Nutrient Loading and Impacts in Lake Champlain, Missisquoi Bay, and the Richelieu River

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For :
International Joint Commission

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Executive Summary

The governments of the United States and Canada, in collaboration with Vermont and Québec, requested International Joint Commission (IJC) assistance to develop a summary and analysis of work completed to date addressing harmful algal (cyanobacteria) blooms in Missisquoi Bay. These algal blooms have become increasingly persistent in recent years in this bi-national embayment of Lake Champlain. A key component of this project was the development of a suite of recommendations for additional work in Missisquoi Bay to be considered by management agencies and organizations in both countries to help achieve common management goals and ultimately reduce the frequency of harmful algal and cyanobacterial blooms.

Lake Champlain's 3,105 km^2 Missisquoi Bay Sub-Basin is shared between the Province of Québec (42%) and the State of Vermont (58%). Missisquoi Bay has long been impaired by excessive phosphorus loads from its Sub-Basin and has one of the highest in-lake phosphorus (P) concentrations of any segment of Lake Champlain (Lake Champlain Basin Program 2018). The 2016 Vermont phosphorus Total Maximum Daily Load (TMDL) for Missisquoi Bay estimates that a 64.3% reduction in load is needed to meet the TMDL allocation for the Missisquoi Bay segment (U.S. EPA 2016). The largest source of phosphorus loading to the bay is from agricultural activities (Vermont DEC 2013 and OBVBM, 2015). Phosphorus rich sediments have accumulated in Missisquoi Bay over many decades, and the release of this phosphorus to the water column presents an additional management challenge.

The project included five main tasks:

- Compilation of materials for a review of existing literature on nutrient loading and impacts on Missisquoi Bay. This compilation is presented in Chapters 1 through 4;
- Analysis of materials assembled through the literature review. This task included interviews with experts in Vermont, New York, and Québec to assess the effectiveness of existing efforts, data gaps, and opportunities for strengthening coordination and governance. This analysis is included in Chapter 4;
- Development of recommended approaches to strengthen current efforts. These recommendations are presented in Chapter 5;
- Consultation with the public and agencies in the Basin on recommended approach options;
- Development of a Project Final Report summarizing key findings and recommendations.

The key management recommendations for reducing the nutrient loads causing the proliferation of cyanobacteria in Missisquoi Bay include:

1. Create and coordinate a Bi-national Phosphorus Reduction Task Force to strengthen cooperation and accountability between the Parties in order to achieve mutually agreed goals.
2. Develop a binational mass balance analysis for phosphorus imports and exports in the Missisquoi Bay watershed.
3. Reduce phosphorus application to land in the Missisquoi Bay watershed.
4. Increase the proportion of crop systems that contribute less phosphorus.
5. Increase the protection and enhancement of floodplains, wetlands, and forest and ensure their reconnection for nutrient storage.
6. Engage with public stakeholders to commit to clean water and healthy ecosystem goals.

These recommendations are more fully described in Chapter 5. Beyond these six priority recommendations, Chapter 5 also includes several additional recommendations organized around the themes of agriculture, regulation and funding, research, developed areas, and legacy sediments in Missisquoi Bay. The development of the recommendations and project report was guided by a Champlain Science Advisory Group comprised of lake and watershed science and management experts in the U.S. and Canada.

1 Introduction

The International Joint Commission works to prevent and resolve disputes between the United States of America and Canada under the Boundary Waters Treaty of 1909 and ensures the common good of the two countries as an independent and objective body advising both governments (Mission statement, IJC).

The governments of the United States and Canada in collaboration with Vermont and Québec requested International Joint Commission assistance to develop a summary of work that has occurred in Missisquoi Bay to address harmful algal (cyanobacteria) blooms, which have recently become persistent in this bi-national embayment of Lake Champlain. This summary of work includes a suite of recommendations for additional management work in Missisquoi Bay that could be considered by management agencies and organizations in both countries to help achieve common management goals and ultimately reduce the frequency of harmful algal and cyanobacterial blooms. A parallel IJC project is underway in the Lake Memphremagog watershed, a binational lake with similar nutrient pollution and cyanobacteria challenges. Both projects are designed to encourage collaborative work across the Canada-US boundary to achieve common water quality goals.

1.1 Background, Purpose, and Scope

Lake Champlain's Missisquoi Bay Sub-Basin, straddling the Vermont-Québec border, includes the drainage areas of the Pike, Rock and Missisquoi Rivers, and the shoreline areas around Missisquoi Bay. The drainage area of 3,105 km^2 is shared between the Province of Québec (42%) and the State of Vermont (58%). Missisquoi Bay has long been impaired by eutrophication caused by excessive phosphorus loads from its Sub-Basin and has one of the highest in-lake phosphorus (P) concentrations of any segment of Lake Champlain (Lake Champlain Basin Program 2018). The 2016 Vermont phosphorus TMDL for Missisquoi Bay estimates that a 64.3% reduction in load is needed to meet the TMDL allocation for the Missisquoi Bay segment (U.S. EPA 2016). These water bodies are particularly vulnerable to the effects of agricultural nonpoint source pollution and stream bank instability (Vermont DEC 2013). Missisquoi Bay sediments are rich in phosphorus and present an additional management challenge.

Cyanobacteria (also known as blue-green algae) blooms have been a significant issue in Missisquoi Bay since the 1990s, which disrupt recreational activities and the drinking water supply for the town of Bedford, Québec. In recognition of the deteriorating water quality of the Bay, on August 26, 2002, the governments of Vermont and Québec established a formal commitment to reduce their share of the pollution entering the Bay. The agreement stated that Vermont will have 60% of the responsibility for reducing phosphorus loads to the Bay, and Québec will assume 40% of the responsibility (*Agreement between the Gouvernement du Québec and the Government of the State of Vermont Concerning Phosphorus Reduction in Missisquoi Bay* 2002). While the governments and citizens of Vermont and Québec have made progress to reduce phosphorus loads to the Bay, these targets have not yet been met.

International Joint Commission

In October 2017, the governments of Canada and the United States mandated the International Joint Commission (IJC) to collect and review information on reducing nutrient loads and harmful algal blooms in Missisquoi Bay, to make recommendations to enhance the combined efforts of Vermont and Québec and accelerate progress toward reaching water quality goals for Missisquoi Bay.

For the fulfillment of this work, the IJC contracted with the *Organisme de Bassin Versant de la Baie Missisquoi* (OBVBM) for the Québec portion and the Lake Champlain Basin Program (LCBP) for the Vermont section. A literature review was completed to provide a picture of the current situation and the state of knowledge concerning Missisquoi Bay and its watershed, including an overview of the programs and policies already in place in both countries. Experts in water quality, including researchers and practitioners from governmental, municipal and agricultural organizations were also consulted to assess legislation and regulations, governance, financial support programs and actions taken, and to help develop a set of water quality management recommendations.

This literature review was conducted with funding from the International Joint Commission (IJC), awarded to OBVBM, LCBP, and the New England Interstate Water Pollution Control Commission (NEIWPCC). Five main tasks comprise the project:

- Compilation of materials for a review of existing literature on nutrient loading and impacts on Missisquoi Bay. This task includes review by the Lake Champlain Basin Program Technical Advisory Committee and the IJC's Champlain Science Advisory Group (CSAG). This task resulted in a draft *Summary Report*. This report represents the first draft of that *Summary Report*.
- Analysis of materials assembled in the *Summary Report*. This task includes interviews with experts in Vermont, New York, and Québec to assess the effectiveness of existing efforts, data gaps, and opportunities for strengthening coordination and governance. This task will result in a draft *Synthesis Report*.
- Development of one or more recommended approaches to strengthen current efforts. This task includes review by the Lake Champlain Basin Program Technical Advisory Committee and the CSAG. This task will result in a recommendations section for the Synthesis Report.
- Consultation with the public and agencies in the Basin on recommended approach options. This task will include public meetings held in Vermont and Québec, and a compilation of public input from those meetings will be developed.
- Development of a Project *Final Report*. This task includes review by the Lake Champlain Basin Program Technical Advisory Committee and the CSAG. This task will result in a *Final Report* summarizing key findings and recommendations.

1.2 Prior IJC Work in the Lake Champlain Basin

Over the past several decades, The International Joint Commission (IJC) had been actively involved in furthering the understanding of the environmental challenges faced in the Missisquoi Bay Sub-Basin and helping to foster management strategies to address those difficulties. This section provides a brief summary of several of the relevant studies in which the IJC has been involved.

1.2.1 Causeway Removal Water Quality Study

The Swanton-Alburgh Route 78 Bridge was constructed in 1937 and consisted of a causeway section extending from each shore, connected by a bridge 170 m in length. With deterioration of the structure, a new fixed-span bridge was constructed in 2004-2005.

In 2004, the governments of the United States and Canada asked the IJC to assess the impact of the causeway at the Missisquoi Bay outlet on the Vermont side. In its 2005 report, the IJC concluded that the causeway produces an increase of about 1% in the concentration of phosphorus (average for the entire bay) and sedimentation rate (fine fractions only) in Missisquoi Bay. It was also determined that the causeway does not hydraulically restrict the flow of water between Missisquoi Bay and the rest of the Northeast Arm (Mendelsohn, Swanson, and Isaji 1997).

The IJC recommended that the improvement of Missisquoi Bay's water quality is dependent on the international agreements and plans and that those agreements should be the focus of future government actions. The IJC also recommended the removal of the causeway. Finally, a 100 m section was removed in 2007 when the new bridge was built.

1.2.2 Identification of Critical Source Areas

From 2004 to 2007, the Province of Québec invested more than $1 million in research, monitoring and modeling of agricultural non-point loading to identify sensitive areas and critical sources of nutrient loads and the effectiveness of best management practices in Missisquoi Bay (IJC reference, 2008).

As an example, the results of a SWAT modeling study in the Ewing subwatershed a Pike's river downstream tributary concluded that "the four components hydrograph model revealed that 46 to 67% of the TP load at the outlet originated from surface runoff during peak flow. Preferential flow was responsible for most of the particulate P and dissolved reactive P loads lost through tile drainage. Groundwater resurgence was a minor source of Total P, whereas other sources such as streambank erosion and resuspended sediments contributed up to 21% of the TP load and from 36 to 41% of the particulate P load at the subwatershed outlet." (Michaud,A.R.,I. Beaudin, F Bonn et C.A. Madramootoo. 2007)

Recognizing those recent advances, in 2008 the IJC asked LCBP to compile and analyze information on critical sources areas (CSAs) of phosphorus loading of the tributary drainage in the Vermont sector of Missisquoi Bay. The goal of the study was to provide an adequate transboundary picture of the watershed when combining this IJC work with work undertaken in Québec (Phosphorus Loading in Missisquoi Bay, IJC, 2012).

Locating CSAs is extremely important for basin management, as it allows managers to prioritize areas of focus and implement the most appropriate best management practices. The Soil and Water Assessment Tool (SWAT) was used to conduct basin model simulations using 30 years of historical climate data, with input parameters including land use categories, sub-basin characteristics, and field-level assessments of phosphorus source areas to identify CSAs (Winchell et al. 2011; Winchell et al. 2015).

The analyses showed that about 74% of the phosphorus load comes from just 20% of the Sub-Basin area, and 92% of the total phosphorus comes from only 50% of the Sub-Basin (Winchell et al. 2015). Approximately 60% of sediment and phosphorus come from upland sources, with the agricultural land use classification accounting for 64% of that area (Winchell et al. 2011). As such, the sub-watersheds with the highest agricultural usages, which includes the Rock, Mud, Pike, and Hungerford drainage areas, are the biggest contributors to phosphorus loading. The remaining 40% of the phosphorus load is due to streambank erosion (Winchell et al. 2011). Several setting characteristics- hydrologic soil group, compound topographic index (CTI), and slope- were the most important factors to determining the phosphorus export quantity and CSA location. Model simulations also evaluated the effectiveness of strategic implementation of three BMPs: manure phosphorus reduction, cover cropping, and changes in crop rotation. Finally, analyses determined that the magnitude of phosphorus loading rates is predicted to increase with of climate change, with a projected 21-57% increase in sediment load. However, these trends do not appear to reorder CSA location or implementation priorities (Winchell et al. 2011).

1.2.3 Lake Champlain-Richelieu River Flood Mitigation Studies

In response to catastrophic flooding in 2011, the IJC established a workgroup to evaluate the causes and impacts of Lake Champlain-Richelieu River flooding and determine possible mitigation strategies. This newly formed International Lake Champlain-Richelieu River Workgroup developed a Plan of Study to address the concerns of the IJC. The Plan of Study was composed of three options and meant to be scalable to best utilize any available resources. These options include basic modeling of the system to evaluate the impacts of past flooding, explore BMPs for floodplain management, investigate potential adaptation strategies, and examine the benefits of flood forecasting and real-time mapping approaches (International Lake Champlain and Richelieu River Plan of Study Workgroup 2013). In addition, the Plan of Study included quantitative and qualitative assessment of possible flood mitigation measures. The workgroup recommended that the IJC conduct an in-depth investigation of current public perceptions on flooding mitigation measures to better inform the individual components of the Plan of Study.

In 2015, the International Lake Champlain – Richelieu River Technical Working Group produced a report detailing their work ("Progress towards an Operational Real-Time Flood Forecasting and Flood Inundation Mapping System for the Lake Champlain and Richelieu River: Preparatory Works and Static Flood Inundation Maps" 2015). The study components addressed in this phase of the project were the development of real-time hydrologic and hydraulic models for predicting water levels in Lake Champlain and the Richelieu River, as well as the creation of static flood inundation maps for the public. This international effort required extensive data collection, organization, and normalization, including the development of vertical datum corrections. While the initial hydrodynamic modeling was found to work well for the lake and Richelieu River to Chambly, more bathymetric data from Chambly to Sorel is needed to more accurately simulate flooding and river flows ("Progress towards an Operational Real-Time Flood Forecasting and Flood Inundation Mapping System for the Lake Champlain and Richelieu River: Preparatory Works and Static Flood Inundation Maps" 2015). The technical working group had many recommendations for the IJC moving forward, including suggestions for model enhancement and refinement, sites for continued data collection, and additional data needs (e.g., a single DEM for the entire Lake Champlain – Richelieu River Watershed). Additionally, the technical working group recommended an international coordination entity to coordinate the efforts of the governmental agencies responsible for forecasting and water-level predictions.

1.3 Study Areas

1.3.1 Lake Champlain

With an area of 1,127 km^2, Lake Champlain has a watershed of 21,326 km^2. The Lake Champlain Basin is home to more than 600,000 people in the states of New York, Vermont, and the province of Québec (Fig. 1). Spanning 193 km in length and holding 26 million m^3 of water, Lake Champlain flows north to the Richelieu River and subsequently to the St. Lawrence River. The Watershed's rich soils provide extensive agricultural opportunities and its waters provide recreation, drinking water, and habitat for abundant wildlife. With waters in the U.S. states of New York and Vermont and the province of Québec, Lake Champlain has a rich history and supports a vibrant, binational economy. Lake Champlain comprises five major unique lake segments (the South Lake, Main Lake, Malletts Bay, Northeast Arm, and Missisquoi Bay) with distinctive bathymetry, water quality issues, and community character. In addition to the challenges associated with several governmental entities managing the Lake, each of the Lake's segments influences the others, making it critical that a basin-wide approach to management continue to be employed.

