MONITORING WATER QUALITY FOR RECREATIONAL USE

MONITORING WATER QUALITY FOR RECREATIONAL USE IN NEARSHORE WATERS OF EASTERN GEORGIAN BAY

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PREFACE

This Master of Science thesis consists of two data chapters with a general introduction and conclusion to provide additional context. As the first author for both data chapters (CH2 and CH3), under the supervision of Dr. Patricia Chow-Fraser, I am responsible for data analysis and preparation of the initial draft and finalization of all drafts for inclusion in my thesis. As well, I collected all field samples from 2020 – 2022 inclusive and carried out all laboratory processing of water samples. Some of the historical data were provided to me by my supervisor (who received the data from the Ontario Ministry of Environment in 2007) and by the Severn Sound Environmental Association under a data-sharing agreement.

GENERAL ABSTRACT

Georgian Bay is well known for its excellent water quality and recreational beauty; however, some regions are showing signs of degradation and eutrophication, threating the way of life for residents and cottagers. The goal of my thesis is to provide the Township of Georgian Bay (TGB) with updated resources, including information on their water quality and a sampling protocol that local community members can use, so water quality can be effectively managed and protected. First, we investigated the changes in water quality from a historic period (2001 – 2009) to the current period (2020 – 2022). We found that 80% of sites had a decrease in *E. coli* (EC) between periods, likely associated with increased dilution from an approximately 1 m increase in water levels. Secondly, we examined regional variation within TGB and found that Honey Harbour and Oak Bay had the highest mean EC and total phosphorus (TP) concentrations and therefore are of greatest concern. Next, we wanted to understand what potential factors could be influencing this regional variation and found that mean EC and TP were positively and significantly correlation with road density and the percentage of modified area. Lastly, we designed a novel method for monitoring nutrient status in nearshore waters using periphyton that can be used by local community members. We found that the periplate results are sensitive to areas of high human disturbance and may be used in volunteer monitoring programs. The results of this study can help the TGB and other similar municipalities make informed management decisions and policies to protect the excellent water quality of Georgian Bay.

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LIST OF ABBREVIATIONS

BAV	Beach Action Value (235 CFU/100 mL)
BC	Brandy's Cove
CCME	Canadian Council of Ministers for the Environment
CFU	Colony forming units
CHLα	Chlorophyll α
CL	Cognashene Lake
COG	Cognashene
EC	*Escherichia coli* (*E. coli*)
FB	Fecal Bacteria
FE	Fecal Enterococcus
GBGLF	Great Lakes Georgian Bay Foundation
GBWQO	Georgian Bay Water Quality Objective (EC density of 10 CFU/100 and TP concentration of 10μg/L)
GHB	Go Home Bay
GLNA	Great Lakes Nearshore Assessment
GLWQA	Great Lakes Water Quality Agreement
IHH	Inner Honey Harbour
MB	Macey Bay
MBC	Macey Bay Channel
MOECP	Ministry of Environment, Conservation and Parks
MPN	Most Probable Number
MST	Microbial source tracking
NB	North Bay
NHH	North Honey Harbour
NP	National Park
OB	Oak Bay
PCF Lab	Pat Chow-Fraser lab
SB	South Bay
SSEA	Severn Sound Environmental Association
SSO	Severn Sound Open
TB	Tadenac Bay

TGB	Township of Georgian Bay
TMB	Twelve Mile Bay
TP	Total Phosphorus
WW	Wah Wah Taysee

CHAPTER 1: GENERAL INTRODUCTION

Water covers 71% of Earth's surface but less than 1% of that is freshwater (USGS, 2019). Despite its relatively small quantity, freshwater plays a vital role in supporting biodiversity and ecosystem health as it is home to 6% of all species (Dudgeon et al., 2006). Not only is freshwater essential for the survival of many terrestrial and aquatic species, but it is also critical to humans who rely on it for drinking, health, sanitation, navigation and economic benefits like tourism and fishing. In Canada alone, surface fresh water is the primary drinking source for approximately 28 million Canadians (Statistics Canada, 2021). Due to the fundamental need for clean water, in 2010, the United Nations declared access to clean water a human right (De Albuquerque, 2014).

The largest source of freshwater within Canada is the Laurentian Great Lakes, accounting for 20% of the world's freshwater (Government of Canada, 2018). Aside from supplying one third of Canadians with drinking water, the Great Lakes are an "unmatched recreational asset" (Krantzberg & Boer, 2006). The use of recreational waters provides many health and economic benefits to North Americans and have been specifically protected under the Great Lakes Water Quality Agreement (GLWQA) (EPA & ECCC, 2012). Around the world, excellent water quality is highly valued by the public and is associated with better general and mental health, with people willing to travel an hour further for cleaner water (Keeler et al., 2015; Keniger et al., 2013; White et al., 2013). Recreational water also has huge economic benefits. In the Great Lakes alone, recreational boating is valued at $2.2 billion and the commercial, recreational, and tribal fisheries are worth $7.5 billion annually (Krantzberg & Boer, 2006).

These recreational benefits, however, are reduced when water quality is degraded. Fish populations suffer, human health is threatened and property values decrease upwards of 22% when located near turbid and algal infested water (Gibbs et al., 2002; Wolf & Klaiber, 2017). Unfortunately, fresh water is under immense threat from anthropogenic activities and from extreme weather events linked to climate change; in fact, it has been classified as the most threatened resource on the planet, and inland waters specifically, are most at risk of being degraded (Dudgeon et al., 2006; Garcia Moreno et al., 2014). As vast as the Great Lakes are, climate change and human activities have led to degraded water quality due to pollutants in runoff from agricultural and urban development, as well as industrial and domestic effluents (Dudgeon, 2019; Kerr et al., 2016; Reid et al., 2019), particularly in the more highly populated southern Great Lakes (Erie and Ontario) and southern Lake Michigan (Host et al., 2019). One notable exception is Georgian Bay, the eastern arm of Lake Huron, which has been assessed as generally having excellent water quality and having great recreational appeal to tourists (Sly & Munawar, 1988).

Georgian Bay, the Sixth Great Lake

Georgian Bay is located entirely within Canada and covers approximately 15,000 km^2 (Sly & Munawar, 1988), making it almost 80% the size of Lake Ontario (19,000 km^2; Herdendorf, 1982). Named in honour of King George IV by Captain Bayfield's Admiralty survey of 1819-22 (Landon 1944 in Sly & Munawar, 1988), it is joined to the main part of Lake Huron by a channel formed by Manitoulin Island to the north and the Bruce Peninsula to the south, with a width of ~30 km. There are, however, several large islands in the channel, namely Fizwilliam Island and Cove Island, and the longest distance of unimpeded water is ~14 km (measured in GIS). Unofficially, Sly & Munawar (1988) called it the sixth

Great Lake due to its relatively large size, and James Barry wrote a book entitled "Georgian Bay: the Sixth Great Lake", noting that Samuel de Champlain, the famous explorer, called it the "Freshwater Sea" when he first encountered it (Barry, 1995). In his book, he emphasized that Georgian Bay is not merely an appendage or arm of Lake Huron, but a body of water with as big a history and character as other Great Lakes. It is worth mentioning that this naming of Georgian Bay as the Sixth Great Lake precedes the brief period in 1998 during which Lake Champlain (surface area of only 1,269 km^2) was declared by the U.S. Senate as the sixth Great Lake.

Georgian Bay is great in other respects as well. In recognition of the 30,000 islands in eastern Georgian Bay (from Port Severn to French River), making it the largest freshwater archipelago in the world, the United Nations Educational, Scientific and Cultural Organization designated it as a Biosphere Reserve. This highlights its importance as an area for migratory and island-nesting birds and overall high biodiversity which includes 840 native plant species, 170 types of breeding birds, 44 mammal species and 34 species of reptiles and amphibians (50 of which are species at risk; Georgian Bay Biosphere, n.d.). Its world class trophy muskellunge fishery is also of economic and ecological importance because it is the only self-reproducing muskellunge fishery in the Laurentian Great Lakes (Leblanc et al. 2014). Another unique feature is the Precambrian Shield bedrock and thin acidic soil that underlies this region, making it unsuitable for agricultural development (Weiler, 1988) and thus free of the negative effects of agricultural runoff. The many stands of windswept white pine that grow between rock outcrops have been captured in the iconic paintings of the Group of Seven and have become instantly recognizable as a symbol of Georgian Bay.

Until the 19th century, the only human settlements in Georgian Bay were by Indigenous communities that had lived there for 9000 years (Stone, 2008). During the 1600s, the Huron people settled on the southern shores of Georgian Bay and began to farm and trade with the early French explorers (Ketcheson, n.d.). Fur trade was very lucrative during the 17th and 18th centuries, but European villages did not become established around the many fur-trade posts until the 19th century. As fur trade declined, however, European settlers began to exploit the abundant fish, including a thriving commercial fishery of lake trout and whitefish, as well as pickerel, pike, sturgeon, herring, and bass (Ketcheson, n.d.). The Georgian Bay Lumber district began in 1872 and was the most important district for producing pine lumber in Ontario (Electric Canadian Company, n.d.). Pine lumber operations were active in eastern Georgian Bay until largescale wildfires (Meek, 1991) and dwindling stock eventually led to their demise by the 1920s (Scott, 2018). According to McCuaig (2004), the Ministry of Natural Resources estimated that there was almost complete removal of the virgin stands of pine, hemlock and yellow birch from 1880 until the early 1940s.

During the late 1800s, freight and passenger vessels began to transport goods and people to various parts of eastern Georgian Bay and this allowed development of fishing camps, general stores and cottages; more and more steamship passengers liked what they saw and expressed an interest in overnight stays, and this led to the building of summer resorts and hotels such as the Bellevue, Ojibway and Skerryvore Hotels during the first decade of the 20th century in Pointe au Baril (McCuaig 2004; see **Figure 1.1**). Further south in the hamlet of Honey Harbour, the Victoria House located in the present day Delawana Inn, opened in 1897, and the Royal House was opened in 1903 (Stone, 2008). Because of lack of roads, guests of these hotels had to take a steamer from Victoria Harbour (near Midland) to Honey Harbour and other points north (i.e. Go Home Bay and Parry Sound; Floren & Gutsche, 1994).

Because Georgian Bay is primarily a summer destination, few cottages have been built for year-round use and many cottages are still only accessible by boat due to the limited road development. Both of these factors explain why the water quality of Georgian Bay has been kept in excellent condition compared to Lakes Erie and Ontario, and is also the primary reason why there is high biodiversity (DeCatanzaro et al., 2009; Maynard & Wilcox, 1996; Weiler, 1988). To maintain good water quality, the two townships responsible for the quality of nearshore waters established long-term monitoring programs to track changes in water quality beginning in the 2000s. Twelve Mile Bay is the boundary between the two townships; the Township of the Archipelago (TOA) stretches from Twelve Mile Bay north to the French River and includes the city of Parry Sound while the Township of Georgian Bay (TGB) stretches south from Twelve Mile Bay to Severn Sound and includes the towns of Port Severn and Honey Harbour (see **Figure 1-1**). Being located closer to large urban centers in southern Ontario, TGB has the highest cottage and road densities, and attracts the greatest number of summer visitors, particularly in Honey Harbour and Severn Sound (Fischer & Associates & Murray Consulting, 2014).

Water-Quality Monitoring Programs

Water-quality monitoring programs vary greatly according to the type of water bodies being surveyed and the purpose of the monitoring. Typical parameters in surface-water monitoring programs include physico-chemical variables (e.g. temperature, specific conductance, pH, dissolved oxygen, and water turbidity, total alkalinity), primary nutrient concentrations (e.g. forms of phosphorus and nitrogen), major anions and cations (e.g. calcium, carbonate, bicarbonates, chloride, sodium, potassium, sulfate), biotic variables (e.g. fecal bacteria, planktonic and periphytic chlorophyll, zooplankton and benthic invertebrates), and sometimes trace elements and metals (Alexander et al., 1998; Chow-Fraser, 2006; O'Brien et al., 2016; Vasistha & Ganguly, 2020).

For recreational use in areas such as Georgian Bay, most monitoring programs tend to focus on presence of pathogens such as bacteria and viruses that can cause health issues in humans including cholera, gastroenteritis, typhoid fever, diarrhea and skin irritation (Dufour, 1984; Payment et al., 2003; Wade et al., 2003). Even though these pathogens tend to occur in low densities, presence of only a small number will pose a risk to human health (Ishii & Sadowsky, 2008; Rodrigues & Cunha, 2017). A common indicator of fecal pathogens is *Escherichia coli* (EC), which itself is not necessarily pathogenic, but which resides in the intestinal tracts of animals where fecal pathogens originate. Another concern is elevated levels of phosphorus, the most limiting nutrient in freshwater, which can result in eutrophication and lead to algal blooms, reduced water clarity, depleted dissolved oxygen levels and aquatic dead zones (Bhateria & Jain, 2016; Conley et al., 2009). In extreme cases, such as in Sturgeon Bay (TOA) and Port Severn (TGB), toxic blue-green algae blooms (also referred to as cyanobacteria) have occurred as recently as 2021 (see Figure 1.1; Conley et al., 2009; Heisler et al., 2008). Therefore early detection of increased concentrations of total phosphorus (TP) is particularly important in Georgian Bay to prevent cultural eutrophication (Lambert et al., 2008).

Volunteer monitoring programs

Successful monitoring programs have often involved volunteers and local citizens (Stepenuck & Genskow, 2018). Such programs often use simplified tools (e.g. Secchi disk) and/or methods that rely on use of bioindicator species that are sensitive to environmental conditions (Holt & Miller, 2010; Rosenberger et al. 2008). These alternative methods must be inexpensive and require minimal training and laboratory equipment. For nearshore waters of Georgian Bay, the two target variables of interest are densities of EC and concentrations of TP. Traditional methods used to measure these variables have involved tedious protocols, expensive equipment and caustic chemicals that are not suitable for volunteer programs (Byappanahalli et al., 2012; Schang et al., 2016). The Coliplate™ (Bluewater Biosciences, Toronto, ON) was introduced as an alternative to the traditional culture-based, membrane filtration method used to quantify fecal coliform densities and has proven to be effective for quantifying *E. coli* density in inland streams and rivers (Gibson et al., 2021). The biomass of benthic algae growing on rocks and sediment (periphyton) and or on leaves of plants (epiphyton) have been related to the concentration of TP in wetlands (McNair & Chow-Fraser, 2003) and streams (Tedeschi & Chow-Fraser, 2021) because these single-celled algae respond quickly to changing nutrient status (Lowe & Pan, 1996; Rosenberger et al., 2008). Therefore, they may be a good bioindicator of TP concentration in freshwater ecosystems (Aloi, 1990; Lambert et al., 2008).

Existing Monitoring Stations in Georgian Bay

Besides the question of what to monitor, there is also the question of where to monitor. For Georgian Bay, sampling stations have been established in the bay since April 2000 as part of the Great Lakes Water Quality Monitoring and Surveillance Data Program

(Environment and Climate Change Canada 2023); however, location of these stations do not align well with the nearshore zone of eastern Georgian Bay. By comparison, the provincial Great Lakes Nearshore Assessment (GLNA) was conducted by the Ontario Ministry of the Environment, Conservation and Parks between 2003 and 2005, with the objective of documenting ambient water quality conditions (nutrients, major ions, and physico-chemical parameters) in coastal areas of eastern and northern Georgian Bay (OMECP 2023). Of the 132 locations surveyed, 69 occurred along the nearshore zone of the TOA, while 40 occurred along the nearshore zone of the TGB; all were sampled primarily in the spring, summer and fall of 2004 and 2005. The Severn Sound Environmental Association (SSEA; unpublished data) has also monitored nutrient concentrations in Severn Sound, including water surrounding the Town of Honey Harbour (North Bay, South Bay, Honey Harbour, Oak Bay; **Figure 1-2**). By far, the only comprehensive dataset for fecal bacteria in nearshore waters of TOA and TGB had been surveyed by Schiefer and Schiefer (2009 and 2010, respectively), who monitored EC densities throughout the summers between 2000 and 2009 at over 100 sites in these townships. There are also accompanying TP concentrations at the end of the summer for most sites.

<u>Provincial Guidelines</u>

In 2022, the Canadian government released updated water-quality guidelines for primary contact recreation with respect to fecal bacteria. Primary contact activities are those that involve intentional or incidental immersion in natural waters (e.g. swimming, children wading in water) and do not apply to secondary contact activities such as canoeing, kayaking, fishing (Health Canada, 2022). For EC, the Beach Action Value (BAV;

single cultured sample) is **235 colony-forming units (CFU) per 100 mL**. Health Canada (2022) indicates that the basis of these guidelines is the link between EC densities and the increased risk of adverse human health outcomes from exposure to human sewage. When recreational areas are impacted by wildlife/birds and not by human or ruminant fecal pollution, then the risk of gastrointestinal illness may be lower at the same EC densities because fewer human pathogens are expected to be present. Therefore, microbial source tracking methods should be used to determine probable sources of fecal contamination to help characterize exposure risks in different areas of contamination. Further, Health Canada recommended that when there is very low risk of human or ruminant fecal contamination, development of alternative criteria may be beneficial on a site-specific basis.

There is no guideline for TP in regards to recreational uses; however, the Ontario Ministry of Environment, Conservation and Parks recommends that TP concentrations should not exceed 20 μg/L to avoid nuisance algal growth, and should not exceed 10 μg/L to protect against aesthetic deterioration (MOE, 1998). The Canadian Council of Ministers of the Environment (CCME) has recommended a tiered approach where TP concentrations should not i) exceed predetermined "trigger ranges" and ii) increase more than 50% over the baseline levels (CCME, 2004). Using these recommendations, the Severn Sound Environmental Association (SSEA), proposed a target of 10 μg/L in nearshore locations (Severn Sound Environmental Association, 2021) which is in alignment with the TP guidelines from British Columbia's Ministry of the Environment (British Columbia Ministry of Environment, 2019). Lastly, there are no national or provincial guidelines for planktonic biomass or CHLα concentrations; however, the SSEA has advised that CHLα concentrations should remain below 5μg/L (Severn Sound Environmental Association, 2021).

Specific Guidelines for Georgian Bay

During the synoptic surveys conducted by Schiefer & Schiefer (2009, 2010) in the nearshore regions of eastern Georgian Bay, they found that in undisturbed open water, background levels of EC tended to be below 10 CFU/100 mL and TP concentrations were below 10 μg/L. These findings, as well as the importance of having good water quality to maintain the lifestyle and economy of Georgian Bay, prompted Schiefer & Schiefer to recommend specific Georgian Bay Water Quality Objectives (GBWQO) of 10 CFU/100 mL of EC and 10 μg/L of TP.

Thesis Objectives

The overarching objective of this thesis is to re-assess the current water-quality status of nearshore waters of the Township of Georgian Bay and to compare how EC densities and TP concentrations have changed since the last survey by Schiefer and Schiefer. As well, we wanted to determine if environmental conditions (e.g. year-to-year water levels, weather conditions, etc) and anthropogenic activities (shoreline modifications and recreational development) are influencing water quality in six broad regions within the Township. To achieve these objectives, the Chow-Fraser lab developed a sampling program during the summer of 2020 that included most of the sites sampled by Schiefer and Schiefer and added some additional sites that were of current concern to the Township of Georgian Bay. For this thesis, we calculated mean seasonal densities of EC and concentrations of TP in six major regions within the nearshore waters of the TGB between 2020 and 2022 (majority in 2021 and 2022) and compared these to historic data (mentioned previously). We also correlated pollutant levels with variables of human disturbance (e.g. road density, building density and dock density) to investigate the drivers of water-quality impairment in this region. Finally, we developed and tested a novel method for tracking changes in nutrient status in nearshore waters using periphyton as a bioindicator. This new method could be easily carried out by volunteers with limited training in community-based monitoring programs. Information on current hotspots of fecal bacteria and TP should be followed up with microbial source tracking so that the Township will be able to confirm the source of the pollutants and take steps to protect and preserve the excellent water quality of Georgian Bay.

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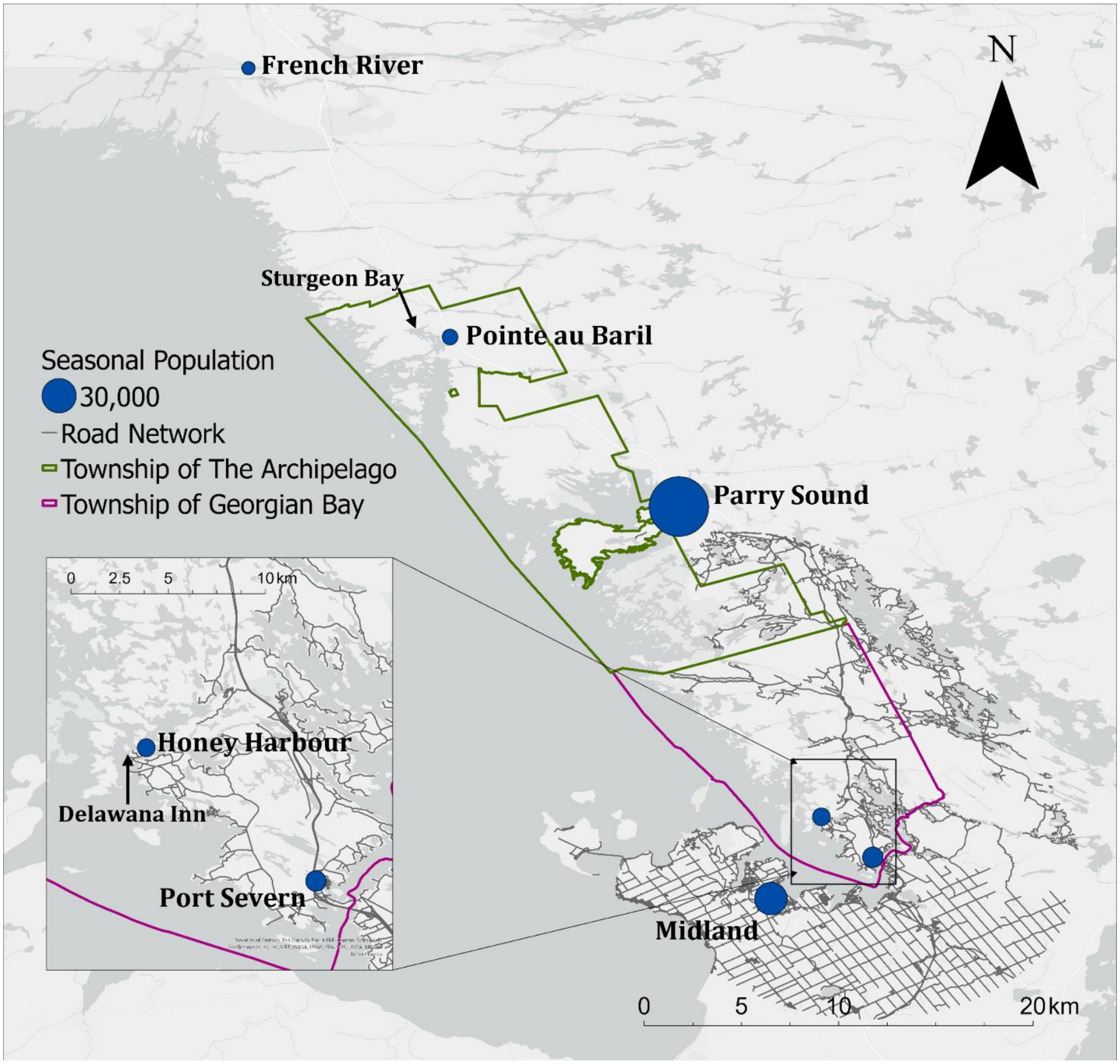

Figure 1.1: District boundaries of the townships along the southeastern shoreline of Georgian Bay and location of the major towns. The size of the circle is proportional to the seasonal population of the towns.

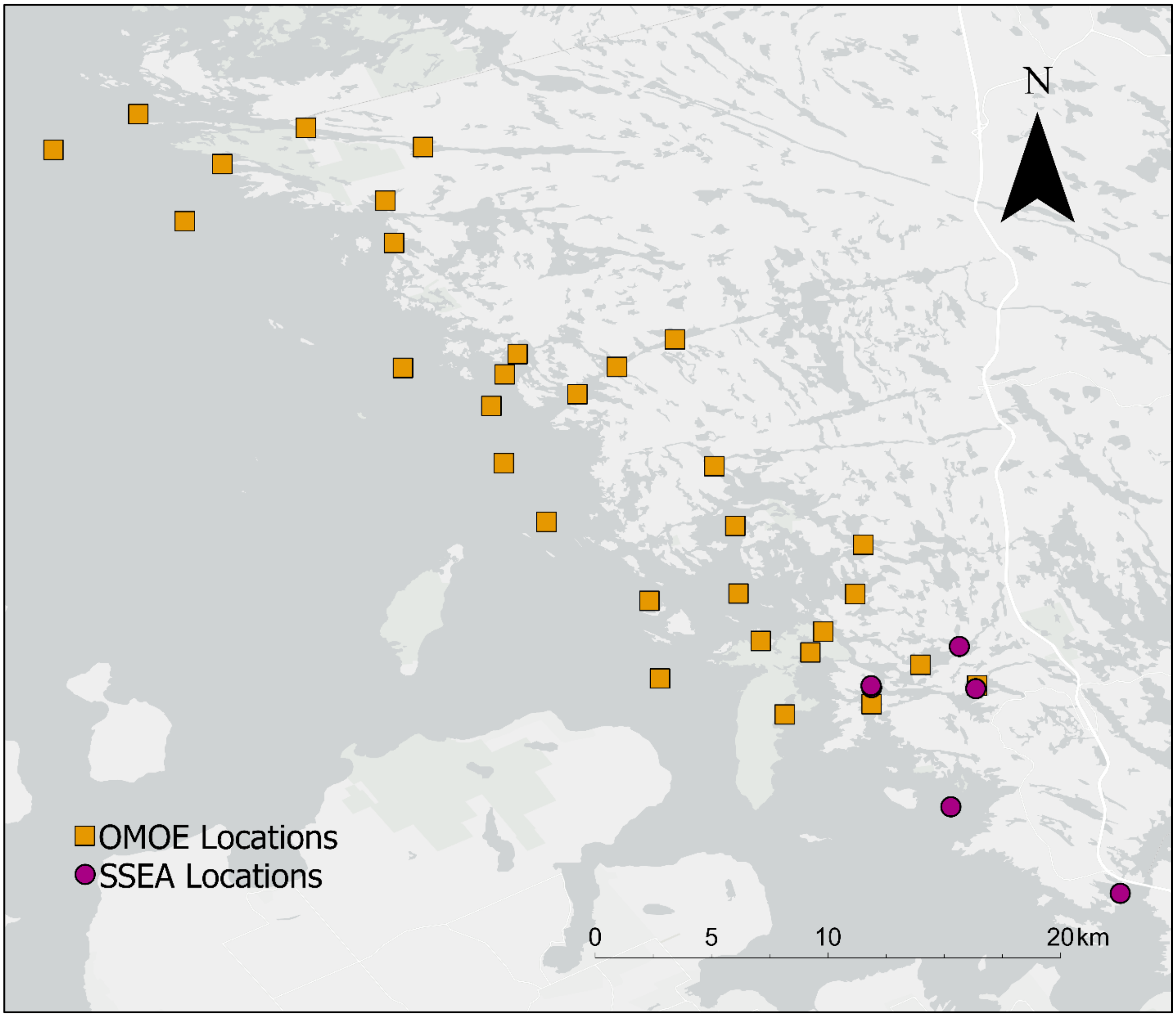

Figure 1.2: Monitoring stations in the nearshore of the Township of Georgian Bay sampled by the Ontario Ministry of the Environment and Energy (currently Ontario Ministry of Environment Conservation and Parks) during the Great Lakes Nearshore Assessment between 2003 and 2005 as well as those sampled by the Severn Sound Environmental Association.

CHAPTER 2: Regional drivers of water-quality impairment in nearshore waters of the Township of Georgian Bay

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ABSTRACT

The Township of Georgian Bay (TGB), located in the southern portion of eastern Georgian Bay, includes six major regions (Twelve Mile Bay (TMB), Wah Wah Taysee (WW), Go Home Bay (GHB), Cognashene (COG), Honey Harbour (HH) and Oak Bay (OB)) and is a very popular cottage and tourist destination, known for its excellent water quality, diverse recreational opportunities, and striking natural beauty. Despite the importance of good water quality, there is no on-going long-term monitoring program in TGB except in the most southerly region near the town of HH, the most recent long-term study of the entire shoreline in the TGB having been carried out between 2001 and 2009 (Period 1). Between 2020 and 2022 (Period 2), we re-sampled 36 long-term sites for *E. coli* (EC) densities and total phosphorus (TP) concentrations in HH, COG, GHB and TMB (which includes WW). Here, we compare EC and TP between Periods 1 and 2, using only data collected under fair-weather conditions during peak summer months. For 80% of the sites that had been sampled at least twice, we found a general decrease in EC from Period 1 to Period 2, and we attribute this to effects of dilution associated with a mean increase in water levels of over 1 m between time periods. Honey Harbour and Oak Bay had the highest mean EC and TP values and the greatest exceedances with respect to the Georgian Bay Water Quality Objective of 10 CFU of EC and 10 µg/L of TP. The significant positive correlation between EC and TP with road density and percentage modified land use supports our hypothesis that cottage and recreational development has been the driver of water-quality impairment and that increased use and access to cottages have led to failing septic systems and subsequent pollution of nearshore waters by fecal bacteria and nutrients.

