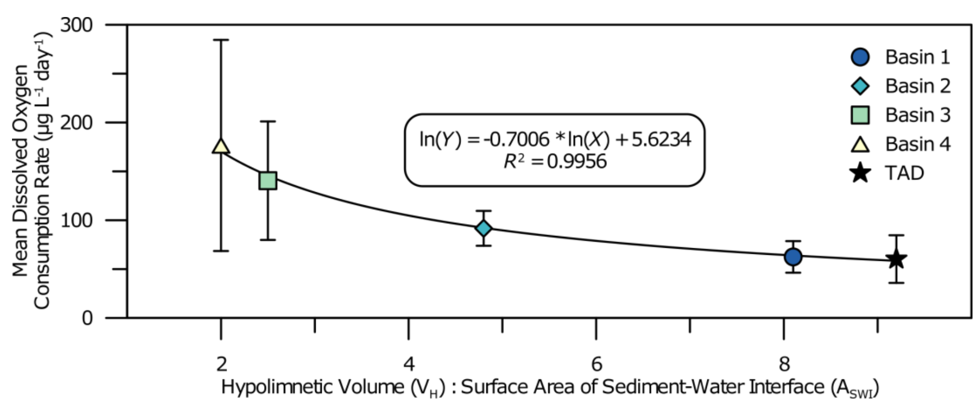


Figure 3. The V_H:A_{SWI} is a very good predictor of the mean dissolved oxygen consumption rate.

(P1.i.iii) PHOSPHORUS AND IRON ARE RELEASED FROM THE SEDIMENTS DURING HYPOXIC EVENTS

Changes in DO are coupled to release/uptake of P (Fig. 4a) and redox metals (Fig. 4b) such as iron (Fe) and manganese (Mn). Under oxygenated conditions, iron oxyhydroxides precipitate out of solution and settle on the surface of the lake sediment. These minerals have a large capacity to bind with and/or adsorb phosphate. Under anoxic conditions, however, these minerals are reduced, solubilized, and the previously-bound P becomes bio-available. This causes large increases in P and Fe concentrations.

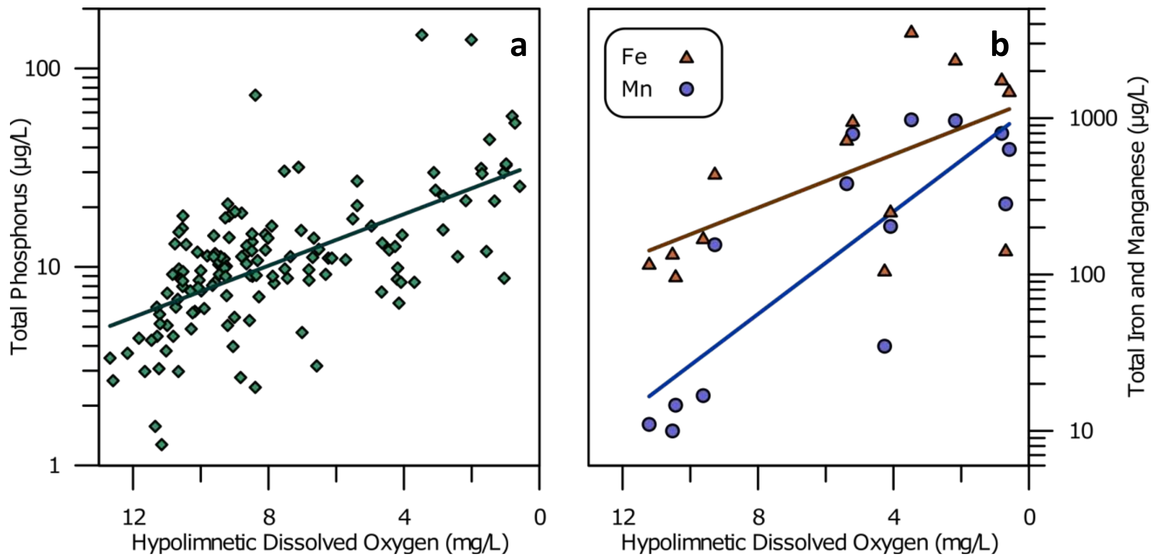


Figure 4. The concentrations of P and redox metals in the hypolimnion increase exponentially as DO concentrations decline. Total P samples were collected 2 m above the lake sediment from all stations in North Bay and South Bay (a), and metals were collected 2 m above the lake sediment from Basins 1 and 2.