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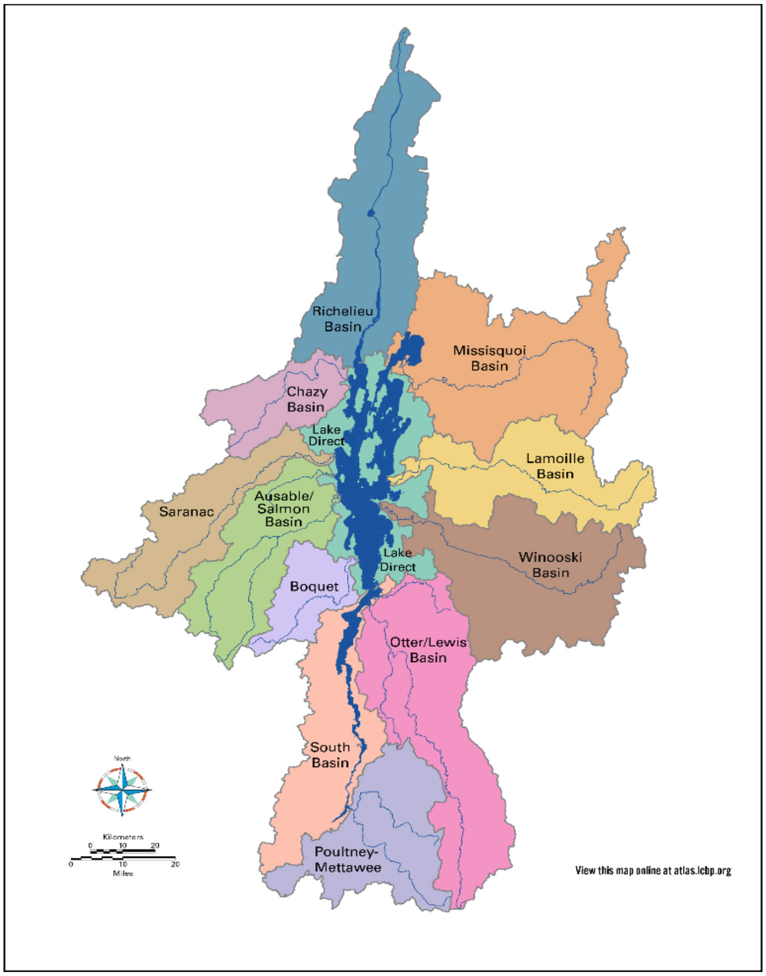
Figure 1. The Lake Champlain Watershed is 21,326 km2 and made up of 11 major sub-Watersheds. Map from (“Lake Champlain Basin Atlas” 2018)



1.3.2 Richelieu River

The Richelieu River, which stretches along 124 km, flows out of Lake Champlain and is one of the main tributaries of Lake Saint-Pierre in the St. Lawrence River. The Richelieu River watershed covers an area of 2,546 km^2 (excluding Lake Champlain). Due to rich soils and a mild climate, agriculture is a major activity throughout the watershed, covering nearly 70% of the land, of which 76.9% consists of field crops. Anthropogenic habitats account for 9.7% of the total area, while forest and wetland habitats account for 15% and 2.4% respectively (Simoneau *et al.,* 2017). In 2014, the permanent population of the Richelieu River watershed was 469,113, with a population density of 184/km^2 (COVABAR 2015).

1.3.3 Missisquoi Bay

Missisquoi Bay covers an area of 77.5 km^2 (46.1 km^2 in Québec), representing approximately 7% of the total area of Lake Champlain (1,127 km^2). The bay has an average depth of 2.8 m, and a maximum depth of 5 m. The ratio of the Missisquoi Bay area to that of its watershed (3,122 km^2) is 40:1—a relatively high ratio that makes Missisquoi Bay more vulnerable to potential negative effects of land use (Levine *et al.,* 2012). The natural features of Missisquoi Bay make it particularly vulnerable to eutrophication with its low mean depth and complex hydraulic circulation, relatively high bottom temperature, and lack of thermal stratification (EXXEP 2004). The three main waterways flowing into Missisquoi Bay are the Missisquoi River, the Pike River and the Rock River.

Table 1. Area of Missisquoi Bay Sub-basins

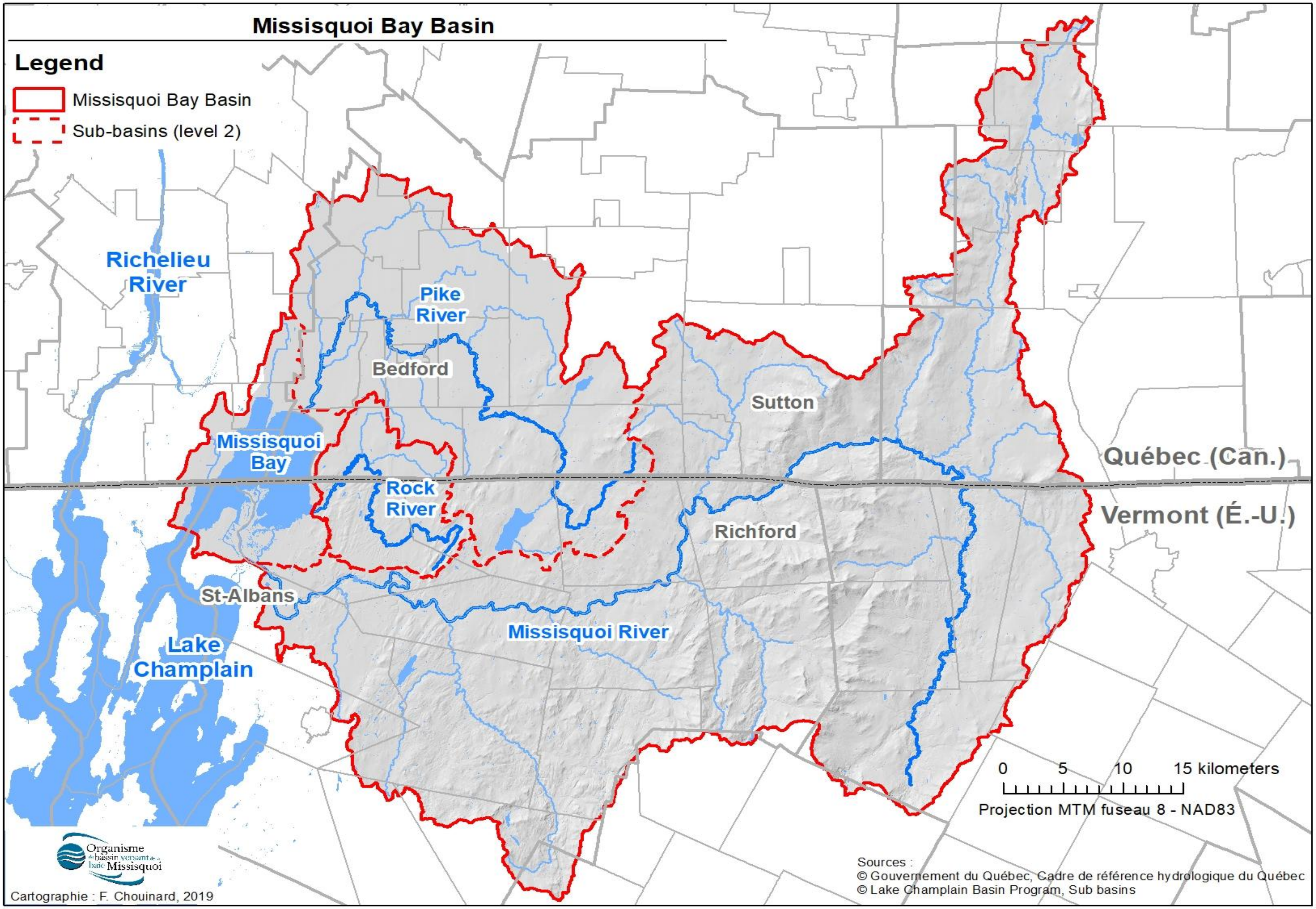
Sub-basin	**Area in Québec**		**Area in Vermont**		**Total area**	
	km²	*% in Qc*	*km²*	*% in Vt*	*km²*	*% of total*
Direct drainage to Bay	56	51%	54	49%	110	4%
Rock River	52	36%	92	64%	144	5%
Pike River	552	84%	102	16%	653	21%
Missisquoi River	652	29%	1562	71%	2214	71%
TOTAL Missisquoi Bay basin	**1311**	**42%**	**1810**	**58%**	**3122**	**100%**

Sources: DEH, 2018; LCBP, HUC12 2013 v2

The permanent population for the Québec portion of the Missisquoi Bay watershed was estimated to be 23,650 in 2017, and it has increased by 17% since 1996 (ISQ, 2018). The seasonal population, which includes occupants of secondary residences and cottages mainly located in Sutton, Venise-en-Québec, Potton, and Eastman, is estimated to be approximately 15,300 (MRC Brome Missisquoi, 2013). The total summer population of the Québec portion of the watershed is therefore approximately 39,000. In 2010, the Vermont portion of the watershed had an estimated population of 25,620 (US *Census Bureau*, 2010). However, seasonal population data are not available for the Vermont portion. The total population of the watershed (Québec and Vermont) is estimated to be 49,270 permanent residents.

Missisquoi Bay is the source of drinking water for thousands of people, an important economic and recreational resource for the region. The bay has several beaches and campgrounds that include about 900 sites**.** Missisquoi Bay is a popular spot for boaters, sailors especially for windsurfer and kitersurfer.

Figure 2. Missisquoi Bay watershed is 3,108 km² in area. OBVBM 2019



1.4 Literature Review and Quality Assurance

This literature review is intended to be representative of the current state of knowledge of nutrient loading and cyanobacteria issues in Lake Champlain, the Richelieu River, and Missisquoi Bay. The review addresses the major sources, causes, and dynamics of nutrients in the study areas and how those nutrients impact the growth of cyanobacterial blooms. Additionally, this review provides an analysis of the efficacy of various policies and programs that have aimed to manage nutrients and cyanobacteria and control their impacts on public health and the environment.

This review was conducted in accordance with an approved Quality Assurance Project Plan (QAPP). Information was obtained from peer-reviewed journals, approved graduate theses, government and other technical reports, as well as active research information from the Lake Champlain Basin Program. Original sources were collected for references that cited the data of other studies. Zotero, a free, open-source reference management software, was used in order to collectively manage and organize reference documents.

In Vermont, 171 references were collected and reviewed of which 65 are cited herein. All non-peer reviewed sources were internally reviewed to ensure that they represent high-quality information published by reputable authors. Work concerning the study areas of Lake Champlain, Richelieu River, and Missisquoi Bay was given precedence over studies conducted elsewhere.

In Québec, 150 references were collected and the OBVBM interviewed 65 people, using a questionnaire, and drafted a complete synthesis of the views expressed. The QC CSAG assessed sections of the interviews that were most relevant to the IJC's mandate. Views reflecting a certain consensus or raised by several respondents are included in this report. They are presented in various sections of the report and are referenced as "OBVBM Interviews 2019."

Regarding the mention of phosphorus throughout this report, this nutrient is measured and reported several ways including total phosphorus (TP), soluble reactive phosphorus (SRP), and particulate phosphorus (PP). Moore offers a thorough description of the various forms of phosphorus and the associated nomenclature (2016). Unless otherwise indicated, the term "phosphorus" in this report refers to total phosphorus.

To reduce confusion in this report the Lake Champlain Basin is referred to as "the Basin" or "the watershed" and the Missisquoi Bay Sub-Basin is referred to as the "the Sub-Basin".

2 Key Nutrient Loading and Cyanobacteria Issues

2.1 Overview of Nutrient Loading and Cyanobacteria Issues in Lake Champlain and Missisquoi Bay

Lake Champlain faces several water qualities challenges, including climate change, aquatic invasive species, and nutrient pollution (Smeltzer, Shambaugh, and Stangel 2012; Lake Champlain Basin Program 2018). One of the greatest obstacles that Lake Champlain communities face is cyanobacterial blooms. These blooms pose a multitude of obstacles for local economies and public health, including reductions in recreational use and potential health impacts from exposure to cyanotoxins in drinking and recreational waters. The location, timing, and intensity of cyanobacteria blooms vary from year to year, but often occur in the late summer on Missisquoi Bay and can persist for weeks at a time (Shambaugh 2016; Pearce et al. 2013).

Not all cyanobacteria species produce toxins, and those that can produce toxins do not always do so. Cyanobacterial toxins can be harmful to humans, pets, and wildlife, and can act on several different human systems. In addition to the skin irritation and gastrointestinal symptoms that may be caused by contact with cyanobacteria, hepatotoxins (e.g., microcystin and cylindrospermopsin) can cause liver damage, and neurotoxins (e.g., anatoxin and BMAA, or Beta-Methylamino-L-alanine) can damage the nervous system (Shambaugh 2016). A short-term study which analyzed microcystin and anatoxin-a in the Burlington Water and Champlain Water treatment plants found low levels of these toxins in both raw and finished water samples (Boyer et al. 2004). Ongoing sampling of drinking water facilities utilizing Lake Champlain as a source of supply is discussed further in Section 2.2.3. Aside from Missisquoi Bay and the Northeast

Arm, microcystin concentrations are generally very low in both the Lake as a whole and only very rarely found in raw and finished drinking water (Boyer et al. 2004; Lake Champlain Basin Program 2018; Shambaugh et al. 2017).

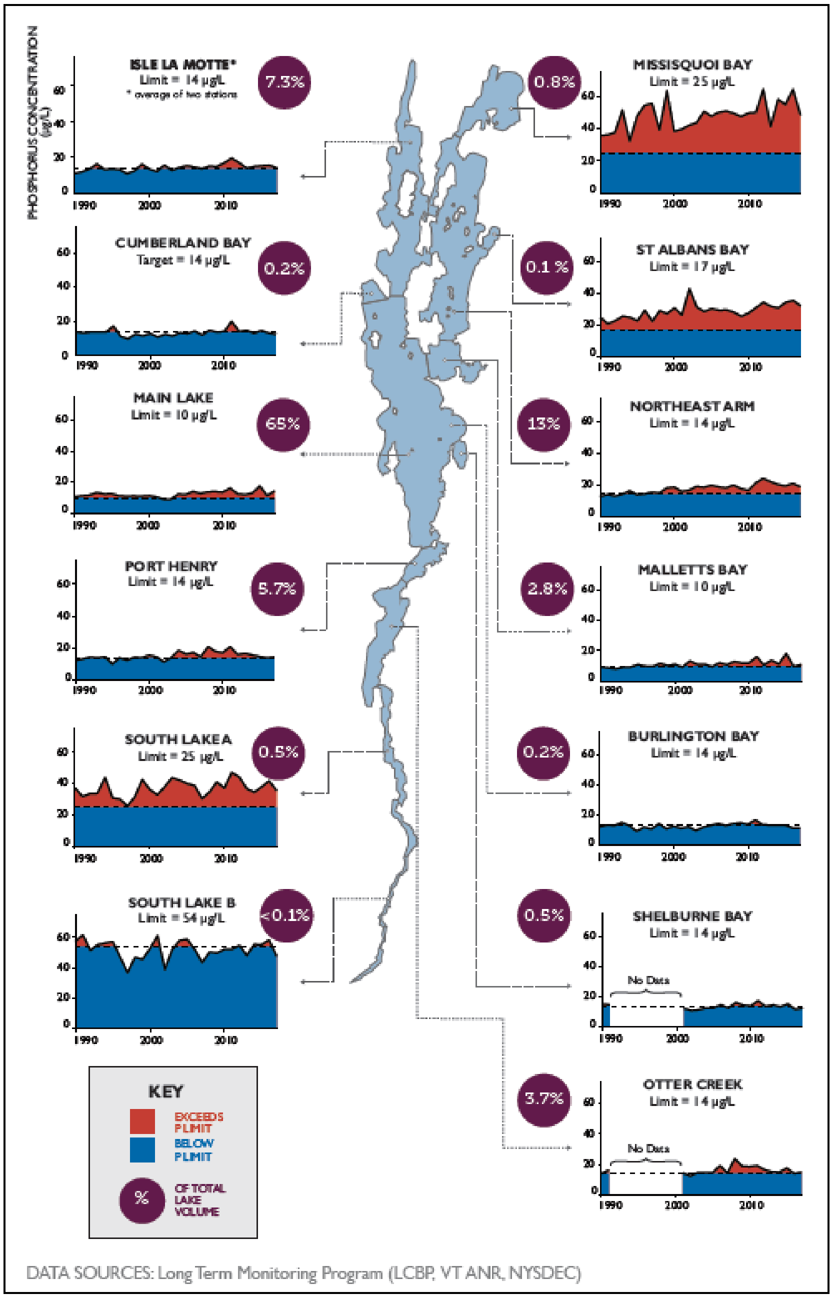
While cyanobacteria are present in Lake Champlain's paleolimnological sediment record (Levine et al. 2012), cyanobacterial blooms are occurring more frequently in concurrence with higher phosphorus inputs from changes in land use and increasing water temperatures (Facey et al. 2012). Climate change projections for Lake Champlain suggest that the Basin's air and water temperatures will increase, leading to more favorable conditions for cyanobacterial growth (Shambaugh 2016; Isles 2016). The *Direction de l'expertise hydrique* of Québec (DEH) has produced the *Hydroclimatic Atlas of Southern Québec,* which presents a portrait of the impact of climate change on the hydrological regimes (floods, low water periods, hydraulicity) of southern Québec by 2050 (CEHQ, 2013 and 2015). In terms of hydraulicity calculated for the Missisquoi River and the Pike River, the DEH predicts a very likely increase in average winter-spring flow and a likely decrease in average summer-fall flow (DEH, 2018). According to data from the DEH and USGS, all hydrometric stations in the bay's watershed have experienced an increase in average annual flows since they began to operate (CEHQ, 201). The spring melt is expected to begin earlier, gradually moving towards February, reaching its maximum in March instead of April (Mehdil, 2013)

Cyanobacterial growth is dependent upon the concentration of bioavailable phosphorus, which is thought to often be a limiting nutrient in freshwater systems (Wetzel 2001; Isles 2016). Excessive phosphorus continues to be an issue in Lake Champlain and work beginning to establish total maximum daily loads (TMDLs) for phosphorus began in the 1990s. For phosphorus concentration management purposes, the lake is divided into 13 segments, 12 of which have a TMDL established by the EPA addressing phosphorus loads from the Vermont portion of the basin (U.S. EPA 2016). A TMDL developed by NYSDEC in 2002 addresses phosphorus loads from the New York portion of the basin. No established long-term trends have been identified in any of the lake segments, other than the Northeast Arm, which demonstrates an increasing trend from 1990-2017 (Lake Champlain Basin Program 2018). The Missisquoi Bay, St. Albans Bay, South Lake A, and Northeast Arm segments all typically exceed their established phosphorus limits (Fig. 3).