INTRODUCTION

Georgian Bay, the eastern arm of Lake Huron, has been referred to as the "Sixth Great Lake" informally by scientists (Sly & Munawar, 1988) and by historians (Barry, 1995). It is well known for its excellent water quality, making it a hotspot for cottagers and tourists who are drawn to diverse recreational opportunities that include swimming, water sports, fishing and appreciating nature. Therefore, good water quality is important for survival of the diverse fish and wildlife populations, but also for maintaining the lifestyle and economy of the township (Fischer & Associates & Murray Consulting, 2014). An important first step to protecting recreational water in Georgian Bay is to regularly monitor its water quality and track incremental changes over time (Dudgeon, 2019; Myers, n.d.). It is also important to understand the specific drivers of water-quality impairment in Georgian Bay so that the management agency can create policies and by-laws to prevent degradation.

An important variable to monitor in recreational waters is fecal bacteria (FB), which in high densities can indicate the presence of human pathogens that could cause severe gastrointestinal illnesses (Health Canada, 2022). FB groups that have been used as fecal indicators include coliform bacteria measured as Total Coliform (TC) or *E. coli* (EC) and Fecal Enterococcus (FE). TC refers to a group of gram-negative bacteria within the *Enterobacteriaceae* family that possess β-galactosidase (Payment et al., 2003) and are found in the intestines of warm-blooded animals, but also occur naturally in nutrient-rich water and decaying plant materials; therefore, TC is not specific for fecal pathogens and is rarely used now for evaluating risk to human health (Rodrigues & Cunha, 2017). FE is a group of gram-positive bacteria (28 species) that possess the Lancefield group D antigen; it is also found in the intestines but do not occur naturally (Fisher & Phillips, 2009; Payment et al., 2003). Lastly, EC a member of TC which has both β-galactosidase and β-glucuronidase enzymes, is only found in the intestines of warm-blooded animals and has been used extensively as an indicator of fecal pathogen in freshwater (Kiran et al., 2018; Payment et al., 2003). It can be accurately detected and is often the bacteria of choice for monitoring freshwater in many countries (Health Canada, 2012; US EPA, 2012; Wade et al., 2003). For marine ecosystems, however, FE is the bacteria of choice because they have a greater salt tolerance compared to EC (Health Canada, 2012; US EPA, 2012). Despite these findings, both EC and FE have been used as fecal indicators in freshwater, and there is equivocal evidence that these FB can be used interchangeably. Gotkowska-Płachta et al (2016) showed a positive correlation between these FB, but others have found contrasting results and concluded that they should not be used interchangeably (Jeng et al., 2004; Kinzelman et al., 2003).

The presence of fecal coliform bacteria in surface waters can be detected in several ways. The gold standard for enumerating FB is by serial dilution of the sample and then using membrane filtration to concentrate the bacteria, after which the filter is cultured on selective medium, incubated at 35°C, and colonies are counted (Byappanahalli et al., 2012). Even though this method is accurate, it can take up to 48 hours for conclusive results to be reached and this lag time can expose the public to unacceptable health risks (Byappanahalli et al., 2012; Schang et al., 2016). The Coliplate™ is an alternative to culture-based and membrane filtration methods that uses defined-substrate technology to detect the enzymes in EC (β-D-galactosidase and β-D-glucuronidase), turning these blue and fluorescent under UV light (Edberg et al. 1991). Growth of EC only requires a 24-h incubation period, and EC densities are calculated based on the Most Probable Number method (MPN). Investigators who compared results of the membrane filtration and culture method with those obtained with Coliplate™ found no significant differences (Lifshitz & Joshi, 1998); however, limitations of the Coliplate™ include subjectivity with deciding if a well is blue or fluorescing, and the logistical difficulty of having a single individual processing a large number of samples (Gibson et al., 2021). The TECTA B-16 (Pathogen Detection System, Kingston, ON; henceforth referred to as the TECTA), is a rapid microbial detection system that detects the two enzymes specific to EC (mentioned above). Investigators found no significant differences among results of the three methods (Bramburger et al., 2015; James et al., 2007; Schang et al., 2016), but the TECTA was able to quantify EC densities within a maximum of 18 hours and detect exceedances of the provincial standard within four hours (Bramburger et al., 2015). The drawback of the TECTA is its high cost, but its small footprint (making it highly portable), and lack of user bias are great advantages (Schang et al., 2016).

The density of EC in recreational waters can be influenced by several natural and anthropogenic factors, and it is important to determine their individual effects to ensure proper interpretation of results, especially with several data sources. Pollutants such as nutrients and FB can vary temporally with hydrological conditions. High water levels can result in a dilution of nutrients (Montocchio & Chow-Fraser, 2021), and these lower concentrations can be misinterpreted as an improvement in water-quality conditions. As well, when water level rises, the dispersal of FB is dampened regardless of an actual increase in FB density or not (Oglesby, 1968; Welch et al., 1992). Increased water levels may also reduce the amount of wind-resuspended FB from the sediment and simultaneously increase the amount of flushing from the open water of GB into enclosed bays, further decreasing bacterial densities (Kann & Walker, 2020; Wang et al., 2022). On the other hand, high water levels may lead to increased density of FB entering the bay via point sources and increase the likelihood of septic systems being flooded when they are located close to the shoreline (Butler & Payne, 1995). Low water levels can reverse the effects of high water levels by concentrating nutrients and FB, decreasing the volume of enclosed bays and reducing the dispersal of pollutants; as well, there is increased probability of nutrients and FB in bottom sediments being stirred up (Leira & Cantonati, 2008; Wang et al., 2022).

Precipitation is another factor that can increase levels of nutrients and FB in surface waters (Ackerman & Weisberg, 2003; Coulliette & Noble, 2008; Lyautey et al., 2011). Rainfall can increase runoff, bringing excess nutrients and other pollutants into the water, as well as resuspend sediments that may contain these pollutants (Levy et al., 2018; Powers et al., 2021; Silva et al., 2014). Runoff may also contain sewage from failing septic systems that have become inundated with stormwater (Withers et al., 2014). These scenarios worsen when extreme rain events occur after long periods of drought because rainwater does not percolate as readily into the soil when the velocity of the runoff is high (Strauch et al., 2014). Since climate change is expected to increase both the frequency and magnitude of extreme precipitation events during the summer, this factor will likely increase the level of nutrients and FB in Georgian Bay (Pendergrass & Knutti, 2018; Prein et al., 2017).

Modification of the shoreline related to cottage and recreational development can also have a negative effect on surface water quality. Numerous studies have shown a positive correlation between increased FB and nutrients and percentage urbanized land in watersheds (Hawbaker et al., 2005; Mallin et al., 2000; Powers et al., 2020; Simpson et al., 2021). Other studies have also shown an increase in pollutants with marinas (Kirby-Smith & White, 2006) and road density (Campbell & Chow-Fraser, 2018; DeCatanzaro et al., 2009; Hawbaker et al., 2005; Houlahan & Findlay, 2004; Simpson et al., 2021). This is because landscape modifications lead to increased impervious surfaces and decreased riparian vegetation (Strauch et al., 2014). Impervious surfaces can lead to a higher volume and frequency of polluted runoff entering GB compared with natural land cover and vegetation (Jacob & Lopez, 2009; Mallin et al., 2000). Runoff amount and concentration of pollutants further increases when there is a direct connection between urbanized areas and streams (Hatt et al., 2004). With increased cottage development, there is increased possibility of raw sewage entering GB from failing septic systems due to improper maintenance, overuse and/or inadequate sizing (Rodrigues & Cunha, 2017; US EPA, 2005).

Lastly, increased nutrient and FB concentrations can be found in boating anchorages, which are often enclosed bays (Schiefer & Schiefer, 2010; Sobsey et al., 2003). In such enclosed bays, water circulation can be limited, and this allows nutrients and FB to accumulate (Campbell & Chow-Fraser, 2018; Payment et al., 2003). This can be worsened by sewage being leaked from holding tanks on live-aboard boats or if there is illegal dumping of blackwater.

Good water quality in the nearshore zone of southeastern Georgian Bay is of great importance to the Township of Georgian Bay (TGB) because all aspects of the economy, culture and lifestyle of its residents depend on this. Despite the importance of good water quality, there is no on-going long-term monitoring program in TGB except in the most southerly region near the town of Honey Harbour. The most extensive sampling program had been coordinated by Schiefer and Schiefer (2010) between 2001 and 2009, in which over 100 sites had been sampled by volunteers for EC and TP during the summer throughout the Township (including inland lakes). There has been no replacement program since this ended over a decade ago. This is problematic because since 2009, there has been increased usage of cottages year-round, as well as intensive recreational development including a residential and golf-course development in Oak Bay. Secondly, between 2009 and 2020, there has been an approximately 1m increase in water levels (US Army Corps of Engineers, 2023), both of which may have led to changes in the nutrient status and FB densities in GB.

Local governance is the most effective way to manage water quality (Withanachchi et al., 2018); therefore, the TGB municipal government is the most appropriate political body to develop programs, policies, and regulations to address water-quality issues in southeastern Georgian Bay. The objective of this thesis chapter is to work closely with the TGB Council to develop a sampling program to monitor the nearshore surface waters in the same areas that had been sampled by Schiefer and Schiefer (2010). Specifically, we will assemble the necessary information to assess long-term changes in EC densities and TP concentrations between Period 1 (2001-2009) when water levels were near record low, and Period 2 (2020-2022), when water levels were ~1 m higher. Secondly, we will identify hotspots of EC densities and TP concentrations within the TGB, and thirdly, we will investigate the potential drivers influencing regional variation in FB and nutrients. These results should allow the TGB Council to determine further steps they need to take to protect and preserve the excellent water quality of Georgian Bay.

METHODS

Description of Study Site

We sampled in nearshore areas of six major regions of the TGB. We will refer to each region according to the closest waterbody or cottage association as follows (from south to north): Oak Bay (OB), Honey Harbour (HH), Cognashene (COG), Go Home Bay (GHB), Wah Wah TaySee (WW) and Twelve Mile Bay (TMB) (**Table 2.1; Figure 2.2**)**.** Of the six cottage regions, OB is accessible by road while COG, GHB and WW are only accessible by boat, and HH and TMB have a mix of boat-accessible and road-accessible cottages. We used ArcGIS to measure the shoreline length within each region and applied a buffer of 1-km to calculate the area of the coastal zone for each region (**Table 2.1**).

Historic data sources for long-term comparison

The first objective was to determine how current water quality in nearshore waters of the TGB compares with historic water-quality conditions in the same regions during the 2000s. We found four primary data sources with data on FB (*E. coli* (EC); colony forming units (CFU)/100 mL) and/or total phosphorus (TP; µg/L) that could be combined to represent water-quality conditions between 2001 and 2009 in five regions of the TGB (i.e., all except OB; **Table 2.2**). The largest and most comprehensive dataset was from Schiefer & Schiefer (2010), who recruited dozens of community volunteers to sample in five nearshore regions (all except OB) between 2001 and 2009 for EC and TP. This dataset had been collected by Schiefer & Schiefer to specifically track changes in water quality of nearshore waters of TGB. The second dataset comes from P. Chow-Fraser (unpub. data), who sampled coastal wetlands and nearshore areas of eastern Georgian Bay from 2003 to 2019. The sampling locations and variables collected differed each year depending on the purpose of the research projects; we only used data for EC and TP collected between 2004 and 2009. The third dataset was assembled by the Ontario Ministry of the Environment (currently the Ministry of Environment, Conservation and Parks) who surveyed nearshore waters that corresponded to the TGB during 2005 (Great Lakes Nearshore Assessment; see Chapter 1); their dataset included many variables and sites, but we only used TP for long-term comparisons. The last dataset comes from the Severn Sound Environmental Association (SSEA) and contains TP concentrations collected at various locations in Severn Sound since 2003 to present.

Differences in sampling schedule

Historic (Period 1)

When all data sources were combined, there was a total of 126 sites that had been sampled on 2,103 occasions between 2001 and 2009 in five regions of TGB (all regions in **Figure 2.2** except OB; **Table 2.3**). For simplicity, we will refer to this time interval as Period 1. EC densities were available for 80 sites (sampled 1,704 times) whereas TP concentrations were available for only 69 sites (sampled 383 times). These sites had been sampled from one to twelve times between May and November (day 123 to day 314) over the 9 years. While EC samples were collected from 1 to 6 times over a single year, TP was generally sampled only once a year in late summer (early to mid-September).

Current (Period 2)

Between 2020 and 2022, we sampled 97 sites on 907 occasions in all six regions of the TGB (all regions in **Table 2.3; Figure 2.2**). For simplicity, we will refer to this time interval as Period 2. The sites we sampled included a subset of those sampled in Period 1 by Schiefer & Schiefer's (2010) as well as new sites that were identified as being areas of concern by the TGB Council. These new sites included those associated with increased recreational activity and where septic systems were at risk of being flooded during Period 2 in the five historic regions. As well, we included sites in OB, where a golf course and condominium complex had been built after 2009 and that had NOT been previously sampled by Schiefer and Schiefer. During Period 2, we visited 78 sites and analyzed 428 water samples for EC densities; in addition, we visited 85 sites and analyzed 479 samples for TP concentrations. All data were collected between mid-June to early September (day 156 to day 252). See Appendix 1 for a complete list of sites and Appendix 2 and 3 for maps of all sites. We aimed to sample all hotspots (sites with elevated values) in all regions at least once a year during Period 2 and to sample sentinel sites (sites that had high EC and TP values in Period 1) from 2 to 4 additional times each year.

Differences in timing of sampling

Schiefer and Schiefer's (2010) data were collected largely by individuals from various community associations who volunteered their time, and in many cases their boats, to collect water samples for testing; however, more detailed and intensive water-quality sampling in the HH and COG areas were carried out by graduate students under the supervision of Dr. Michael Goss, University of Guelph, during 2002 and 2003. Bacterial testing was frequently conducted following intensive use in mooring bays (Sunday evening or Monday morning) in mooring bays and following major rain events in bays with high cottage density. By comparison, we carried out our sampling between 08:00 and 20:00, during fair-weather conditions and before, during and after rain events.

Sampling methods

Water samples for EC were collected in sterile containers from a depth of ~30 cm (approximately where adult volunteers can submerge their arms from a boat). All water samples were placed in a cooler containing a freezer pack and then brought to a cottage (historic) or lab (in current period) for processing, usually within 8 hours of collection. If processing had to be delayed, samples were kept in a refrigerator and processed within 12 hours of collection. Water samples for TP were collected in the same way as for EC except that sample containers were previously acid washed to avoid contamination. Water samples collected by volunteers in Schiefer and Schiefer's (2010) program were kept in coolers and sent to be analyzed by Maxxam Laboratories (Mississauga, Ontario) or the OMOE laboratory (Dorset, Ontario). Samples collected in Period 2 were kept in a freezer in a lab in Honey Harbour and transported to McMaster University at the end of the season.

Analytical methods

E. coli

Volunteers in Period 1 used Coliplate™ Test Kits (https://bluewaterbiosciences.com//), which uses the defined substrate method to detect *E. coli*. The plates contain substrate with 4-methylumbelliferyl-ß-D-glucoronide, which is selective for detection of ß-glucoronidase activity when *E. coli* is present. The 96 wells of the Coliplates™ were filled with raw water and incubated at 35°C for 24 hours; after incubation, we determined the number of wells that turned blue, which were interpreted as positive for Total Coliform (TC) and the number of blue wells that fluoresced under UV light, which were interpreted as positive for EC. The number of positive wells were counted and converted to density (colony forming units (CFU)/100 mL) based on the Most Probable Number (MPN) table. Fecal bacteria samples were generally processed within 4-6 hours of water collection. In Period 2, *E. coli* samples were enumerated with the Pathogen Detection System (PDS) TECTA B-16. The TECTA is an automated microbiological platform that uses Polymer Partition technology (Bramburger et al., 2015). Our unit was professionally installed by PDS in a temporary lab space that was made available for this project by the TGB Council. As recommended, we performed calibrations using local water at the start of the 2020 sampling period and used a validation cartridge each week before the first set of tests were run. We poured a 100-mL aliquot of raw water into a PDS cartridge containing proprietary media for *E. coli* and swirled it gently until all the reagents had been dissolved. Samples were incubated for a period of 2 to 18 hours at a temperature of 35°C; highly contaminated samples with *E. coli* could elicit a positive result within two hours, whereas uncontaminated samples (< 0 CFU/100 mL) would remain negative when incubated for up to 18 hours.

Total Phosphorus

All water samples were stored frozen until the day they were processed for TP. First, samples were taken out of the freezer to thaw, and once they reached room temperature, we digested 50 mL of unfiltered raw water with persulfate in an autoclave. After the sample cooled, we used the molybdenum method of Murphy and Riley (1962) to measure TP concentrations. Samples submitted to Maxxam Laboratories and the OMOE laboratory at Dorset were also analyzed for TP with a version of the molybdenum blue method.

Standardizing data for comparison

Coliplate™ vs Tecta for EC

We had to first determine if the Coliplate™ and Tecta yielded EC densities that were directly comparable. For this direct comparison, we collected 38 water samples from OB, HH and GHB during July and August in 2021 and 2022. These samples were split and measured with both the Coliplate™ and TECTA. We found a highly significant relationship between EC_{Tecta} and $EC_{Coliplate}$ ($r^2 = 0.626$; $p<0.0001$; **Figure 2.3a**); we also found a significant relationship between TC_{Tecta} and $TC_{Coliplate}$, although there was greater unexplained variation ($r^2 = 0.151$; $p<0.0144$; **Figure 2.3b**). We applied Equation 1 to convert EC_{Tecta} to $EC_{Coliplate}$ to facilitate long-term comparison of EC densities between Periods 1 and 2.

Eq 1: $EC_{Tecta} = 0.3667 + 0.7455\ EC_{Coliplate}$ R^2-value = 0.626, $P<0.0001$

Effect of rain intensity

Since samples had been collected under different weather conditions, and effects of rain events on water quality are well established (Ackerman & Weisberg, 2003; Coulliette & Noble, 2008; Lyautey et al., 2011), we had to investigate the specific effect of precipitation on EC density and TP concentrations in our regions. We first classified rain events into 3 "Rain Intensity" categories, considering the amount of precipitation that had fallen immediately before or during sampling. Categories 0, 1, 2, and 3 corresponded to 0 mm, <2.5 mm, 2.6 – 7.5 mm and >7.6 mm, respectively. EC Data from 19 sites and TP data from 17 sites were used to test the effect of rain intensity. We confirmed a significant effect of precipitation categories on both TP (Kruskal Wallis test; 0.0007) and EC data (Kruskal

Wallis test; p=0.025) (**Figure 2.4a and b**). These results indicated that we must control for the effect of precipitation when conducting comparisons across time.

Monthly differences

We also compared differences in EC and TP values among months (June, July and August), and given the possible confounding effect of precipitation, we only included fair-weather data for this comparison. We used EC data from 23 sites in 2021 and 15 sites in 2022 and TP data from 16 sites in each of 2021 and 2022 (**Figure 2.4c and d**). In 2021, we found no significant differences in TP concentrations among the three months (**Figure 2.4c**) but found significantly lower values for June EC compared with July (Steel-Dwass test; P=0.0009; **Figure 2.4d**); it is noteworthy, however, that the lower values collected in June were all collected during the first half of the month. There was no significant difference between EC densities in July and August (**Figure 2.4d**). In 2022, we found no significant differences among months for either EC or TP. We also noted that the June EC samples had been collected during the second half of the month. These results indicated that data from mid-June to end of August would be comparable.

Steps to facilitate comparisons among datasets

We used Eq. 1 to convert EC densities enumerated with the TECTA to be directly comparable with Coliplate™ data. To avoid confounding effects of rain intensity, we used archived daily rainfall data to exclude data from the historic data sources that had >1 mm rain immediately before or on the day of sampling. We similarly excluded any data we collected during Period 2 that corresponded to >1 mm rain. Finally, we restricted data to only those sampled between June 19 (day 170) and September 7 (day 250) to minimize seasonal variation associated with level of cottage activities. We had to extend the time period to early September because almost all of the TP samples collected in Period 1 occurred once per year between end of August and September 9.

Anthropogenic disturbance factors

We first downloaded the relevant shapefiles for the TGB from Scholars GeoPortal (*Scholars GeoPortal*, n.d.). The layers included the Ontario Road Network (ORN; with data as recent as January 2023) and the South-Central Ontario Orthophotography Project (SCOOP; pixel = 16 cm resolution) imagery acquired in the spring and fall of 2018/2019 under snow-free and leaf-off conditions. Within each region, we further delineated focal areas based on location of sites and spatial characteristics such as density of cottages in the area and presence of built-up areas (e.g. commercial properties) (see **Table 2.1**). We used the 2018 SCOOP image in ArcGIS Pro (v. 3.03; ESRI Inc., 2022) to trace the shoreline of the TGB and waterbodies (i.e. lakes, rivers) and to digitize the location of each dock and building within the township. Finally, we delineated areas such as lawns, marinas, trailer parks, golf courses and parking lots and commercial areas and will refer to these as "modified areas".

To calculate densities of roads, cottages, docks, etc, we created a 1-km buffer around the landward side of the shoreline. We also calculated densities using 500-m and 2-km buffers but found the 1-km buffer produced the most ecologically relevant information. We then calculated the total area of the buffer (ha) and the total area of water (ha) and subtracted the latter from the former. This removed bodies of water, like lakes and streams, from the total area since these landcover features are not developed/modified. Finally, buildings and dock densities (#/ha), road density (m of roads/ha) and area of modified and commercial land were calculated for each focal area within the six regions (**Table 2.4**).

Statistical Analysis

We used SAS JMP 15.2.0 for PC (SAS Institute Inc., 2020 – 2021) to conduct all statistical analyses, which included the non-parametric Spearman's Correlation, linear regression analysis, the Kruskal-Wallis test and the Steel-Dwass test for multiple comparisons. Prior to analyses, we log-transformed EC, TP and TC values and arcsine-transformed proportions. All means reported are arithmetic.

RESULTS

Long-term Changes

E. coli

To conduct a direct comparison between Periods 1 and 2, we first standardized the dataset to remove data collected during rain events as well as those sampled outside the period from mid-June to early September. There were 77 sites from Period 1 (2001 – 2009) and 56 sites from Period 2 (2020 – 2022), and of these, 36 sites had been sampled at least twice in both periods (**Figure 2.5**). They were distributed unevenly throughout the Township, with 2 in TMB, 9 in GHB, 6 in COG, and 19 in HH. During Period 1, all samples taken exceeded the GBWQO of 10 CFU/100 mL) whereas during Period 2, the overwhelming percentage of samples (81%) had mean EC densities <10 CFU/100 mL (**Table 2.5**). There were 4 sites that exceeded the BAV guideline (235 CFU/100 mL) during Period 1 compared with only 2 sites in Period 2. In pairwise comparisons, mean EC densities among regions were significantly lower in Period 2 than in Period 1 (**Table 2.6**).

Despite the overall reduction in EC densities during Period 2, 19% (7 sites) of the sites that had exceeded the GBWQO in Period 1 continued to be above 10 CFU/100 mL during Period 2 (see **Figure 2.6**). In fact, at three sites, there was an increase between Periods 1 and 2: in Bloody Bay (TMB), mean densities increased from 14.7 (±1.0) CFU/100 mL in Period 1 to 71.6 (±64.9) CFU/100 mL in Period 2; similarly, the mean of 19.1 (±2.0) CFU/100 mL in Freddy's Channel (COG) increased to 95.3 (±94.8) CFU/100 mL from Period 1 to Period 2; and within a bay south of the North Bay Wetland (HH), mean densities increased from 16.6 (±1.82) CFU/100 mL in Period 1 to 31.0 (±30.0) CFU/100 mL in Period 2. (**Figure 2.7**; **Table 2.5**).

Total Phosphorus

After standardizing the data for meteorological conditions and timing of sampling (i.e. during mid June to early September), we found very little overlap between Periods 1 and 2, with only 3 sites that had been sampled in both periods; of the 58 sites that had been sampled for TP in Period 2 (2020 – 2022), only 2 sites fit the criteria (i.e. having been sampled at least twice in both periods) (**Figure 2.8**). These sites were Cow Island and Inner North Bay, both in HH. TP concentrations in both sites had decreased, with Inner North Bay falling from a mean of 12.6 (±0.45) μg/L in Period 1 to a mean of 9.6 (±2.11) μg/L in Period 2, while TP concentrations for Cow Island fell from a mean of 14.3 (±0.96) μg/L in Period 1 to a slightly lower mean of 13.0 (±2.62) μg/L in Period 2. Only Cow Island had a mean TP concentration that exceeded 10 μg/L in both periods whereas Inner North Bay had a mean TP concentration < 10 μg/L in Period 2 (**Figure 2.9**).

Current Areas of Concern

E. coli

Fifty-six sites had been sampled at least twice during fair-weather conditions within the peak summer months in Period 2. Two sites were located in TMB, 9 in GHB, 7 in COG, 34 in HH and 4 in OB. Of these, 70% were below 10 CFU/100 mL, but 11% had a mean between 10-25 CFU/100 mL, 5% had a mean between 25-50 CFU/100 mL, 5% had a mean between 50-100 CFU/100 mL and 9% had a mean >100 CFU/100 mL (**Table 2.7; Figure 2.10**). When ranked in descending order of mean EC densities, HH was the region with highest density, followed by TMB, OB, COG and GHB (**Table 2.8**). By comparison, when we sorted the regions according to percentage of sites that exceeded the GBWQO, OB was highest, followed by TMB, HH, COG and GHB. Therefore, HH, OB, and TMB consistently had higher mean EC and a higher percentage exceedance compared to the other regions. We must point out, however, that only two sites in TMB were included in this comparison and only one site (Bloody Bay) accounted for all elevated EC densities. Based on the generally low EC densities measured at other TMB sites during Periods 1 and 2, we believe Bloody Bay is not representative of other sites in TMB.

Fifteen samples collected at 9 monitoring stations exceeded the BAV of 235 CFU/100 mL for a single sample (**Table 2.8**). Seven of these were in HH and included Brandy's Cove, North Picnic Island Marina, North Bay Wetland, a site located outside of Macey's Bay wetland and 3 within the wetland; another one was located in Freddy's Channel in COG and Bloody Bay in TMB. There were also 8 sites that had a mean EC density >50 CFU/100 mL. Six of these were in HH, and 1 each in OB and COG. Specifically, they were in Golf Course Point (51.8 CFU/100 mL), Outer Macey Bay (143.6 CFU), Macey Bay wetland at the open-water site (1354.2 CFU/100 mL), Macey Bay wetland at floating vegetation (127 CFU/100 mL) and Macey Bay wetland at emergent vegetation (352 CFU/100 mL). The three remaining sites were in the small bay south of North Bay wetland (111.4 CFU/100 mL), Freddy's Channel (95.3 CFU/100 mL) and Bloody Bay (71.6 CFU/100 mL).

Total Phosphorus

We standardized the dataset according to rain events and timing of sampling during Period 2. Of the 58 sites included in this analysis, 2 were distributed in TMB, 7 in GHB, 6 in COG, 38 in HH and 5 in OB (**Figure 2.10; Table 2.9**). Sixty-two percent (36 sites) of the sites met the GBWQO, while 29% had a mean TP between 10-20 μg/L, 7% had a mean TP between 20- 50 μg/L and 2% had a mean TP concentration that exceeded 50 μg/L (**Figure 2.10; Table 2.9**). The region with the greatest mean TP was OB, followed by HH, TMB, GHB and COG (**Table 2.10**). Similarly, the region with the highest percentage exceedances was OB, followed by TMB, HH, GHB and COG (**Table 2.8**). In general, sites in OB, HH and TMB consistently had higher mean TP and a higher percentage of exceedances compared with those sites in COG and GHB. As was the case for EC densities in TMB, all elevated TP concentrations in TMB were measured at Bloody Bay.

Of the 21 sites that had TP concentrations exceeding 10 μg/L, 71% were in HH, 14% were in OB, 10% in COG and 5% in TMB; notably, none were in COG (**Table 2.10**). Thirteen sites had a mean TP concentration >15 μg/L, which is the trigger point for classifying a water body as eutrophic and five sites had a mean TP concentration >20 μg/L, the provincial water quality guideline. Sites exceeding 15 μg/L were Golf Course Point (19.8 μg/L), inner and outer Potato Island Wetland (33.8 μg/L and 18.2μg/L respectively), Lily Pond (18.8 μg/L), Bayview Marina Resort (26.8 μg/L), South Bay Cove Marina (17.6 μg/L), outer Macey's Bay (20.7 µg/L), and at all three sites in the Macey Bay Wetland, specifically in open water (29.1 µg/L), in floating vegetation (65.7 µg/L) and in emergent vegetation (31.4 µg/L). Of the remaining two, one was in Woods Landing Wetland (25.2 µg/L) and the other in the Sand Run (28.7 µg/L). The maximum TP concentrations in these sites all exceeded 18.0 µg/L, some in excess of 100 µg/L.