(P1.i.iv) THE INTERNAL PHOSPHORUS LOAD

The fate of the sediment-derived P (a.k.a. the internal P load) is not explicitly known at this point. Quantitative information may become available when this data is combined with the hydrodynamic models. Generally, the sediment-derived P follows two possible fates: once turnover occurs and the overlying waters become oxygenated, the P could be re-deposited into the sediment; alternatively, the P could be exported to Georgian Bay by internal water currents/movement. The average residence times in North Bay and South Bay vary widely (Fig. 5), so the ultimate fate of the sediment-derived P may largely be dependent on the geographical location of the basin. Basin 1 has a long residence time, and a large internal P load and flux (Table 1). In contrast to other basins, the sediment-derived P in Basin 1 may build-up from year-to-year because it has a long residence time, which prevents P export 'downstream' to Georgian Bay.

Table 1. Estimated P Load & Flux from the Sediments During Hypoxic Periods

Location	*Internal P Load (kg)*	*Internal P Flux (mg m^{-2})*	*Timing of Observed Max. TP Concentration*	*Approximate Residence Time (days)*
Basin 1	223	1196	Oct-Nov	110+
Basin 2	36	121	Sep-Oct	90
Basin 3	18	186	Sep-Oct	45
Basin 4	5	102	Aug-Sep	55
TOTAL	**282**			

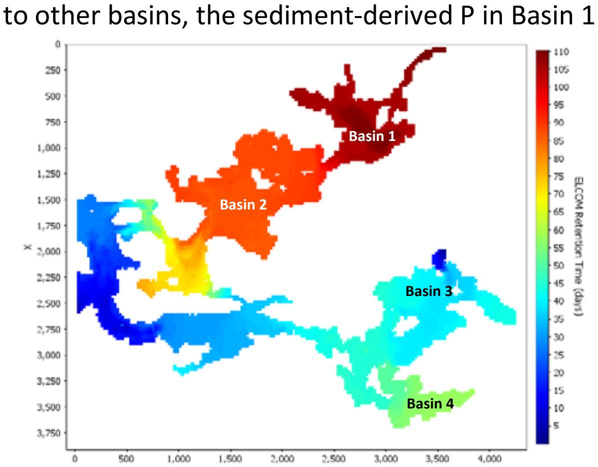


Figure 5. Average residence times in North Bay and South Bay (figure provided by Craig McCrimmon).

(P1.ii) HYPOLIMNETIC OXYGEN DECLINE IS NOT RELATED TO BULK CARBON CONCENTRATIONS

Declines in hypolimnetic DO cannot be explained by changes in hypolimnetic dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC), or total carbon (TC). Although organic matter respiration is the dominant sink for DO, most of this respiration occurs within the upper few cm of the sediment. Observations from other lake studies have showed that the sediment oxygen demand is usually much greater than the water-column oxygen demand. Given this, perhaps it is not surprising that hypolimnetic measurements of carbon species do not reflect changes in DO.

In this study, the consumption of DO is tightly linked to the hypolimnetic volume and surface area of the sediment (Fig. 3). This suggests that DO consumption is largely controlled by physical factors such as lake morphometry and its effect on oxygen dynamics, rather than water-column oxygen demand.

Samples of organic matter from the embayments are currently being analyzed using excitation–emission fluorescence spectroscopy, which will provide information on the origin of dissolved organic matter compounds (autochthonous vs. allochthonous) and their potential association with low oxygen conditions. This work is on-going.

(P1.iii.i) NORTH BAY AND SOUTH BAY HAVE EXPERIENCED END-OF-SUMMER HYPOXIA FOR MANY DECADES

Three years of monitoring (2013-2015) revealed that North Bay and South Bay experienced consistent hypoxia (Fig. 1). Paleolimnological techniques revealed that these embayments have experienced hypoxic conditions (Fig. 6) for at least ~150 yrs (North Bay) or ~100 yrs (South Bay). This strongly suggests that cottage development is not the major cause of DO decline in these embayments, and that natural processes drive annual hypoxic events. That being said, the frequency and severity of low DO could be exacerbated by anthropogenic pressures if they increase in the future.