Frequently, phosphorus is imported via widespread fertilizer/manure use and animal feed, making agricultural production the largest source of phosphorus input to the Lake (U.S. EPA 2016). The phosphorus load from agricultural land in the Vermont portion of the Missisquoi Bay watershed is about 58 mt/yr, which accounts for about 42% of the total phosphorus load from this portion of the watershed (USEPA 2016). Lake Champlain Basin-wide phosphorus exports per animal unit have more than doubled between 1925 and 2012 (Wironen, Bennett, and Erickson 2018). A major challenge to addressing the phosphorus loading to the lake is that part of the contribution is from legacy phosphorus that has been added to the soil from long-term agricultural practices. This legacy phosphorus will continue to reach the waterways despite active reduction efforts (Lake Champlain Basin Program 2018).

Two other phosphorus sources of concern are developed lands and streambank sediments. Developed lands account for around 4% of the Lake Champlain Basin's total area, and around 16% of its total phosphorus load (U.S. EPA 2016; Lake Champlain Basin Program 2018). Most of this phosphorus comes from the alteration of the hydrologic cycle by impervious surfaces. Those impervious surfaces generate pollutant loads associated with the wash off of accumulated sediment, and the increased surface runoff can also exacerbate streambank erosion. Streambank sediments often enter waterways from stream corridor areas lacking sufficient vegetation or floodplain connectivity to provide stability. This important source contributes 165 mt of phosphorus to the lake each year, accounting for approximately 18% of the total phosphorus load (Lake Champlain Basin Program 2018).

Figure 3. Annual phosphorus means concentrations and TMDL targets for the 13 lake segments from 1990-2017(Lake Champlain Basin Program 2018).



As shown in Fig. 3, Missisquoi Bay remains the most problematic lake segment for phosphorus concentration.

Point source discharges from wastewater treatment facilities are a relatively minor contributor to the phosphorus problem in Missisquoi Bay, adding up to just 1.7% of the total load to the Bay between 2001 and 2010 (USEPA, 2016). Lake-wide, from 1991 to 2009, improved phosphorus removal by wastewater treatment facilities has resulted in an 83% decrease in wastewater phosphorus loading to Lake Champlain.

In addition to the external contributions, internal phosphorus loading is an issue in the Bay. Sediments that have been deposited into the lake bottom store phosphorus and act as a reservoir that can release phosphorus over time when the water conditions are conducive. The amount of phosphorus released from bottom sediments is dependent on wind, river discharge, and other factors affecting mixing, water column stability, and oxygen levels at the sediment/water interface (Giles et al. 2016). A study by Levine et al. (2011) on the evolution of Missisquoi Bay sediments found that the rate of accumulation of the oldest sediment characterized was approximately 0.6 kg/m^2/year by the end of the 19th century. This rate grew gradually, followed by a significant increase from the 1990s to 1.4 kg/m^2/year. Phosphorus in sediments contributes to cyanobacteria blooms, the accelerated eutrophication of the lake and the degradation of its aquatic ecosystem. In addition, this internal loading makes reaching the target attainment of phosphorus concentration of 0.025 mg/L for Missisquoi Bay more difficult.

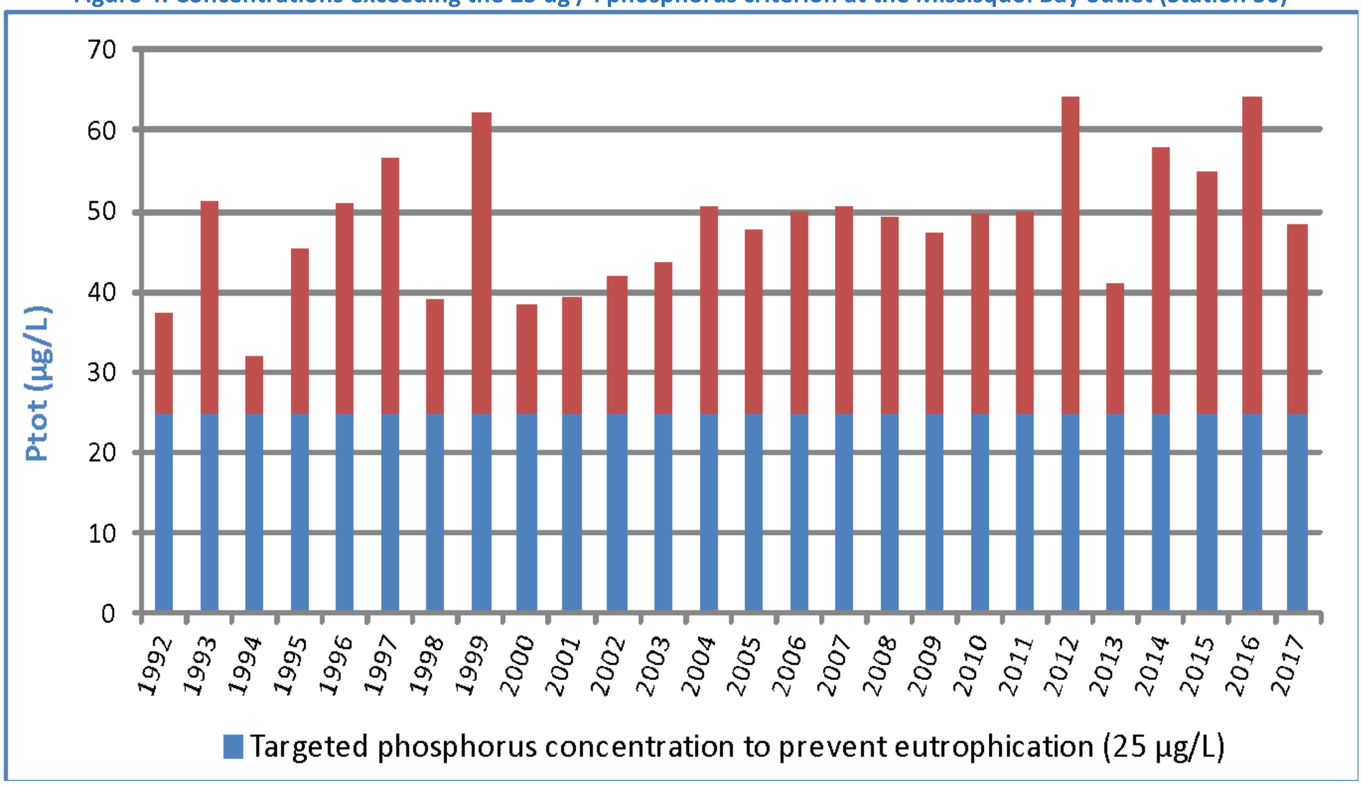
2.2 Detailed Analyses of Missisquoi Bay and Its Sub-Basin

Missisquoi Bay is a relatively warm, shallow eutrophic segment of Lake Champlain. The character of its watershed (e.g., land: water ratio, elevation), along with land-use practices within its catchment, magnifies the water quality degradation and nutrient enrichment issues faced throughout Lake Champlain.

Missisquoi Bay has been affected by eutrophication for decades. For example, from June to September 1967, the average phosphorus concentration was 0.085 mg/L at the Canada-U.S. border (Fontaine et al., 1968). Examination of the data shows that from 1979 to 2009 the concentration of phosphorus increased by 72% and that of chlorophyll a doubled (Smeltzer et al., 2012).

Figure 4 illustrates the magnitude of exceedances of annual average phosphorus concentrations at Station 50 since 1992, relative to the target of 0.025 mg/L (LCBP, 2018).

Figure 4: Concentrations exceeding the 25 ug / l phosphorus criterion at the Missisquoi Bay outlet (Station 50)



Source: LCBP, 2018

Based on the 2016 TMDL, the estimated load from 2001 to 2010 was 72.4 MT (35%) for Québec and 136.3 MT (65%) for Vermont, for a total of 208.7 MT (TetraTech, 2015). The total target loading to be achieved under this new TMDL, to reach the target concentration of 0.025 mg/L in Missisquoi Bay, would be 81.0 MT of phosphorus per year—32.4 MT for Québec and 48.6 MT for Vermont (TetraTech, 2015). The internal loading of phosphorus was considered in the review of this 2016 TMDL, which required Vermont and Québec to further reduce inputs from tributaries.

Table 2. Missisquoi Bay total maximum daily loads (base loads and loading capacities) 2002 and 2016

	Qc-Vt Agreement (TMDL 2002		TMDL 2016	
	Base load (1991) (% allocation)	Total loading capacity (% reduction)	Base load (2001-2010) (% allocation)	Total loading capacity (% reduction)
Québec	66,2 (40%)	38,9 (41%)	72,4 (35%)	32,4 (55%)
Vermont	101,1 (60%)	58,3 (42%)	136,3 (65%)	48,6 (64%)
TOTAL	167,3 (100%)	97,2 (42%)	208,7 (100%)	81,0 (61%)

Sources: Hegman et al., 1999, TetraTech, 2015

Despite an actual increase in loadings to Missisquoi Bay, the comparative analysis of concentration-flow relationships between 2001-2005 and 1990-1992 showed a significant decrease in phosphorus concentrations for the low flow range (< 100 hm^3/year), reflecting the effect of urban and industrial remediation measures and a significant decrease in the high flow range (≥ 100 hm^3/year), suggesting an improvement associated with agricultural remediation (Smeltzer and Simoneau, 2008). For example, in comparison to 1991 data, phosphorus loadings from wastewater treatment decreased by 73% in Vermont and 74% in Québec between 2001 and 2005 (Simoneau and Smeltzer, 2008.). The study of trends for the period 1990-2008, published in 2009 by the LCBP in collaboration with the *Ministère de l'Environnement et de la Lutte contre les changements climatiques* (MELCC), indicated that phosphorus loadings from the Missisquoi River, calculated based on two-year blocks, have remained stable (Smeltzer et al., 2009). Loads in the Pike River have shown a slight downward trend, considered to have little significance. But both rivers, loads decreased between 1990 and 2000, and then increased between 2000 and 2008, as average flows increased over that period (Smeltzer et al., 2009).

In the Québec portion, the downward trends observed since 1999 in some tributaries of Missisquoi Bay show significant improvements in low flow ranges and point source inputs, with positive signals coming from some agricultural sub-watersheds. However, since 2006, loadings appear to remain stable despite the efforts deployed. The relative stability of phosphorus loadings observed from 2006 onwards is explained by the fact that residual loadings are mainly from diffuse sources (Simoneau, OBVBM Interviews, 2019). The combination of remediation efforts has helped to reduce phosphorus inputs. However, the high concentrations that are still associated with the river's high flows mean that the reduction in loads is slower (Ibid.).

Several assumptions have been made to explain the stationarity of concentrations in some streams:

- Inadequate and unsustainable responses to drive measurable change;
- Interventions did not sufficiently affect critical areas;
- Sufficient interventions that are too recent to have caused change;
- The implementation of agro-environmental practices cannot erase the effects of previous fertilization practises that have led to excessive soil enrichment

  and that remain part of the current degree of soil fertility and internal loading of the bay, in the form of accumulated sediments.

In the absence of evidence of improvement since 2006, however, this stability indicates that interventions have to some extent prevented degradation in the quality of waterways despite pressures on them (Simoneau, 2018). However, in the main tributaries of Missisquoi Bay, nutrient and sediment concentrations and loads remain excessive in relation to targets and criteria for the protection of ecosystems and the bay. Significant efforts are still required to reduce phosphorus inputs, including those from nonpoint sources, into the Missisquoi Bay watershed.

While the drainage area to Missisquoi Bay makes up only 15% of the lake's total watershed, it contributes about 23% of the total phosphorus load to the lake. The effects of this disproportionately high phosphorus loading from the Bay watershed are compounded by the Bay's shallowness and limited connectivity to the rest of the lake. The resulting excessive phosphorus levels threaten Missisquoi Bay's ecosystem, public drinking water supply, and recreational opportunities. (Troy et al., 2007; TetraTech, 2015).

2.2.1 Hydrodynamics

Missisquoi Bay is the most northern embayment of Lake Champlain, with relatively straightforward hydrodynamics due to the shallow depth and limited connection with the rest of Lake Champlain through Alburgh Passage. The restricted opening at the southern end of the Missisquoi Bay focuses water flow out of the Bay, with 86% of the volume flowing outward through Alburgh Passage and Carry Bay (Marsden and Langdon 2012). The Missisquoi Bay outfall, with a natural width of approximately 1,350 m, features a significant narrowing of two embankments totalling 1,080 m, remnants of the former Alburgh-Swanton Causeway, with a 270 m opening in the centre, or 20% of the original width.

The Bay receives water from three tributaries: the Missisquoi, Pike, and Rock Rivers. The longest of the three is the Missisquoi River, at approximately 142 km. The land use of this tributary comprises 60%, 24%, and 6% of forested, agricultural, and urban coverages, respectively (Vermont DEC 2013). The Missisquoi River accounts for 79% of the discharge to the Bay (Limnotech 2012). The Pike River has a similar land use composition with 51%, 34%, and 5% of forested, agricultural, and urban uses, respectively (Vermont DEC 2013). Finally, the Rock River is composed of 40%, 41%, and 5% forested, agricultural and urban uses, with an additional 7% of the land coverage identified as wetlands. The Pike and Rock Rivers contribute 18% and 3% of discharge to the Bay, respectively (Limnotech 2012).

The hydrodynamics of Missisquoi Bay are primarily wind-driven (Manley et al. 1999), but also affected by thermal dynamics, solar radiation, and discharge quantity (Isles 2016). There are four identified circulation modes: wintertime sluggish, spring melt, well-mixed summer, and two-layer summer (Manley et al. 2018).

There are 25 dams throughout the Missisquoi Sub-Basin, with varying uses and statuses, altering flow and affecting water quality and sediment transport (Vermont DEC 2013). Tile drainage also alters the hydrology of the Sub-Basin, increasing total water output from field, but reducing the quantity of surface water (Moore 2016). Approximately 75% of the Missisquoi basins stream channels and water bodies have adjustment resulting from modifications to land cover and hydrology, as well as anthropogenic channel re-alignments (Potter et al. 2008).