Potential drivers of water-quality impairment

To investigate potential drivers of water-quality impairment within the TGB, we organized the database according to 13 focal areas based on metrics that reflected the degree of human development along the shoreline. The metrics included building density, dock density, road density, percentage modified land-use and percentage commercialized land (which is part of the modified land-use) (**Table 2.4; Figure 2.2**). In general, highest building density was associated with BC, highest dock density with IHH, and highest road density with OB. Areas with little to no road density were located in GHB, COG and WW. The percentage modified land use was highest in OB, and only slightly lower in BC and IHH, while very minimal land-use alteration was associated with COG, GHB, and TMB. In general, the five most northern focal areas (TMB, WW, GHB, COG and CL) experienced the lowest human disturbances (low cottage and dock densities, no road density, and <1% of modified and commercialized land along the shoreline) while the focal areas in the two most southern regions generally had high cottage and dock densities, high road density and a high percentage of modified and commercialized area (1-14%).

When we correlated the two pollutants (TP and EC) with the metrics of human disturbances, we found a significant positive correlation between both mean TP and mean EC and road density (0.75 and 0.63 respectively) (**Table 2.11**)**.** Mean EC (0.50) and TP

(0.66) were also positively correlated with the proportion of modified land use but only the correlation with TP was statistically significant. No other pairwise correlation was statistically significant.

DISCUSSION

Temporal changes

Of the 36 sites that were eligible for comparisons between periods, 81% had lower EC densities in Period 2. This general reduction in EC densities is likely a reflection of the dramatic increase in Georgian Bay water levels between periods rather than an actual reduction in loading of fecal bacteria in recent years. Year-to-year water levels in Lake Huron have historically fluctuated by almost 2 m over a cycle of 8 to 12 years; in 1999, water levels dropped and stayed at record low levels for 14 years, and then steadily rose (Montocchio & Chow-Fraser, 2021), reaching historic highs in 2020, and has continued to be relatively high until 2022 (US Army Corps of Engineers, 2022). High water levels have increased the volume of water in embayments so that even without reducing loading of nutrients and suspended solids, concentrations of total P and turbidity levels in wetlands and embayments would be decreased (Chen 2022; Wang et al., 2022). A greater volume of water and more flushing between enclosed bays and the open water of GB has probably allowed for greater dispersal of fecal bacteria and led to reduced bacterial densities (Kann & Walker, 2020; Wang et al., 2022).

There can be exceptions to the diluting effect of high-water levels. For example, rising water levels could flood septic systems (septic tanks and/or drainfields) and disrupt the proper treatment of waste effluent (Butler & Payne, 1995; Withers et al., 2014), especially when they are sited too close to the high water mark. This may have led to untreated sewage directly contaminating bay water with fecal bacteria and nutrients (Butler & Payne, 1995; Withers et al., 2014). Three sites in Period 2 had higher EC densities in Period 2 compared with Period 1, and these were Bloody Bay in TMB, Freddy's Channel in COG, and a bay south of North Bay Wetland within HH. Of these, Bloody Bay and Freddy's Channel measured EC densities that exceeded the BAV for a single sample. All three sites have relatively high cottage densities. In addition, Bloody Bay is road accessible and has a public boat ramp while Freddy's Channel is a popular mooring spot for live-aboard boats (see satellite images of these sites in **Figure 2.11**). We attribute the elevated densities of fecal bacteria to the relatively high cottage densities and high recreational activities associated with these sites.

For the two sites that we could compare directly between time periods, we found TP concentrations to be lower in Period 2. Like what we observed for EC densities, we attribute these lower concentrations to the diluting effect of increased water volume associated with the 1-m increase in water levels between time periods. Montocchio & Chow-Fraser (2021) also found no obvious change in land use or reduction in population size to account for such a drop in nutrient concentration in coastal marshes in Georgian Bay. Therefore, we expect nutrient concentrations to increase again in the short term when water levels return to low levels.

<u>Current Areas of Concern</u>

Majority of measured EC densities (70%) and TP concentrations (62%) were below the GBWQO proposed by Schiefer and Schiefer (2010), indicating that overall water quality in the nearshore surface water of TGB is still in very good condition. Nevertheless, some sites in HH, OB and TMB consistently exceeded the GBWQO for both EC and TP (see **Table 2.8 and 2.10**). Since only a single site was responsible for all elevated pollutant levels, we believe the water-quality impairment is restricted to Bloody Bay in the TMB region. For HH and OB, however, the problem seems to be more widespread. All except one of eleven sites that had TP concentrations >15 µg/L (a trigger point for eutrophication) were within OB and HH. The three sites in Oak Bay were adjacent the Oak Bay Golf and Marina Community (**Figure 2.11**). Golf courses are known be significant sources of nutrient loading to both groundwater and surface water (Baris et al., 2010; Lewis et al., 2002). Bock and Easton (2020) estimated typical losses of 1.5-5 kg/ha/y of P and 2-20 kg/ha/y of N, although there is a large variation in export rates of up to 2-3 orders of magnitude. They emphasized the need for best management practices to reduce nutrient leaching and runoff, including the installation of vegetative stream buffers.

Fifteen of our sites had EC densities that exceeded the BAV (235 CFU/100 mL), which Health Canada uses as a basis for public health advisories (2022). Seven of them were in HH and four of these were in wetlands (Macey Bay Wetland; **Figure 2.13** and North Bay Wetland; **Figure 2.12**). Macey Bay Wetland is adjacent to a former 165-acre trailer park, where there had been 35 trailers and two sewage lagoons, and where currently there is a site plan agreement for 180 new trailers. Chow-Fraser (unpub. data) used the Tecta B16 to measure EC densities in 13 wetlands throughout southern Ontario and Georgian Bay during the summer of 2018 (**Figure 2.15**). Only two of these exceeded the BAV guideline, these being Grenadier Pond and the Tommy Thompson Embayment D located in the heavily urbanized city of Toronto. Notably, EC densities in three of the GB wetlands were well below those of Macey Bay and North Bay wetlands. Therefore, there is no reason to assume that all wetlands would have high EC densities. Microbial source tracking should be used to identify the fecal sources contaminating the North Bay and Macey Bay Wetlands to ensure that the source is not from human sewage.

All but one of the 13 sites that had elevated TP concentrations >15 μg/L were found in HH and OB. Two of the 3 OB sites were wetlands abutting the Oak Bay Golf Course (Hole #6 straddles the Potato Island Wetland), and 5 of the HH sites were also wetlands. Wetlands tend to have higher TP concentrations than adjacent open waters, even when they are pristine (deCatanzaro & Chow-Fraser, 2011), with mean TP concentrations of 16.4 μg/L (range from 9.3 to 33.8 μg/L); however, on average, maximum TP concentrations reached 72 μg/L, with the Macey Bay wetland having the highest TP concentration of 219.9 μg/L, values that are excessively higher than unimpacted GB wetlands. The Macey Bay Wetland has dense vegetation and low flushing rate. It is located < 400m from an old sewage lagoon of the trailer park, and during rain events, may receive some runoff from the lagoon. Both Lily Pond and Woods Landing Wetlands are located at the end of narrow channels in close proximity to marinas and trailer parks. There were 23 marinas in TGB as of 2014, and 19 (83%) of these were sited in HH (Fischer & Associates & Murray Consulting, 2014). Previous studies have shown that impervious surfaces associated with marinas and trailer parks can lead to elevated nutrients, especially during rain events (Hawbaker et al., 2005; Simpson et al., 2021).

In general, the pollutant levels in GHB and WW have met the water-quality guidelines proposed by Schiefer and Schiefer (2010) and have not changed over the past two decades. By contrast, both HH and OB have hotspots with elevated EC densities and TP concentrations that should be investigated further. Some isolated bays in TMB (Bloody

Bay) and COG (Freddy's Channel) have shown signs of degradation. Schiefer and Schiefer (2010) also found the highest levels of EC and TP to be at HH sites during their almost decade-long surveillance program and they attributed this to high levels of lakeshore development and human activity. NB, which is road accessible, and SB, with several marinas and trailer parks, were specifically mentioned in the report as examples of areas with high levels of lakeshore development and low flushing, which has been confirmed to impact water quality by Campbell and Chow-Fraser (2018). Therefore, drivers of water-quality impairment should be related to indices of human development (road density, building density, % impervious surfaces).

Indices of human development

The significant positive correlations between mean TP vs road density, TP vs proportion of modified area, and EC vs road density are consistent with the literature that show impervious surfaces are a significant source of fecal and nutrient loading (Hatt et al., 2004; Jacob & Lopez, 2009; Powers et al. 2020). Precipitation falling on bare pavement and unvegetated surfaces, especially those with a direct connection to water bodies, are more rapidly conveyed into water bodies (Strauch et al., 2014), carrying with it nutrients and other pollutants that would otherwise be filtered out by vegetation (Mallin et al., 2000). This effect is increased when there is a direct delivery mechanism to water bodies, like boat ramps, pipes, or roadways since there are no riparian zones to impede the flow. Secondly, roads allow greater access to the GB shoreline, increasing frequency of cottage use, and extending the season when cottages can be used. Hawbacker et al. (2005) found that as roads became established, housing and cottage development soon followed across 19 predominantly forested counties in northern Wisconsin.

Roads also allow for a great number of people to visit cottages at a higher frequency compared to cottages that are only accessible by boat. Chiandet & Sherman (2014) found that the number of residences increased dramatically due to increased road access in HH over the past several decades. With increased cottage use, septic system usage also necessarily increases. This is important in the TGB as residents rely heavily on septic systems to treat waste since the only piped sewer services are located in MacTier and Port Severn (Fischer & Associates & Murray Consulting, 2014). When aging septic systems are not maintained properly and begin to fail, they can discharge untreated sewage directly into GB (Butler & Payne, 1995; Withers et al., 2014).

Future Sampling Recommendations

Long-term water-quality monitoring is vital to understand how conditions have changed overtime; however, the type of synoptic surveys conducted in regular surveillance programs by Schiefer and Schiefer (2010) and by us cannot be used to pinpoint the exact location of leakages from cottages or from live-aboard boats in boat anchorages, because sites cannot be sampled with sufficiently high temporal and spatial resolution to detect leakages. As well, leakages tend to be amplified during storm events and most sampling programs are conducted during fair-weather conditions for comparison purposes. These synoptic programs can, however, identify hotspots of elevated EC and TP that should then be strategically sampled. Since the highest percentage exceedances for both EC and TP were associated with the HH and OB regions, a future strategic sampling program should focus on these two regions. In addition, Bloody Bay, Freddy's Channel and Sand Run should also be sampled more frequently and during storm events to determine sources of the fecal bacteria and/or elevated TP concentrations.

Within the HH and OB regions, we recommend sampling near locations with increased human development since TP and EC levels are positively correlated with road density and percentage modified area. This includes continued sampling at Hidden Glen in HH (enclosed bay with a trailer park), Woods Landing Marina in HH and Brandy's Cove Marina in HH. The TGB should be prepared for increased pollutant levels again when water levels decrease, since dispersal of pollutants will be reduced (Leira & Cantonati, 2008; Montocchio & Chow-Fraser, 2021). TMB is a long, narrow bay with limited mixing with GB proper, especially at the east end (Campbell & Chow-Fraser, 2018). It is also the only bay in the northern region of the township with road access. As discussed earlier, road access leads to increased development and cottage use which can expose GB water to increased levels of fecal bacteria and nutrients (Hawbaker et al., 2005). This could be more problematic for cottages in TMB with steep shorelines and shallow soils, which are less than ideal for proper siting of septic systems.

Health Canada (2022) recommends that Microbial Source Tracking (MST) be conducted wherever elevated EC densities are found. FB in recreational water can come from numerous sources including discharged sewage, wild and domesticated animals, runoff from agricultural and urban areas and from swimmers (Health Canada, 2022). Host-specific microbial DNA markers, including human sewage and gulls, are used to determine the source of FB and has been used to successfully source EC in the Humber River in Toronto (Staley et al., 2016), Toronto Harbour and the Don River (Edge et al., 2021). Sourcing FB allows governments to make informed decisions in terms of safeguarding public health and site remediation since pathogens from human waste are considered to have the most significant risk to human health (Edge et al., 2021; Health Canada, 2022). If the high counts of EC are due to human sewage, then TGB would be well advised to inspect all septic systems in the affected area to ensure that failing systems are fixed to prevent further leakages. Monitoring water quality during and after rain events should also be conducted within TGB because rainfall can mobilize pathogens from the land, especially after prolonged dry periods that can concentrate them (Levy et al., 2018). Increased surface runoff from rain events can lead to elevated FB in standing water and in beaches (Levy et Powers et al., 2021; Silva et al., 2014); surface runoff can increase EC in urban creeks and stormwater outfalls from illegal sewage hookups (Edge et al., 2021; Staley et al., 2018).

Health Canada recommends adopting management strategies to reduce water-quality impairment by identifying factors that may lead to the introduction of harmful pollutants before remediation is required (2022). One way is to limit the number of road-access lots along the shoreline since regions that are only accessible by boat (like COG, GHB and WW) have lower incidence of exceedances and appear to have better water quality overall. Policies and programs should be developed to ensure cottage owners inspect their septic systems regularly and maintain them properly. Future research should focus on understanding how increased rain intensity and duration may affect water-quality impairment, especially in areas that do not have good water exchange with GB water.

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Table 2.1: Description of sampling stations (with abbreviated codes in bracket) in the five regions and focal areas in this study. Bolded numbers are the shoreline length and area of the coastal zone. See locations in Figure 1.

Region	Focal Area	Description
Oak Bay (OB) **31 km, 1000 ha**	Oak Bay (OB)	Most southern region, not sampled historically; near golf course and condominium development
Honey Harbour (HH) **120 km, 5050 ha**	Macey Bay (MB)	Marsh adjacent former trailer home park and sewage lagoon, not sampled during Period 1
	Venning's Bay (VB)	Open water outside Vennings Bay, not sampled historically
	Severn Sound Open Water (SSO)	Open water of Severn Sound
	Quarry Island (QI)	Shoreline and shoals of Quarry Island
	Brandy's Cove (BC)	Brandy's Cove Marina, Tobies Bay and Sunset Bay; near Yachting Centre, surrounded by cottages and docks
	Inner Honey Harbour (IHH)	Church Bay, Nautilus Marina, Picnic Island, shoreline of Honey Harbour and Mermaid Island;
	National Park (NP)	Shoreline of Beausoleil Island, Georgian Bay Islands National Park; Chimney Bay, Long Bay, Treasure Bay, open water
	North Honey Harbour (NHH)	Channel to Cognashene; Frying Pan Bay, Deer Island Channel
	South Bay (SB)	East of Inner Honey Harbour; South Bay Cove Marina, South Harbour Marina; cottages
	North Bay (NB)	Northeast of Inner Honey Harbour; Woods Landing Marina, Hidden Glen Trailer Park, community centre; cottages
Cognashene (COG) **150 km, 3770 ha**	Cognashene (COG)	Open water and boating anchorages; Longuissa Bay, Hockey Stick Bay, Freddy's Channel
	Cognashene Lake (CL)	Rocky lake with cottages and access to greater Cognashene
Go Home Bay (GHB) **110 km, 2930 ha**	Go Home Bay (GHB)	Open water and narrow bay primarily with cottages
Wah Wah TaySee (WW) **91 km, 2580 ha**	Wah Wah Taysee (WW)	Open water and islands, American Camp, King Bay Marina
	Tadenac Bay (TB)	Owned by private fishing club
Twelve Mile Bay (TMB) **81 km, 3020 ha**	Twelve Mile Bay (TMB)	Most northern region, long and narrow bay; Moose Deer Point Marina

Table 2.2: Data sources for long-term comparison of fecal bacteria and nutrients in the nearshore waters of the Georgian Bay Township. SSEA = Severn Sound Environmental Association, OMOE = Ontario Ministry of Environment (now the Ministry of Environment, Conservation and Parks).

Source	Years	Location	Sampling Frequency	Month	Day of Year	Variables	# of Sites	# of Samples
Schiefer	2001	HH, COG, GHB, WW TMB	Between 1 – 8 times	June - Sept	181 – 246	EC, TP	46	235
	2002	HH, COG, GHB, WW, TMB	Between 1 – 8 times	June - Sept	181 – 261	EC, TP	36	147
	2003	HH, COG, GHB, WW, TMB	Between 1 – 9 times	May - Sept	137 – 257	EC, TP	42	252
	2004	HH, COG, GHB, WW, TMB	Between 1 – 6 times	June - Sept	182 – 250	EC, TP	40	160
	2005	HH, COG, GHB, WW, TMB	Between 1 – 12 times	June - Sept	178 – 265	EC, TP	50	242
	2006	HH, COG, GHB, WW, TMB	Between 1 – 6 times	July - Sept	184 – 253	EC, TP	68	271
	2007	HH, COG, GHB, WW, TMB	Between 1 – 8 times	June - Sept	181 – 264	EC, TP	65	290
	2009	HH, COG, GHB, WW, TMB	Between 1 – 10 times	May - Oct	179 – 279	EC, TP	66	271
Chow-Fraser	2004	OB	Once	June	154 - 160	TP	3	3
	2005	HH	Once	Aug	243	TP	1	1
	2008	OB	Once	July	184	TP	3	3
	2009	HH	Once	June	161	TP	1	1
This study	2020	OB, HH, COG, GHB, TMB	Between 1 – 5 times	June – Aug	170 – 232	EC, TP	51	91
	2021	OB, HH, COG, GHB, WW TMB	Between 1 – 8 times	June – Sept	156 – 252	EC, TP	82	303
	2022	OB, HH, GHB, TMB	Between 1 – 7 times	June – Sept	171 – 244	EC, TP	63	165
SSEA	2003	HH	Biweekly	May – Sept	142 – 273	TP	3	24
	2005	HH	Biweekly	May – Oct	123 – 301	TP	3	38
	2008	HH	Biweekly	May – Oct	127 – 302	TP	3	33
	2009	HH	Biweekly	May – Nov	125 – 314	TP	3	38
OMOE	2005	HH, COG, GHB, TMB	3 times a year	End of April, July and Oct	115 - 300	TP	31	93

Table 2.3: Frequency, location, and time of sampling for EC and TP in all years in the nearshore waters of TGB. --- indicates no samples were collected.

Year	Region	Variable	Sampling Frequency	Month	Day of Year	# of sites	# of samples
2001	HH	EC	1 – 8 times	July – Sept	191 – 246	13	46
		TP	Once	Sept	---	3	3
	COG	EC	5 – 8 times	July – Sept	191 – 246	10	70
		TP	---	---	---	---	---
	GHB	EC	7 times	June - Sept	181 – 244	7	49
		TP	---	---	---	---	---
	WW	EC	7 times	June – Aug	181 - 241	5	35
		TP	---	---	---	---	---
	TMB	EC	5 times	June – Sept	201 - 244	6	30
		TP	---	---	---	---	---
2002	HH	EC	---	---	---	---	---
		TP	Once	Sept	---	7	7
	COG	EC	---	---	---	---	---
		TP	Once	Sept	---	1	1
	GHB	EC	6 times	July – Aug	182 – 217	11	66
		TP	Once	Sept	---	6	6
	WW	EC	7 or 8 times	July – Sept	195 - 261	5	37
		TP	---	---	---	---	---
	TMB	EC	3 or 4 times	June – Aug	181 – 243	6	23
		TP	Once	Sept	---	6	6
2003	HH	EC	7 or 8 times	May – Sept	137 – 257	8	62
		TP	1 or 8 times	May – Sept	142 – 27	6	27
	COG	EC	7 or 8 times	May – Sept	137 – 257	5	36
		TP	---	---	---	---	---
	GHB	EC	8 or 9 times	June – Sept	172 – 245	12	99
		TP	Once	Sept	---	6	6
	WW	EC	4 times	July – Aug	202 – 243	4	16
		TP	---	---	---	---	---

Table 2.3 continued

Year	Region	Variable	Sampling Frequency	Month	Day of Year	# of sites	# of samples
2003	TMB	EC	4 times	July – Aug	186 – 242	6	24
	TMB	TP	Once	Sept	---	6	6
2004	OB	EC	---	---	---	---	---
		TP	Once	June	154, 160	3	3
	HH	EC	1 or 5 times	July – Sept	192 – 250	6	26
		TP	Once	Sept	244	7	7
	COG	EC	4 or 5 times	July – Sept	192 – 250	4	17
		TP	---	---	---	---	---
	GHB	EC	4 or 5 times	June – Aug	182 - 236	14	69
		TP	---	---	---	---	---
	WW	EC	2 times	Aug	218, 228	3	6
		TP	---	---	---	---	---
	TMB	EC	5 times	July – Sept	186 - 250	6	30
		TP	Once	Sept	---	6	6
2005	HH	EC	5 – 12 times	July – Sept	183 – 253	11	72
		TP	1 – 16 times	May – Oct	115 - 301	12	66
	COG	EC	6 times	July – Sept	185 – 253	8	48
		TP	3 times	May – Oct	116 - 300	4	8
	GHB	EC	2 – 6 times	June – Aug	178 – 241	14	69
		TP	3 times	May – Oct	116 – 300	4	8
	WW	EC	--	--	--	--	--
		TP	3 times	May – Oct	117 – 299	3	9
	TMB	EC	5 times	July – Sept	206 – 265	6	30
		TP	3 times	May – Oct	117 – 299	11	27

Table 2.3 continued

Year	Region	Variable	Sampling Frequency	Month	Day of Year	# of sites	# of samples
2006	HH	EC	5 or 6 times	July – Sept	184 – 253	18	96
		TP	Once	Sept	---	13	13
	COG	EC	5 times	July – Sept	186 – 246	8	40
		TP	Once	Sept	---	5	5
	GHB	EC	5 times	July – Aug	184 – 240	14	70
		TP	---	---	---	---	---
	WW	EC	4 times	July – Aug	199 – 243	4	16
		TP	---	---	---	---	---
	TMB	EC	4 times	July – Aug	190 – 240	6	26
		TP	Once	Sept	---	6	6
2007	HH	EC	5 or 6 times	June – Sept	181 – 251	19	103
		TP	Once	Sept	---	12	12
	COG	EC	2 or 5 times	July – Aug	183 – 242	8	37
		TP	Once	Sept	---	2	2
	GHB	EC	6 times	July – Sept	183 – 264	14	84
		TP	Once	Sept	---	5	5
	WW	EC	8 times	July – Aug	190 – 243	2	16
		TP	---	---	---	---	---
	TMB	EC	4 times	July – Aug	188 – 230	6	24
		TP	Once	Sept	---	6	6
2008	OB	EC	---	---	---	---	---
		TP	Once	July	184	4	4
	HH	EC	---	---	---	---	---
		TP	11 times	May – Oct	127 – 302	3	33
2009	HH	EC	1 or 6 times	June – Sept	179 – 249	19	74
		TP	1 – 15 times	May – Nov	125 – 314	14	56
	COG	EC	5 times	July – Aug	184 – 239	8	45
		TP	1 or 2 times	May, Sept	---	3	5
	GHB	EC	6 times	July – Oct	201 – 279	14	84

Table 2.3 continued

Year	Region	Variable	Sampling Frequency	Month	Day of Year	# of sites	# of samples
2009	GHB	TP	2 times	May, Sept	---	5	10
	WW	EC	4 times	July – Sept	199 - 248	6	24
		TP	---	---	---	---	---
	TMB	EC	2 times	July – Aug	190 – 235	6	12
		TP	---	---	---	---	---
2020	OB	EC	---	---	---	---	---
		TP	1 – 3 times	June - Aug	175 – 232	2	4
2020	HH	EC	1 – 2 times	July, Aug	202, 230	22	24
		TP	1 – 5 times	June - Aug	170 – 230	28	53
	COG	EC	1 – 2 times	Aug	218, 226	8	10
		TP	1 – 3 times	June - Aug	170 – 226	9	17
	GHB	EC	Once	Aug	224	5	5
		TP	1 – 3 times	June - Aug	181 – 224	7	10
	TMB	EC	Once	Aug	231	2	2
		TP	1 – 2 times	June - Aug	181 – 231	2	3
2021	OB	EC	5 times	June - Sept	158 – 250	4	20
		TP	1, 6 times	June - Sept	158 – 250	5	25
	HH	EC	1 – 7 times	June - Sept	156 - 251	39	141
		TP	1 – 7 times	June - Sept	156 - 251	38	118
	COG	EC	1 – 7 times	June - Aug	159 - 231	11	39
		TP	1 – 7 times	June - Aug	159 - 217	8	31
	GHB	EC	2 – 5 times	June - Sept	167 - 252	11	46
		TP	2 – 7 times	June - Sept	167 - 252	9	40
	WW	EC	---	---	---	---	---
		TP	2 times	June, Aug	167, 221	2	2
	TMB	EC	1 or 5 times	June - Sept	167 - 252	4	8
		TP	1 – 6 times	June - Sept	167 - 252	4	10

Table 2.3 continued

2022	OB	EC	3 – 5 times	June - Aug	172 - 228	4	16
		TP	1 – 5 times	June - Aug	172 - 228	5	18
	HH	EC	1 – 7 times	June – Sept	171 - 244	46	110
		TP	1 – 7 times	June – Sept	171 - 244	52	138
	GHB	EC	Once	July	195	4	4
		TP	Once	July	195	5	5
	TMB	EC	3 times	June – Aug	173 - 221	1	3
		TP	3 times	June - Aug	173 - 221	1	3

Table 2.4: Mean EC (CFU/100 mL) and Total P (TP; μg/L) measured during Period 2 (2020-2022) in focal areas in nearshore waters of the Township of Georgian Bay. Building density (count/ha), dock density (count/ha), road density (m/ha), % area modified (MOD; e.g. marinas, trailer parks, golf courses, parking lots, lawns) and % commercial area (COM) within 1 km circular buffer around the shoreline of each focal area.

Region	Focal Area	Mean EC	Mean TP	Building Density	Dock Density	Road Density	%MOD	%COM
OB	OB	31.2	15.7	0.88	0.51	0.0474	13.49	12.89
HH	IHH	12.2	9.9	0.05	2.09	0.0030	11.09	6.85
	SB	5.3	14.3	0.48	0.24	0.0166	1.57	0.77
	NB	30.6	9.5	0.74	0.61	0.0057	2.88	2.13
	MB	358.7	36.7	0.61	0.08	0.0276	1.60	0.52
	BC	3.9	9.5	1.79	1.48	0.0033	11.29	4.61
	NP	0.7	15.0	0.17	0.09	0.0000	0.18	0.00
COG	COG	18.2	6.3	0.25	0.06	0.0000	0.01	0.00
	CL	2.8	4.8	0.25	0.25	0.0000	0.00	0.00
GHB	GHB	3.0	9.5	0.13	0.04	0.0000	0.02	0.00
WW	WW	1	5.0	0.11	0.16	0.0011	0.68	0.18
	TB	1	2.2	0.01	0.01	0.0000	0.00	0.00
TMB	TMB	40.1	9.3	0.11	0.03	0.0060	0.40	0.18

Table 2.5: Mean ± SE of EC (colony forming units (CFU)) in nearshore waters of the TGB for focal areas sampled between Period 1(2001-2009) and Period 2 (2020-2022). N refers to the number of samples used to calculate means. All surface water samples were collected under rain-free conditions between June 19 and Sept 7 inclusive. All historic sites exceeded 10 CFU.