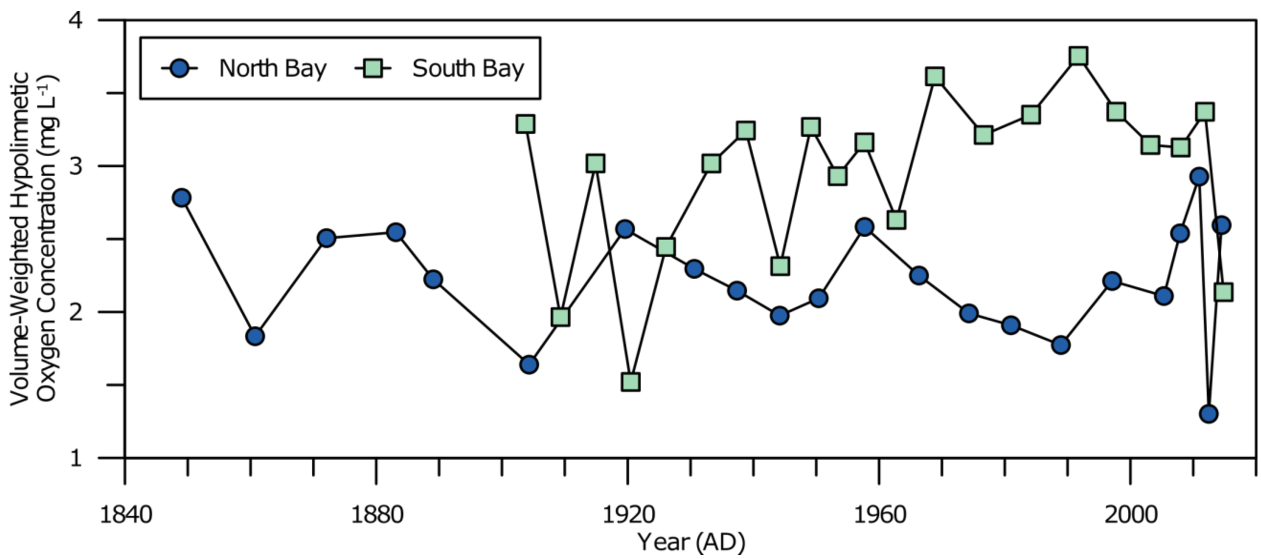


Figure 6. A paleolimnological reconstruction of the end-of-summer volume-weighted dissolved oxygen concentrations in the hypolimnia of North Bay and South Bay. Sediment cores were taken from Basin 1 (North Bay) and a sampling site in South Bay (HON5) located ~600 m south-west of Basin 3 and ~600 m north-west of Basin 4. HON5 is the deepest basin in South Bay and it was expected to be a hypoxic area during the summer-fall. This was not the case, however, because thermal stratification rarely persisted at this location (possibly due to high exposure and wind-driven mixing events). As such, the core taken from HON5 infers that DO concentrations were higher in South Bay than in North Bay. In reality, if the core were sampled from Basin 3 or Basin 4, the DO concentrations may have been lower than in North Bay. Also note, the sedimentation rate in South Bay is higher than in North Bay. As a result, the 44 cm long core retrieved from South Bay dated back to 1892 (AD) and the 40 cm long core retrieved from North Bay dated back to 1840 (AD). [Paleolimnological reconstruction was completed by PEARL Lab, Queen's University, under contract with ECCC].

(P1.iii.ii) IMPACTS OF SHORELINE DEVELOPMENT WERE MINOR, BUT CLIMATE CHANGE HAS INCREASED PRODUCTIVITY

Diatom analysis of North Bay and South Bay sediments dating back to 1890 and 1930, respectively, demonstrated that shoreline development has only resulted in modest increases in nutrient concentrations (Sivarajah 2016). Diatom analysis of Tadenac Bay sediments dating back to 1860 demonstrates no appreciable increases in nutrient concentrations (Sivarajah 2016). Chlorophyll-a pigment analysis in sediments of all three embayments revealed that rates of primary production have increased in the last 50 years, and is the result of climate warming (Sivarajah 2016). These results support and corroborate our ECCC work, and are found in Branaavan Sivarajah's MSc thesis, found at: https://qspace.library.queensu.ca/handle/1974/14272. Branaavan completed his MSc in the PEARL Lab at Queen's University and collaborated with ECCC to generate the data shown in Fig. 6.

(P1.iii.iii) FURTHER EVIDENCE THAT PRIMARY PRODUCTION INCREASES ARE INDUCED BY CLIMATE WARMING

The total nitrogen (N) and organic carbon (C) contents in North Bay and Tadenac sediments have increased since 1970 (Fig. 7). This corroborates independent studies that found increased rates of primary production in these embayments beginning at this time (Sivarajah 2016). Tadenac Bay is a pristine, virtually undeveloped embayment. This strongly suggests that increased rates of primary production observed in both bays are a result of climate warming.