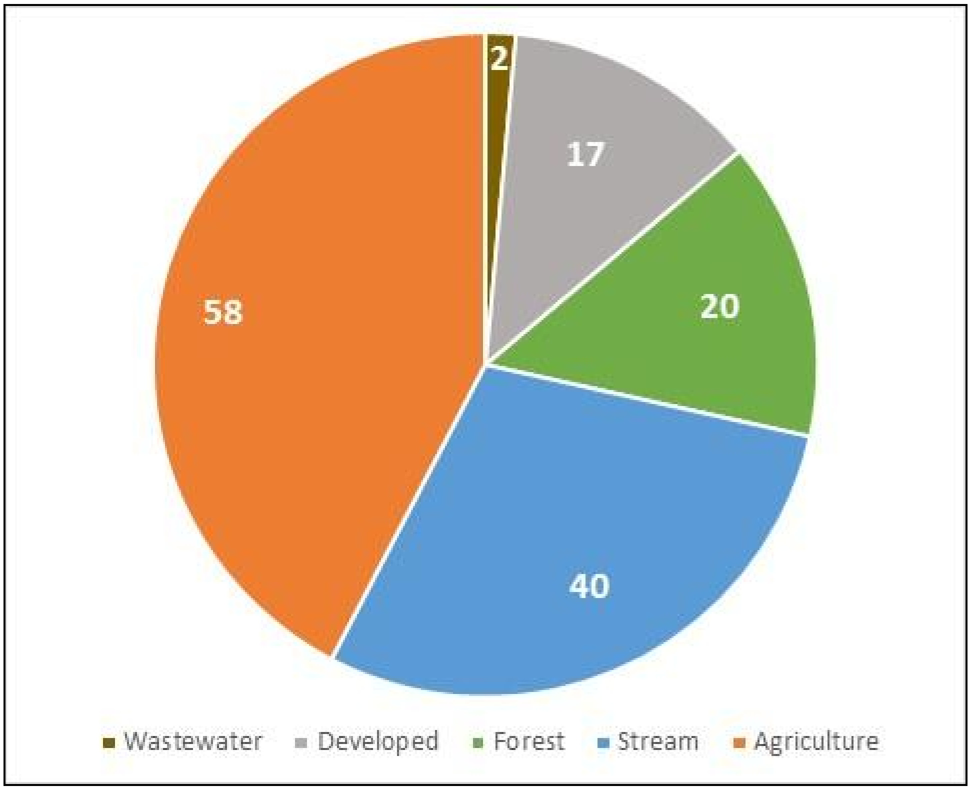
2.2.2 Nutrient Enrichment

Dynamics, Sources, and Causes

Phosphorus concentrations typically exceed water quality standards both in Lake Champlain as a whole and in Missisquoi Bay. The Lake is on the US EPA's 303(d) list of impaired water bodies for phosphorus and TMDLs have been developed for all 13 (US EPA 2016). The Missisquoi Bay watershed, when considering both the Vermont and Québec contributions (136 and 72 mt y^{-1}respectively) accounts for 23% of Lake Champlain's total phosphorus load (922 mt y^{-1}).

During the period of 2001-2010, Vermont sources contributed an average of 136 mt y^{-1} of phosphorus, 42% of which was from agricultural sources and 29% from streams, primarily streambank erosion (U.S. EPA 2016) . Mean phosphorus loading rates have been analyzed for sub-watersheds within the Missisquoi Bay Sub-Basin. Sub-watersheds determined to have the highest mean phosphorus loading rates were the Lower Missisquoi, Pike, Missisquoi Nord, and Upper Missisquoi (Smeltzer and Simoneau 2008). Water in Missisquoi Bay consistently exceeds its Vermont phosphorus criteria of 0.025 mg/L. The phosphorus loads from sources such as developed, forested and agricultural lands are some of the highest amongst all the Lake Champlain segments (U.S. EPA 2016). The pie chart below illustrates the major role that agricultural sources play in enriching Missisquoi Bay.

Figure 5. Phosphorus loading (mt y^{-1}) to Missisquoi Bay from the Vermont portion of the Sub-Basin, 2001-2010.

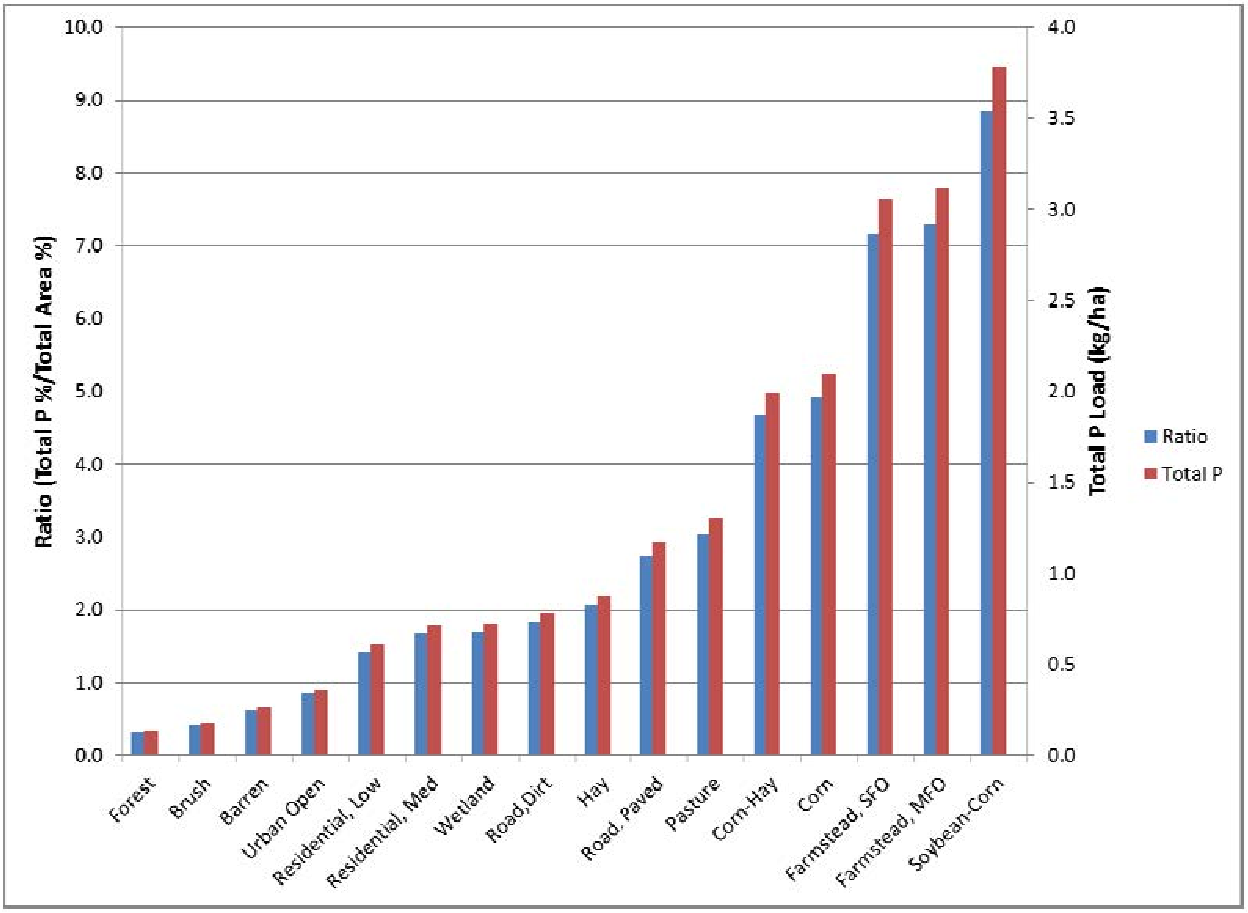


Data from U.S. EPA 2016.

Point sources are found throughout the Sub-Basin. Vermont has seven municipal and one industrial wastewater treatment facility, while Québec has eight municipal wastewater discharges (Missisquoi Bay Phosphorus Reduction Task Force 2000). However, wastewater discharges have been found to be a relatively small source of phosphorus loading to Missisquoi Bay. During 2002-2005 they represented only 2% of the total phosphorus load from Vermont, and 3% of the total load from Québec (Smeltzer and Simoneau 2008). Other urban or developed land uses have average phosphorus loading rates compared to other land-use classifications, but with developed land accounting for only 6% of the land area in the Missisquoi Bay Sub-Basin, the associated phosphorus loading is small (Winchell et al. 2011).

Streambank erosion is a significant source of nutrients, contributing approximately 29%-40% of phosphorus to the Bay (Morrissey and Rizzo 2010; Winchell et al., 2011; Langendoen et al. 2012; U.S. EPA 2016) and approximately 29-42% of total suspended solids delivered to the Bay annually (Langendoen et al. 2012). Phosphorus mass-balance mixing studies have found that deposited sediments play a significant role in the Bay's phosphorus cycle, with legacy sediment acting as both a source and sink of phosphorus (Limnotech 2012). Sediment fluxes are responsible for 20% and 43% of total phosphorus inputs during the whole year and summer, respectively (Limnotech 2012). In addition to streambank sources, erosion from agricultural or forestry practices can also play a role in nutrient deposition. The annual tillage of corn fields, as well as bank instability due to animal traffic can also contribute to erosion and, thereby, sediment and phosphorus contributions to streams and Missisquoi Bay (Potter et al. 2008).

Figure 6. Total P loading rate and load to area ratio for major land uses (CSA assessment area)

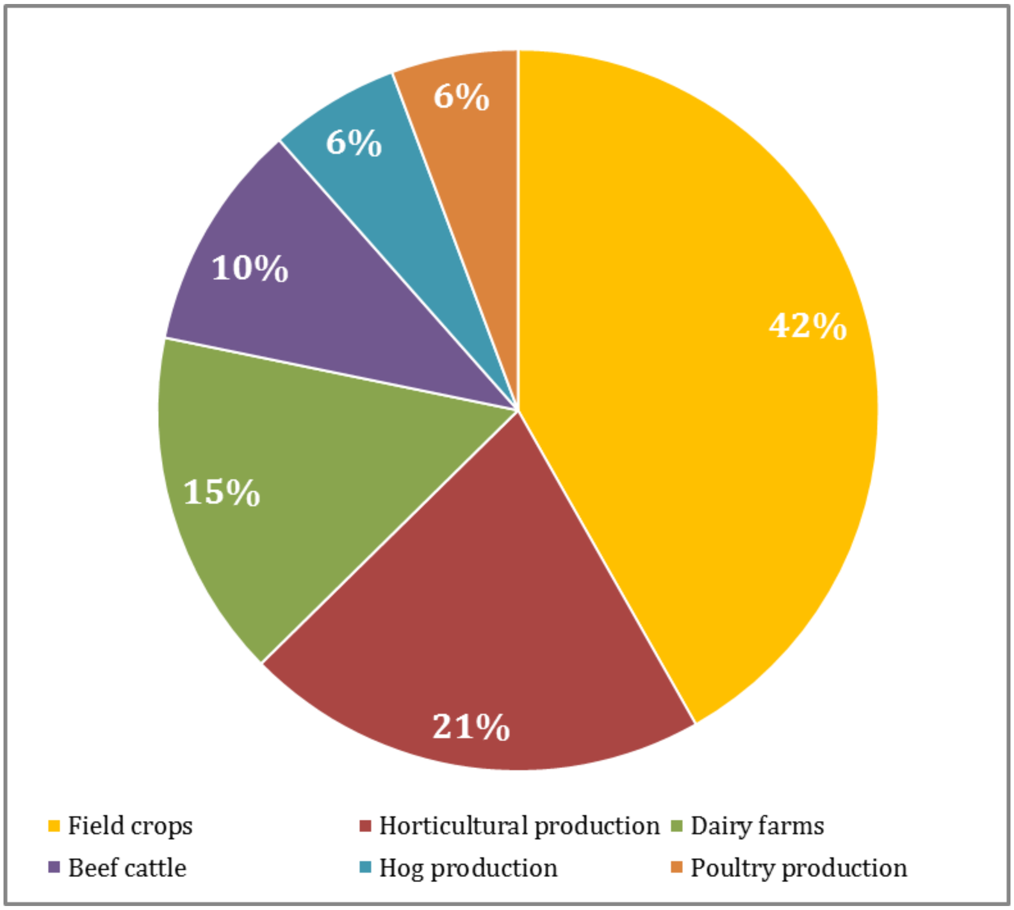


Source: Stone Environmental CSA.

Nutrients from agricultural sources within the Missisquoi Watershed have been identified as the leading causes of impairment (Smeltzer and Simoneau 2008; U.S. EPA 2016). There are 290 dairy farms in the Vermont portion of the watershed, with an additional 100 animal-related farms (Vermont DEC 2013).

In the Québec portion of the Missisquoi Bay watershed, according to MAPAQ data from the 2019 farm registration records, there are 490 farms with a primary operating site located in the watershed (MAPAQ, 2019). Farms producing field crops (265) and dairy farms (99) are the most common, followed by horticultural production (field berries (45)), orchards (54), field vegetables (33), beef cattle (65), hog production (37), chicken and turkey production (36). The Pike River's sub-basin has by far the largest number of farms at 359, followed by the Missisquoi River (70). The watersheds of the Rock River (34) and direct drainage to the bay (27) have a smaller number. In 2005, the Missisquoi Bay watershed (Québec and Vermont) was the Lake Champlain sub-basin that had the most farms and animal units per hectare (Watzin, 2005).

Figure 7. Farms by category in Québec's Missisquoi Bay Watershed

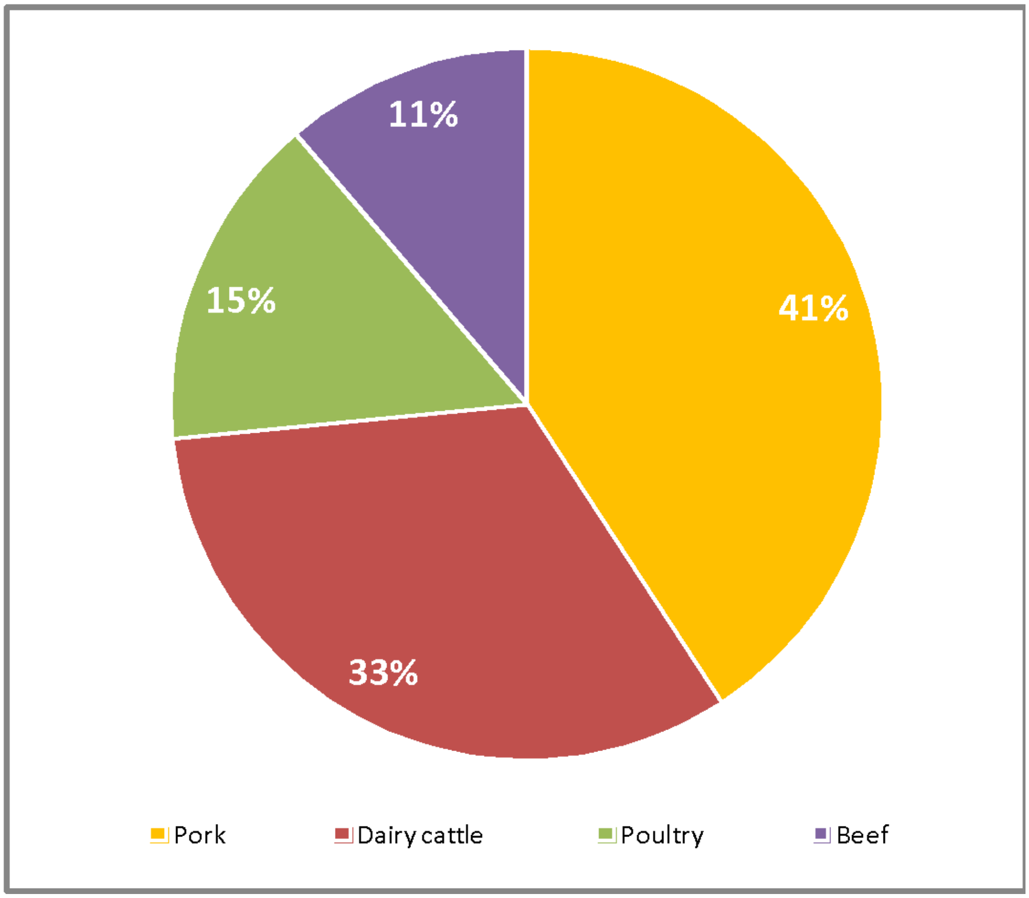


Source: MAPAQ, 2019

The 490 farms located in the watershed are using 52,375 ha of agricultural land in 2019. Of this total, 20,357 ha (39%) are used for field crops (mainly grain corn, soybeans and straw cereals), 10,154 ha for grasslands and pastures (19%), 1,135 ha for silage corn (2%) and 1,134 ha for fruit, vegetable and horticultural production (2%). Forest areas (including maple syrup operations) account for 16,744 ha (32%) and other uncultivated areas (including fallows and brownfields) for 2,500 ha (5%) (MAPAQ 2019)

There are approximately 248 livestock farms in the Québec portion of the watershed, for a total of 30,131 animal units (a.u.) broken down as follows: 41% pork production; 33% dairy cattle production; 15% poultry production; and 11% beef cattle production (MAPAQ, 2019).