Focal Area	ID	$N_{Period\ 1}$	$N_{Period\ 2}$	$Mean_{Period\ 1}$	$Mean_{Period\ 2}$	% > 10 Period 2
BC	1001	10	7	33.3 ± 6.7	4.0 ± 1.3	0
	1002	2	4	17.5 ± 2.1	6.5 ± 5.5	25
	1003	10	7	36.1 ± 5.5	6.7 ± 5.2	14
	1049	6	4	21.5 ± 5.5	2.0 ± 1.2	0
	1050	8	6	76.7 ± 40.8	2.8 ± 2.0	17
	1053	6	7	35.2 ± 6.7	1.4 ± 0.8	0
IHH	1007	10	5	21.4 ±1.9	8.4 ± 4.3	40
	1008	10	6	197.8 ± 168.0	30.8 ± 23.6	50
	1051	6	7	38.6 ± 5.9	11.0 ± 7.7	29
QI	1054	6	3	27.0 ± 4.3	0.7 ± 0.3	0
	1074	6	5	29.6 ± 6.7	11.4 ± 8.8	20
	1075	7	3	20.6 ± 4.2	1.0 ± 0.0	0
	1076	4	4	14.2 ± 0.8	3.3 ± 1.9	0
NB	1055	10	2	19.9 ± 2.5	1.0 ± 0.0	0
	1057	9	2	**16.6 ± 1.82**	**31.0 ± 30.0**	**50**
	2024	6	3	13.4 ± 1.0	4.0 ± 1.7	0
NHH	1013	15	5	21.2 ± 2.4	16.6 ± 9.6	40
	1058	14	2	18.4 ± 1.6	0.5 ± 0.5	0
OSS	1052	8	4	15.0 ± 2.8	0.3 ± 0.3	0
CL	1019	10	3	14.9 ± 1.0	4.7 ± 4.2	33
COG	1015	13	2	22.7 ± 3.0	6.0 ± 5.0	50
	1016	29	2	17.5 ± 1.9	1.0 ± 0.0	0
	1018	24	3	**19.1 ± 2.0**	**95.3 ± 94.8**	**33**
	1038	21	4	101.2 ± 80.5	5.3 ± 2.8	25
	1069	21	2	17.2 ± 0.8	0.5 ± 0.5	0
GHB	1022	38	2	18.3 ± 1.6	1.0 ± 0.0	0
	1023	39	2	16.5 ± 1.2	0.0 ± 0.0	0
	1024	31	2	16.0 ± 0.9	8.5 ± 8.5	50
	1025	39	2	17.5 ± 1.2	0.0 ± 0.0	0
	1027	28	3	16.4 ± 0.9	7.3 ± 4.1	33
	1070	33	3	26.6 ± 7.5	0.7 ± 0.7	0
	1071	21	3	14.9 ± 0.9	6.3 ± 1.7	0
	1072	38	3	19.7 ± 2.1	1.3 ± 0.7	0
	1090	36	2	21.1 ± 3.7	2.0 ± 1.0	0
TMB	1035	19	2	17.3 ± 1.0	1.0 ± 0.0	0
	1036	20	5	**14.7 ± 1.0**	**71.6 ± 64.9**	**60**

Table 2.6: Change in distribution of sites in density categories of EC (CFU/100 mL) in nearshore waters of the Township of Georgian Bay for samples measured during both Period 1 (2001-2009) and Period 2 (2020 – 2022). The Beach Action Value (BAV) is 235 CFU/100 mL (Health Canada 2022). Numbers in bracket correspond to mean EC densities (CFU/100 mL).

EC Densities CFU/100 mL	**% of sites in density category**	
	Period 1	**Period 2**
< 10	0%	81%
10-25	72%	8%
25-50	19%	6%
50-100	3%	6%
>100	6%	0%
Exceeding BAV	**Musquash Channel** (COG) (1709) **W of Brandy's Island** (HH) (354) **North Picnic Island Marina** (HH) (1709) **Monument Channel** (GHB) (257)	**Freddy's Channel** (COG) (285) **Bloody Bay** (TMB) (331)

Table 2.7: Mean ± SE EC densities (CFU/100 mL) in nearshore waters of the Township of Georgian Bay measured during Period 2 (2020 – 2022). Samples were collected at least twice between June 19 and Sept 7 in surface water during rain-free days. Bolded sites have EC density > 10 CFU.

Region	Focal Area	Site Number	# of Samples	Mean ± SE	% > 10
HH	OB	**1011**	**6**	**51.8 ± 32.6**	**50**
		1012	6	7.2 ± 4.6	17
		1205	**6**	**43.2 ± 14.9**	**67**
		1206	**6**	**22.5 ± 9.4**	**50**
HH	BC	1001	7	4.0 ± 1.3	0
		1002	4	6.5 ± 5.5	25
		1003	7	6.7 ± 5.2	14
		1049	4	2.0 ± 1.2	0
		1050	6	2.8 ± 2.0	17
		1053	7	1.4 ± 0.8	0
HH	IHH	1007	5	8.4 ± 4.3	40
		1008	**6**	**30.8 ± 23.6**	**33**
		1009	3	2.3 ± 1.3	0
		1010	3	1.7 ± 0.7	0
		1051	**7**	**11.0 ± 7.7**	**29**
HH	MB	**1004**	**5**	**143.6 ± 63.4**	**80**
		1005	4	9.3 ± 4.1	50
		1006	3	0.3 ± 0.3	0
		2080	**5**	**1354.2 ± 1260.8**	**100**
		2081	**6**	**127.0 ± 64.2**	**50**
		2082	**6**	**352.0 ± 157.3**	**83**
HH	QI	1054	3	0.7 ± 0.3	0
		1074	**5**	**11.4 ± 8.8**	**20**
		1075	3	1.0 ± 0.0	0
		1076	4	3.3 ± 1.9	0
HH	NB	1055	2	1.0 ± 0.0	0
		1057	**2**	**31.0 ± 30.0**	**50**
		1059	2	4.0 ± 3.0	0
		1065	**2**	**16.5 ± 15.5**	**50**
		1066	2	4.5 ± 4.5	0
		1067	4	1.8 ± 0.3	0
		1068	**5**	**111.4 ± 108.9**	**20**
		2024	3	4.0 ± 1.7	0
HH	NHH	**1013**	**5**	**16.6 ± 9.6**	**40**
		1058	2	0.5 ± 0.5	0
HH	NP	1020	3	0.7 ± 0.3	0

Table 2.7 (continued)

Region	Focal Area	Site Number	# of Samples	Mean ± SE	% > 10
HH	SB	1064	3	10.0 ± 9.0	33
HH	SSO	1052	4	0.3 ± 0.3	0
COG	CL	1019	3	4.7 ± 4.2	33
COG	COG	1014	3	1.3 ± 0.3	0
		1015	2	6.0 ± 5.0	50
		1016	2	1.0 ± 0.0	0
		1018	**3**	**95.3 ± 94.8**	**33**
		1038	4	5.3 ± 2.8	25
		1069	2	0.5 ± 0.5	0
GHB	GHB	1022	2	1.0 ± 0.0	0
		1023	2	0.0 ± 0.0	0
		1024	2	8.5 ± 8.5	50
		1025	2	0.0 ± 0.0	0
		1027	3	7.3 ± 4.1	33
		1070	3	0.7 ± 0.7	0
		1071	3	6.3 ± 1.7	0
		1072	3	1.3 ± 0.7	0
		1090	2	2.0 ± 1.0	0
TMB	TMB	1035	2	1.0 ± 0.0	0
		1036	**5**	**71.6 ± 64.9**	**60**

Table 2.8: Comparison of EC densities (CFU/100 mL) in each site or region measured in samples collected in Period 2 under fair-weather conditions. Sites that were highest are bolded. BAV=Beach Action Value of 235 CFU/100 mL. Site codes are in brackets—see explanation of site code in Appendix 1. Sites that are underlined are marinas whereas sites that are bolded are wetlands.

Category	OB	HH	COG	GHB	TMB
Mean EC	31.2	**82.6**	17.9	3.2	51.4
% sites exceeding GBWQO	**75%**	35%	14%	0%	50%
# sites above BAV	0	7 (<u>1001</u>) (1004) (<u>1008</u>) (**1068**) (**2080**) (**2081**) (**2082**)	1 (1018)	0	1 (<u>1036</u>)
Mean EC densities > 50	1 (1011)	6 (1004) (1057) (**2080**) (**2081**) (**2082**)	1 (1018)	0	1 (<u>1036</u>)

Table 2.9: Mean ± SE Total Phosphorus (TP; µg/L) concentrations in the nearshore waters of the Township of Georgian Bay during Period 2 (2020 – 2022). Samples were collected at least twice between June 19 and Sept 7 in the surface water during rain-free days. Bolded sites have a mean TP concentration >10 µg/L.

Region	Focal Area	Site Number	# of Samples	Mean ± SE	% > 10
HH	OB	**1011**	**6**	**17.4 ± 2.0**	**100**
		1012	8	10.0 ± 1.7	50
		1202	2	8.6 ± 1.3	0
		1205	**6**	**23.5 ± 2.0**	**100**
		1206	**6**	**15.6 ± 2.0**	**83**
HH	BC	1001	9	9.4 ± 0.6	44
		1002	4	9.6 ± 0.7	50
		1003	**8**	**11.0 ± 0.7**	**75**
		1049	3	7.6 ± 2.5	33
		1050	5	5.9 ± 1.1	0
		1053	5	8.5 ± 1.2	60
HH	IHH	**1007**	**8**	**11.2 ± 2.5**	**38**
		1008	**7**	**10.1 ± 0.7**	**43**
		1009	6	9.0 ± 1.3	50
		1010	7	9.0 ± 1.4	43
		1051	5	6.4 ± 0.8	0
		2017	**2**	**16.4 ± 1.2**	**100**
HH	MB	**1004**	**9**	**21.5 ± 3.3**	**89**
		1005	**5**	**15.1 ± 1.9**	**100**
		1006	2	9.0 ± 3.9	50
		2080	**5**	**35.8 ± 6.6**	**100**
		2081	**6**	**88.7 ± 29.8**	**100**
		2082	**6**	**35.3 ± 5.6**	**100**
HH	QI	**1054**	**2**	**10.1 ± 3.6**	**50**
		1074	4	6.4 ± 1.7	0
		1075	2	6.2 ± 0.4	0
		1076	3	8.8 ± 1.7	33
HH	NB	1055	2	4.0 ± 1.1	0
		1057	2	5.2 ± 0.7	0
		1059	3	8.9 ± 3.4	33
		1065	2	4.5 ± 0.1	0
		1067	4	8.0 ± 1.1	25
		1068	**5**	**14.6 ± 3.2**	**80**
		2019	**3**	**18.8 ± 3.9**	**100**
		2023	4	6.7 ± 0.7	0
		2024	4	9.6 ± 2.1	25
		2025	3	8.7 ± 1.4	33

Table 2.9 (continued)

Region	Focal Area	Site Number	# of Samples	Mean ± SE	% > 10
HH	NHH	1013	5	5.1 ± 0.9	0
		1058	2	6.8 ± 0.2	0
HH	NP	**1020**	**2**	**15.0 ± 7.0**	**50**
HH	SB	**1064**	**3**	**14.4 ± 2.6**	**100**
		2026	**3**	**13.0 ± 2.6**	**67**
HH	SSO	1052	3	7.6 ± 1.7	0
COG	CL	1019	2	4.8 ± 1.1	0
COG	COG	1014	4	5.3 ± 0.6	0
		1015	2	6.8 ± 4.6	50
		1016	2	6.4 ± 1.1	0
		1018	2	9.1 ± 0.8	0
		1038	3	6.3 ± 0.9	0
GHB	GHB	1022	3	6.8 ± 0.4	0
		1024	2	9.9 ± 4.5	50
		1027	**5**	**16.3 ± 6.2**	**60**
		1070	2	2.6 ± 2.6	0
		1071	2	2.6 ± 1.8	0
		1072	3	8.7 ± 1.4	33
		1090	**3**	**12.8 ± 2.5**	**67**
TW	TW	1035	2	8.1 ± 0.6	0
		1036	**6**	**12.1 ± 3.3**	**67**

Table 2.10: Comparison of mean TP concentration (µg/L) in each site or region measured in samples collected in Period 2 (2020 – 2022) under fair-weather conditions. Sites that were highest are bolded. Site codes are in brackets—see explanation of site code in Appendix 1. Sites that are underlined are marinas whereas sites that are bolded are wetlands.

Category	OB	HH	COG	GHB	TMB
Mean TP	**15.6**	14.9	6.3	9.9	11.1
% sites exceeding GBWQO	**60%**	40%	29%	0%	50%
# sites with TP >10 µg/L (GBWQO)	3	**15**	0	2	1
# sites with TP > 15 µg/L (Trigger for eutrophication)	3 (1011) (**1205**) (**1206**)	**9** (1004) (1051) (1064) (**2017**) (**2019**) (**2080**) (**2081**) (**2082**)	0	1 (1027)	0
# sites with TP > 20 µg/L (Provincial Guideline)	1 (**1205**)	**4** (1004) (**2080**) (**2081**) (**2082**)	0	0	0

Table 2.11: Spearman's Rank Correlation Coefficients between mean TP concentration and mean EC densities with road density, dock density, building density, proportion of modified area and proportion of commercialized area for the 13 focal areas.

Factor	Variable	ρ	P-value
Building density	Mean EC	0.4069	0.1676
	Mean TP	0.4875	0.0910
Dock density	Mean EC	0.0935	0.7612
	Mean TP	0.3260	0.2771
Road density	**Mean EC**	**0.7499**	**0.0032***
	Mean TP	**0.6252**	**0.0223***
Proportion of modified area	Mean EC	0.4972	0.0838
	Mean TP	**0.6611**	**0.0139***
Proportion of commercialized area	Mean EC	0.5314	0.0617
	Mean TP	0.4739	0.0564

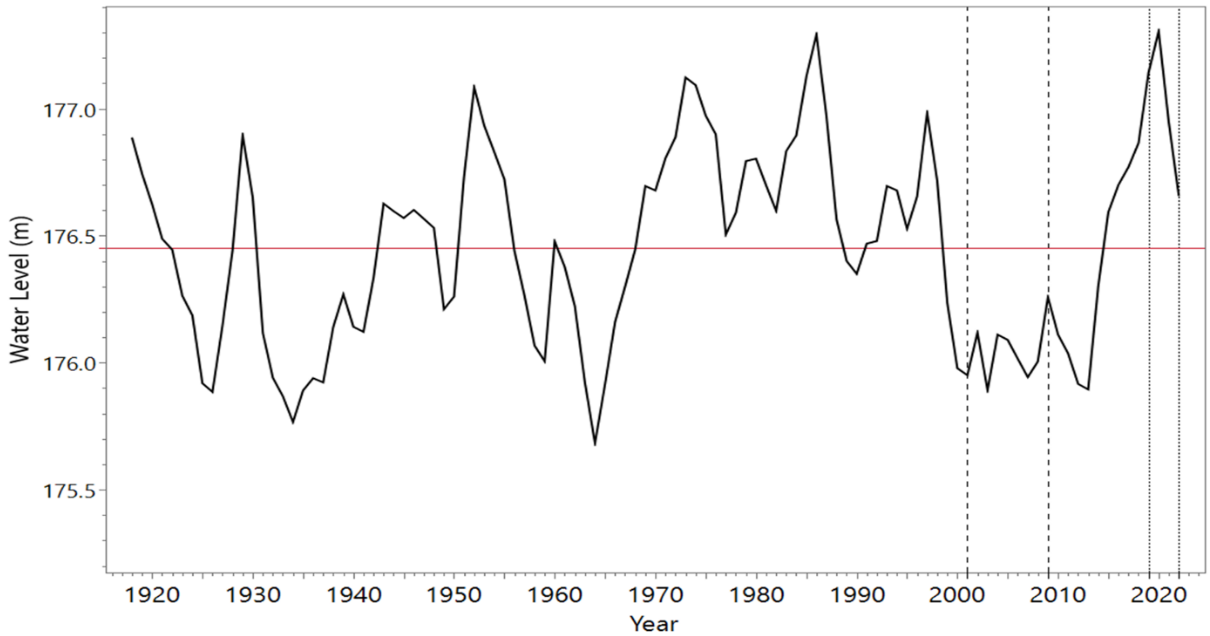

Figure 2.1: Water-level changes (m) between 1918 to 2022 for Lake Michigan-Huron. The average water level for this period (red line) is 176.45 m. Period 1 (big-dotted line) and Period 2 (small-dotted line) are indicated. Data retrieved from US Army Corps of Engineers, 2022 (https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/).

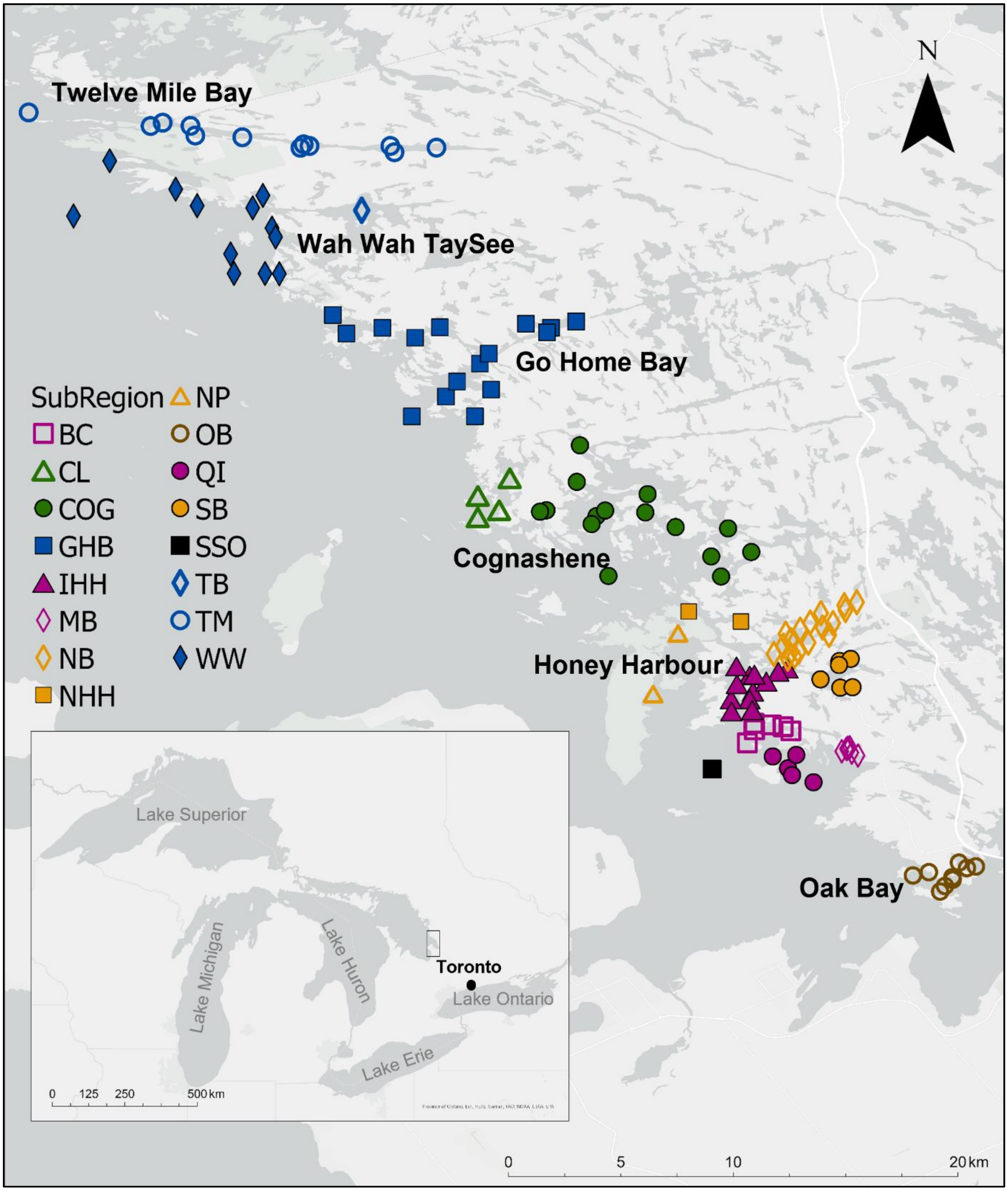

Figure 2.2: Location of the regions and focal areas of the Township of Georgian Bay in relation to the Great Lakes and Toronto, Ontario. See abbreviation list in Appendix 1.

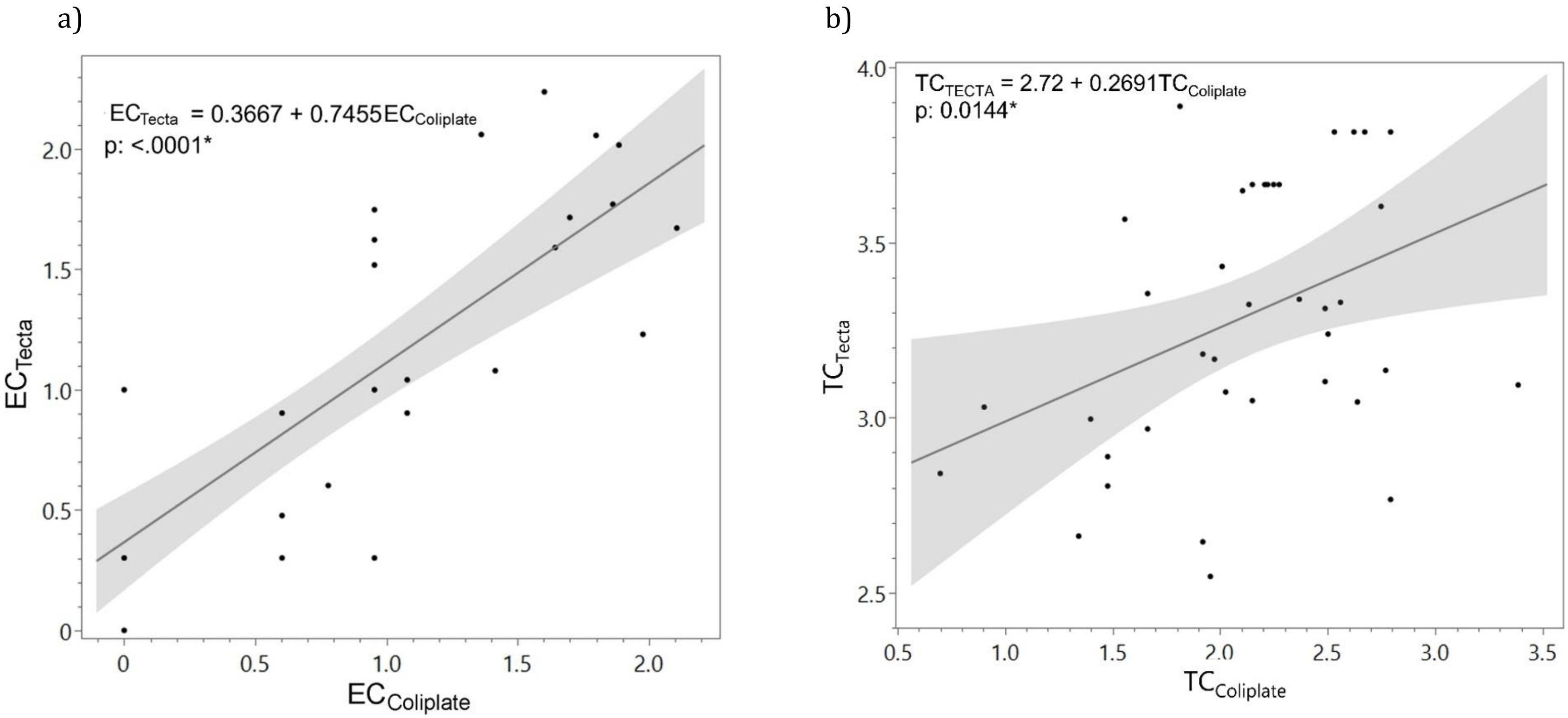

Figure 2.3: Relationship between Tecta vs Coliplate™ for a) *E. coli* and b) Total coliforms. There were 38 water samples collected in early July and August of 2021 and 2022 in OB, HH and GHB in the Township of Georgian Bay.

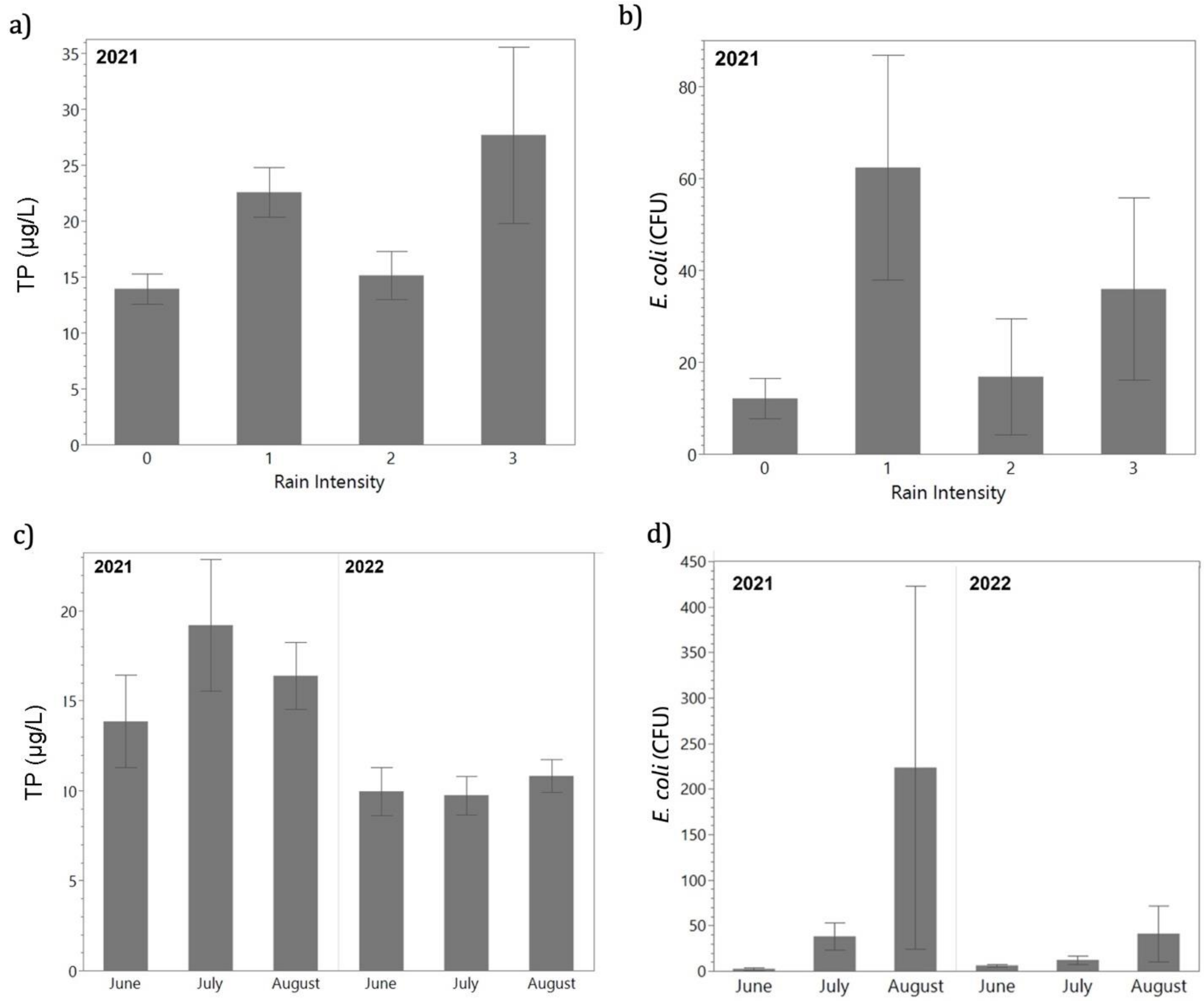

Figure 2.4: Effects of rain intensity on a) total phosphorus (TP; µg/L) and b) *E. coli* (EC; 100 CFU/100 mL) during 2021. Monthly differences in c) total phosphorus (TP; µg/L) and d) *E. coli* (EC; 100 CFU/100 mL) during 2021 and 2022. We only included data from sites that had been sampled for TP or EC a minimum of 3 occasions at different rain intensities for a) and b). Similarly, we only included data from sites that had been sampled for TP or EC at least once during June, July and August for c) and d).