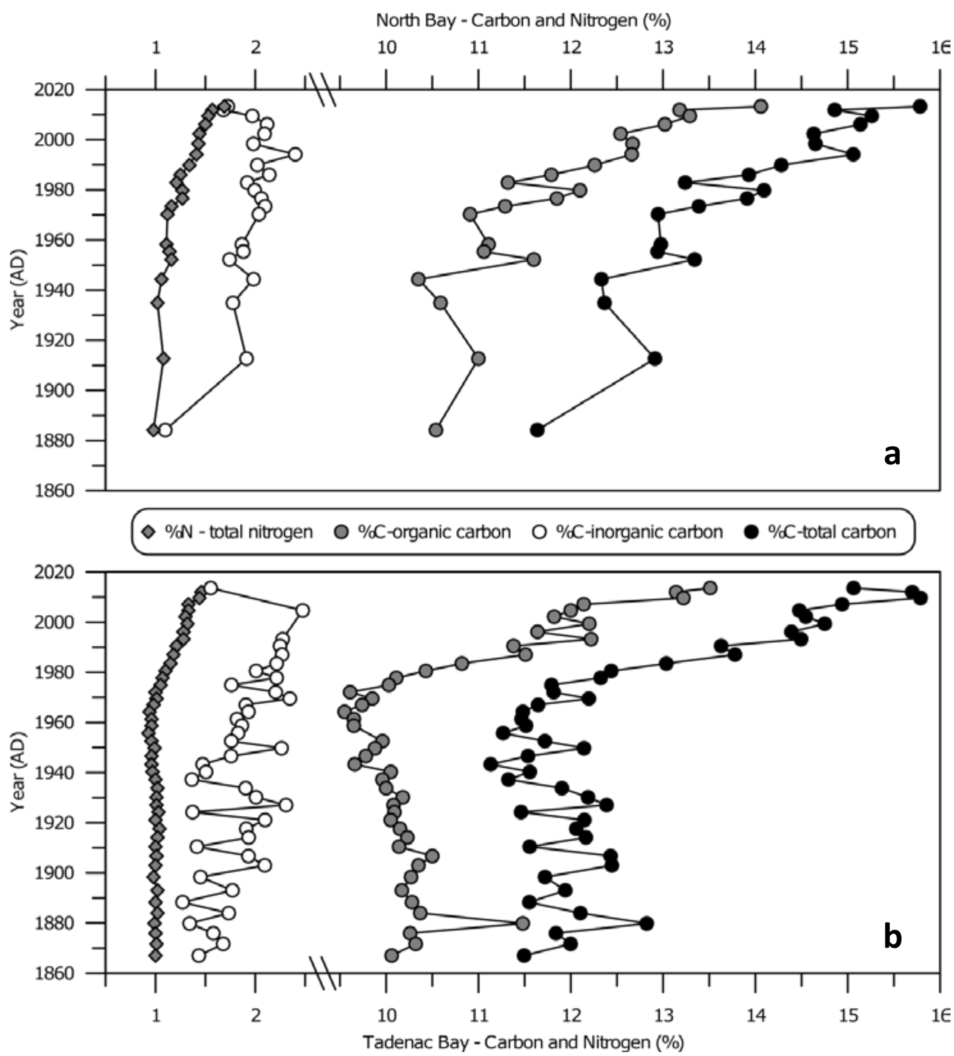


Figure 7. A nitrogen (N) and carbon (C) compositional analysis of sediments taken from (a) North Bay (Basin 1) and (b) Tadenac Bay. The %N and %C-organic have increased in both embayments since 1970.

(P1.iii.iv) ISOTOPIC EVIDENCE SHOWS PRIMARY PRODUCTION INCREASED IN THE EARLY 1970'S.

North Bay sediments show significant changes in the δ^{13}C-organic carbon and δ^{15}N-total nitrogen values from 1970's-onward, consistent with increasing rates of primary production. During photosynthesis, there is a large $^{13}C/^{12}C$ fractionation (~20‰) that occurs when plankton fix carbon from CO_2. Given the dissolved CO_2 pool is near saturation, the autochthonous endmember could be close to –36‰ at our site [based on values determined by K. Chomicki (2009) from Dorset, ON lakes]. Assuming the sedimentation of allochthonous carbon has remained constant at our site, an increase in primary production would shift the sediment δ^{13}C-organic carbon values lower closer to the autochthonous δ^{13}C endmember (Fig 8a, North Bay core). Note: many researchers studying eutrophic or hyper-eutrophic systems have found an opposite relationship; δ^{13}C-organic carbon values have increased with rising primary production. These lakes have very high rates of primary production, and the internal CO_2 pool becomes δ^{13}C-enriched because lake-atmosphere gas exchange cannot replenish the internal CO_2 pool fast enough. In essence, the dissolved CO_2 pool is well-below saturation and the CO_2 pool becomes enriched in δ^{13}C. This enrichment is expressed in the δ^{13}C of the plankton biomass. It is hypothesized that if production increased greatly at our site, then a similar pattern in δ^{13}C-sediment organic carbon would also be observed at our site.

The North Bay sediments also show a decrease in δ^{15}N-total nitrogen (Fig 8b). This suggests that the abundance of N-fixers has increased in North Bay. Nitrogen fixers do not fractionate atmospheric N_2 when they synthesize ammonia or organic N, so an increase in their abundance would drive the δ^{15}N-total nitrogen in the sediment toward zero. Although a similar pattern is observed in the δ^{15}N of the Tadenac core (Fig 8b), there is little change in its δ^{13}C over time (Fig 8a). The interpretation of these data is ongoing.