Figure 8. Animal units by category in Québec Missisquoi Bay Watershed



Source: MAPAQ, 2019

This livestock seems to have decreased over time, because there were 42,060 animal units (a.u.) in the watershed according to the 2006 Census (STC 2006). The Pike River basin has the vast majority (70%) of livestock farms, 78% of the animal units in the entire basin and the highest animal density with 1.4 a.u./hectare cultivated (Statistics Canada, 2006) As previously demonstrated, agricultural land is the main source of phosphorus in the Québec portion of the watershed, generating around 75-80% of the loading to Missisquoi Bay. The eutrophication of Missisquoi Bay is closely correlated with the intensification of agriculture in its watershed (Levine et al., 2012). Despite remedial actions and improvements in agricultural practices, the main determinant of median phosphorus concentrations remains land use and more specifically, the proportion of annual crops grown in watersheds (Simoneau, 2018).

Based on MELCC modelling of 25 watersheds in Québec, the proportion of annual crops in a watershed explains 65% of the variance observed in the median phosphorus concentrations measured at monitoring stations and 85% of the nitrogen. Cattle (number of animal units), account for 14% of the observed phosphorus variance (4% for nitrogen) and loads from wastewater account for only 2% of the total phosphorus (Hébert & Blais, 2017).

In addition, according to a study by the Research and Development Institute for the Agri-environment (IRDA), overall, about 33% of soil analyses collected in municipalities in the Pike River watershed had saturation rates above the vulnerability threshold for a phosphorus loss of 10% (Agrosol, 2002).

According to the report, the main source of diffuse phosphorus in agricultural land in the Québec portion of the bay is not mineral phosphorus; it comes from animal manure (Michaud et al., 2006). Therefore, manure management is a priority issue. Also, it was noted that waste, especially manure, is mainly applied to meet crop nitrogen needs while significantly exceeding phosphorus requirements which are lower given the high concentration of phosphorus in the soils**.**

The type of vegetation cover and the surface application of chemical or organic fertilizers also account for the highest proportion of dissolved phosphorus that has been measured in perennial crops and direct seeding (Stamm et al., 1998, Gasser et al., 2016, Weighting, 1987, Messiga et al., 2009). An IRDA study on the effect of soil types, crop types and manure application on phosphorus export showed that the soil type is responsible for 70% of the bioavailability of particulate phosphorus, while manure application alone accounts for 35% of the variability in dissolved reactive phosphorus (Michaud e al, 2004). The study of the links between phosphorus concentration and agricultural activities showed that the correlation is stronger with long-spaced crops because the soil is barer and more prone to erosion between rows than for narrow-spaced crops. There is a correlation with perennial crops, while there is an inverse correlation with forests (Gangbazo, Roy and Le Page, 2005). Soil richness and supply balances are significantly correlated in the watershed and contribute to explaining more than 85% of the spatial variability in phosphorus flows in the Pike River's subwatershed (Deslandes et al. 2006 et Michaud et al., 2007).

Studies have been conducted, particularly in the Pike River sub-watershed, to assess the mobility of phosphorus in agricultural underground drainage. It was observed that groundwater was the main outlet with about 80% of total water exports and that up to 40% of the phosphorus was exported through tile drains. Losses of dissolved and particulate phosphorus and nitrogen are particularly high in clay soils through preferential channels. However, according to this study, surface runoff contributed to the majority (60%) of phosphorus losses, as phosphorus was, on average, 10 times more concentrated in surface runoff than in drains (Jamieson et al., 2003; Enright and Madramootoo, 2004).

Nitrogen and nitrates are highly soluble and therefore very mobile, particularly in groundwater (Thériault, 2013). A study published in 2002 concluded that 90% of annual nitrate losses occurred through agricultural drains, with measured concentrations ranging from 1 to 40 mg/L (Giroux et al., 2002). Only 10-15% of nitrate losses are from surface runoff.

2.2.3 Cyanobacteria Blooms

Cyanobacteria & Cyanotoxins

Globally, there are 2,698 defined species of cyanobacteria, with some estimates suggesting that the true number could in fact be near 8,000 (Nabout et al. 2013). The most common cyanobacteria genera that occur in Missisquoi Bay are *Microcystis*, *Anabaena*, and *Aphanizomenon* (Davis et al. 2009; Isles et al. 2015; Pearce et al. 2013). Several studies have shown that there is great inter-annual variation in the presence and dominance of different cyanobacteria species (Isles et al. 2017; Bowling, Blais, and Sinotte 2015). The complexity of Missisquoi Bay's nutrient dynamics is largely responsible for the community's heterogeneity. In fact, one study showed that on any given day different taxa could be the dominant species at different sampling sites (Bowling, Blais, and Sinotte 2015).

Coincident with an increase in nonpoint source nutrient inputs to Missisquoi Bay, the cyanobacteria problem has been a growing one since the latter half of the 1900s. Smeltzer, Shambaugh, and Stangel (2012) describe an increasing dominance of cyanobacteria in Missisquoi Bay in the past fifty years. There was little awareness and limited uniform monitoring for blooms in the region prior to the 2000s (Shambaugh 2016). At the turn of the century several dog deaths were associated with severe blooms in Lake Champlain, which brought public scrutiny and concern about the presence of cyanobacteria (Boyer et al. 2004). Data stations monitoring water quality since 2003 show the severity of some conditions diminishing and, in some locations, a decrease in the frequency of blooms (Shambaugh 2016).

Cyanobacteria blooms in Missisquoi Bay are more severe in Québec because blooms are concentrated in the Québec sector of the Bay (Blais, 2002). Between 2000 and 2008, the area most heavily affected by cyanobacteria was the eastern portion of Missisquoi Bay, the *Grande Baie* sector, which extends from Pointe Jameson to Saint-Armand, and the

Philipsburg sector. The bay of Venise sector is in second place, while the Missisquoi Bay's central sector is the least affected (Blais, 2014). Cyanobacteria blooms are typically observed from the second half of June to mid-October and are more prevalent beginning in the second half of July. The prevailing winds from the southwest encourage cyanobacteria blooms predominantly towards the eastern portions of the bay, as well as towards the bay of Venise (Blais, 2014).

Scientists are still grappling with a means to better understand the relationship between cyanobacteria and cyanotoxins. This correlation is complicated by the fact that, even within a genus, some taxa may be incapable of producing toxins while others are capable of toxin production but may not express the toxin-producing gene (Shambaugh 2016). Cyanobacteria can produce a wide variety of toxins with different chemical structures and human health impacts. For instance, while there is only one known analog of anatoxin-a, there are over 80 known microcystin variants with a wide range of toxicities (Boyer et al. 2004).

The ability to better understand when and where a bloom may occur and when it might be toxic is important to managing health advisories, beach closures, and drinking water withdrawals. A variety of environmental and water quality factors have been utilized, with various accuracy, in efforts to predict bloom toxicity. These include testing for nutrients, pigments such as phycocyanin and chlorophyll, and newer methods such as molecular testing for toxin-producing cyanobacteria genes. New molecular methods to detect the *mcyE* gene hold promise for more clearly understanding and accurately detecting microcystin-producing cyanobacteria (Francy et al. 2015).

The most commonly found cyanotoxins found in Missisquoi Bay are microcystin and anatoxin-a (Shambaugh 2016; Boyer et al. 2004). There is no way to identify toxicity by sight alone. Therefore, in unmonitored waterbodies it has been the occurrence of animal and human health effects that have indicated high levels of cyanotoxins (Shambaugh 2016; Rosen et al. 2001).

Of the common cyanotoxins, microcystins have generally been the most common in Lake Champlain and Missisquoi Bay (Boyer et al. 2004). As with anatoxin-a, microcystin is often found in low concentrations. Of the 80 known variants of microcystin, the most common and toxic being microcystin-LR (Graham et al., 2010). Cyanobacteria likely produce microcystins as a response to conditions of oxidative stress that arise at the surface during blooms (Zilliges et al. 2011).

Multiple strains of cyanobacteria can produce a cyanotoxin, and a strain of cyanobacteria may produce multiple cyanotoxins. For instance, *Anabaena* can produce any of the cyanotoxins commonly found in Missisquoi Bay, while *Microcystis* can produce microcystin and anatoxin-a (Boyer et al. 2004; Thorne and Schlesinger 2017). Despite this, microcystin is most commonly produced by *Microcystis*, anatoxin-a is most commonly produced by *Anabaena* (Boyer et al. 2004).

Cyanotoxins are not typically found in high concentrations in Missisquoi Bay. However, that does not mean that their potential effects can be disregarded. While studies have found that levels of anatoxin-a in Missisquoi Bay tend to be very low, anatoxin-a can negatively affect human health even at low concentrations because it has a higher toxicity at low concentrations (Osswald et al. 2007).

An example of a cyanobacteria bloom in Lake Champlain. Photo: LCBP.

Lake Champlain serves as a drinking water source for approximately 20% of the Basin's population. Several public water supplies withdraw and treat water for their customers, and there are also private homes along the Lake which withdraw water and provide very minimal, if any, treatment prior to consumption (Lake Champlain Basin Program 2018). A short-term study which sampled 16 locations along the Lake, as well as both raw and treated water from 5 water treatment plant intakes, found cyanotoxins at low levels in about half the samples collected. Low levels were detected in a few of the raw and treated drinking water samples, but all below the current Vermont Drinking Water Health Advisory levels (Vermont Department of Health 2018). Microcystin was the predominant cyanotoxin detected, and higher concentrations of this toxin were found in the more northerly portions of the Lake, such as Missisquoi Bay. Water collected from shallower water treatment plant intakes showed higher concentrations than those drawn from deeper in the Lake (Boyer et al. 2004).

Public concern about potentially toxic cyanobacteria blooms in the Lake has led the state of Vermont to provide microcystin and cylindrospermopsin testing for public water supplies that draw drinking water from Lake Champlain. Since the summer of 2014, the Vermont DEC Drinking Water Program, in collaboration with the Vermont Department of Health has implemented a voluntary, no-cost monitoring program for water of 22 public water supplies that utilize Lake Champlain for drinking water. Microcystin and cylindrospermopsin levels are tested weekly during the 12 summer weeks. Both raw and treated water is tested (2015-2018 Cyanobacteria Monitoring Reports, VT DEC).

Of the 22 public water supplies participating in the testing, Swanton Village, Alburgh Village, and Alburgh Fire District #1, and Grand Isle Fire District #4 withdraw and deliver drinking water from the northernmost portions of Lake Champlain for their service populations. Data collected, to date, from this sampling show only one of the participating water suppliers, Grand Isle Fire District #4, with a detection (0.16µg L^{-1} microcystin in raw water, August 2016) (2015-2018 Cyanobacteria Monitoring Reports, VT DEC).

The city of Bedford's drinking water intake (which also supplies the Philipsburg sector in Saint-Armand) is in Missisquoi Bay at an average depth of 3.5 m (2.5 m in low water periods and 4.5 m in high water periods) (Blais, 2014). In Missisquoi Bay in 2001, the criterion of 1.5 µg/L for microcystins in drinking water was surpassed in 31% of samples taken from the scum, with a maximum concentration of 2,204 µg/L (Blais, 2002). In 2002, a cyanobacteria bloom was found inside the plant's treatment system. The existing treatment system was no longer able to ensure the safety of the water supply. As a result, a drinking water avoidance advisory was issued on August 13, and lifted on September 6, 2002.

The challenges posed by cyanobacteria in the intake required significant investments to properly treat drinking water. Activated carbon processing had to be added and follow-up ensured. The costs of drinking water treatment have increased significantly with the advent of cyanobacteria. The bill for chlorine and activated coal has increased exponentially in Bedford since 1994, as operating expenses for the water system have gone from $200,000 to $600,000 per year in a decade (Hébert, 2018). From 2001 to 2006, a raw and treated water monitoring survey of six drinking water treatment plants, including Bedford, sourced from aquatic environments where cyanobacteria proliferate, was implemented by the MELCC as part of its drinking water quality monitoring program. According to the study, despite the high presence of cyanobacteria and cyanotoxins in source samples, the maximum concentrations of microcystin-LR and anatoxin-a measured in treated water were 30 to 50 times lower than the INSPQ recommended guidelines (Robert et al., 2004; Robert, 2008).

Drinking water treatment for cyanobacteria and cyanotoxins may not be part of the operation and design considerations of many drinking water treatment plants. Cyanobacteria cells may be removed by certain clarification and filtration processes, but this process can be complicated by the breakthrough of cyanobacterial cells and may result in treatment disruption leading to compromise of plant operations. Additionally, treatment processes, such as chlorination, may lyse cyanobacteria cells, releasing toxins. It is important to consider appropriate treatment techniques where eutrophic surface water is used as a source of drinking water (Sklenar, Westrick, and Szlag 2016).

Starting in 2018 through 2020, the United States Federal Safe Drinking Water Act will require extensive testing for cyanotoxins. Public water systems serving more than 10,000 customers, a representative sample of smaller public water systems, and all systems using surface water (or ground water under the direct influence of surface water) will be required to sample for nine cyanotoxins and one cyanotoxin group (total microcystins) (U.S. EPA 2016). This testing may identify further drinking water cyanotoxins issues in Lake Champlain and help identify drinking water systems at risk. However, this testing will not apply to the private homes that draw their water directly from the lake.

Sources and Causes

It is generally accepted that through the course of human development in the Lake Champlain Basin, as anthropogenic contributions of nutrients increased, so did the frequency and severity of blooms (Isles et al. 2017; Winslow 2016; Boluwade and Madramootoo 2015). Missisquoi Bay specifically has experienced a similar fate as it became eutrophic following the expansion of agricultural production and moderate urbanization in the 1970s, coincident with an increase in the occurrence and magnitude of blooms (Levine et al. 2012).

The proliferation of cyanobacteria is the result of complex interactions between several factors including water temperature, sunlight, pH, nutrient content and currents in the water body in question (Duy et al., 2000). Missisquoi Bay has natural features that make it particularly vulnerable to cyanobacteria blooms. It is shallow bay. This condition promotes greater productivity and can exacerbate the problem of cyanobacteria throughout the water column. The shallow depth of the bay allows for warming of the water column, with a lot of sunlight reaching the sediments. These conditions can stimulate the metabolic activities of cyanobacteria, including the synthesis of gaseous vacuoles (Hyenstand et al*.,* 1998). In addition, the lack of thermal stratification observed in Missisquoi Bay and the abundant light provide cyanobacteria with optimal growing conditions. They can photosynthesize across the water column because light and nutrients are sufficiently abundant.

Cyanobacteria have characteristics that allow them to dominate algal species that make up the phytoplankton of lakes. For example, they can move vertically in the water column through gaseous vacuoles. They can also accumulate phosphorus reserves near sediments and rise to the surface near light to photosynthesize (EXXEP, 2004).

Like the complex interface of the many factors affecting nutrient dynamics in the Bay, cyanobacteria dynamics vary readily within and between years (Isles et al. 2017; Bowling, Blais, and Sinotte 2015). Understanding bloom variability on an inter-annual timescale is important to evaluating options for mitigation. The interaction of various meteorological and hydrodynamic factors further exacerbates the complexity of understanding the causes of blooms.

The Missisquoi Bay bloom season is often split into four distinct time periods: pre-bloom/post ice-out, bloom initiation, peak bloom, and post bloom. The pre-bloom period is often associated with cold air and water temperatures and lower cell counts of cyanobacteria. Bloom initiation is when temperatures start to warm and the nutrients in the lake reach a point where cyanobacteria can become dominant. Peak bloom corresponds to the densest growth of cyanobacteria, often attributed to late summer months when the water temperature reaches 20°C, coinciding with most blooms in Missisquoi Bay occurring in late summer/early fall (Davis et al. 2009; Hart et al. 2013). Generally, post bloom periods indicate a reduction in cyanobacteria as temperatures decrease (Giles et al. 2016).

Nutrient dynamics strongly affect bloom forming conditions. Phosphorus tends to be the driver of cyanobacteria growth, while nitrogen may affect the density and toxicity of some blooms (Gobler et al., 2016, Davis et al., 2009). While it is generally accepted that phosphorus is the limiting nutrient in freshwater systems, there is debate on the importance and role of nitrogen. Human and environmental factors may cause fluctuations in limiting nutrient over months and years, as the quantity of both nitrogen and phosphorus can affect each other and the system as a whole (Doering et al. 1995; Gobler 2016).