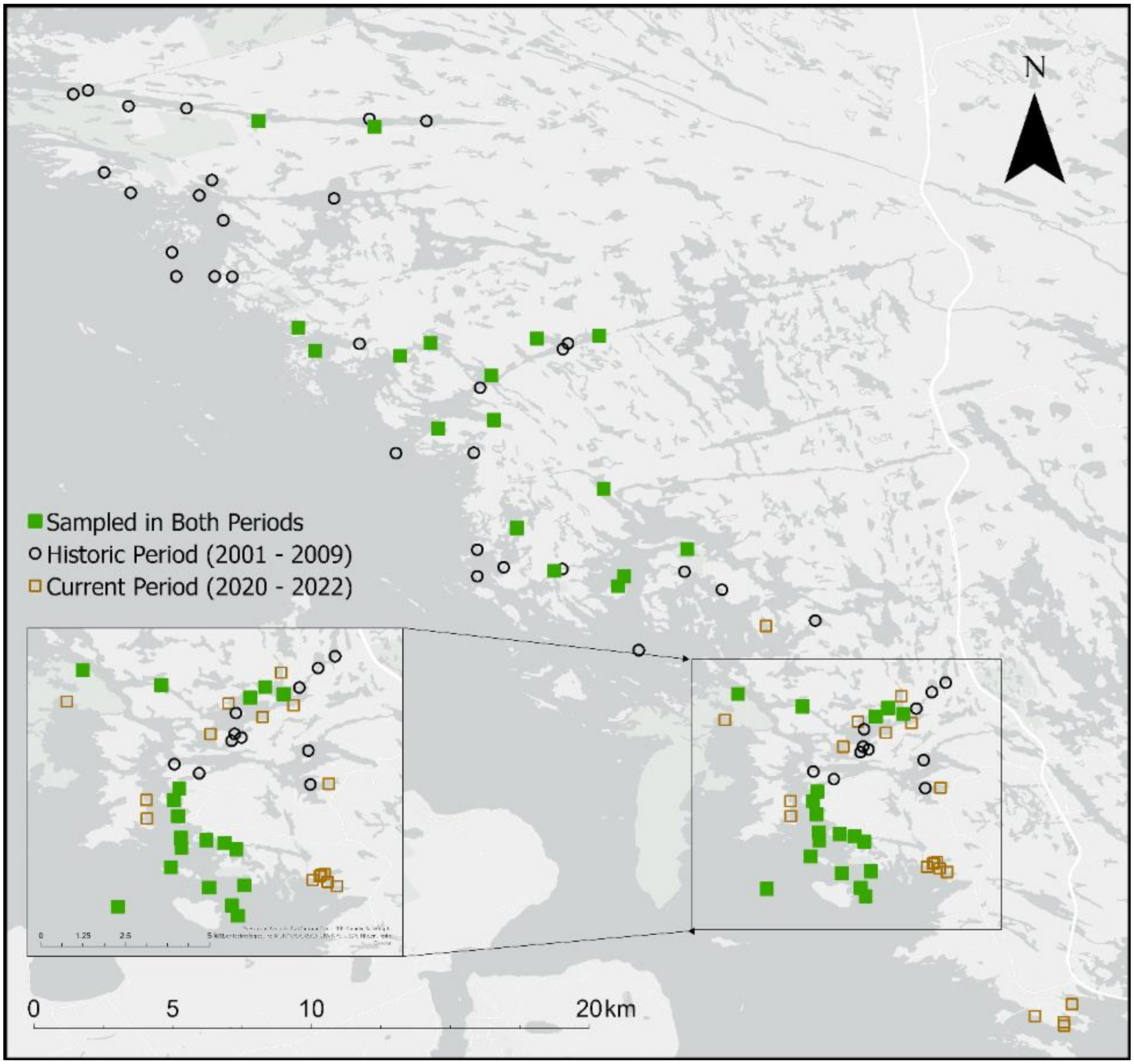

Figure 2.5: Location of sites sampled for EC during Period 1 (historic: 2001 – 2009; open circles) and Period 2 (current: 2020 – 2022; open squares), and those sampled in both periods (solid squares) in the nearshore waters of the Township of Georgian Bay.

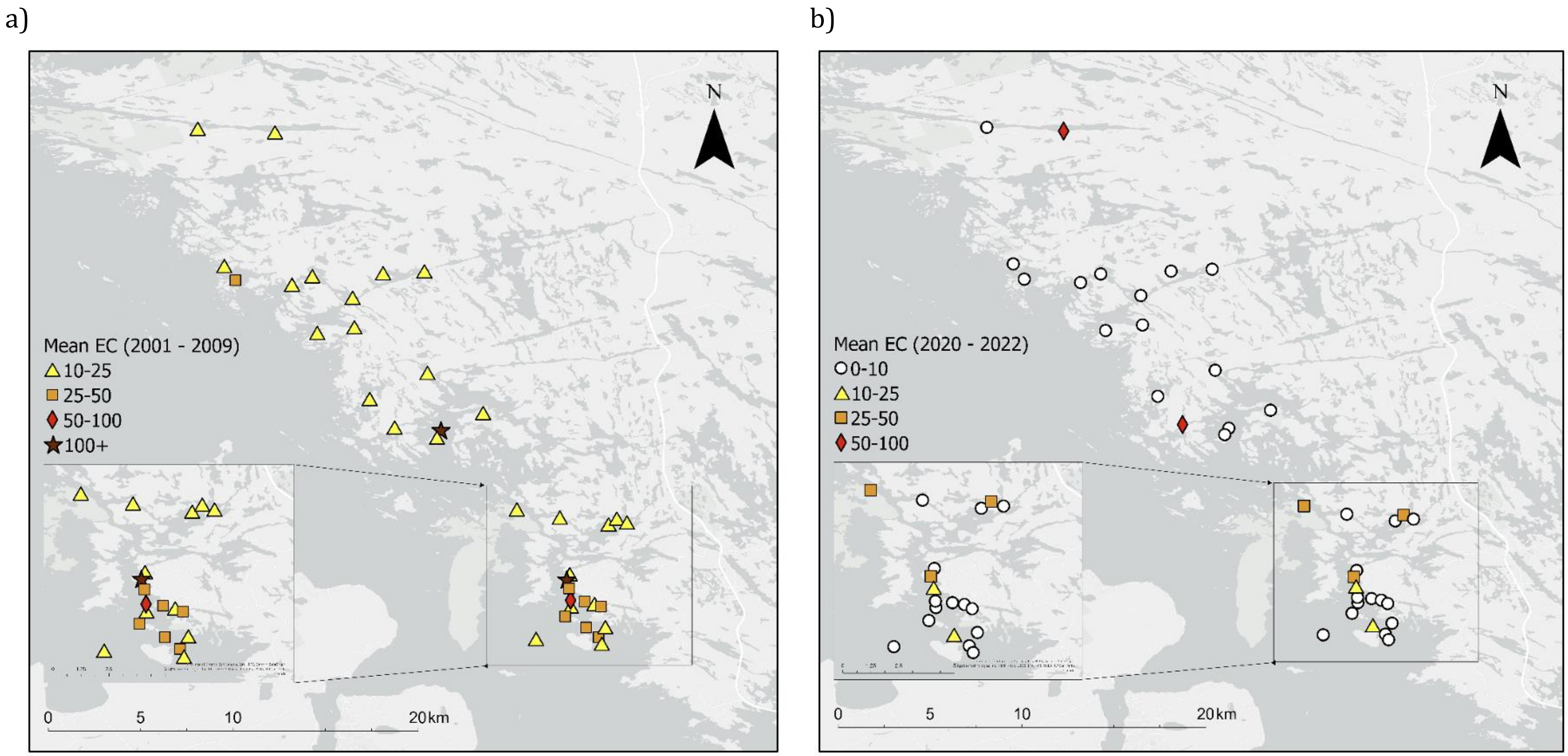

Figure 2.6: Mean EC (Colony Forming Units (CFU)/100 mL) measured during the a) Period 1 (2001-2009) and b) Period 2 (2020-2022) at sites sampled at least twice in both periods in nearshore waters of the Township of Georgian Bay. No samples during Period 1 were below 10 CFU.

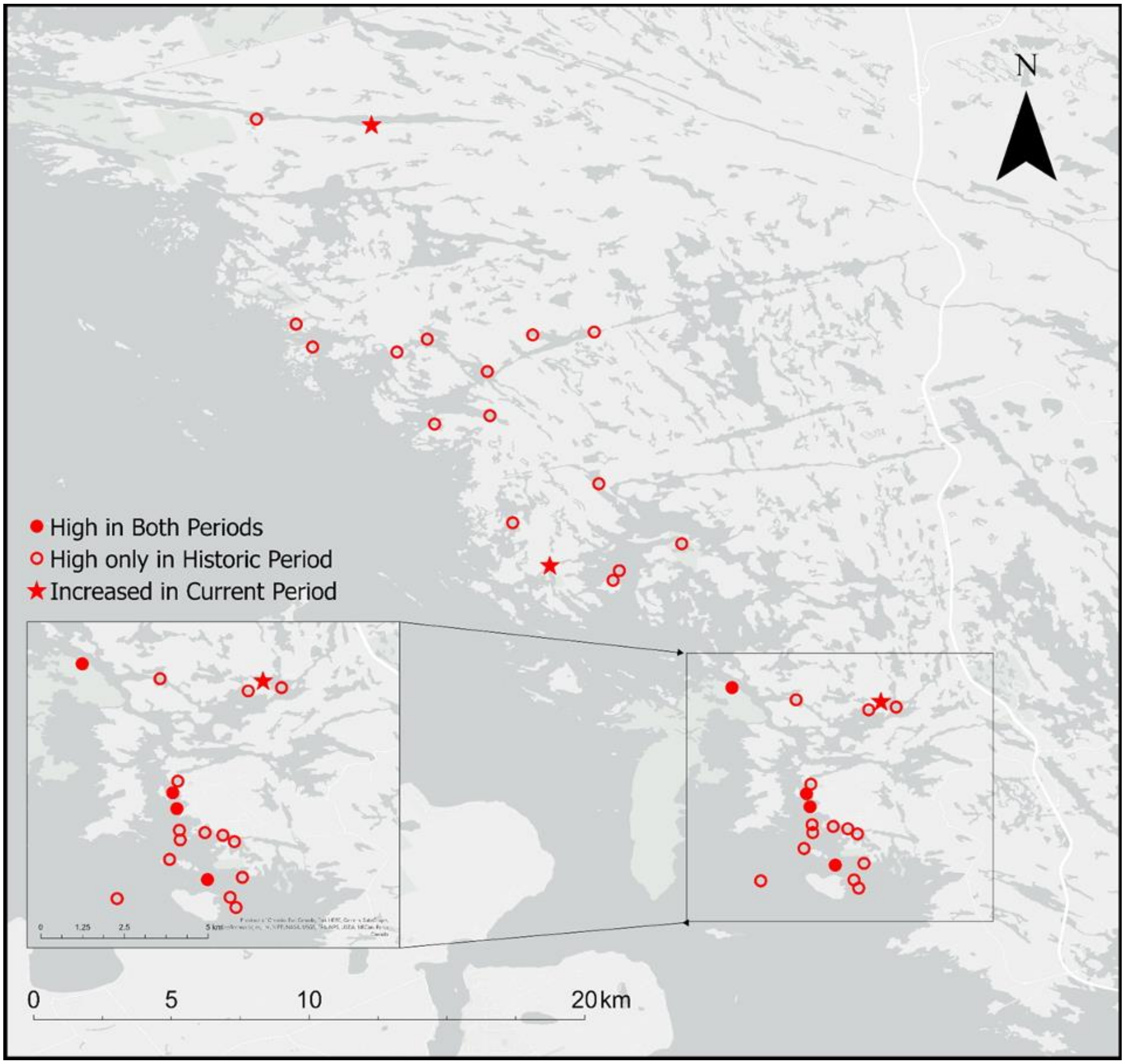

Figure 2.7: Changes in *E. coli* (EC) densities from Period 1 (2001 – 2009) to Period 2 (2020 – 2022) in the nearshore waters of the Township of Georgian Bay. Sites with high EC (>10 CFU/100 mL) in both periods are indicated by a solid circle; sites that were high only in Period 1 are indicated by an open circle and sites that had an increased in EC densities from Period 1 to Period 2 are indicated by a solid star. CFU = colony forming units.

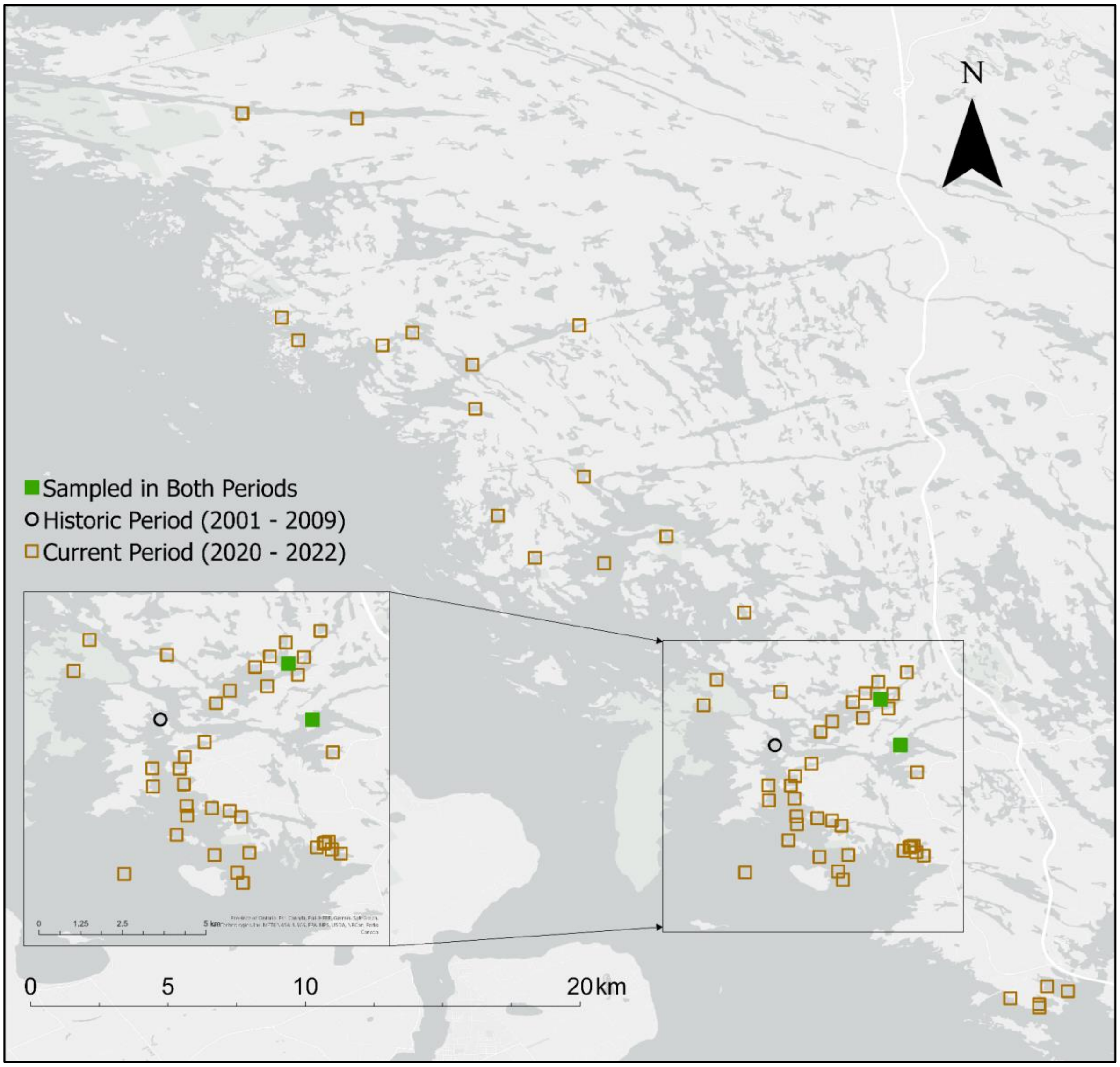

Figure 2.8: Location of sites sampled for total phosphorus (TP) in the nearshore waters of the Township of Georgian Bay during Period 1 (historic: 2001 – 2009; open circles) and Period 2 (current: 2020 – 2022; open squares) and during both periods (solid square).

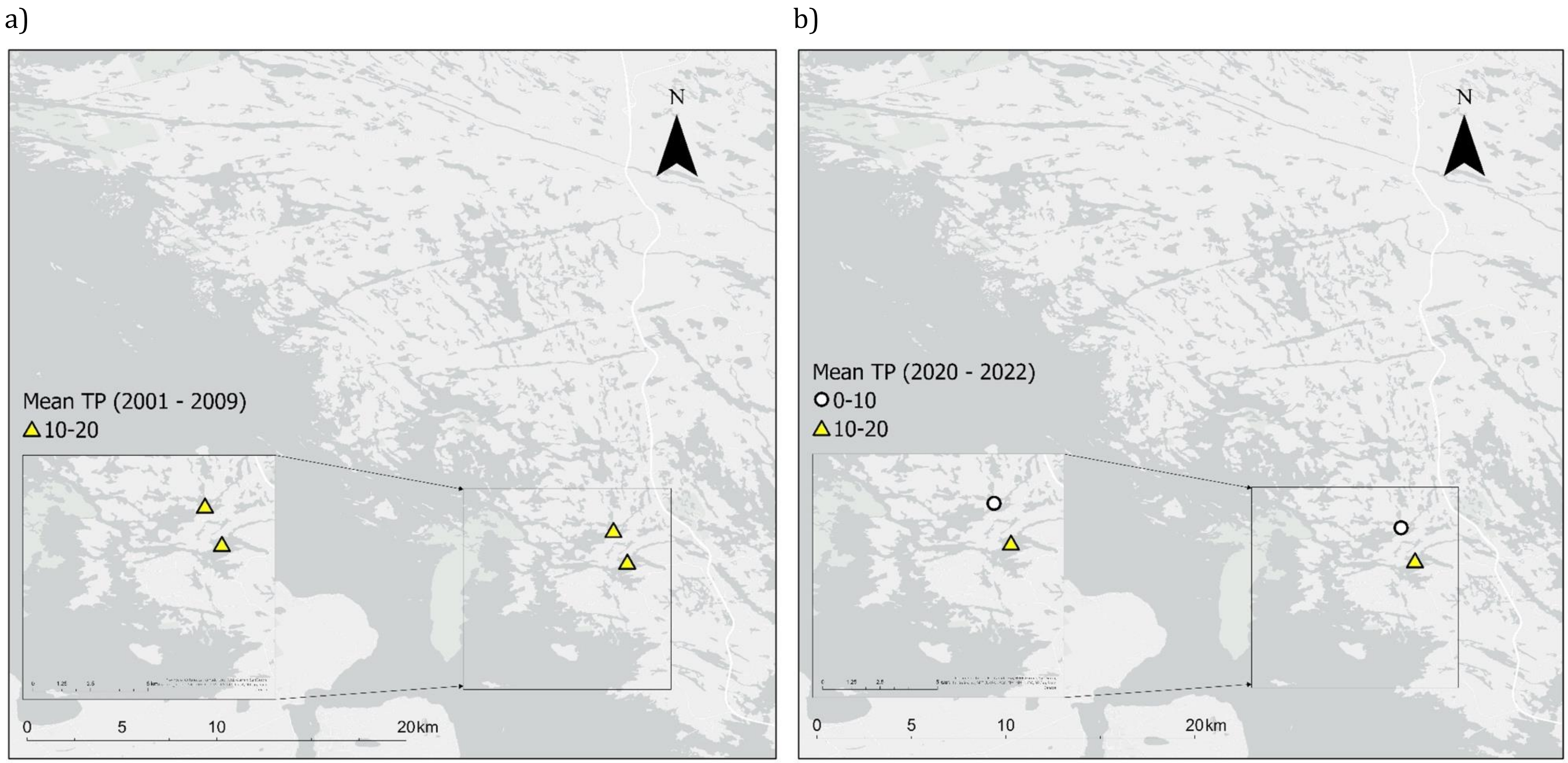

Figure 2.9: Total Phosphorus (TP; µg/L) measured during a) Period 1 (2001-2009) and b) Period 2 (2020-2022) at sites sampled at least twice in both periods in the nearshore waters of the Township of Georgian Bay.

a) b)

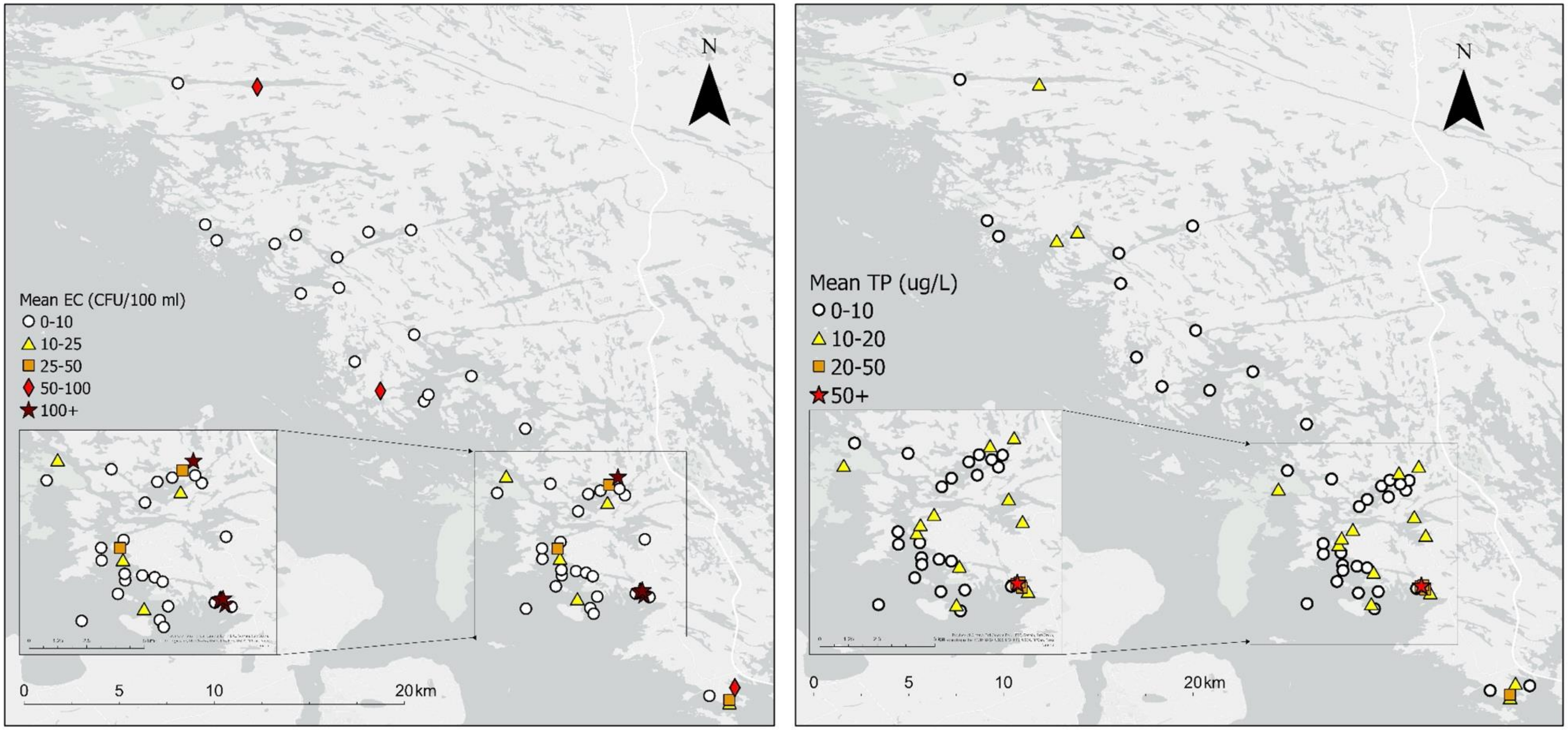

Figure 2.10: Mean a) *E. coli* (Colony Forming Units; CFU) and b) total phosphorus (µg/L) measured during Period 2 (2020-2022) at sites sampled at least twice in the nearshore waters of the Township of Georgian Bay.

a) b)

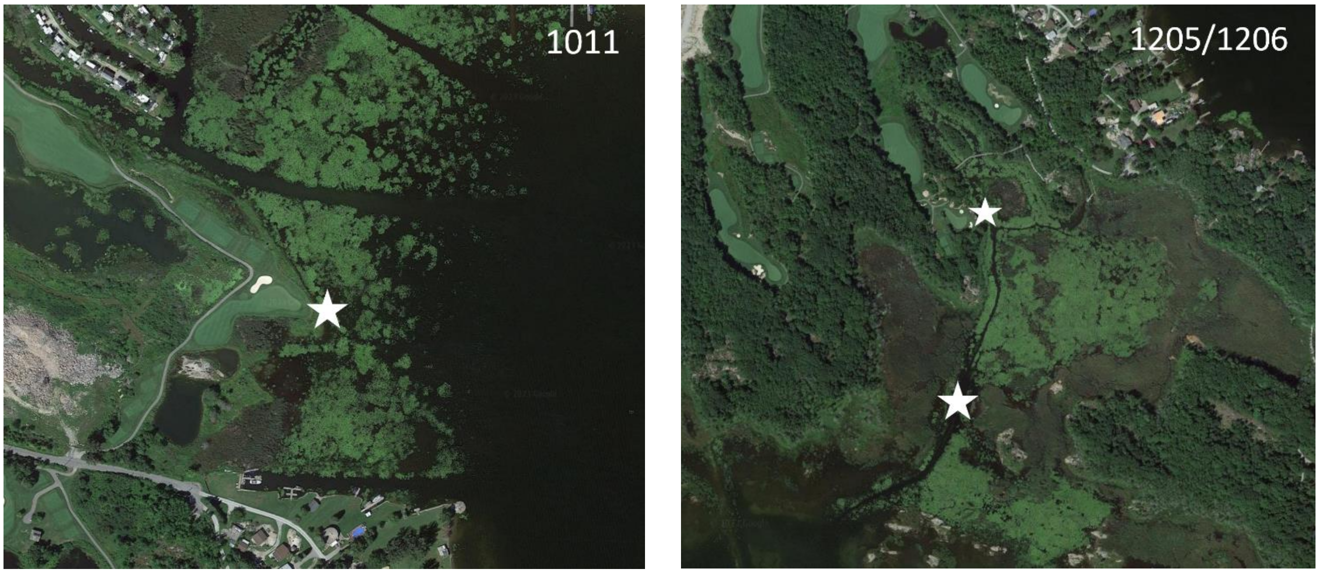

Figure 2.11: Satellite images of current hotspots (TP concentrations >15 µg/L AND/OR EC densities > 50 CFU/100 mL) in Oak Bay in the Township of Georgian Bay. a) Golf Course Point. b) Potato Island Wetland (Inner and Outer). Numbers in upper right corner refer to site numbers (see Appendix 5).

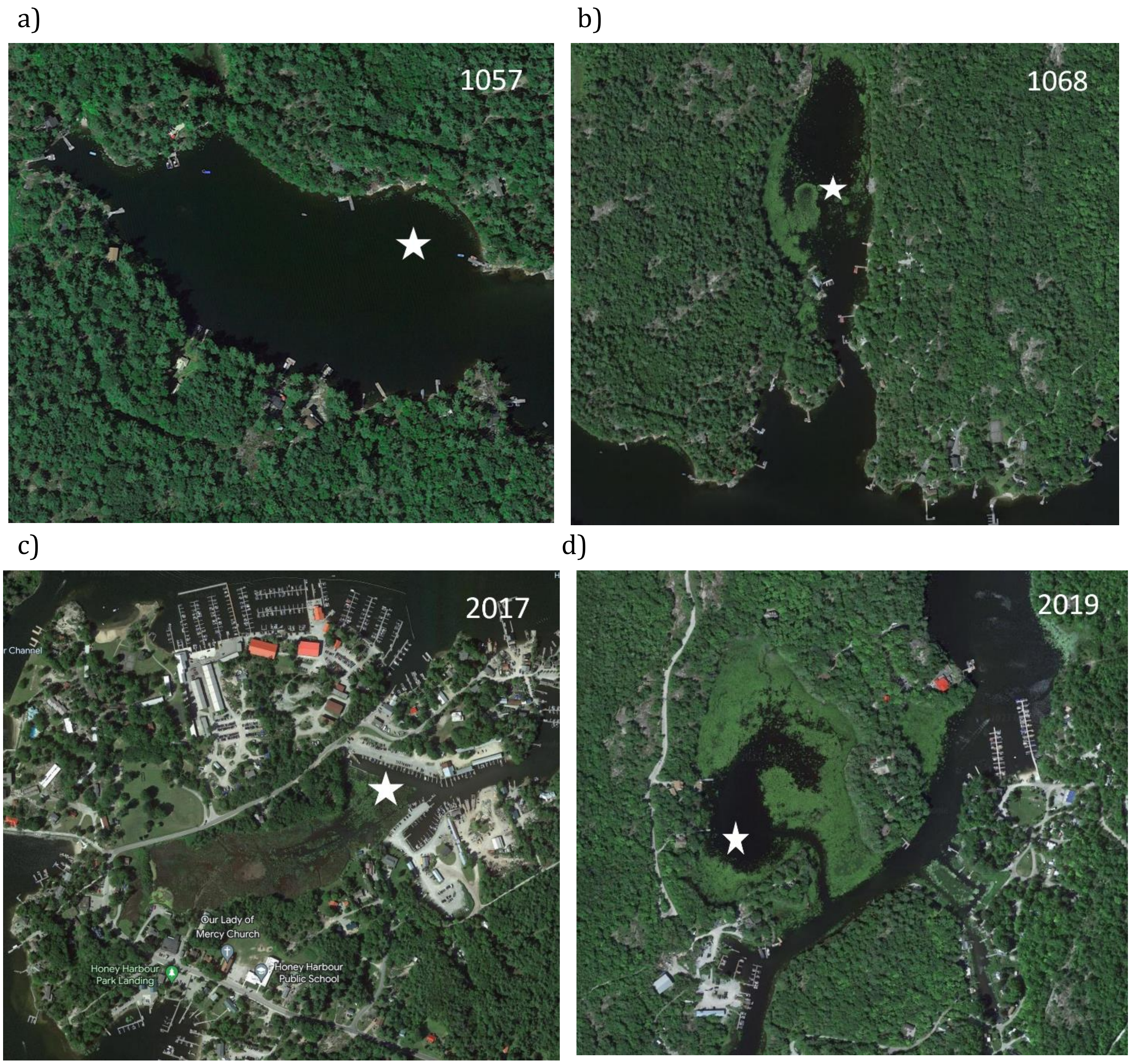

Figure 2.12: Satellite images of current hotspots (TP concentrations >15 µg/L AND/OR EC densities > 50 CFU/100 mL) in Inner Honey Harbour and North Bay in the Township of Georgian Bay. a) Bay South of North Bay Wetland. b) North Bay Wetland. c) Lily Pond. d) Woods Landing Wetland. Numbers in upper right corner refer to site numbers (see Appendix 5).

a) b)

Figure 2.13: Satellite images of current hotspots (TP concentrations >15 μg/L AND/OR EC densities > 50 CFU/100 mL) in Macey Bay in the Township of Georgian Bay. a) Outer Macey's Bay and Venning's Bay. b) Open water of the Macey Bay Wetland, amongst the emergent vegetation of the Macey Bay Wetland and in the floating vegetation of the Macey Bay Wetland. Numbers in upper right corner refer to site numbers (see Appendix 5).