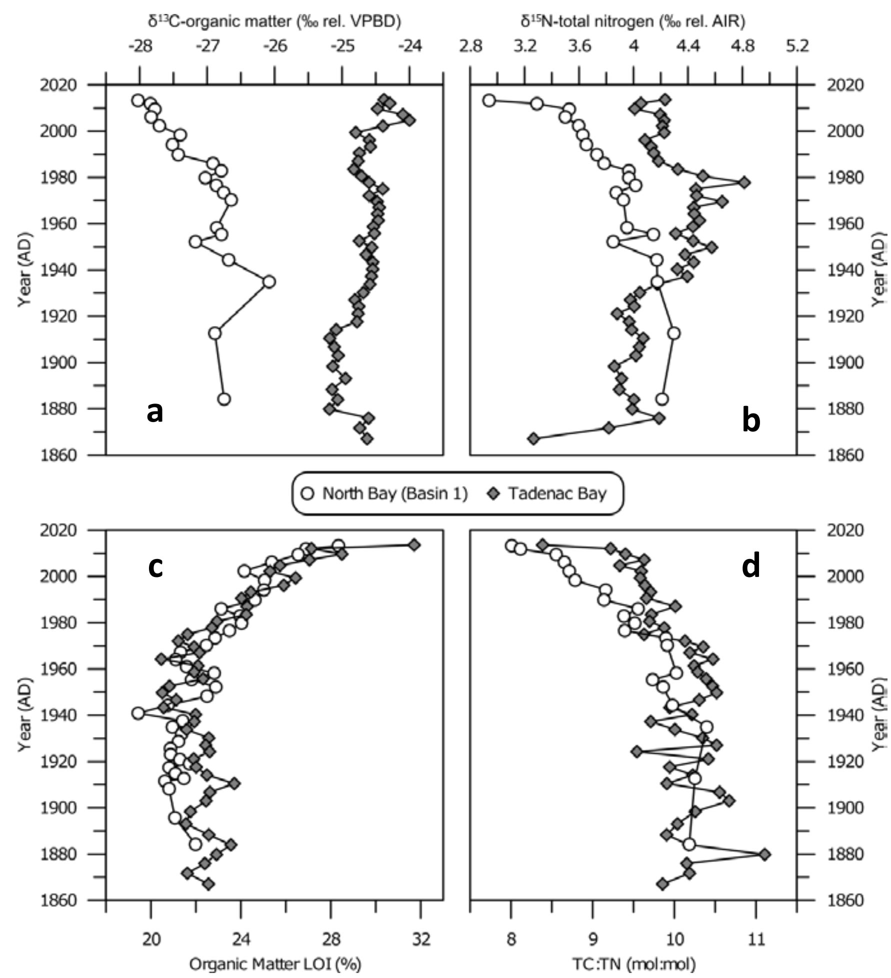
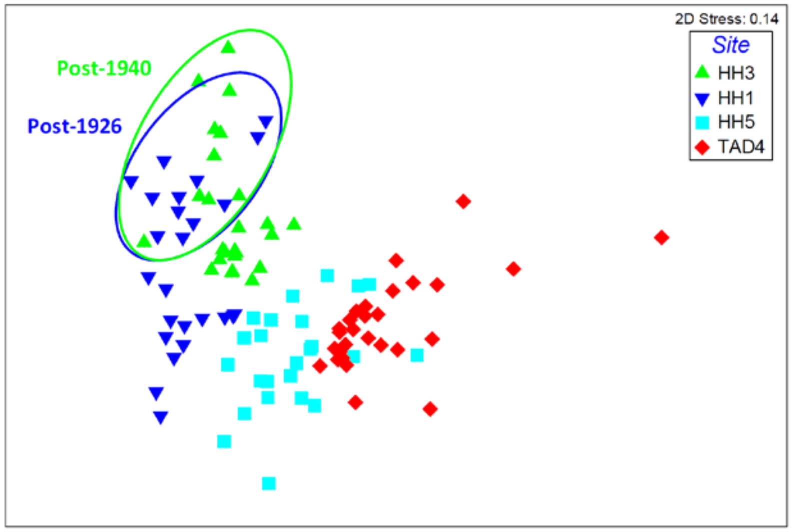


Figure 8. Carbon (a) and nitrogen (b) isotopic analyses of sediments taken from North Bay (Basin 1) and Tadenac Bay. Also shown are the % organic matter (c) and the C:N ratio (d) of the sediments.