When the TN:TP ratio is low, as it tends to be in Missisquoi Bay, it is likely that blooms of cyanobacteria will occur as they thrive and hold an advantage over phytoplankton in low-N environments (Davis et al. 2009; Pearce et al. 2013). Missisquoi Bay has had years in which the TN:TP ratio never rose above 16 (Hart et al., 2013), and some cases where late summer samples showed a TN:TP ratio less than 10 (Fortin et al. 2013). According to the Redfield ratio (atomic ratio of carbon, nitrogen, and phosphorus found in phytoplankton) 16 is the average for TN:TP, and any counts under 10 show clear nitrogen limitation, and any counts above 30 show clear phosphorus limitations. It is not unheard of for a freshwater system to see a switch in the limiting nutrient, either year to year, or even over the course of one summer (Gobler et al. 2016). For example, there are instances where parts of western Lake Erie have been N-limiting in the late summer months (Thorne and Schlesinger 2017).

Key to the argument for phosphorus-limitation is the idea that nitrogen fixation helps cyanobacteria make up for the lack of nitrogen in the system. Nitrogen fixation is the process of turning atmospheric nitrogen into ammonia, which cyanobacteria use to grow and multiply. In Missisquoi Bay, *Anabaena* and *Aphanizomenon* utilize nitrogen-fixation (Davis et al. 2009; Hart et al. 2013; McCarthy et al., 2016; Boyer et al., 2004) and are typically more prominent by count earlier in the typical bloom season (late spring and early summer). This implicates phosphorus as the limiting nutrient for these two species. Contrarily, the growth rates of *Microcystis*, being non-nitrogen-fixing, was significantly increased for both toxic and non-toxic strains with increased concentrations of nitrogen (Davis et al. 2009). Increased phosphorus loads have also led to higher counts of *Microcystis* (Davis et al., 2009), showing the importance of both phosphorus and nitrogen as nutrients. This was showcased in July 2009 when hypoxic conditions at the sediment-water interface lowered denitrification rates and consequently increased the bioavailable nitrogen, possibly triggering a *Microcystis* bloom five days later (McCarthy et al. 2016).

2.2.4 Health Risks and Recreational Impacts

Missisquoi Bay and the water bodies within the Missisquoi Bay Sub-Basin support drinking, swimming, boating, fishing, and other recreational water uses. Missisquoi Bay and the streams, rivers, lakes, ponds and wetlands in its Sub-Basin contribute much to the economy of the region. While fishing activity may not be restricted during cyanobacteria blooms, public health agencies often advise precautions prior to consuming any fish from compromised areas.

Cyanobacteria blooms in Missisquoi Bay may create low oxygen conditions in the water column, which can lead to multiple health and recreational issues. The Missisquoi Bay segment of the Lake has received a “poor” score for cyanobacteria blooms (Lake Champlain Basin Program 2018). In August 2012, during a large cyanobacteria bloom and period of hot weather, thousands of dead fish were washed up on the Missisquoi Bay shoreline, and the Philipsburg, Québec water supply issued a notice to all its customers warning them to not consume their drinking water unless it was adequately boiled prior to consumption (Schuett 2012).

Cyanotoxin-tainted water may cause health issues via recreational contact and consumption of the water. A study of residents living near Missisquoi Bay kept a daily journal of symptoms and record of their contact with the Bay water, and corresponding samples were collected to document cyanobacteria and microcystin concentrations during the study period. Residents' gastrointestinal symptoms were correlated with their recreational contact, and residents' consumption of drinking water was correlated with increased muscle pain and ear symptoms (Lévesque et al. 2014).

In Canada, the Algal Blooms project, Treatment, Risk Assessment, Prediction and Prevention through Genomics (ATRAPP) is a major international study initiated in 2016 that includes Missisquoi Bay. One of the components of the study aims to predict toxic blooms in order to transmit this information to the Health Agency and municipalities for their drinking water systems. Two plants in the region are included in the study including Bedford. The National Research Council Canada, which is also involved in this large project, is also participating in Genomics Research and Development Initiative, a multidisciplinary program involving several federal government departments to study the impact of eutrophication on Canadian water bodies, including Missisquoi Bay. As part of the ATRAPP/Ancrage project, a team of researchers attached to the *Université du Québec* are developing geomatics models to evaluate certain scenarios for implementing practices and developments aimed at reducing phosphorus loads, particularly in agricultural in the watershed of Missisquoi Bay, in order to evaluate the best costs/benefits. The results are not yet available.

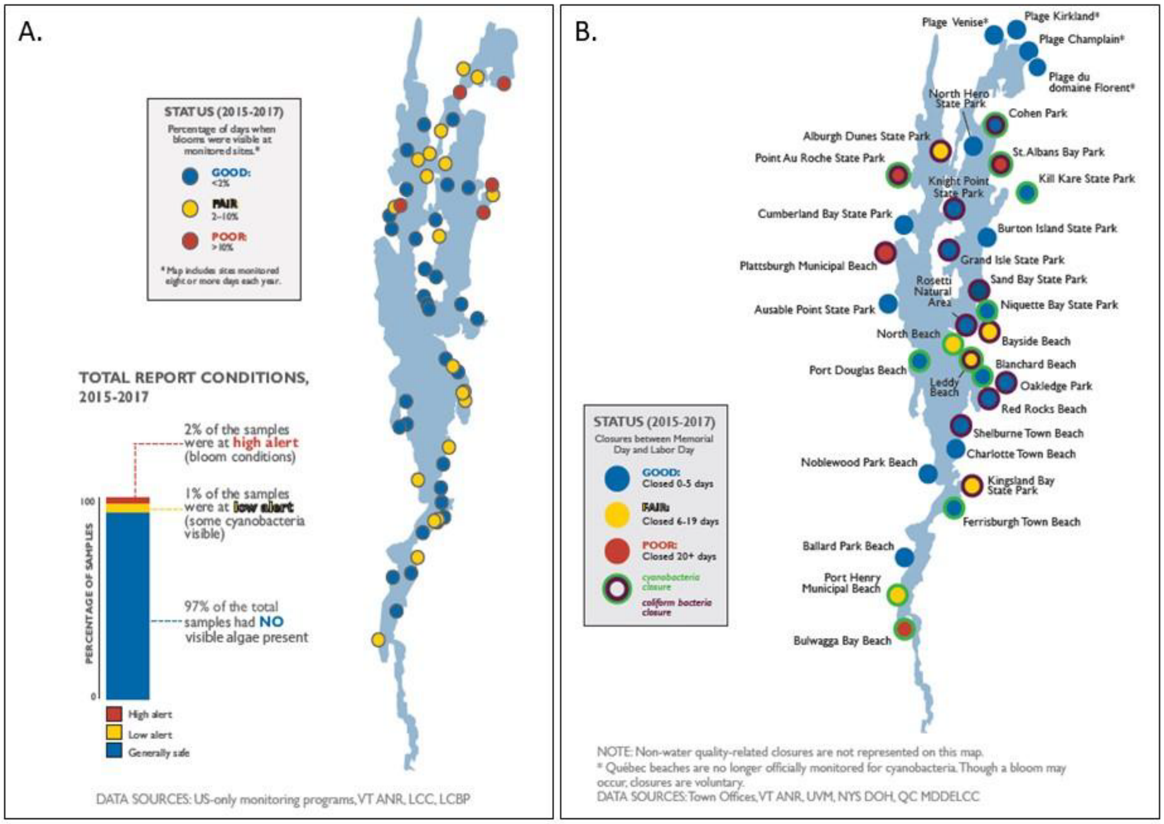
In Vermont, public beaches are usually closed when there is a visible cyanobacteria scum on the water, and beach closures are generally followed by testing for cyanotoxins. To date, there have been no known human deaths associated with cyanobacteria blooms though there have been multiple unconfirmed reports of human illness ranging from skin irritations to respiratory issues and severe gastrointestinal illness (Vermont Department of Health 2015).

In the past decades there has been extensive education of the public and resource managers on the proper identification of cyanobacteria blooms for the purpose of visually monitoring Lake Champlain's beaches (Vermont Department of Health 2015). Additionally, the development of easier, cheaper testing methods for cyanobacteria and toxins has allowed for more frequent testing for cyanobacteria and cyanotoxins throughout Lake Champlain. This has allowed for more rapid and accurate data informing public beach closures (Shambaugh 2016).

In 2007 the Vermont Department of Health and the Vermont Department of Environmental Conservation (DEC) initiated a program with the public water suppliers to establish best practices to respond to cyanobacteria detections, later expanded to include a free voluntary summer cyanotoxin monitoring program for public water suppliers drawing water from Lake Champlain. Additionally, 140 recreational locations around the state are monitored for cyanobacteria and monitored for cyanotoxins if blooms are found. These programs have allowed for the compilation of regular data available to resource managers responsible for advising health and recreational uses of the Bay, as well as to the public. Reports are displayed on an online cyanobacteria tracker map, which is updated weekly: http://www.healthvermont.gov/tracking/cyanobacteria-tracker.

Monitoring data from these programs show that Missisquoi Bay is a relative "hotspot" for both cyanobacteria and microcystin in Lake Champlain (Fig. 5A), with shoreline and downwind Bay locations particularly vulnerable and health guidelines occasionally exceeded at locations in the Bay (Shambaugh 2016). A compilation of data on public beach closures across the Lake between Memorial Day and Labor Day (2015- 2017) shows a number of sites along the north end of the Lake where closures were due to cyanobacteria blooms (Fig. 5B) (Lake Champlain Basin Program 2018).

Figure 9. Cyanobacteria alerts (A) and beach closures (B) on Lake Champlain from 2015-2017.



Note that the monitoring stations in Missisquoi Bay are characterized as "Fair" or "Poor". Beaches on the northern banks of Lake Champlain are characterized as "Good," meaning that they were closed less than 5 days during the monitoring period. However, those numbers may be inaccurate, as Québec beaches are not monitored for cyanobacteria and closures are voluntary. Both graphics from (Lake Champlain Basin Program 2018).

2.2.5 Economic Impacts

Quantifying the economic impact of eutrophication of our lakes is beset with complexities and data gaps. A national study of fourteen level III ecoregions (Omernik 1987), where median total nitrogen and total phosphorus values for rivers and lakes exceed reference median values, calculated the potential annual value of losses in recreational water usage, waterfront real estate, spending on recovery of endangered species, and drinking water. The combined economic losses in these twelve ecoregions were calculated at approximately $2.2 billion annually, with the greatest economic losses attributed to lakefront property values and recreational use. The authors stated that their evaluation likely underestimated these economic losses, and that gaps in current records (e.g., accounting for frequency of algal blooms) suggest further research is necessary. (Dodds et al. 2009).

Limited information is available on the economic impact of eutrophication of Lake Champlain. A 2015 study utilized scenario analysis to determine how increasing phosphorus concentrations and climate change may affect values of properties near Lake Champlain. The study used lake water clarity as a visible and strongly correlated indicator of phosphorus concentrations. The study found that for the four counties in Vermont abutting the lake, a one-meter decrease in water clarity in the months of July and August would lead to a loss of approximately 195 full-time equivalent jobs, a $12.6 million reduction in tourism expenditures, and a total economic reduction of nearly $16.8 million (Voigt, Lees, and Erickson 2015).

Such costly economic impacts may provide impetus for environmental programs and policies which can also be costly. Studies have analyzed the willingness to pay for programs and regulations to address Lake Champlain's water quality issues. Surveys of Vermonters show that greater education and outreach on water quality issues throughout Vermont (not just in the Lake Champlain Basin) are likely to increase voter support for regulations and programs to address water quality (Scheinert et al. 2014; Koliba et al. 2016).

In Québec, recreational tourism development is very important for the municipalities along the bay, including *Venise-en-Québec, Saint-Georges-de-Clarenceville* and *Saint-Armand* (Philipsburg area). This tourism is mainly water-focused: primarily camping, navigation, recreational fishing, and swimming. Therefore, when beaches are closed due to cyanobacteria and cyanotoxins in the bay's water, businesses and the entire immediate region incur significant economic losses estimated at more than $2 million per year, according to the *Regroupement des gens d'affaires de la région du lac Champlain* (EXXEP, 2004).

In 2004, just over 100 questionnaires were compiled by the OBVBM, including 60 from residents and 40 from visitors to Missisquoi Bay. The condition of the bay influenced the activities of residents for 65% of respondents, mainly by restricting swimming and fishing, selling of recreational watercrafts, changing the area of the bay used for activities, and decreasing the frequency of aquatic activities (OBVBM, 2004a). Philipsburg residents reported the presence of unpleasant odours in the summer that would sometimes force them to close their windows due to the intensity (OBVBM, 2004a). Some economic impacts were reported during interviews. For example, renting cottages was more difficult. Rental durations were shorter than before, lasting until about mid-August instead of mid-September (Jacques Landry, Mayor of Venise-en-Québec, OBVBM interview, 2019).

Established economic policies and mechanisms such as tax exemptions, loans, grants, subsidies and free technical assistance can encourage more sustainable environmental practices and help shape the environmental future of the Missisquoi Sub-Basin. Additionally, newer market mechanisms such as phosphorus taxes, nutrient cap and trade policies, and incentives to implement sound ecological farming, stormwater, and development best management practices, may provide viable future options to help address water quality issues in Missisquoi Bay (Koliba et al. 2016).

3 Overview of Potential In-Lake Restoration Measures and Technologies

3.1 International Overview of Restoration Efforts and Results

In general, nutrient loads to lakes come from watershed and atmospheric sources (external loading), and from re-suspension and reductive dissolution of lakebed sediments (internal loading). In-lake treatments may be a useful tool to reduce internal nutrient loading in eutrophic lakes where external nutrient loads have been reduced to target levels (Lewtas et al. 2015; Cooke 2005; NALMS, 1990). Common sense dictates that in-lake restoration measures are best implemented after land-based controls are in place, or at least coincident with land-based control measures

3.1.1 Canada

In 2004, the OBVBM commissioned an extensive study (*Solutions phosphore baie Missisquoi*, EXXEP, 2004) to assess *in situ* measures to reduce phosphorus problems in Missisquoi Bay. In addition, as part of the *Plan d'intervention détaillé sur les algues bleu-vert 2007-2017*, the MELCC issued a call for proposals in 2008 to fund four pilot projects on Brome, Waterloo, Saint-Augustin and l'Anguille lakes to evaluate the effectiveness of eutrophic lake restoration techniques (MDDEP, 2009). Several other restoration projects were also monitored by MELCC (Fallu and Roy, 2015).

The study by EXXEP showed that restoration solutions applied directly to the bay are costly and not effective in the long term without a reduction of phosphorus in the watershed and sediment inputs into the bay (EXXEP, 2004). The results of this study suggested that the best long-term solution is to reduce phosphorus inputs from the watershed (EXXEP, 2004).

The main finding of the MELCC pilot projects is that results of in-lake restoration techniques are mixed, but that no effective and affordable "quick fix" was found. The MELCC also recommends prioritizing source phosphorus management throughout the watershed of eutrophic lake (Boudreau e al, 2017). In addition, several concerns were raised regarding the costs associated with such projects, their actual effectiveness, impacts on the ecosystem, interference with other uses, ability to withstand harsh weather conditions such as flooding and high winds, as well as necessary maintenance (Boudreau et al., 2017). Assessing enclosed pilot projects that take place in conditions different from those of an open lake makes it difficult to interpret results on a larger scale (Boudreau et al, 2017); however, it would be difficult to implement projects in larger areas like Missisquoi Bay because the Bay is an open environment as the water interchange between the bay and other lake segments (Fallu and Roy, 2015).

In situ restoration techniques all have significant limitations, particularly in the duration of their effectiveness. The chemical content of a lake is usually a reflection of what flows into it. If external inputs of nutrients remain excessive, any one-time *in situ* restoration effort is likely to have a limited duration. In specific cases where the main source of nutrients is lake sediments, it may be useful to apply substances that can immobilize phosphorus (e.g., Phoslock).

Given that Missisquoi Bay has an area of 78 km^2, as well as strong winds and waves no technique seems suitable for this type of condition unless substantial funding is available. Even with a massive financial investment to "treat" the bay's waters, the bay will continue to receive large loads of sediment and phosphorus from its tributaries, likely negating the effectiveness of such *in situ* restoration techniques. Controlling nutrient and sediment inputs remains a critical step before undertaking any *in situ* approach, such as the removal or inactivation of phosphorus in sediment.

It is important to note that these treatment methods require authorizations and pre-studies from MELCC, *Ministère de la Faune, Forêts et des Parcs* (MFFP)and sometimes from Fisheries and Oceans Canada. Before granting approval for *in situ* treatment, MELCC first consider whether nutrient sources from the watershed are controlled, so that the response does not become a recurring approach to problem management, since *in situ* treatments should be viewed as a last resort (Boudreau, 2017).