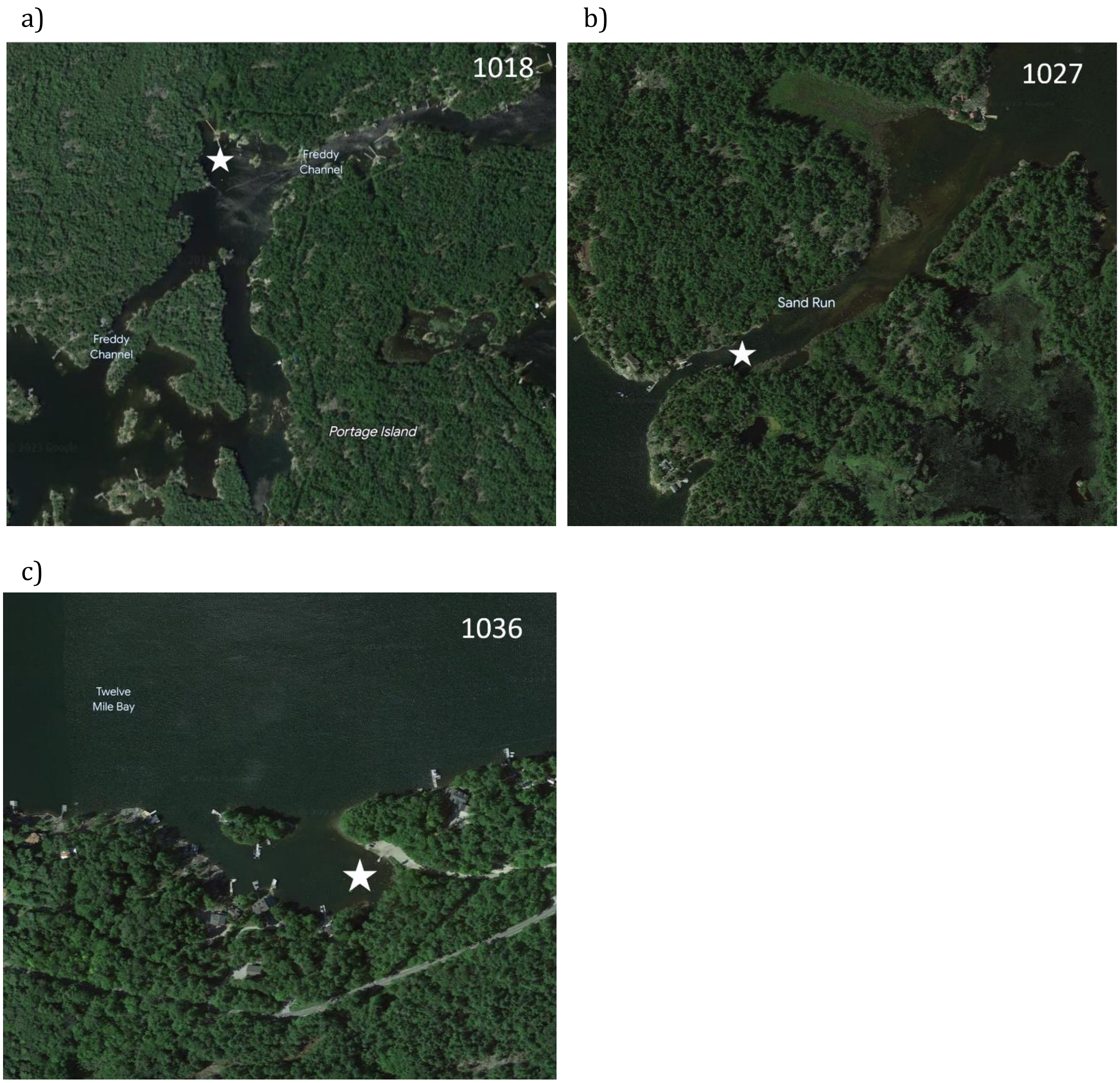

Figure 2.14: Satellite images of current hotspots (TP concentrations >15 µg/L AND/OR EC densities > 50 CFU/100 mL) in Cognashene, Go Home Bay and Twelve Mile Bay in the Township of Georgian Bay. a) Freddy's Channel. b) the Sand Run. c) Bloody Bay. Numbers in upper right corner refer to site numbers (see Appendix 5).

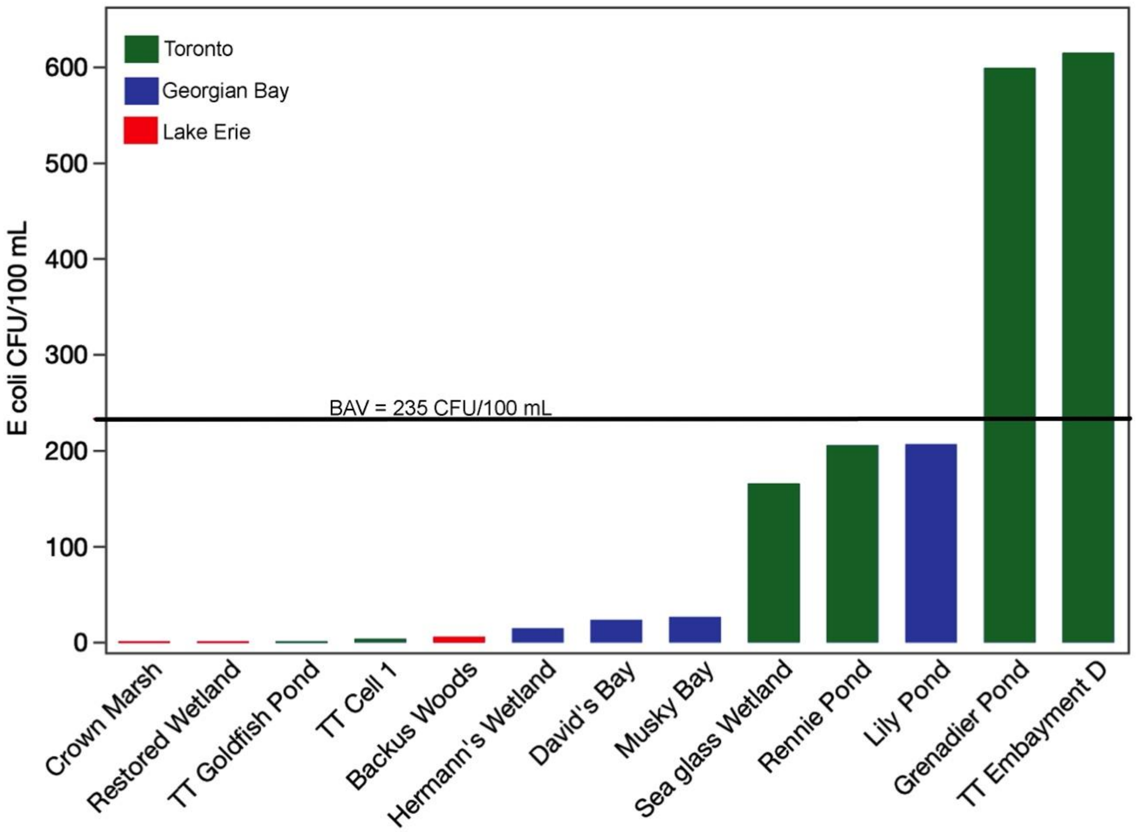

Figure 2.15: EC densities measured in wetlands throughout southern Ontario and in eastern Georgian Bay during summer of 2018 (fair-weather conditions and between mid-June to early September). TT= Tommy Thompson Park. Hermann's Bay and David's Bay are located in TMB region while Musky Bay is located between Macey's Bay and Oak Bay.

CHAPTER 3: The periplate: a novel way to track nutrient status in nearshore recreational waters by volunteers

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Keywords: biological indicators, periphyton, community science, total phosphorus, recreational development

ABSTRACT

The economy of Georgian Bay (GB), the eastern arm of Lake Huron, is heavily reliant on excellent water quality as it is needed to sustain diverse recreational activities. Unfortunately, increased cottage and recreational development can threaten the excellent water quality that is the basis of this lifestyle, because loading of phosphorus (P) can increase from aging or improperly sited septic systems, grey water discharge from live-aboard boats, and runoff from modified land. This form of cultural eutrophication is challenging to monitor because it is a non-point source, and a comprehensive monitoring program is often too expensive for governments with limited budgets. Here, we investigate using the amount of periphyton (benthic algae) to assess the nutrient status of waters in nearshore GB. We hypothesize that the amount of accumulated algae (measured as chlorophyll) grown on glass slides (periplates) that are suspended in the water column for a standardized incubation period (2 weeks) should be proportional to nutrient status at the site. We incubated sets of periplates at five sites in Honey Harbour: 1) a busy channel exposed to wind and heavy boat traffic, 2) a busy marina near a loading dock, 3) along a rocky shoreline with minimal boat traffic, 4) a dock protected from wind, and 5) a wetland behind the cottage of the dock. The amount of periphytic chlorophyll were similar at sites 1 and 2 and significantly highest, while those in sites 3 and 4 were similar and significantly lowest, and the amount measured at site 5 was intermediate. The trend in periphytic algae matched that for the grab sample of planktonic chlorophyll collected after the incubation period but did not match that for the single sample of total P. This bioassay could be a volunteer-friendly method for cottagers to assess and track long-term changes in nutrient status at sentinel sites in GB.

INTRODUCTION

Globally, recreational water is a valuable resource that improves human health and is a large contributor to local, national, and global economies (Keniger et al., 2013; Krantzberg & Boer, 2006; White et al., 2013). Cultural eutrophication, however, degrades water quality needed to support the diverse recreational opportunities, including swimming, boating, fishing and wilderness appreciation since increased nutrient loading can lead to agal blooms, reduced water clarity, depleted dissolved oxygen levels and aquatic dead zones (Bhateria & Jain, 2016). Phosphorus (P) is the most limiting nutrient in freshwater ecosystems (Correll, 1999; Elser et al., 2007; Schindler, 1971) and total P (TP) is traditionally measured to indicate trophic status of lakes. Methods to measure TP are costly and time consuming as frequent sampling is needed to get an accurate picture of water quality (Holt & Miller, 2010). Therefore, beginning in the 1960s, researchers began using bioindicators to monitor nutrient status (Barinova & Dyadichko, 2022; Burger, 2006; Holt & Miller, 2010).

Bioindicators are organisms that are relatively abundant and moderately tolerant of changes in their environment (Burger, 2006; Holt & Miller, 2010; Markert et al., 2003). Typically, they are a low-cost method that provides a picture of the health of the biotic community and can be used to make an inference of the general water quality of an area (DeNicola & Kelly, 2014). Numerous bioindicators have been used historically to estimate water quality including macroinvertebrates (Burton et al., 1999; Nichols et al., 2016), zooplankton (Lougheed & Chow-Fraser, 2002) and periphyton (McCormick & Stevenson, 1998; McNair & Chow-Fraser, 2003; Tedeschi & Chow-Fraser, 2021). For this study, we will be focusing on using periphyton as a bioindicator.

Periphyton is algae that grows on submerged surfaces rather than in the water column (Goldsborough et al., 1986; Parker, 2018). It can grow on a variety of substrates including rocks, wood, plants, silty sediment and sand (Aloi, 1990; Lambert et al., 2008) as well as on artificial substrates like glass. It relies on light and nutrient availability to grow and can be effected by flow rate and the abundance and species of invertebrate grazers present (DeNicola & Kelly, 2014; Hansson, 1992; Parker, 2018). In oligotrophic bodies of water, periphyton can be responsible for 99% of the primary production, playing an important role in the cycling of nutrients within aquatic ecosystems (Vadeboncoeur & Steinman, 2002). It is the trophic link between the chemical and biotic components in the aquatic food web as it assimilates nutrients like P and is also the source of food for numerous invertebrates (Lowe & Pan, 1996). Unlike phytoplankton, which can drift in the water column, periphyton is stationary. This, paired with its ability to respond rapidly to environmental changes due to its short life cycle, makes periphyton an ideal bioindicator of non-static conditions (Lowe & Pan, 1996; Parker, 2018; Rosenberger et al., 2008).

Periphyton has been used as a bioindicator in streams (Tedeschi & Chow-Fraser, 2021), wetlands (McCormick & Stevenson, 1998; McNair & Chow-Fraser, 2003) and lakes (Lambert et al., 2008). Past studies showed a strong positive relationship between periphyton biomass and TP concentrations (Lambert et al., 2008; McNair & Chow-Fraser, 2003; Tedeschi & Chow-Fraser, 2021); as well, periphyton has also been a good indicator when there are strong hydrological pressures like boat traffic and water-level changes

(DeNicola & Kelly, 2014). Therefore, we propose to use periphyton as a bioindicator within the Georgian Bay Township to monitor nutrient status in nearshore waters.

The Township of Georgian Bay (TGB), located along the southeastern shoreline of Georgian Bay, is a tourist and cottage destination well known for its excellent water quality (see Vinden & Chow-Fraser 2023; Chapter 2). Unfortunately, like other water bodies within the Great Lakes, some areas in the nearshore of TGB have experienced symptoms of eutrophication due to increased recreational development and increased frequency and use of cottages (see Vinden & Chow-Fraser 2023; Chapter 2). In extreme cases, toxic blue-green algal blooms have occurred, such as those in Sturgeon Bay and Port Severn as recently as in 2021. Therefore changes in the nutrient status of Georgian Bay should be detected as soon as possible so that sources can be identified and reduced and eventually eliminated (Lambert et al., 2008).

There has been a long history of citizen science within TGB. Between 2001 to 2009, Schiefer & Schiefer (2010) conducted a volunteer program in which cottagers measured densities of *Escherichia coli,* an indicator of fecal pathogens, using the Coliplate™ method (see Vinden and Chow-Fraser 2023; Chapter 2). Our primary objective is to develop a method using periphyton to integrate nutrient information over time so that volunteers in cottage associations can track changes in nutrient status at sentinel sites in TGB. In this chapter, we will first determine the ideal sampling protocol and then ascertain its sensitivity to different levels of recreational activities. We hypothesize that the amount of accumulated algae grown on standardized substrate and incubation period should be proportional to nutrient status at the site. This will be an inexpensive method that volunteers can use with simple training for long-term monitoring.

METHODS

Periphytometers

We created the periphytometer to hold glass slides (periplates) on which periphyton would grow (see **Figure 3.1**). These are 210 mm long, 84.5 mm wide and 38 mm tall, and can hold up to 46 standard glass microscope slides. We suspended these slide-loaded periphytometers with ropes that were tied to wooden frames that floated on the water surface. The periphytometers were suspended at a depth of 50 cm, and to ensure there was no light limitation, we only used a maximum of 23 slides in each.

Sampling protocol

We wanted to first determine the minimum number of slides to use that would be sufficient to extract a measurable amount of periphytic chlorophyll ($CHL_{periphyton}$) and that would be associated with minimum standard error. Two periphytometers were placed side by side at a depth of 50 cm in Oak Bay on 21 June 22 and left to incubate for 13 days (until 4 July 22). We took four sets of slides ranging from 1 to 4 slides per group, and then processed them. To determine the ideal length of incubation time, three periphytometers were placed side-by-side in the water in North Bay at a depth of 50 cm. The devices were deployed on July 18th and four slides were removed in triplicate every three days starting one week after deployment. Slides were removed on the following days: July 25 (7 days), July 28 (10 days), July 31 (13 days), Aug 3 (16 days), Aug 6 (19 days), Aug 9 (22 days), Aug 12 (25 days) and Aug 15 (28 days).

Differences in nutrient status among sites

To investigate if the amount of $CHL_{periphyton}$ measured with periplates is sensitive to different environmental conditions throughout Honey Harbour, we chose five locations that had varying levels of recreational development (**Table 3.1**; **Figure 3.4**). Locations varied from areas with high recreational development and activities (site 1, busy boating channel and site 2, busy marina) to an area with low recreational development and activities (site 3, a rocky shoreline; site 4, the dock of a single cottage; and site 5, wetland adjacent the dock). The periphytometers were deployed on August 7th and removed on August 31st after 24 days in the water, at which point, three sets of four slides were removed from each location. For all experiments, slides and filters were wrapped in tin foil and frozen for processing at McMaster University later in the summer. To ensure slide placement in the periphytometer was not affecting results, we removed slides from the left, centre, and right section of the periphytometer for each set of slides. At the same time slides were removed, we used sterile containers to take grab samples of 120 mL of water at approximately 30cm below the water surface. These samples were taken for measurement of TP. As well, we collected 1L of water at the same depth using a sterile container to measure planktonic CHL ($CHL_{planktonic}$). Once the water was brought back to a field lab, we filtered 300mL of water through glass-fibre filters and froze them in triplicate.

Analytical Methods

Our procedure was adapted to glass slides from those of McNair and Chow-Fraser (2003) and Tedeschi and Chow-Fraser (2021). Frozen samples were thawed and unwrapped from foil when they reached room temperature. We used a straight-edged knife to scrape off periphyton from each slide into a clean glass container containing 10 mL of 90% reagent grade acetone. Samples were then placed in a freezer for 48 hours to extract the chlorophyll. After extraction, samples were centrifuged for five minutes at approximately 3000 rpm to settle out sediments. Using the Genesys 10UV spectrophotometer (Fisher Scientific, Toronto, ON), we read the absorbance of the sediment-free samples at 665 nm and 750 nm before and after three drops of 0.3 M HCl was added. The absorbance values were converted to periphyton biomass according to the following equations:

$$665\ before = (665nm - 750\ nm\ before\ acidicfication)$$

$$665\ after = (665nm - 750\ nm\ after\ acidicfication)$$

$$\frac{[(28.4(Ab\ 665\ before - 665\ after)) * volume\ extracted]}{surface\ area * path\ length}$$

$CHL_{planktonic}$

Frozen samples were thawed and analyzed when they reached room temperature. Using forceps, filters were placed in glass jars containing 10mL of 90% reagent-grade acetone and extracted in the freezer between 2 to 4 hours. Using the fluorometer, the absorbances of samples were read before and after six drops of 0.1N HCL was added.

Total Phosphorus

Frozen samples were thawed and analyzed when they reached room temperature. Potassium persulfate was added to 50 mL of mixed raw water in a Kimax tube and autoclaved to digest the contents. After the sample was cooled, we used the molybdenum blue method of Murphy and Riley (1962) to measure TP concentrations in triplicate.

Statistics

We used SAS JMP 15.2.0 for PC (SAS Institute Inc., 2020 – 2021) to conduct all statistical analyses, which included the repeated measures ANOVA, Tukey's post hoc test and the non-parametric Spearman's Rank Correlation. Prior to analyses for incubation duration, we $\log_{10}$-transformed $CHL_{periphytic}$ values. All means reported are arithmetic.

RESULTS and DISCUSSION

All results are reported as uncorrected CHL which includes the biomass of both the living and non-living algae. We compared the $CHL_{periphytic}$ of four sets of slides ranging from 1 to 4 slides and found that the amount of chlorophyll from the replicates of 3 and 4 slides were statistically similar and higher than when only one or two slides were processed (**Figure 3.2**). Since there is high slide-to-slide variability of periphyton growth (see **Figure 3.1c**), there is a high likelihood that results from a single slide would be biased (Carr et al., 2005). By including more slides, we would obtain more representative results, but to include too many slides would be wasteful. Given that there was no statistical significance between 3 and 4 slides, it would be most cost-effective to process three sets of slides, but if time and resources permit, processing 4 sets of slides would result in higher precision.

We calculated $CHL_{periphytic}$ every 3 days from day 7 to day 28 of incubation to determine the ideal time that slides should remain in the water. CHL increased linearly from day 7 to day 16 and then began to decrease from day 23 to day 28. Peak concentrations of $CHL_{periphytic}$ were found on day 19. Using only data up to and including day 19, we obtained a highly significant positive linear relationship between $CHL_{periphytic}$ and time ($p<0.0001$, $R^2 = 0.911$) (**Figure 3.3**). Decrease in periphyton biomass can occur because of physical disturbances (waves, animals, boats), storm events and algae sloughing off due to weight (Biggs, 1988; Lowe & Pan, 1996). Ideally, the incubation period should not exceed the exponential growth phase (**Figure 3.4**), and therefore, future experiments should not exceed 16-18 days of incubation to avoid obtaining an underestimate. This is consistent with other studies that found 2 weeks to be an ideal incubation period (Lowe & Pan, 1996). Based on these results, we recommend the ideal incubation period to be 14-18 days and that samples be measured in triplicate in groups of four slides.

We incubated the periplates at five sites in Honey Harbour for 24 days. This incubation period was longer than that corresponding to the peak $CHL_{periphytic.}$ and may represent an underestimate. Since the same incubation period was used at all sites, the results should be directly comparable; on the other hand, periphyton in highly developed recreational areas with high nutrient concentrations may have been able to regrow quickly even if some of the benthic algae had been removed by waves and currents (Campbell & Chow-Fraser, 2018; Hatt et al., 2004). The site with the highest $CHL_{periphytic}$ was measured at the marina (14.1 μg/m^2), followed by the main channel (12.6 μg/m^2) but there are no significant differences between these high-impact sites. The $CHL_{periphytic}$ in the wetland (6.2 μg/m^2) was significantly lower than these values at sites 1 and 2, but higher than those measured at the rocky shoreline (3.0 μg/m^2) and at the dock (2.0 μg/m^2) (**Figure 3.6**). By comparison, the marina had the highest $CHL_{planktonic}$ concentration (7.7 μg/L), followed by the channel (5.2 μg/L), the rocky shoreline (4.6μg/L), the wetland (3.2 μg/L) and the dock (2.7 μg/L). By contrast, mean TP concentration for the wetland was highest (10.2 μg/L), and were not significantly different from any other site. In fact, we found no significant relationship between TP vs $CHL_{periphytic}$ or vs $CHL_{planktonic}$, but we found a significant positive correlation between $CHL_{periphytic}$ and $CHL_{planktonic}$ ($p = 0.0019$, $\rho = 0.7321$).

These results indicate that the periplate was sensitive to differences in recreational development and activities, with the highest biomass in the busy marinas and boat channel compared with those at the protected dock and along the rocky shoreline. These findings are consistent with the literature that shows periphyton biomass increasing along a gradient of anthropogenic disturbances and shoreline modification (McNair and Chow-Fraser, 2003; Lambert et al., 2008; Planas et al., 2000). Lambert et al. (2008) found that periphyton biomass was significantly related to building density and percentage of cleared land which were thought to be responsible for increased loading of nutrients. As demonstrated in Vinden & Chow-Fraser (2023; Chapter 2), TP concentration was significantly and positively correlated with road density and the percentage of modified land within TGB, both indicators of recreational development. Since periphyton requires nutrients (i.e., TP) to grow, we would expect to see an increase in periphyton biomass in areas with increased TP concentrations.

While some investigators reported a strong positive correlation between TP and periphyton (Hao et al., 2020; Pacheco et al., 2022; Planas et al., 2000), others only found a weak relationship or no relationship at all (Lambert et al., 2008). Lack of a correlation between TP and $CHL_{periphytic}$ biomass in this study may be attributed to several factors including limited light availability, physical disturbances and sloughing off of periphyton (DeNicola & Kelly, 2014; Hansson, 1992; Hill & Fanta, 2008). Although we attempted to control for light limitation by building the suspension frames in such a way as not to block sunlight from passing through to the periphytometers, and all periplates were incubated at a depth of 50 cm, some periplates may have been light limited at the dock and in the wetland. Reduced light availability would have hindered the growth of periphyton and might explain why both sites had lower periphyton growth relative to the TP concentrations.

$CHL_{periphytic}$ biomass and TP may not have been significantly related because CHL integrates the influence of nutrients over 24 days, whereas the TP concentration reflects a single sample at only one point (Lambert et al., 2008). Since TP concentrations at a site can vary throughout the day due to the movement and flushing of water, it may be difficult to get a representation of the nutrient status of a site without repeated sampling. We know from previous studies that mean nutrient concentrations measured in wetlands tend to be higher than those in open waters, and the $CHL_{periphytic}$ measured in the wetland was higher than that at the dock or rocky shoreline, but corresponding TP concentrations were not significantly different.

Though this was only a small study, the results are promising. Further trials should be conducted in TGB throughout regions with water-quality impairment (e.g., focal areas in OB and HH, Bloody Bay and Sand Run; Chapter 2). In these trials, periplates should be incubated between 14 to 18 days to ensure that algal colonization has not peaked. Additional modification could be explored to allow volunteers to use a colour sensor rather than the spectrophotometer to estimate CHL concentrations (Tedeschi and Chow-Fraser, 2021). This is in keeping with developing a method that is safe, cost-effective and that does not require specialized and expensive equipment. Long-term monitoring of nutrients is an important aspect of protecting water quality from eutrophication and harmful algae blooms, especially as increases in summer temperatures and urbanization escalates the frequency and intensity of harmful algal blooms (Wolf & Klaiber, 2017). The local community of TGB is deeply concerned about their water quality. We hope that cottage volunteers can use periplates to assess and track the nutrient status at sentinel sites in their region and help the township make informed decisions to protect the excellent water quality in Georgian Bay.

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Table 3.1: Description of sampling stations in Honey Harbour in the Township of Georgian Bay. Mean $CHL_{periphytic}$ ($mgCHL/m^2/day$), $CHL_{planktonic}$ (µg/L) and mean TP (µg/L). See locations of regions in Figure 4.

Site #	1	2	3	4	5
Site Name	**Main Channel**	**Marina**	**Shoreline**	**Dock**	**Wetland**
Latitude	44.875256	44.872578	44.882225	44.881939	44.882206
Longitude	-79.810547	-79.815735	-79.803894	-79.803055	-79.801903
Depth	50 cm	50 cm	50 cm	50 cm	50 cm
Disturbances	Exposed to wind and heavy boat traffic	Busy marina, near a loading dock	Within an inlet on North Bay. Exposed to wind and minimal boat traffic	Amongst docks with protection from wind	Protected wetland with no boat access
Notes	Sandy with some periphyton on rocks	Surrounded by rocks with visible periphyton and minimal vegetation	Rocky, vegetation is present	Deeper area, no visible vegetation or periphyton	Ample vegetation, beaver dam present
Mean $CHL_{periphytic}$	12.6	14.1	3.0	2.0	6.2
Mean $CHL_{planktonic}$	5.2	7.7	4.6	2.7	3.2
Mean TP	7.3	8.7	8.7	5.8	10.2

a) b) c)

Figure 3.1: a) The 3D printed slide holder (periphytometer). b) Wooden floating frame used to keep the periphytometer suspended ~50 cm below water surface. c) Glass slide with periphytic growth following the incubation period and before it was processed.