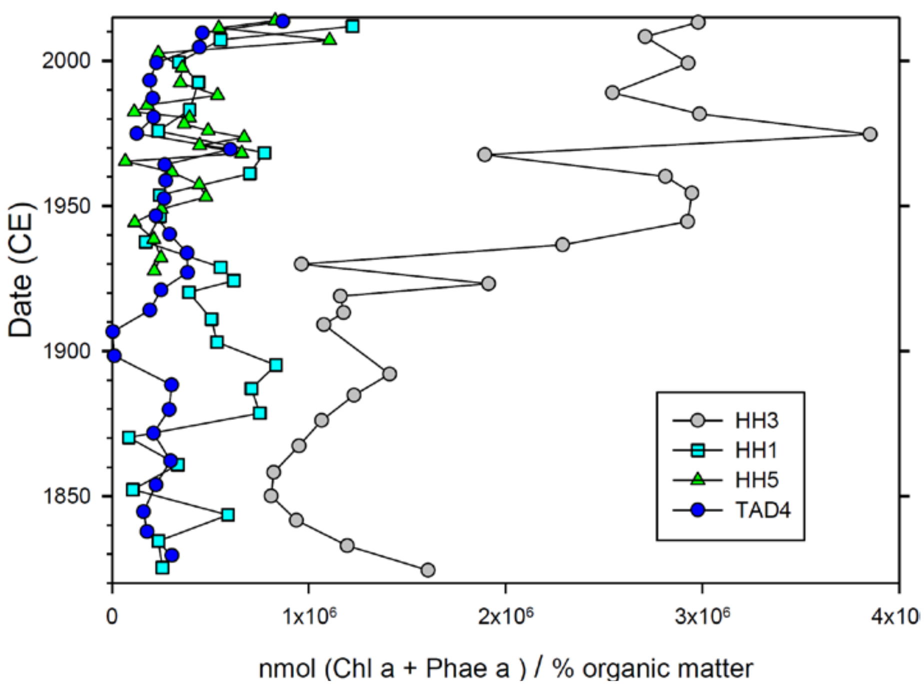
Finally, the C and N isotopes in Tadenac Bay have not changed appreciably through time, despite the recent increases in primary production at this site. The results of a pigment analysis done on these sediments suggests the assemblage phytoplankton present in North Bay and Tadenac Bay are different (Fig. 9), so this may help explain the different trends in the isotope data observed at these sites. The interpretation of this data is ongoing.

Figure 9. Non-metric multi-dimensional scaling (2D-MDS) plot of sediment pigment data (expressed as % abundance) collected from North Bay-Basin 1 (HH3), North Bay-Basin 2 (HH1), South Bay (HH5), and Tadenac Bay (TAD4). The distance between sample points is proportional to the dissimilarity of photosynthetic pigment composition. This work was completed by Johan Wicklund and Roland Hall (University of Waterloo, Dept of Biology) under contract with ECCC.



(P1.iii.v) PIGMENT ANALYSIS SHOWS PRODUCTIVITY ONLY INCREASED IN NORTH BAY, AND IT BEGAN EARLIER THAN 1970.
An independent analysis of photosynthetic pigments completed at the University of Waterloo showed that total algal productivity at all locations has varied over time, but that productivity in North Bay (Basin 1) has consistently exceeded productivity in all other locations. Further, it appears that primary production in Basin 1 has increased since ~1940. This is about 30 years earlier than similar conclusions derived from Chl-a analysis and isotopic analysis (iii.ii-iv, above). Concurrent increases in primary production in Tadenac Bay were not observed with this pigment analysis. The interpretation of this data is ongoing.

Figure 9. Pigment-inferred changes in total algal productivity in North Bay-Basin 1 (HH3), North Bay-Basin 2 (HH1), South Bay (HH5), and Tadenac Bay (TAD4) as inferred from the sum of Chlorophyll *a* and Phaeophytine *a* normalized per unit sediment organic matter.



Project 2: Purpose

The purpose of this project was to use concentrations of artificial sweeteners (AS) in North Bay, South Bay, and Tadenac Bay to trace inputs of phosphorus (P) derived from wastewater (i.e., cottage septic systems). This involved calculating a catchment-wide mass balance (numerical model) of acesulfame, one of the AS that behaves most conservatively in the environment. Note: the bulk of the AS and nutrient modelling is being completed by R. Yerubandi and C. McCrimmon. The results shown here are only rough estimations.