3.1.2 U.S.

Commonly Used In-Lake Restoration Techniques

This section will focus on four techniques that have been commonly used in the Northeast to reduce and control internal nutrient loading: hypolimnetic aeration and oxygenation, artificial circulation, phosphorus inactivation and capping, and hypolimnetic withdrawal.

This section does not include details on other techniques sometimes used in the Northeast, such as dredging or algicide treatments, as these are not likely appropriate solutions for Missisquoi Bay. Additionally, this chapter does not address techniques used in other areas, which do not have a record of use in the Northeast, including: floating treatment wetlands, dilution and flushing, biomanipulation, and removal of macrophytes (Lewtas et al. 2015).

The below Table 3 summarizes and compares the above techniques used to control nuisance algae. This table is extracted from and based upon the consensus of a panel of lake and reservoir restoration experts (NALMS, 1990).

Table 3. Comparison of lake restoration and management techniques for control of nuisance algae.

Treatment (One Application)	**Short-Term Effect**	**Long-Term Effect**	**Cost**	**Chance of Negative Effects**
Phosphorus Inactivation	E	E	G	L
Artificial Circulation	G	Unknown	G	F
Hypolimnetic Aeration	F	Unknown	G	F
Hypolimnetic Withdrawal	G	G	G	F

E = Excellent F = Fair

G = Good P = Poor

H = High L = Low

Excerpted from "The Lake and Reservoir Restoration Guidance Manual, Second Edition," North American Lake

Management Society, 1990.

Regional Lake Restoration Efforts

Although in-lake restoration efforts are utilized throughout the world, this review focused on the most commonly utilized technologies implemented in the northeastern United States. Table 4 profiles 9 representative regional water bodies that have actively addressed nutrient enrichment issues and cyanobacteria blooms in Vermont. Table 5 in Québec. Available treatment cost information is provided if available.

Table 4. Representative in-lake restoration efforts completed in Northeast US lakes. Lake vital statistics are included to facilitate comparison to Missisquoi Bay, which has a surface area of 7,800 ha, watershed area of 310,800 ha, and maximum depth of 4.6 m (Vermont DEC, 2013). It must be pointed out that none of the example have a comparable scale. The largest lake here are still 10x smaller than Missisquoi Bay. All the efforts profiled here were conducted with the intent to reduce in-lake phosphorus loading from sediments. Some of these data are of unknown quality and are presented here for illustrative purposes only. No inferences regarding the impacts of nutrient loading and cyanobacteria blooms on water quality in the Lake Champlain Basin should be made based on these data until their quality can be determined.

Water Body	Area (ha)	Watershed Area (ha)	Max Depth (m)	Treatment Type and Year	Result	Cost
Lake Carmi[1]	567	3120	10	Hypolimnetic Oxygenation To begin in 2019	Model simulations of planned treatment show improvements in hypolimnetic dissolved oxygen	Approx. $1.5 M/year including O&M
Lake Morey[2]	220	1900	13	Aluminum Sulfate/Aluminate 1986	Substantial decrease in P and increases in clarity for 3 + years after treatment	Approx. $177,000/133 ha treatment (1986) with alum donated
Morses Pond[3,4]	40.5	2145	7	Aluminum Sulfate/Aluminate, Polyaluminum Chloride 2009-2018 Plant Harvesting: 2007-2018	Substantial decrease in P, increases in clarity, decreases in blooms	P inactivation only: $312,000/5 years
Kezar Lake[5]	73.5	2770	8.2	Aluminum Sulfate: 1984 Upstream Wetland Manipulation	Decrease in total P and P variance for 3+ years, increased clarity, poor wetland attenuation	$1,367/ha (1984)
Lake Waramaug[6,7,8,9,10,11]	275	3723	12.2	Hypolimnetic Withdrawal: 1983-2015 Aeration Ongoing Since 1989	Decrease in P (epilimnetic P concentrations were below 18 mg/m^3 in 1993) and increases in water clarity	$500,000 for original pumping system (1983) 2015 installation of two aerators - initial cost of $140,000

Water Body	Area (ha)	Watershed Area (ha)	Max Depth (m)	Treatment Type and Year	Result	Cost
Cochnewagon Lake[5,12,16,17]	159	727	8.5	Aluminum Sulfate/Aluminate 1986	Increased clarity for nearly 20 years, recent blooms	Chemicals, Labor, & Equipment = $81,840; Personday/ha = 0.41; Cost/ha=$844
Annabessacook Lake[5,12,13,14]	572.6	4294	15	Copper Sulfate Algicide Treatments: 1964-1971	Algicides had short term impact, but lost efficacy with emergence of resistant algae species	Aluminum salts treatment: Chemicals, Labor, & Equipment = $234,000; Personday/ha = 1.12; Cost/ha = $1,934
				Hypolimnetic Aerators: 1972 & 1974	Aerators were ineffective. They did not mix waters more than 50 meters beyond the units and may have disturbed sediments increasing the internal phosphorus loading of the lake	
				Aluminum Sulfate/Sodium Aluminate: 1978	Aluminum salt treatment led to dramatic decrease in internal loading of P, with calculated longevity of reduced P at 13 yrs	
Threemile Pond[5,12,14]	475.1	2414	11	Aluminum Sulfate/Sodium Aluminate: 1988	Calculated longevity of decrease in P of 4 years	Chemicals, Labor, & Equipment = $170,240; Personday/ha = 0.06; Cost/ha = $640
Chickawaukie Lake[12,14,15]	143	670	10	Aluminum Sulfate/Sodium Aluminate: 1992	Calculated longevity of decrease in P of 39 years	

Water Body	Area (ha)	Watershed Area (ha)	Max Depth (m)	Treatment Type and Year	Result	Cost
Ticklenaked Pond[18,19]	21.9	584.4	14.5	Alum Treatment May 2014	3 months post-treatment: water clarity improved from 1.7 to 7.2 m total and dissolved phosphorus decreased, especially at surface	$95,990 Grant Received
Nutting Lake[20]	31.6	292.7	2.1	Dredging of ~275,000 m^3 of sediment 1978-1981		~$688,000
Lake Waccabuc[21, 22, 23]	52.0	317	14	Hypolimnetic Aeration Two aerators installed in 1972	decrease in the in-lake nutrient concentrations and improvement in water quality conditions through decreased hydrogen sulfide, iron, manganese levels	as of 2004- annual operation of aerators is $9000
Lake Wononscopomuc[24]	24	599	15.2	Hypolimnetic Withdrawal 1981	TP decreased during summer stratification (25 to 12 ppb) and maximum hypolimnetic (473 to 89 ppb)	
Sebasticook Lake[25]	1735	21995	15	Lake Drawdown 1982- 2001 (confirmed)	Internal load of TP reduced by 50% (4,000 to 2,000 kg)	
Irondequoit Bay, Lake Ontario[26,27]	694	43583	25	Alum Treatment 1986	60-75% reduction in hypolimnetic P	
				Hypolimnetic Aeration 1993- Present	Epilimnion TP maintained (approximately 20 ppb) in target range during the summer sampling seasons	

Table Data Sources: 1: (Reservoir Environmental Management, 2018); 2: (Smeltzer, 1990); 3: (Water Resources Services, INc, 2018); 4: (Way and Box, 2005); 5: (Connor and Martin, 1989); 6: (Healy and Kulp, 1995); 7: (Lake Waramaug Task Force); 8: (Kortmann, 2010); 9: (Verhovek, 1988); 10: (Lake Waramaug Association); 11: (CT Institute of Water Resources, 2008); 12: (Vaux, 2015); 13: (EPA, 1980); 14: (Huser et al., 2016); 15: (City of Rockland, ME, 2002); 16:(Charles Eichacker, 2016); 17: (Maine DEP, 2011); 18: (Vermont ANR, 2009); 19: (Meringolo, 2016); 20: (Purcell & Taylor, P.C., 1981); 21: (NYSDEC, 2017b); 22: (Fast et al., 1975); 23: (NYSFOLA, 2009); 24: (Nürnberg, 2007); 25: (Maine DEP, 2001); 26: (Sansone, 2016); 27: (Sansone, 2018).

Table 5: In-Lake Restauration Pilot Projects in Québec

Water Body	Area (ha)	Watershed Area (ha)	Max Depth (m)	Treatment Type	Year	Result	Cost
Lake Heney (Gracefield) Outaouais	1233	5248	32,5	Immobilization of phosphorus with iron chloride (217 t, once). Test on the entire surface of the lake (preliminary tests on the bay). The largest attempted lake restoration project in Québec	2007	Total phosphorus concentrations in the water column have changed from 0.024 mg/l to approximately 0.015 mg/l during the 2008-2013 monitoring period. Chlorophyll-a also decreased by 50%.	NA
Three Lake (Asbestos)	240	51000	8	Amphibious dredging with pump bucket (Amphibex) over 51,000 m2 (31% of lake)	2011 2014	Perception of increased water circulation in dredged areas, low rates of seagrass recovery measured over a short-term period (1-3 years), Decreased thickness of sediment deposition	$3,04 M
Lake Tomcod (Saint-François-Xavier-de-Brompton)	180	1850	2	Several solutions to reduce inputs upstream of the lake, including the use of steel slag. Algal Growth Control by Ultrasound (Quatro-DB Device from AlgaeControl Company)	2017 2018	Bloom in August 2017. Presence of cyanobacteria constant at different stages between May and September 2018. Since 2009, annual average chlorophyll a was 71.6 ug/l. In 2018, it stands at 106.2 ug/l	NA
Lake Bromont (Bromont)	46	2380	7,6	Immobilization of phosphorus by the application of Phoslock. 174 tonnes of this lanthanum enriched clay (bentonite) was dispersed throughout the lake to capture 1738 kg of phosphorus	2017	The total phosphorus concentrations measured at depth (6.2m) in June 2019 are 70% lower than in June 2017. However, cyanobacterial bloom were still observed in 2018 and 2019, forcing the closure of the beach.	$650 000
Lake Pierre-Paul (Mauricie)	61	440	7,9	Precipitation/inactivation of phosphorus. Liming	1996 2016	Total phosphorus in sediments decreased from 2274 mg / kg in 1996 to 1233 mg / kg in 2007, a reduction of approximately 54%. However, cyanobacterial blooms have been recorded 6 years since 2007.Treatment effectiveness outcomes assessed by the MELCC were inconclusive as an effective medium and long-term restoration solution	NA
Lake Saint-Augustin (Québec)	62	750	6,1	Immobilization of phosphorus in sediments by adding alum for coagulation / flocculation and calcite for active recovery. Pens have been	2009	The treatment alum + calcite compound achieved the best reduction of phosphorus dissolved in the water column. Alum alone would have obtained a reduction at the beginning which would have	NA

				installed to test the different compounds (alum, calcite, alum + calcite, control)		subsequently increased. The authors of the study recommend recovery by calcite alone in deeper areas. The MELCC recommends an intermediate in situ calcite-alum recovery test in an isolated area of the lake with a longer follow-up period to verify stability	
Lake Saint-Augustin (Québec)	62	750	6,1	Hydraulic and mechanical dredging of the superficial layer of sediments. Several pens have been installed to compare techniques (hydraulic dredging, mechanical, control)	2011	A significant decrease in dissolved phosphorus was measured in the hydraulic dredging pen after two weeks. As for mechanical dredging, a downward trend following treatment was reversed after one week to become an increase in phosphorus concentration that remained during the follow-up period	NA
Lake Waterloo (Montérégie)	136	3040	5,3	Aerators/Circulators	2004	Cyanobacterial water blooms were observed and persisted, this technique did not seem efficient or poorly adapted	NA
Lake Waterloo (Montérégie)	136	3040	5,3	Removal of sediment. Hydraulic dredging of the surface layer of phosphorus-laden sediments	2009	No trend in phosphorus concentration in the water column was observed following pumping. Tested on reduced surface	$37 M estimated for the full lake
Lake Waterloo (Montérégie)	136	3040	5,3	Floating beds of duckweed (with and without sediment mixing)	2009	Difficulties encountered: development of variable lenses, optimal density of water lenses difficult to maintain, distribution of lenses difficult to control with the wind, etc. Conclusion: not applicable at the scale of a lake	NA
Lake Carré (Laurentides)	14	197	8,4	Aerators/Circulators (*Speece Cone)*	2002 2010	No improvement in oxygenation of the hypolimnion observed. In 2010 and 2011, Lake Carré still had an anoxic hypolimnion	NA
Lake Selby (Montérégie)	117	1852	10,3	Wind turbines serving as water aerators	2015	No significant changes have been reported. These wind turbines have been removed.	NA
Bay Charrette (Saint-Donat)				Removal of more than 50,000 m3 of sediment	2011 2012	The depth of the water column increased from 0.3-0.5 m to 1.5-2.5 m	NA
Lake Anguille	98		12	Floating plant island of 20 m2 including 400 plants of 8 species. The most effective species were: Typha latifolia, Iris pseudocarus, Spartinapectinata and	2008 2012	The results indicate a withdrawal rate of 1000 mgP / m2. The number of floating islands needed to treat a large area is very important. For example, 1650 blocks covering 3.5% of the lake area would be required to reduce phosphorus by 50%	$45 000\ 0,1 ha

				Glyceriacanadensis			
Lake Saint-Louis (La Tuque, Mauricie)	Small lake		9,8	Ultrasonic irradiation	2008	The City has reported a decrease in cyanobacteria but there is insufficient data to draw conclusions	NA
Petit lac de l'Aqueduc (Saguenay)	Small lake			Ultrasonic irradiation	2012	decrease in chlorophyll was observed but a proliferation of macrophytes (aquatic plants) also	NA
Missisquoi Bay (Venise-en-Québec)	7800	312 200	4,5	Collection and cutting of macrophytes. Project to collect and compost aquatic plants on 365 m3	2003	According to samples taken in 2003 at Missisquoi Bay and analyzed by MELCC, aquatic plants contain an average of 400 mg P/kg of dry matter and 2200 mg of nitrogen per kg of dry matter. We multiply by a factor of 5 for the wet matter which gives us for a crop of one square meter of aquatic plants the equivalent of about 734 mg of phosphorus and 4035 mg of nitrogen would collect approximately 734 kg of phosphorus per hectare/year in the bay (about 1-2%).	$20 000 to 30 000/year

Sources : Boudreau, 2017; Boudreau *et al.*, 2013; MDDEFP, 2013; Carignan, 2009; Denis Brouard et Associés inc., 2007; EXXEP, 2004; MDDELCC, 2018f; Roy, 2015; Galvez-Cloutier et al., 2012; Dessau, 2008; Richer-Bond, 2013; Bolduc et Kedney, 2005; Questionnaire OBVBM-MELCC, 2019; OBVBM, 2011; ACBVLB, 2019; Paulin, 2017 et 2018; Roy, 2016; Thibault, 2016.

3.2 Effectiveness Results and Analysis, Estimated Cost-Benefit, and Adaptability to Missisquoi Bay

The effectiveness and cost/benefit of in-lake restoration efforts in Missisquoi Bay should be determined by further studies and pilots that test selected technologies, similar to the process undertaken at Lake Carmi in Vermont and lake Bromont in Québec. One confounding factor here is that many of the in-lake restoration technologies addressed in this chapter may not adaptable to a water body as large as Missisquoi Bay, or may become cost-prohibitive when scaled up to Bay size.

An upcoming study on Missisquoi Bay will conduct an internal loading assessment and make use of updated modeling tools to better characterize internal phosphorus loading in the Bay. This study will be funded with FY'19 EPA funds and overseen by The Lake Champlain Basin Program. Results of this study may help to inform a plan of action for Missisquoi Bay, including the viability of in-lake restoration efforts.

4 Programs and Policies Influencing Key Issues and Their Effectiveness

4.1 History of phosphorus management in the Lake Champlain Basin

The late 1980s and 1990s saw an increase in policy focus on Lake Champlain from state, provincial, and federal governments, laying the groundwork for clean water policy in the decades to come. In 1988, the three jurisdictions signed the *Vermont, New York, and Québec Memorandum of Understanding on Environmental Cooperation on the Management of Lake Champlain (MOU)*, and in 1990 the Lake Champlain Management Conference supplied an opportunity to discuss in-lake phosphorus concentration targets for each Lake segment. In the 1993 Water Quality Agreement, the three jurisdictions agreed to phosphorus reduction goals. This MOU led to the creation of:

- The Lake Champlain Basin Program in 1990;
- The Steering Committee for the Coordination and Implementation of the MOU;
- The Québec - Vermont Phosphorus Reduction Task Force in 1996.