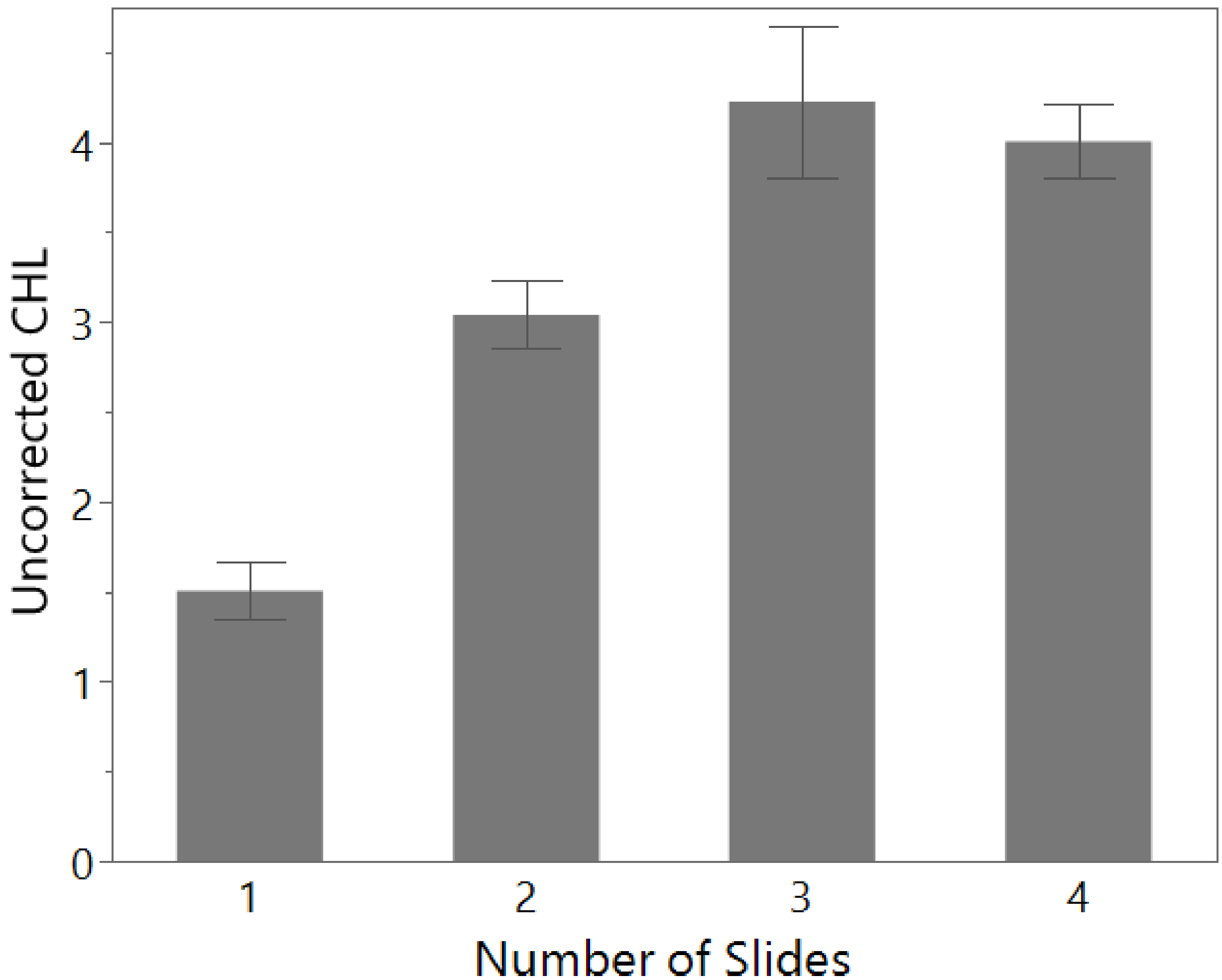

Figure 3.2: The number of slides required for scientific rigour after incubating for 14 days. $CHL_{periphytic}$ refers to uncorrected chlorophyll-α (μg/m^2).

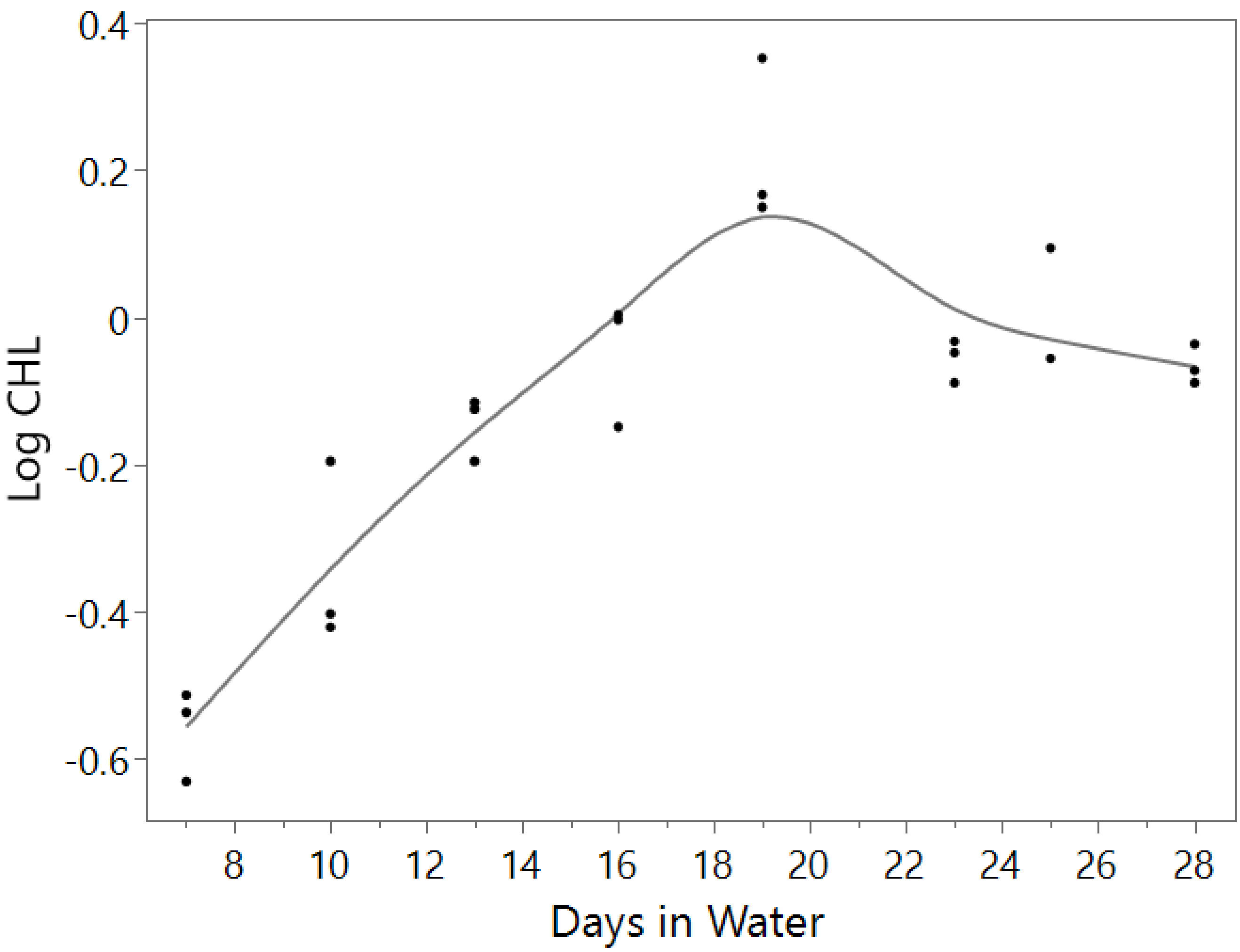

Figure 3.3: Relationship between periphyton growth and incubation period (days). Three periphyton samples were collected in 3-day intervals in August 2022 in Honey Harbour. $CHL_{periphytic}$ refers to the log of the uncorrected chlorophyll-α (µg/m^2).

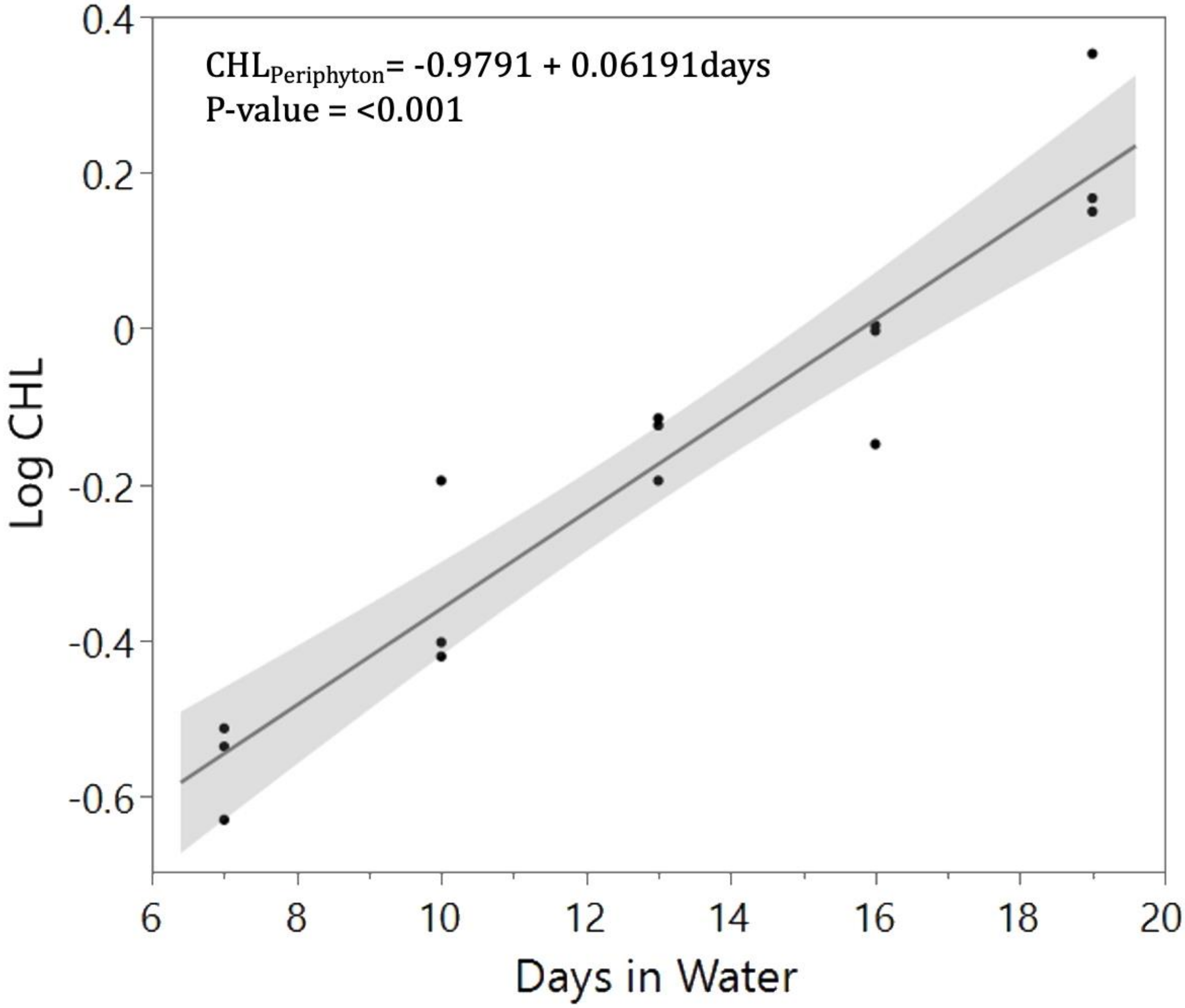

Figure 3.4: Standard curve and equation that can be used to compare samples of periphyton taken on different days. $CHL_{periphytic}$ refers to the $\log_{10}$ of the uncorrected chlorophyll-α (μg/m^2).

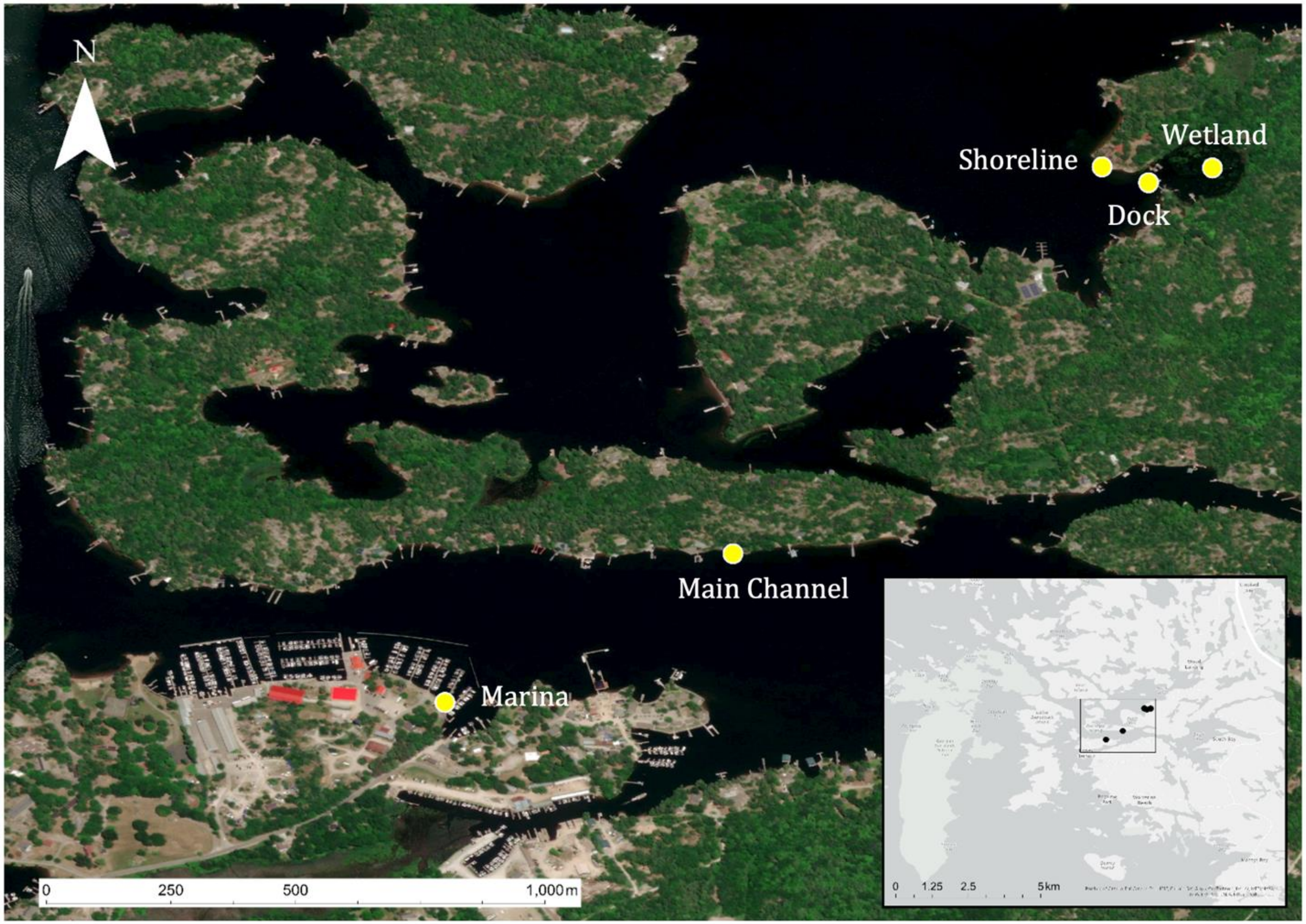

Figure 3.5: Locations where periplates were incubated *in situ* in Honey Harbour during August 2022. Marina and main channel have high levels of recreational development while the shoreline, dock and wetland have low levels of recreational development.

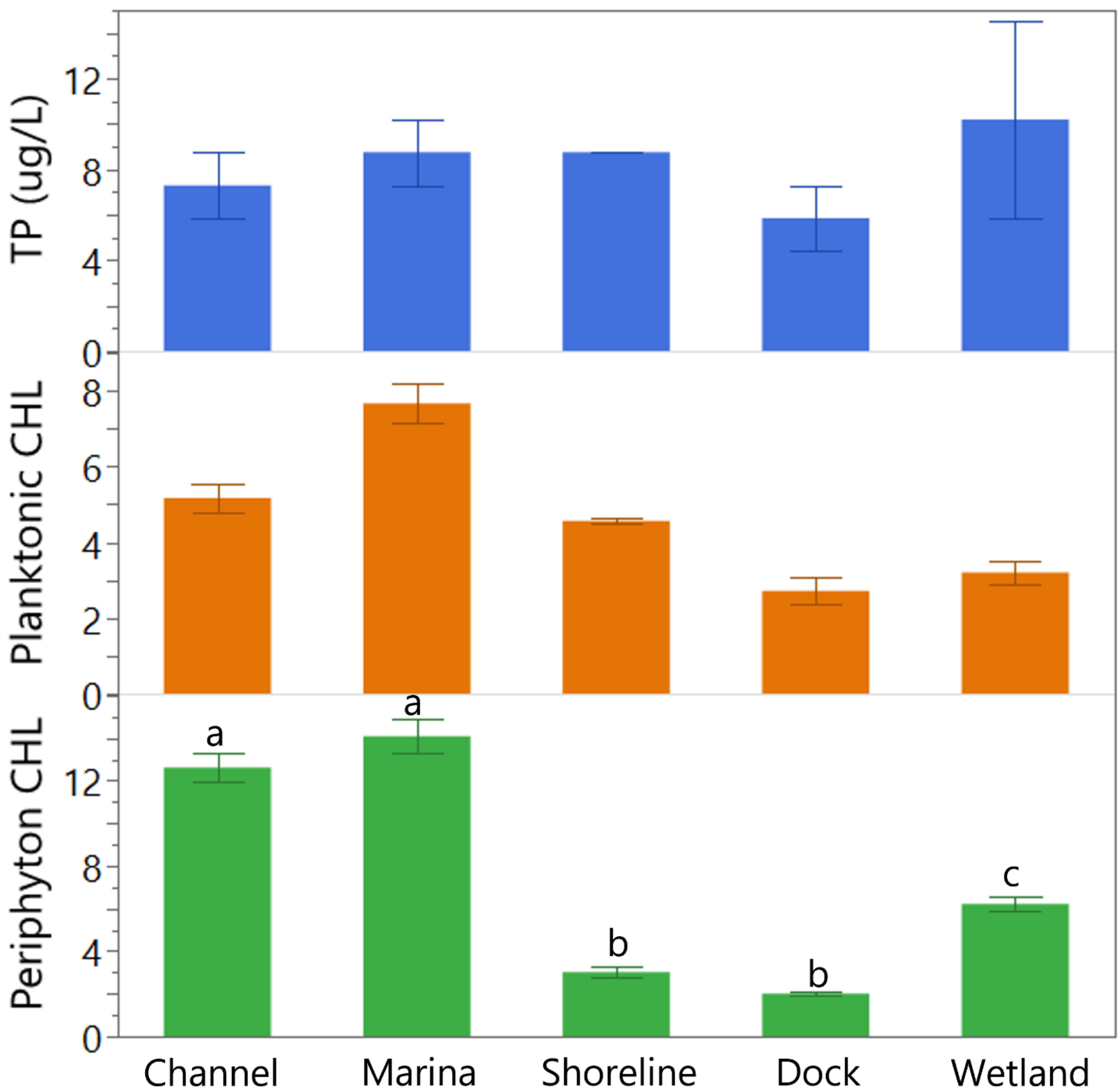

Figure 3.6: Comparison of TP (μg/L) and $CHL_{planktonic}$ (μg/L) and $CHL_{periphytic}$ (mgCHL/m^2/day) for five locations in Honey Harbour. $CHL_{periphytic}$ growth was measured after 24 days of incubation, at which point grab samples of TP and $CHL_{planktonic\ samples}$ were taken. CHL in both cases refers to uncorrected chlorophyll-α. The biomass of $CHL_{periphytic}$ at sites with the same letter are statistically homogeneous. See Figure 3.4 for location of sites.

CHAPTER 4: GENERAL CONCLUSION

Our study shows that although water quality within the Township of Georgian Bay (TGB) is generally below the Georgian Bay Water Quality Objective (GBWQO) of 10 colony forming units (CFU) for *E. coli* (EC) and 10 μg/L for total phosphorus (TP), regions with high levels of shoreline development are experiencing worsening water quality. There has been a general decrease in pollutant levels between Period 1 (2001 – 2009) and Period 2 (2020 – 2022), although this should not be interpreted as a decrease in nutrient loading, but rather a dilution effect due to an increase of approximately 1-m in water levels between periods (Montocchio & Chow-Fraser, 2021; Wang et al., 2022). There continues to be several sites within TGB that have surpassed both the GBWQO and Beach Action Value (235 CFU/100 ml), most of which are located within Honey Harbour and Oak Bay. We found that both Honey Harbour and Oak Bay were the regions with the highest means of EC and TP and had the greatest percentage of sites that exceeded the GBWQO.

We found that mean EC and TP were significantly and positively correlated with road density and the percentage of modified area. Cottage and recreational development, reflected in higher road density and the percentage of modified area, increased the amount of impervious surfaces and therefore led to higher loading of nutrients in runoff entering Georgian Bay (Campbell & Chow-Fraser, 2018; Hatt et al., 2004; Jacob & Lopez, 2009). Increased road density also provided easier access to cottages and development, increasing the possibility of failing septic systems (Chiandet & Sherman, 2014; Hawbaker et al., 2005). Both Honey Harbour and Oak Bay currently have the highest road density and percentage of modified area and is the main reason why these regions have a high level of water-quality impairment.

We also designed a bioassay to assess nutrient status in nearshore waters using periphyton. We found that that ideal sampling protocol to be 14-18 days of incubation and using triplicate sets of 4 slides for processing. This reduces the variation amongst samples while also minimizing the possibility of physical disturbances and sloughing. We also found that the periplate results were sensitive to changes in the level of human activities and may be a useful method to monitor water quality in a volunteer monitoring program.

Information from this thesis can be used to help the TGB make informed decisions about water-quality management. Long-term monitoring of all areas of TGB is important; however, more frequent and intensive monitoring and management should be conducted in Honey Harbour and Oak Bay, as they have the highest levels of EC and TP and highest road density. Although water quality within TGB is still relatively good, degradation and eutrophication are occurring in focal areas such as Brandy's Cove Marina, Macey's Bay and Oak Bay that have not gone unnoticed by local community members. Community members are concerned about the water conditions within TGB and the periplate method may be a cost-effective option to use in long-term monitoring by volunteers. Providing resources and tools for local communities to understand and monitor their own water quality is a powerful way to help protect the local environment. This is even more pertinent as water levels are predicted to decrease and development pressures increase.

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Appendix 1: Spatial and temporal information for every site sampled in the nearshore waters of the Township of Georgian Bay from 2001 – 2009 and 2020 – 2022. Presence of samples for *E. coli* (EC) and total phosphorus (TP) and during the historic period (2001 – 2009) and current period (2020 – 2022) are indicated with an X. Latitude and longitude are measured in decimal degrees.

Region	Focal Area	Site #	Site Name	Latitude	Longitude	EC	TP	Historic	Current
OB	OB	1011	Golf Course Point	44.7976741	-79.7384271	X	X		X
		1012	Oak Bay Development Marina	44.7938168	-79.7504523	X	X	X	X
		1201	Tug Channel South of 400	44.7995700	-79.7262800	X			X
		1202	Open Water Oak Bay	44.7961390	-79.7316402		X	X	X
		1203	Inner Open Water Oak Bay	44.7980100	-79.7356600		X	X	
		1204	Northeast of Eden Oak Homes Development	44.7955110	-79.7352447		X		X
		1205	Potato Island Wetland (Inner)	44.7918429	-79.7410390	X	X	X	X
		1206	Potato Island Wetland (Outer)	44.7907996	-79.7409689	X	X	X	X
		1208	East of Potato Island Road	44.7925550	-79.7568250		X	X	
		1209	West of Green Island	44.7872500	-79.7572000		X		X
		1210	East of Green Island	44.7833400	-79.7391500		X		X
		1212	Green Island Channel	44.7883333	-79.7440333		X		X
		1213	Channel North of Green Island	44.7886167	-79.7490000		X	X	
		1214	Green Island North Wetland	44.7861100	-79.7459300		X		X
HH	BC	1001	Brandy's Cove Marina	44.8527087	-79.8135222	X	X	X	X
		1002	Tobies Bay	44.8519785	-79.8087258	X	X	X	X
		1003	Sunset Bay	44.8502881	-79.8056168	X	X	X	X
		1049	Close to Bayview Marina	44.8507208	-79.8201925	X	X	X	X
		1050	West of Brandy's Island	44.8533243	-79.8203664	X	X	X	X
		1053	West of David's Island Dock	44.8455183	-79.8230148	X	X	X	X
	IHH	1007	Church Bay Marina	44.8664954	-79.8207998	X	X	X	X

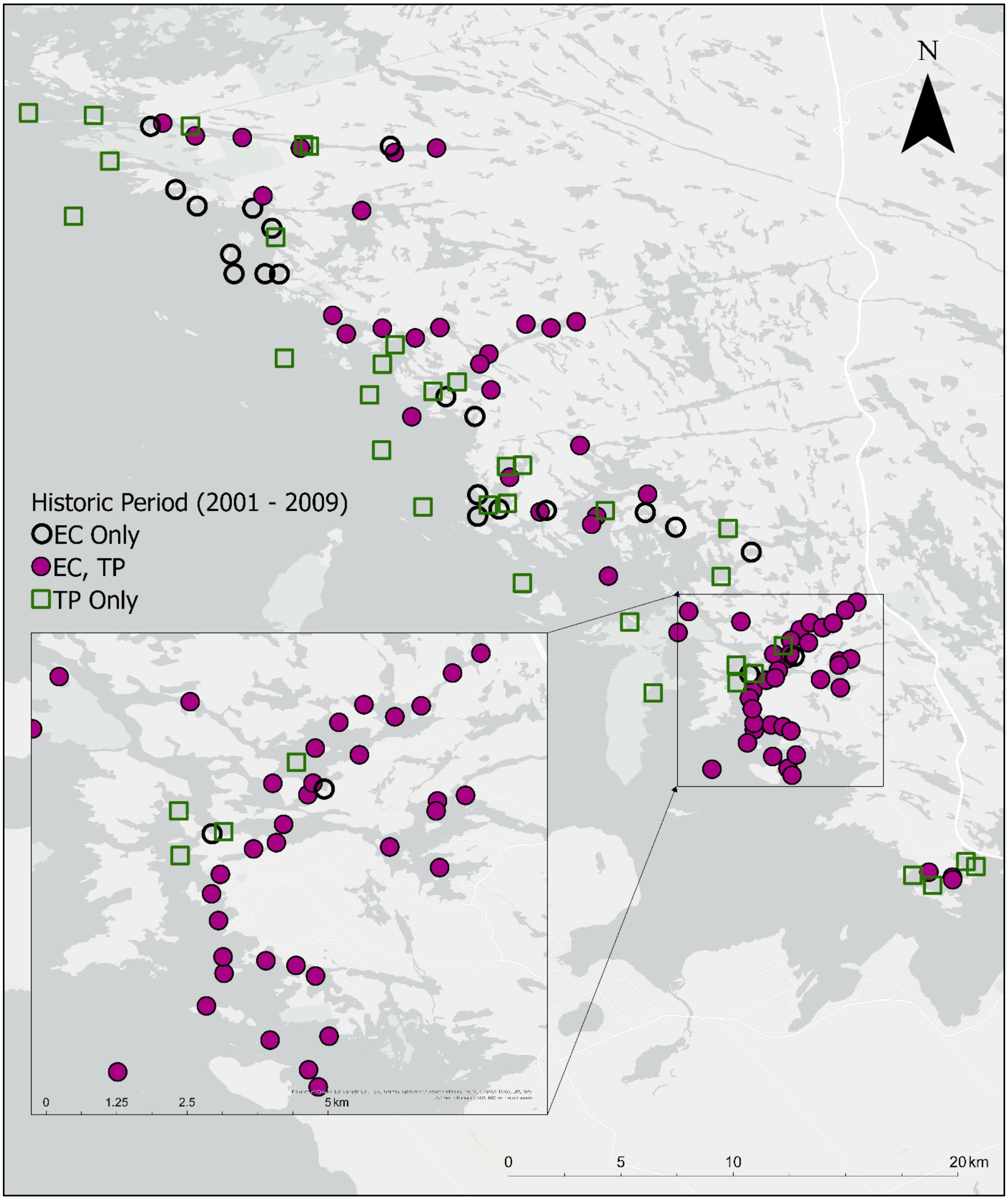
HH (cont'd)	IHH (cont'd)	1008	North Picnic Island Marina	44.8633886	-79.8221928	X	X	X	X
		1009	Robert's Island Central	44.8634302	-79.8295385	X	X		X
		1010	Robert's Island South	44.8585435	-79.8293859	X	X		X
		1048	East of Mermaid Island	44.8757163	-79.8070115	X	X		X
		1051	Bayview Marina Resort	44.8591288	-79.8210753	X	X	X	X
		1060	South of Mermaid Island	44.8744641	-79.8107020	X	X	X	X
		1106	Delawana Beach	44.8729600	-79.8221080	X		X	
		2017	Lily Pond	44.8705382	-79.8154910	X	X	X	X
		2021	Honey Harbour Small Motors	44.8715400	-79.8118610	X	X	X	
		2028	Boat Club Marina	44.8732973	-79.8202490		X	X	X
		2033	Honey Harbour Inner Channel	44.8694900	-79.8271900		X	X	
		2068	Main Channel	44.8766076	-79.8274003		X	X	X
	MB	1004	Outer Macey's Bay	44.8416089	-79.7812573	X	X		X
		1005	Venning's Bay	44.8404566	-79.7787962	X	X		X
		1006	Macey Bay Development	44.8421452	-79.7852717	X	X		X
		2080	Macey Bay Trailer Park (Open Water)	44.8436958	-79.7820867	X	X		X
		2081	Macey Bay Wetland (Floating Veg)	44.8434776	-79.7829408	X	X		X
		2082	Macey Bay Wetland (Emergent Veg)	44.8431312	-79.7834042	X	X		X
	NP	1020	Chimney Bay	44.8896817	-79.8507366	X	X	X	X
		2030	Outflow of Long Bay	44.8938800	-79.8699800		X	X	
		2031	Outflow of Treasure Bay	44.8654700	-79.8606900		X	X	
		2032	West of Beausoleil Island Open Water	44.8793900	-79.9089200		X	X	
	NB	1055	South of Wetland Outflow	44.8907232	-79.8019083	X	X	X	X
		1056	Pratt Bay	44.8791904	-79.8068496	X	X	X	X
		1057	Bay South of North Bay Wetland	44.8935271	-79.7979023	X	X	X	X