Project 2: Key Findings

(P2.i) BAXTER RIVER IS A MAJOR SOURCE OF ARTIFICIAL SWEETENERS

Baxter River is the only major tributary to the North Bay–South Bay system that flows year-round. At the onset of the study, it was not apparent that the Baxter River had hydrologic connection to the Trent-Severn Waterway. It turns out that the Baxter River is an important and dominant source of AS to these embayments. The cumulative annual AS loads from Baxter River were determined from daily flow and ~monthly AS concentration measurements from Apr-Nov for 2014 and 2015. For other months of the year, flow and AS concentrations were estimated based on winter measurements conducted Dec 2015 to Feb 2016. The annual AS load from Baxter River was calculated as 1637 g (2014) and 1450 g (2015). The actual loads may be higher because the ~monthly sampling frequency did not adequately characterize septic system flushing (high concentration periods) that occurred in the late-fall and spring with increased precipitation and snowmelt. These high loads were not expected at the outset of this study, and they impeded our ability to discern internal wastewater inputs. Lake mixing model simulations using OneLay-Poltra (C. McCrimmon) suggest that Baxter River loadings contribute to AS concentrations in both South Bay and North Bay.

(P2.ii) DETERMINING REPRESENTATIVE ARTIFICIAL SWEETENER CONCENTRATIONS FOR COTTAGE SEPTIC WASTEWATER

While AS are known to be a common constituent in domestic wastewater, there is little information available on typical concentrations for septic wastewater. This information is needed, along with typical P concentrations in this same wastewater, for determining AS and potential P contributions from cottage septic systems using the lake mass balances. In this work, samples were obtained from septic tanks at 8 cottages in North Bay and South Bay, the Tadenac Bay lodge, and 2 nearby Provincial Parks. These data were combined with our previous measurements (in collaboration with Dr. Will Robertson, University of Waterloo) of septic tanks at nearby cottages (Honey Harbour, Sturgeon Bay, Killarney) and Provincial Parks and other residences throughout Ontario. This information is currently being written up for publication in the peer-reviewed literature.

(P2.iii) ESTIMATED LOADS OF ARTIFICIAL SWEETENERS FROM SEPTIC SYSTEMS

Using the data collected from Honey Harbour cottage septic tanks with the Lakeshore Capacity Model (adapted for AS), we estimated the annual acesulfame loads from septic systems to North Bay and South Bay as 442 g (± 40) and 409 g (± 37), respectively. This model assumes that all the wastewater AS reach the lake, and thus this represents a maximum possible load. For comparison, the septic system acesulfame load to South Bay is 25-28% of the acesulfame load coming in from Baxter River.

The average residence time in the entire South Bay is 48.6 days. This means South Bay is refreshed ~7.5 times each year. The volume of South Bay is 4,859,392 m^3. If Baxter River were the only source of acesulfame to South Bay, the average daily <u>calculated</u> concentration would be 42.3 ng L^{-1}. If Baxter River and South Bay septic systems were sources of acesulfame to South Bay, the average daily <u>calculated</u> concentration would be 53.5 ng L^{-1}. The average <u>measured</u> acesulfame concentration in South Bay for the entire study period was 61.7 ng L^{-1}. This is an average of 118 observed values collected from all South Bay stations (all depths), and is very close to the calculated concentrations shown above. This suggests that the calculated loads are close to the actual loads; however, the uncertainty involved with these calculations still does not allow for differentiation of the Baxter River and potential septic inputs.

(P2.iv) BAXTER RIVER IS A SIGNIFICANT SOURCE OF PHOSPHORUS

The average P load from Baxter River is 245 kg (283 kg in 2014; 207 kg in 2015). The Baxter River P load was derived from continuous flow measurements and daily measurements of TP concentrations (composite sample collected every 12 hours). Measurements were conducted between Apr-Nov (2014-2015) and loads were estimated for other months of the year based on winter samples collected Dec 2015-Feb 2016.

(P2.v) CALCULATED LOADS OF PHOSHORUS FROM SEPTIC SYSTEMS - ARE THEY REASONABLE?

Using the septic tank P concentration data (noted above in P2.ii) with the Lakeshore Capacity Model, we estimated annual P loads from septic systems to North Bay and South Bay as 154.1 kg (± 80.1) and 142.6 kg (± 74.2), respectively. The total septic P load to the North Bay-South Bay system is 296.7 kg (± 109.2). This would represent a <u>maximum</u> septic P load, given that the Lakeshore Capacity Model does not account for any possible attenuation of phosphorus within the groundwater system. For comparison, the calculated septic P load to South Bay is 58% of the P load from Baxter River.

The average residence time in the entire South Bay is 48.6 days. This means South Bay is refreshed ~7.5 times each year. The volume of South Bay is 4,859,392 m^3. If Baxter River were the only source of P to South Bay, the average daily calculated TP concentration would be 6.7 $\mu g\ L^{-1}$. If Baxter River and South Bay septic systems were sources of P to South Bay, the average daily <u>calculated</u> TP concentration would be 10.6 $\mu g\ L^{-1}$. The average <u>measured</u> TP concentration in South Bay for the entire study period was 15.3 $\mu g\ L^{-1}$. This is a mean of 112 measured values from all South Bay stations (surface and bottom depths), but excludes those samples with elevated TP concentrations during hypoxic periods. Excluding these high TP/low DO samples removes most of the effect of sediment P loading.

There are several possible reasons why the calculated average TP concentrations in South Bay are lower than the measured average TP concentration, including:

- Despite excluding high TP/low DO samples, there may be a contribution of P from the sediments.
- Mixing conditions throughout South Bay are not uniform.
- TP concentrations in Baxter River were measured daily from Apr-Nov. Concentrations were not measured during the winter, but estimated based on a few winter samples collected in 2016. Maybe we underestimated the Baxter TP load?
- TP concentrations varied over the summer and the TP loads were episodic. As a result, the daily average value that we measured could actually under/over-estimate the true daily load.
- There is a large uncertainty in septic system P load (± 52%). This is a result of large variability in the measured septic tank P concentrations.
- There may be P contributions from additional (unaccounted) sources, such as wetlands, regional groundwater (background) inputs, or decaying organic matter along the shoreline that is washed in via overland runoff.

(P2.vi) COMPARING PHOSHPORUS LOADS ACROSS THE CATCHMENT

The maximum P load from septic systems is 297 kg (± 109). This assumes all the septic P makes it to the lake and none is attenuated in the septic bed or along the groundwater flow path to the lake. The estimated sediment P load is 278 kg (total mass of P released from sediments of Basin 1-4; note that much of this P could be re-deposited). The average P load from Baxter River is 245 kg (283 kg in 2014; 207 kg in 2015). Therefore, septic systems could account for up to one-third of the total P load to the North Bay-South Bay embayment system. Septic systems could also be insignificant, however current uncertainty in the data does not allow us to answer this at this time.

1. Please indicate the specific geographic location(s) in which you performed your LSGBCUF science activities. For example Sturgeon Bay, Go Home Bay, Minesing wetlands, Nottawasaga Bay, etc.
   All work for these two projects was performed in North Bay, South Bay, and Tadenac Bay.

2. Below is a list of science topics/issues. Please identify which area/issue(s) that your research contributes to or addresses. Feel free to identify more than one area or suggest categories that are not covered within the list.
   - Algal Blooms (including Cyanobacteria)
   - External Nutrient Loading
   - External Nutrient Contributions and/or Dynamics
   - Internal Nutrient Dynamics
   - Hypoxia
   - Fluctuating Water Levels
   - Enclosed Embayments (Limited Georgian Bay Mixing)
   - Fish Health Indicators
   - Baseline Data Collection
   - Shoreline Development
   - Model Building and Forecasting
   - Climate Change
   - Wetlands Health
   - Monitoring

3. What are the policy implications that you see as they relate to the science you conducted under the LSGBCUF?
   - Managing nutrients in oligo-mesotrophic systems may have little impact on reducing the frequency and severity of hypoxic events. Lake morphometry appears to be the dominant control on hypoxia in our study sites. However, reducing anthropogenic nutrient loads to surface waters is still an important effort because eutrophication and changing trophic status leads to other undesirable outcomes.
   - The findings suggest that policies or management controls on preventing septic wastewater P inputs to North Bay and South Bay will only have a moderate impact on the total P loads. Septic systems contribute a maximum of one-third of the total P load, but potentially much less.

4. What science gaps still exist that are pertinent to the issue(s) you are investigating?
   - What is the fate of the sediment-derived P? Is it exported to Georgian Bay, or is it re-deposited into the sediment? Both scenarios probably occur, depending on the location of the basin. A quantitative analysis of this requires modelling at short time-steps with a verified and well-calibrated model. This may be resolved soon by ECCC modelers.
   - Climate warming has led to increases in primary productivity over the last ~50 years. What are the biophysical changes that have led to these increases? (Reduced ice cover, higher CO_2 exchange, warmer average temperatures, fluctuating lake levels)
   - Septic system P loads need better quantification. The Lakeshore Capacity Model assumes all the P in the septic tank is exported to the adjacent surface water body. In some cases, this may be a poor assumption. Very few field studies have quantified septic system P loads in the region. There is also little information on seasonal variation in the inputs of septic wastewater (in this region or anywhere, really) whereas most models assume a constant load or consider only annual balances. Unfortunately, the use of artificial sweeteners as a tracer for septic system P

loadings was not able to be adequately tested in this study due to the unforeseen large AS contributions from Baxter River. Thus, testing of this potential tool remains as a science gap.

5. Have you published any of your research conducted under funding received from the LSGBCUF? If so please provide us with a list (with a pdf or copy) of all articles, theses, conference abstracts, posters, reports or other publication material.
   A conference poster was prepared for IAGLR-2016, and a copy was provided to Zoey Sep-2016. Other manuscripts are in preparation.