HH (cont'd)	NB (cont'd)	1059	Pleasant Point	44.8810022	-79.8124444	X	X	X	X
		1065	Southern Shoreline of North Bay	44.8855432	-79.7986292	X	X	X	X
		1066	Rock Inlet in North Bay	44.8891194	-79.8076821	X	X		X
		1067	Small Inlet in North Bay	44.8886481	-79.7903608	X	X		X
		1068	North Bay Wetland	44.8973441	-79.7936304	X	X		X
		1077	Northeast of Pleasant Point	44.8866100	-79.8056725	X	X	X	X
		1079	School House Dock	44.8810215	-79.8060310	X	X	X	X
		1080	Hidden Glen Trailer Marina	44.9017200	-79.7792755	X	X	X	X
		1081	Woods Landing Marina	44.8985800	-79.7837790	X	X	X	X
		1097	Al's Back Bay	44.8819007	-79.8025030	X	X		X
		1107	School House Bay	44.8800870	-79.8042380	X		X	
		2019	Woods Landing Wetland	44.9004804	-79.7842536		X		X
		2023	Outer North Bay	44.8843425	-79.8086784		X	X	X
		2024	Inner North Bay	44.8916091	-79.7929725	X	X	X	X
		2025	North Bay Inflow	44.8933553	-79.7887818	X	X	X	X
	NHH	1013	Frying Pan Bay	44.8980107	-79.8464805	X	X	X	X
		1058	Deer Island Channel	44.8940136	-79.8256016	X	X	X	X
	QI	1054	East of Quarry Island	44.8353256	-79.8067420	X	X	X	X
		1074	North of Quarry Island	44.8400856	-79.8128566	X	X	X	X
		1075	Southeast of Quarry Island	44.8326001	-79.8051846	X	X	X	X
		1076	Southwest of End of Prisque Road	44.8406933	-79.8034652	X	X	X	X
	SSO	1052	Open Water of Severn Sound	44.8350001	-79.8371457	X	X	X	X
	SB	1061	North of Lownie Island	44.8708541	-79.7938012	X	X	X	X
		1062	Beach North in South Bay	44.8781919	-79.7862024	X	X	X	X
		1063	South Harbour Marina	44.8790822	-79.7817310	X	X	X	X
		1064	South Bay Cove Marina	44.8677364	-79.7809521	X	X		X
		2026	Cow Island	44.8766073	-79.7863888	X	X	X	X
		2027	Near South Bay Cove Marina	44.8675694	-79.7858612	X	X	X	X
COG	COG	1014	Webber's Island	44.9200235	-79.8374453	X	X		X

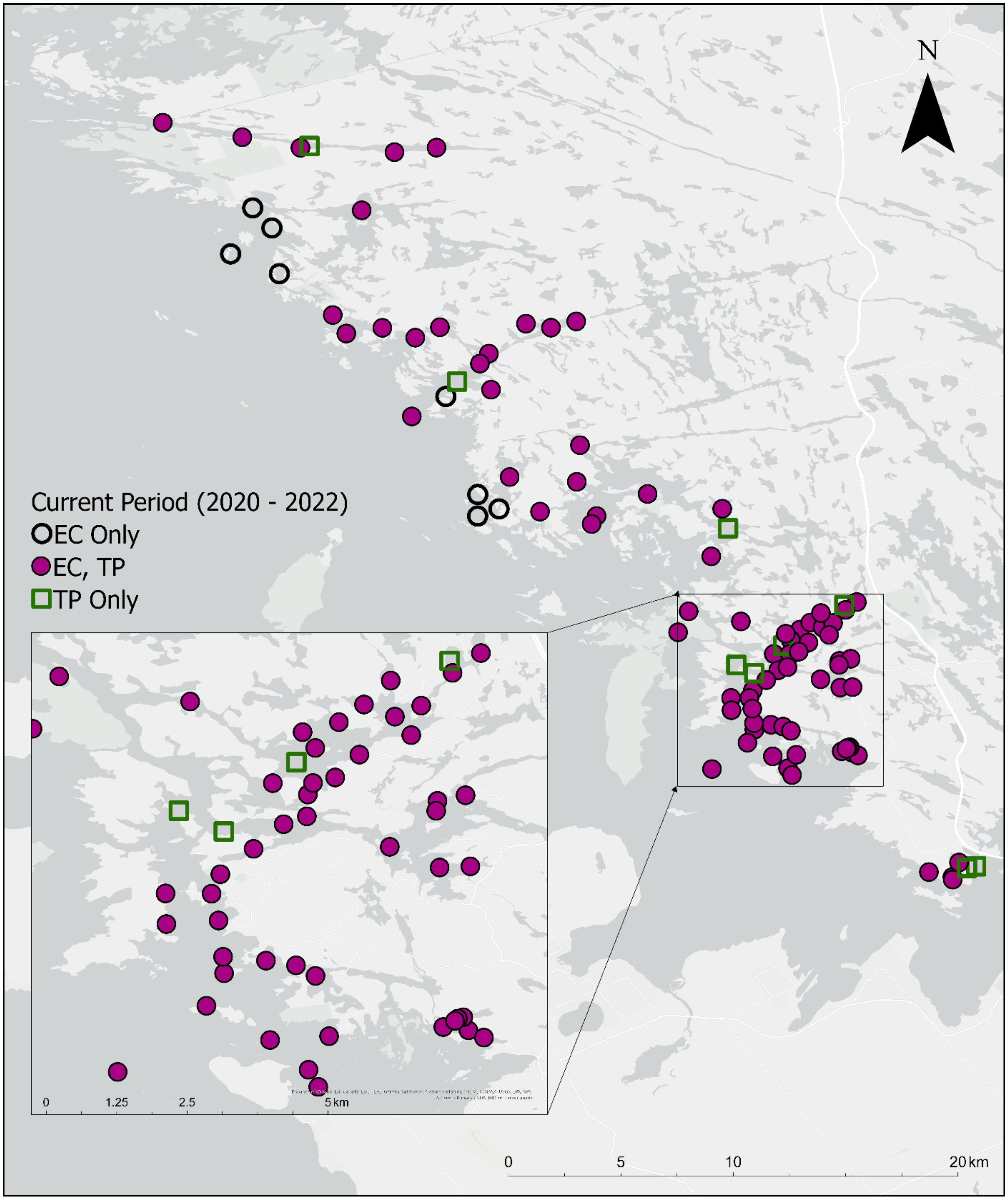
COG (cont’d)	COG (cont’d)	1015	Hockey Stick Bay	44.9449138	-79.8628871	X	X	X	X
		1016	Longuissa Bay	44.9644246	-79.8899362	X	X	X	X
		1017	Brown's Bay	44.9497977	-79.8911833	X	X		X
		1018	Centre Freddy Channel	44.9378825	-79.9059045	X	X	X	X
		1021	Palesaide Bay	44.9390357	-79.8330635	X	X		X
		1038	Musquash Channel	44.9360926	-79.8832895	X	X	X	X
		1069	North of Arthur Island	44.9329218	-79.8852886	X	X	X	X
		1084	East Freddy Channel	44.9384490	-79.9033110	X		X	
		1085	Bone Island	44.9376080	-79.8637810	X		X	
		1101	Southwest Bone Island	44.9317390	-79.8516970	X		X	
		1105	Ganyon Bay	44.9217970	-79.8214480	X		X	
		2035	East of Powwow Island	44.9120000	-79.8335300		X	X	
		2036	Cook Island	44.9311995	-79.8307275		X	X	X
		2037	Whalesback Channel	44.9093700	-79.9129800		X	X	
		2038	East of Penetang Rock	44.9121900	-79.8785700	X	X	X	
		2039	North of Sugar Island	44.9383300	-79.8798400		X	X	
		2041	Open Water East of Eshpabekong Island	44.9398800	-79.9527200		X	X	
	CL	1019	Cognashene Lake Main	44.9517366	-79.9180045	X	X	X	X
		1086	Waubanoka Island	44.9361242	-79.9308108	X		X	X
		1087	Cognashene Lake Narrows	44.9389867	-79.9222617	X		X	X
		1088	Hangdog Channel	44.9446873	-79.9307850	X		X	X
		2042	Outside Cognashene Lake Open	44.9405630	-79.9265840		X	X	
		2043	Cognashene Lake Entrance	44.9413200	-79.9189640		X	X	
		2044	Cognashene Lake Main North	44.9560210	-79.9192890		X	X	
		2045	Cognashene Lake East Bay	44.9565180	-79.9128120		X	X	
GHB	GHB	1022	Go Home Chute	45.0138885	-79.8914365	X	X	X	X
		1023	Go Home Dump Site	45.0129658	-79.9115223	X	X	X	X
		1024	Go Home Inner Bay	45.0010348	-79.9263287	X	X	X	X
		1025	Go Home Southern Inlet	44.9838838	-79.9435082	X		X	X

GHB (cont'd)	GHB (cont'd)	1026	West of Woore Rocks	44.9759407	-79.9571204	X	X	X	X
		1027	Sand Run	45.0073862	-79.9557724	X	X	X	X
		1070	Monument Channel east of Galbraith Island	45.0090408	-79.9832879	X	X	X	X
		1071	North of Bernadette Island	45.0164604	-79.9886956	X	X	X	X
		1072	Riddell's Bay	44.9866407	-79.9254531	X	X	X	X
		1073	Go Home Bay Main Dock Channel	44.9970624	-79.9299006	X	X	X	X
		1089	Go Home River	45.0113864	-79.9014904	X	X	X	X
		1090	Moreau's Bay	45.0115345	-79.9459168	X	X	X	X
		1091	East of High Rock Island	44.9760250	-79.9319160	X		X	
		1092	North of Serpentine	45.0113228	-79.9688956	X	X	X	X
		1102	North of Dump Site	44.0095220	-79.9031160	X		X	
		2047	Open Water West of Donald Rocks	44.9625400	-79.9691800		X	X	
		2048	Bensley Island	44.9898463	-79.9390437		X	X	X
		2050	North of Firth Island	44.9859930	-79.9486840		X	X	
		2053	West Monument Channel	44.9846400	-79.9740000		X	X	
		2054	Between Outer and North Go Home Bay	44.9968400	-79.9688300		X	X	
		2056	North Go Home Bay	45.0047000	-79.9638600		X	X	
		2057	West of Galbraith Island	44.9993400	-80.0081200		X	X	
WW	TB	1096	Tadenac Bay	45.0582960	-79.9771575	X	X	X	X
	WW	1028	Indian Harbour	45.0329500	-80.0100865	X		X	X
		1029	American Camp Island	45.0408668	-80.0295621	X		X	X
		1030	Gillespie Island	45.0512126	-80.0130069	X		X	X
		1031	Outside King Bay	45.0592808	-80.0207269	X		X	X
		1093	King Bay Marina	45.0642291	-80.0166397	X	X	X	
		1094	West of Bands Island	45.0330520	-80.0157980	X		X	
		1099	Niblett Island	45.0667470	-80.0514980	X		X	
		1103	Tully Island	45.0601430	-80.0429270	X		X	

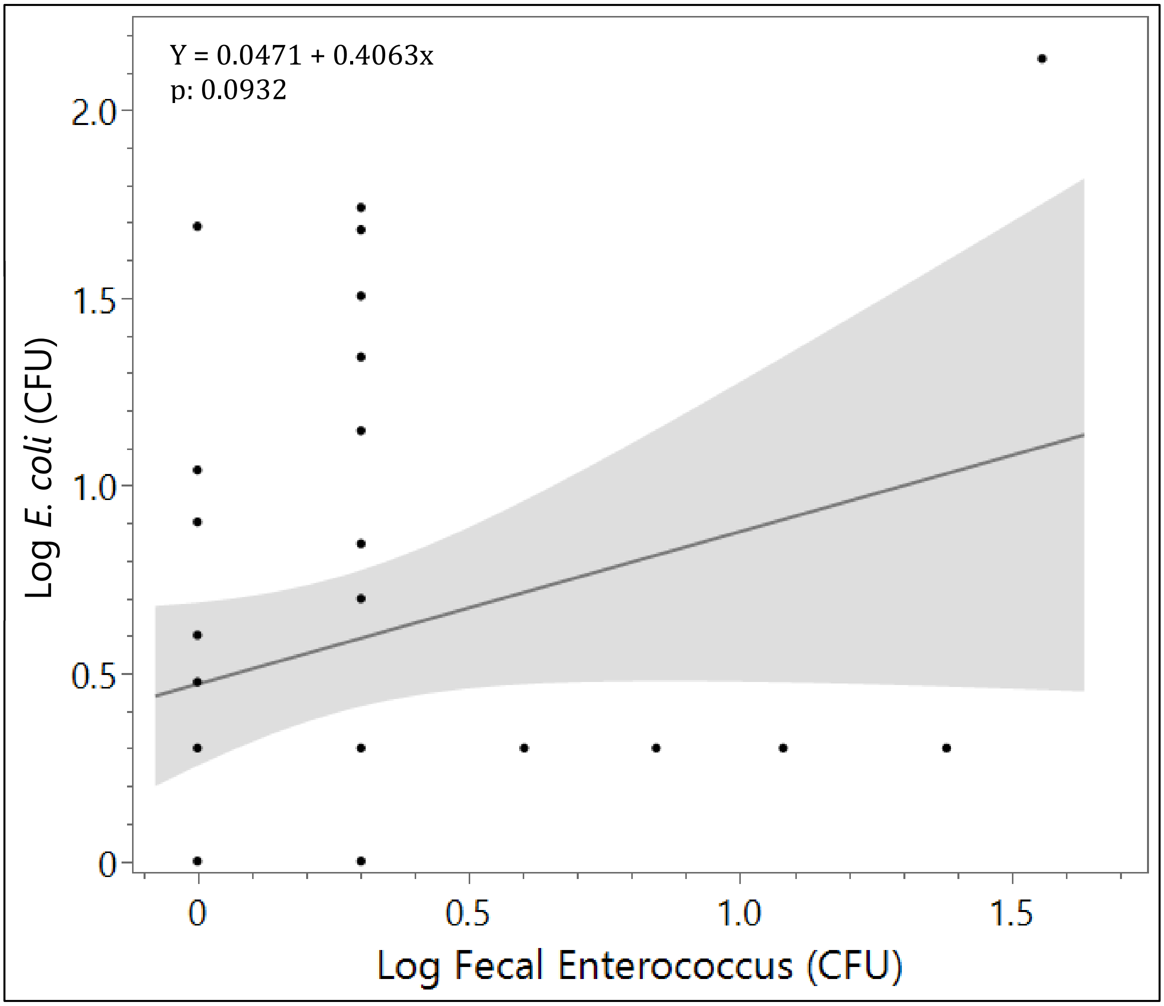
WW (cont'd)	WW (cont'd)	1104	Open Water	45.0330880	-80.0281890	X		X	
		2060	Moose Bay Outlet	45.0780800	-80.0778700		X	X	
		2061	West of Clarke Rock (open)	45.0560300	-80.0923400		X	X	
TMB	TMB	1032	Twelve Mile Bay (Forbes)	45.0932978	-80.0567180	X	X	X	X
		1033	Big David Bay	45.0476400	-80.0115800		X	X	
		1034	Government Docks	45.0874776	-80.0248895	X	X	X	X
		1035	Moose Deer Pt Marina	45.0832924	-80.0016131	X	X	X	X
		1036	Bloody Bay	45.0815152	-79.9640682	X	X	X	X
		1037	Behind Island	45.0833232	-79.9472692	X	X	X	X
		1082	Gordon's Bay	45.0846700	-80.0003600		X	X	
		1083	Northeast of Gordon's Bay	45.0840140	-79.9980145		X	X	X
		1095	Isaac Bay	45.0881753	-80.0436640	X	X	X	
		1098	North of Bloody Bay	45.0840307	-79.9657294	X		X	
		1100	Wanne Harbour	45.0920210	-80.0615400	X		X	
		2062	Twelve Mile Bay (offshore)	45.0835700	-80.1430600		X	X	
		2063	Jacques Island	45.0973800	-80.1102800		X	X	
		2064	Bowes Island	45.0964380	-80.0842510		X	X	
		2065	Outside Isaac Bay	45.0920400	-80.0455800		X	X	



Appendix 2: Location of all sites sampled for *E. coli* (EC; CFU; open circles), total phosphorus (TP; µg/L; open square) and both (solid circle) between 2001 and 2009 in the nearshore waters of the Township of Georgian Bay.



Appendix 3: Location of all sites sampled for *E. coli* (EC; CFU; open circles), total phosphorus (TP; µg/L; open square) and both (solid circle) between 2020 and 2022 in the nearshore waters of the Township of Georgian Bay.



Appendix 4: *E. coli* vs Fecal Enterococcus for 51 samples in Oak Bay, Honey Harbour, Cognashene and Go Home Bay in the Township of Georgian Bay. Data were collected between June to September of 2020 and 2021 and enumerated using the TECTA B

Appendix 5: All sites sampled in this study sorted by site number. See Region Code in List of Abbreviations on p. xvii and xviii.

Region	Site Name	Site Number	Latitude	Longitude
HH	Brandy's Cove Marina	1001	44.8527087	-79.8135222
HH	Tobies Bay	1002	44.8519785	-79.8087258
HH	Sunset Bay	1003	44.8607165	-79.8079256
HH	Outer Macey's Bay	1004	44.8416089	-79.7812573
HH	Venning's Bay	1005	44.8404566	-79.7787962
HH	Macey Bay Development	1006	44.8421452	-79.7852717
HH	Church Bay Marina	1007	44.8664954	-79.8207998
HH	North Picnic Island Marina	1008	44.8633886	-79.8221928
HH	Robert's Island Central	1009	44.8634302	-79.8295385
HH	Robert's Island South	1010	44.8585435	-79.8293859
OB	Golf Course Point	1011	44.7976741	-79.7384271
OB	Oak Bay Development Marina	1012	44.7938168	-79.7504523
HH	Frying Pan Bay	1013	44.8980107	-79.8464805
COG	Webber's Island	1014	44.9200235	-79.8374453
COG	Hockey Stick Bay	1015	44.9449138	-79.8628871
COG	Longuissa Bay	1016	44.9644246	-79.8899362
COG	Brown's Bay	1017	44.9497977	-79.8911833
COG	Centre Freddy Channel	1018	44.9378825	-79.9059045
COG	Cognashene Lake Main	1019	44.9517366	-79.9180045
HH	Chimney Bay	1020	44.8896817	-79.8507366
COG	Palesaide Bay	1021	44.9390357	-79.8330635
GHB	Go Home Chute	1022	45.0138885	-79.8914365
GHB	Go Home Dump Site	1023	45.0129658	-79.9115223
GHB	Go Home Inner Bay	1024	45.0010348	-79.9263287
GHB	Go Home Southern Inlet (Abbott)	1025	44.9838838	-79.9435082
GHB	West of Woore Rocks	1026	44.9759407	-79.9571204
GHB	Sand Run	1027	45.0073862	-79.9557724
TMB	Indian Harbour	1028	45.0329500	-80.0100865
TMB	American Camp Island	1029	45.0408668	-80.0295621
TMB	Gillespie Island	1030	45.0512126	-80.0130069
TMB	Outside King Bay	1031	45.0592808	-80.0207269
TMB	Twelve Mile Bay (Forbes)	1032	45.0932978	-80.0567180
TMB	Big David Bay	1033	45.0476400	-80.0115800
TMB	Twelve Mile Government Docks	1034	45.0874776	-80.0248895
TMB	Moose Deer Pt Marina	1035	45.0832924	-80.0016131
TMB	Bloody Bay	1036	45.0815152	-79.9640682
TMB	Twelve Mile Bay Behind Island	1037	45.0833232	-79.9472692
COG	Musquash Channel (Outside Brown Bay)	1038	44.9360926	-79.8832895
HH	East of Mermaid Island	1048	44.8757163	-79.8070115
HH	Close to Bayview Marina	1049	44.8507208	-79.8201925
HH	West of Brandy's Island	1050	44.8533243	-79.8203664
HH	Bayview Marina Resort	1051	44.8591288	-79.8210753
HH	Open Water of Severn Sound	1052	44.8350001	-79.8371457
HH	West of David's Island Dock	1053	44.8455183	-79.8230148
HH	East of Quarry Island	1054	44.8353256	-79.8067420
HH	South of Wetland Outflow	1055	44.8907232	-79.8019083
HH	Pratt Bay	1056	44.8791904	-79.8068496
HH	Bay South of North Bay Wetland	1057	44.8935271	-79.7979023
HH	Deer Island Channel	1058	44.8940136	-79.8256016

Region	Site Name	Site Number	Latitude	Longitude
HH	Pleasant Point	1059	44.8810022	-79.8124444
HH	South of Mermaid Island	1060	44.8744641	-79.8107020
HH	North of Lownie Island	1061	44.8708541	-79.7938012
HH	Beach North in South Bay	1062	44.8781919	-79.7862024
HH	South Harbour Marina	1063	44.8790822	-79.7817310
HH	South Bay Cove Marina	1064	44.8677364	-79.7809521
HH	Southernn Shoreline of North Bay	1065	44.8855432	-79.7986292
HH	Rock Inlet in North Bay	1066	44.8891194	-79.8076821
HH	Small Inlet in North Bay	1067	44.8886481	-79.7903608
HH	North Bay Wetland	1068	44.8973441	-79.7936304
COG	North of Arthur Island	1069	44.9329218	-79.8852886
GHB	Monument Channel east of Galbraith Island	1070	45.0090408	-79.9832879
GHB	North of Bernadette Island	1071	45.0164604	-79.9886956
GHB	Riddell's Bay	1072	44.9866407	-79.9254531
GHB	Go Home Bay Main Dock Channel	1073	44.9970624	-79.9299006
HH	North of Quarry Island	1074	44.8400856	-79.8128566
HH	Southeast of Quarry Island	1075	44.8326001	-79.8051846
HH	Southwest of End of Prisque Road	1076	44.8406933	-79.8034652
HH	Northeast of Pleasant Point (Elgers)	1077	44.8866100	-79.8056725
HH	School House Dock	1079	44.8810215	-79.8060310
HH	Hidden Glen Trailer Marina	1080	44.9017200	-79.7792755
HH	Woods Landing marina	1081	44.8985800	-79.7837790
TMB	Twelve Mile Bay outside Gordon's Bay	1082	45.0846700	-80.0003600
TMB	Twelve Mile Bay Northeast of Gordon's Bay	1083	45.0840140	-79.9980145
COG	East Freddy Channel	1084	44.9384490	-79.9033110
COG	Bone Island	1085	44.9376080	-79.8637810
COG	Waubanoka Island	1086	44.9361242	-79.9308108
COG	Cognashene Lake Narrows (outside)	1087	44.9389867	-79.9222617
COG	Hangdog Channel	1088	44.9446873	-79.9307850
GHB	Go Home River	1089	45.0113864	-79.9014904
GHB	Moreau's Bay	1090	45.0115345	-79.9459168
GHB	East of High Rock Island	1091	44.9760250	-79.9319160
GHB	North of Serpentine	1092	45.0113228	-79.9688956
TMB	King Bay Marina	1093	45.0642291	-80.0166397
TMB	West of Bands Island	1094	45.0330520	-80.0157980
TMB	Isaac Bay	1095	45.0881753	-80.0436640
TMB	Tadenac Bay	1096	45.0582960	-79.9771575
HH	Al's Back Bay	1097	44.8819007	-79.8025030
COG	North of Bloody Bay	1098	45.0840307	-79.9657294
TMB	Niblett Island	1099	45.0667470	-80.0514980
TMB	Wanne Harbour	1100	45.0920210	-80.0615400
COG	Southwest Bone Island	1101	44.9317390	-79.8516970
GHB	North of Dump Site	1102	44.0095220	-79.9031160
TMB	Tully Island	1103	45.0601430	-80.0429270
TMB	Open Water	1104	45.0330880	-80.0281890
COG	Ganyon Bay	1105	44.9217970	-79.8214480
HH	Delawana Beach	1106	44.8729600	-79.8221080
HH	School House Bay	1107	44.8800870	-79.8042380
OB	Tug Channel South of 400	1201	44.7995700	-79.7262800

Region	Site Name	Site Number	Latitude	Longitude
OB	Open Water Oak Bay	1202	44.7961390	-79.7316402
OB	Inner Open Water Oak Bay	1203	44.7980100	-79.7356600
OB	Northeast of Eden Oak Homes Development	1204	44.7955110	-79.7352447
OB	Potato Island Wetland (Inner)	1205	44.7918429	-79.7410390
OB	Potato Island Wetland (Outer)	1206	44.7907996	-79.7409689
OB	East of Potato Island Road	1208	44.7925550	-79.7568250
OB	West of Green Island	1209	44.7872500	-79.7572000
OB	East of Green Island	1210	44.7833400	-79.7391500
OB	Green Island Channel	1212	44.7883333	-79.7440333
OB	Channel North of Green Island	1213	44.7886167	-79.7490000
OB	Green Island North wetland	1214	44.7861100	-79.7459300
HH	Inner Macey's Bay	1215	44.8429700	-79.7833200
HH	Robert's Island (South)	1216	44.8525700	-79.8346100
HH	Lily Pond	2017	44.8705382	-79.8154910
HH	Woods Landing Wetland	2019	44.9004804	-79.7842536
HH	Honey Harbour Small Motors	2021	44.8715400	-79.8118610
HH	Royal Island	2022	44.8758120	-79.8271880
HH	Outer North Bay	2023	44.8843425	-79.8086784
HH	Inner North Bay	2024	44.8916091	-79.7929725
HH	North Bay Inflow	2025	44.8933553	-79.7887818
HH	Cow Island	2026	44.8766073	-79.7863888
HH	Near South Bay Cove Marina	2027	44.8675694	-79.7858612
HH	Boat Club Marina	2028	44.8732973	-79.8202490
HH	Outflow of Long Bay	2030	44.8938800	-79.8699800
HH	Outflow of Treasure Bay	2031	44.8654700	-79.8606900
HH	West of Beausoleil Island Open Water	2032	44.8793900	-79.9089200
HH	Honey Harbour Inner Channel	2033	44.8694900	-79.8271900
COG	East of Powwow Island	2035	44.9120000	-79.8335300
COG	Cook Island	2036	44.9311995	-79.8307275
COG	Whalesback Channel (North Governor Island)	2037	44.9093700	-79.9129800
COG	Musquash (East of Penetang Rock)	2038	44.9121900	-79.8785700
COG	Musquash (North of Sugar Island)	2039	44.9383300	-79.8798400
COG	Open Water East of Eshpabekong Island	2041	44.9398800	-79.9527200
COG	Outside Cognashene Lake Open	2042	44.9405630	-79.9265840
COG	Cognashene Lake Entrance	2043	44.9413200	-79.9189640
COG	Cognashene Lake Main North	2044	44.9560210	-79.9192890
COG	Cognashene Lake East Bay	2045	44.9565180	-79.9128120
COG	Cognashene Lake Wetland	2046	44.9599360	-79.9126880
GHB	Open Water West of Donald Rocks	2047	44.9625400	-79.9691800
GHB	Go Home Middle (near Bensley Island)	2048	44.9898463	-79.9390437
GHB	North of Firth Island	2050	44.9859930	-79.9486840
GHB	Wetland Southeast of King Bay	2051	45.0054080	-79.9128930
GHB	West Monument Channel	2053	44.9846400	-79.9740000
GHB	Between Outer and North Go Home Bay	2054	44.9968400	-79.9688300
GHB	Channel Southwest of Burwash Lake	2055	44.9967100	-79.9541800
GHB	North Go Home Bay	2056	45.0047000	-79.9638600
GHB	West of Galbraith Island	2057	44.9993400	-80.0081200
TMB	Moose Bay Outlet	2060	45.0780800	-80.0778700
TMB	West of Clarke Rock (open)	2061	45.0560300	-80.0923400

Region	Site Name	Site Number	Latitude	Longitude
TMB	Twelve Mile Bay (offshore)	2062	45.0835700	-80.1430600
TMB	Twelve Mile Bay (Jacques Island)	2063	45.0973800	-80.1102800
TMB	Twelve Mile Bay (Bowes Island)	2064	45.0964380	-80.0842510
TMB	Twelve Mile Bay Outside Isaac Bay	2065	45.0920400	-80.0455800
TMB	Twelve Mile Bay end	2067	45.0826500	-79.9275100
HH	Main Channel	2068	44.8766076	-79.8274003
HH	Macey Bay Open Water	2069	44.8297880	-79.7965920
HH	Macey Bay Trailer Park (Open Water)	2080	44.8436958	-79.7820867
HH	Macey Bay Wetland (Floating Veg)	2081	44.8434776	-79.7829408
HH	Macey Bay Wetland (Emergent Veg)	2082	44.8431312	-79.7834042