The Lake Champlain Basin Program (LCBP) is a key part of Lake Champlain's water management and is the forum for cooperation among the governments concerned. The Lake Champlain Basin Program has led to the creation of several committees to implement the MOU.

The first action plan, Opportunities for Action: An Evolving Plan for the Future of the Lake Champlain Basin was approved for the period 1996-2016. The main priority of this action plan was the reduction of phosphorus loads into Lake Champlain. The concentration of 0.025 mg/L adopted in 1993 for the Missisquoi Baywas considered achievable by the 2016 deadline, considering that the median concentration was 0.037 mg/L in 1992. The 1996-2016 plan was renewed in 2003 and 2010. When it was renewed in 2003, Québec formally agreed to join the Opportunities for Action plan and made a commitment to meet its objectives. It was renewed in 2017 and accompanied by a message from the premier of Québec in support of its signatories. Phosphorus reduction remains the plan's top priority, but it does not identify everything that should be done to achieve the goals for Missisquoi Bay (LCBP, 2017).

4.1.1 Agreement on the Reduction of Phosphorus levels in Missisquoi Bay between the Government of Québec and the Government of the State of Vermont

The governments of Québec and Vermont signed the Québec-Vermont Phosphorus Reduction Task Force in 1997 to assess phosphorus inputs from the watershed and propose a division of responsibilities between Vermont and Québec. The report tabled in 2000 proposed the development of an agreement between Vermont and Québec on the reduction of phosphorus levels in the Missisquoi Bay. The Agreement on the Reduction of Phosphorus levels in Missisquoi Bay between the Governments of Québec and of the State of Vermont (Québec-Vermont Agreement) was signed on August 26, 2002 (Gouv. du Québec, 2002a). This agreement stipulates that the reduction of phosphorus loads in the Missisquoi Bay watershed was to reach a target of 97.2 metric tonnes per year in 2016 to meet the target concentration of 0.025 mg/L.

The Québec-Vermont Agreement represents a historic step in the efforts to reduce phosphorus levels in Missisquoi Bay. This agreement defined for the first time a shared responsibility for a total phosphorus target load from the Missisquoi Bay watershed of 38.9 t/yr (40%) for Québec (a reduction of 27.3 MT/yr) and 58.3 t/yr (60%) for Vermont (a reduction of 42.8 MT/yr) (CICBM, 2003). The MELCC is responsible for implementing and renewing this agreement. This agreement expired on December 31, 2016, and, despite efforts, the average phosphorus concentration in Missisquoi Bay is still 0.050 mg/L.

However, this agreement has resulted in several projects, funding for a few studies, and advancing knowledge about phosphorus levels in the Missisquoi Bay watershed. The renewal of this Agreement on the Reduction of Phosphorus loads in Missisquoi Bay by the Government of Québec and the State of Vermont is of utmost importance for many interviewers in Québec regarding the commitment of both governments to address the degradation of Missisquoi Bay (OBVBM Interview, 2018-2019).

An Inter-Agency committee for cooperation on Missisquoi Bay-Estrie and Montérégie and Region was created to coordinate the actions of the Québec Government and ensure alignment among the various agencies under the Agreement for the reduction of phosphorus in Missisquoi Bay. The Inter-Agency Committee, coordinated by the MELCC, consists of representatives from the agriculture, municipal, wildlife, transport, health and security agencies (MAPAQ, MAMH, MFFP, MTQ, MSSS, and MSP), which are the agency partners essential to the implementation of projects that support the achievement of objectives.

An initial Action Plan 2003-2009 on the reduction of phosphorus in Missisquoi Bay was developed in consultation with main office of the MELCC, MAPAQ and MAMH. The actions listed in these response plans are also included in the LCBP's Opportunities for Action plan. From 2003 to 2009, the Québec government and its partners invested more than $25 million in various measures to reduce phosphorus supplies from the Missisquoi Bay watershed, including $14 million from MAMH (wastewater), $4 million from MAPAQ (Ag BMPs), and $3.5 million for research projects in the watershed. This is in addition to the significant amounts invested prior to 2003 for urban and agricultural sanitation, which is to say, approximately $24 million for wastewater treatment plants and $3 million for manure storage, for a total of over $52 million (Mimeault and Simoneau, 2010).

A first state concluded that "Although phosphorus concentrations have not decreased in Missisquoi Bay, it is encouraging to see a downward trend in phosphorus concentrations and loadings in the Pike River as a result of the full implementation of the Action Plan 2003-2009. In 2009, the Inter-Agency Committee renewed the initial plan and adopted the Action Plan 2019-2016. This plan was in line with the first one, but intensified actions in identified priority sub-basins" (Mimeault and Simoneau, 2010). A few examples of Québec's actions have been partially incorporated in the State of the Lake 2015 and on the LCBP's Opportunities for Action document online.

Since 2015, the OBVBM Water Master Plan (PDE) approved by the MELCC groups together the actions of the various ministries and the actions listed in the Inter-Agency Committee Action Plan (OBVBM, 2015).

4.2 Total Maximum Daily Load

In 2002, the states of Vermont and New York developed a Total Maximum Daily Load (TMDL) for phosphorus in Lake Champlain; in 2011, the EPA disapproved the Vermont portion of this TMDL for two major reasons: the 2002 plan did not adequately address a margin of safety to account for uncertainty in the original analysis, and did not provide sufficient assurance that nonpoint source reductions would occur (U.S. EPA, 2016).

This disapproval of the Vermont portion of the 2002 TMDL and subsequent reissuance of the 2016 TMDL was triggered as a result of a lawsuit from the Conservation Law Foundation (CLF) (Chapman and Duggan 2015; *Conservation Law Foundation v. Environmental Protection Agency* 2008). In 2008, CLF filed a federal lawsuit appealing the EPA's approval of the Lake Champlain TMDL, citing the reasons above and two additional factors: failure to accurately consider point sources of phosphorus, and a lack of consideration for the long-term effects of climate change in the Basin (*Conservation Law Foundation v. Environmental Protection Agency* 2008). The EPA and CLF signed a settlement agreement in 2010 to allow EPA Region 1 to reconsider whether the 2002 TMDL was consistent with Section 303(d) of the Clean Water Act (U.S. EPA, 2016). The 2011 disapproval of the 2002 VT Lake Champlain TMDL compelled EPA Region 1 (New England) to reestablish a new phosphorus TMDL in order to conform with section 303(d)(2) of the Clean Water Act (*Federal Water Pollution Control Act* 1978).

As discussed in section 2.1 and 2.2.2, the 2002 and 2016 TMDLs set phosphorus loading targets for individual segments of Lake Champlain. Twelve out of thirteen of these segments, all except Cumberland Bay, are directly affected by Vermont sources of phosphorus; five segments are entirely within Vermont's borders, and the rest are shared with New York and/or Québec. These discrete targets are based on the amount of phosphorus already present in the segment's waters and the amount of phosphorus entering the segment from the surrounding Basin, and take into account the movement of phosphorus from adjoining segments (U.S. EPA, 2016).

4.3 Vermont

4.3.1 Clean and Clear Action Plan

In 2003, Vermont Governor James Douglas released the Clean and Clear Action Plan, a water quality initiative designed to accelerate the phosphorus reduction efforts laid out in LCBP's 2003 release of *Opportunities for Action* (Douglas 2003, 2004). Fittingly, Governor Douglas announced this new effort on the shores of Missisquoi Bay, with the support of Québec Premier Jean Charest and then New York Governor George Pataki (Douglas 2003).

Douglas's six-year Clean and Clear Action Plan called for $150 million in increased funding for clean water work, including working with Lake Champlain's congressional delegation to pursue increased federal appropriations and a request to the Vermont Legislature to issue Citizen Environmental Bonds. In 2007, the Vermont State Treasurer's Office sold approximately $5 million in these Series C Citizen

Environmental Bonds (Vermont State Treasurer's Office 2007, 2015a); later, they were replaced by more general Green Bonds, designed to target a broader selection of environmental issues including water quality and wastewater (Vermont State Treasurer's Office 2015b). Douglas's Clean and Clear efforts were spurred by recent algal and cyanobacterial blooms in Lake Champlain, and proposed prioritizing restoring riparian wildlife habitat and sediment retention on eroding streambanks, better agricultural management of phosphorus, and capital funding to improve nutrient removal at wastewater treatment facilities (Douglas 2003).

By 2011, the State of Vermont had invested over $57 million in Lake Champlain funding as part of the Clean and Clear program, and had leveraged an added $68 million in federal funding (Vermont State Treasurer's Office 2015b). These funds were focused on a handful of Vermont state programs: wastewater discharges, river management, better backroads, stormwater management, and erosion control at construction sites. However, while substantial progress was made in reducing phosphorus in wastewater, nonpoint runoff had not significantly decreased (Smeltzer, Dunlap, and Simoneau 2009; Lake Champlain Basin Program 2005).

4.3.2 Act 64: Vermont's Clean Water Act

In May 2015, the Vermont General Assembly passed H.35, "An act relating to improving the quality of state waters." H.35, subsequently named Act 64, also known as the Vermont Clean Water Act, was signed into law by Governor Peter Shumlin on June 16, 2015 (U.S. EPA, 2016). Governor Shumlin had emphasized the need for comprehensive clean water legislation in his 2015 State of the State Address (Shumlin 2015). Act 64 addressed Lake Champlain's phosphorus TMDL by setting deadlines for many of the EPA-required programs, increased clean water staffing and resources, required tactical basin planning to prioritize subwatersheds of the greatest need, and created a "Clean Water Fund" (Martin 2015). The Clean Water Fund was initially supported by a 0.2% surcharge on all property transfers over $100,000.

Notably, Act 64 revolutionized agricultural policy in Vermont by shifting the framework of regulation from "accepted agricultural practices" to "required agricultural practices (*No. 64. An Act Relating to Improving the Quality of State Waters* 2015). This new designation came with additional staff and funding resource to inspect farms and enforce regulations, rather than relying on the former complaint-based system. It also requires that the Vermont Agency of Agriculture, Food and Markets collaborate with the Agency of Natural Resources in implementing enforcement and new clean water policy (Martin 2015).

4.3.3 Additional Vermont Policy

In May of 2019, the Vermont Legislature passed Act 76, referred to as Vermont's Clean Water Funding law ("No. 76: An Act relating to the provision of water quality services"). Act 76 was signed by Vermont Governor Phil Scott on June 19th, 2019. Act 76 sets up a long-term clean water funding source, by designating 6% of Vermont's rooms and meals tax for the state's Clean Water Fund. The Act also provides for the designation of regional clean water service providers, such as regional planning districts, to implement clean water practices locally and report to the Vermont Agency of Natural Resources annually, and establishes four new water quality grant programs ("No. 76: An Act relating to the provision of water quality services").

While the Clean and Clear Action Plan and Act 64 are the most topically and temporally relevant Vermont policies to this report, Vermont has additional acts, programs, and regulations that address water quality. Act 250, Vermont's land use and development law, was enacted in 1970 to govern new construction in the state through a public review process by the Natural Resources Board (*Act 250: Land Use and Development Law* 1970). This review involves the assessment of nine statutory criteria, including several that may affect Lake Champlain: air and water pollution, water supply, impact on water quality, and erosion and the capacity of soil to hold water (Vermont Natural Resources Board 2019). While these criteria do not explicitly address phosphorus or cyanobacteria, the focus on diligent review of high impact land development has almost certainly impacted Lake Champlain's water quality. Act 250 is now nearly 50 years old, and is currently in the final stages of review by a state commission to address the law's success and ensure that the law adequately addresses emerging challenges like climate change (Dillon 2018).

4.4 New York

As Missisquoi Bay is not a New York segment of Lake Champlain, we have devoted less focus of this chapter to the state's water policy. However, New York does have significant regulatory policy that addresses Lake Champlain's water quality.

Segments of the Lake are individually classified based on New York's criteria: the Main Lake and South Lake segments are designated Class A overall, considered appropriate "as a source of water supply for drinking, culinary or food processing purposes, primary and secondary contact recreation, and fishing" (*Class A Special (A-S) Fresh Surface Waters* 1972). More specifically, the shoreline waters in these segments are Class A, while the deeper open waters are designated the more pristine Class AA. Two exceptions exist: Bulwagga Bay is Class B, and Deep Bay is Class C (New York Department of Environmental Conservation 2018; *Class AA Fresh Surface Waters* 1972; *Class B Fresh Surface Waters* 1972; *Class C Fresh Surface Waters* 1972), meaning that their most appropriate usages are primary and secondary recreation, and fishing, respectively. Phosphorus in each of these class designations should be limited to an amount that will not cause "growths of algae, weeds, and slimes" (*Narrative Water Quality Standards* 1972). Regulatory and permitting authority of New York waterbodies rests with the New York Department of Environmental Conservation (Wroth 2012).

In 2018, New York Governor Andrew Cuomo announced in his State of the State address that the state would appropriate $65 million to aggressively combat harmful algal and cyanobacteria blooms; Lake Champlain was identified as a high priority source of drinking water and site for recreation (Governor's Press Office 2017). In June 2018, following four cyanobacteria stakeholder summits, Governor Cuomo announced the release of a tailored action plan for Lake Champlain (Governor's Press Office 2018).

4.5 Québec

According to the Canadian Constitution, the management of natural resources including water is a provincial jurisdiction. The federal government is responsible for navigable and transboundary waters and the protection of fish habitat (Gouv. du Québec, 2017).

The MELCC is responsible for coordinating water management in Québec. To ensure the protection of this resource, to manage water in a sustainable development perspective and, in doing so, to better protect public and ecosystem health, in 2002, Québec launched the National Water Policy (PNE).

The PNE approach sought to:

- Implement integrated management of all watersheds to reform water governance;

- Implement this approach of management in the Saint Lawrence while recognizing the special status and importance of this waterway;
- Protect water quality and aquatic ecosystems;
- Continue to clean water and improve water service management;
- Promote recreational tourism activities related to water.

The PNE led to the recognition of 33 priority watersheds, including the Missisquoi Bay watershed, and to the creation of a network of watershed organizations (OBVs) responsible for their integrated and collaborative management. In Missisquoi Bay, this resulted in official recognition of the *Corporation de bassin versant de la baie Missisquoi*, which would become the Organisme de bassin versant de la baie Missisquoi in 2009. In addition, the PNE mandated these watershed agencies to complete the first Water Master Plans (PDE) and suggested their implementation through basin agreements among the various stakeholders

Subsequently, the adoption in 2009, the Act Affirming the Collective Nature of Water Resources and aimed at Strengthening their Protection confirmed the legal status of water resources as part of the heritage of the community, clarified the responsibilities incumbent to the state as custodian of the resource on behalf of the citizens and defined the rights and duties of the community. This act has clarified the mission of the watershed organizations, now numbering 40, that is, "to develop and update a water master plan, to promote and monitor its implementation ensuring a balanced representation of the users and the various interested parties, including the governmental, aboriginal, municipal, economic, environmental, agricultural and community milieu, in the composition of this body "(Article 14). This law was amended in 2017 and is now called the Act Affirming the Collective Nature of Water Resources and Promoting Better Governance of Water and Associated Environments.

As part of the implementation of integrated watershed management in Québec, the water master plan helps structure the process and help decision-making. This planning process, carried out in consultation with water stakeholders in a watershed, is intended to be adaptive, iterative and prospective. It is thus a mode of participative governance.

Finally, in 2018, the Government of Québec unveiled the Québec Water Strategy 2018-2030 (Water Strategy), which takes over from the 2002 National Water Policy (Gov. Du Québec, 2018

4.5.1 Agricultural Regulatory Framework

Québec's first environmental framework for agricultural activities was created in 1981 with the adoption of the *Regulation respecting the prevention of water pollution in livestock operations* (RPPEEA), which aimed to protect water by making manure storage structures impermeable. It also required that spreading take place on available areas by considering the nitrogen concentration in the manure and the spreading capacity as needed (CAAAQ, 2008). In 1996, the concept of municipalities with a surplus was introduced into the RPPEEA. In 1997, the *Regulation respecting the reduction of pollution from agricultural sources* (RRPOA) introduced *Agro-Environmental Fertilization Plans* (PAEF), a phosphorus standard as well as spreading manure practices standards. Phosphorus is now considered a major cause of waterway eutrophication. Restrictions on the spreading of phosphorus, imposed by regulation since 1997, would have favoured the optimal use of mineral phosphorus in animal feed and crop fields (Patoine & D'Auteuil-Potvin, 2013). The development of agroenvironmental farm plans has led to a significant reduction in mineral fertilizer discharge across Québec, and increased recognition of the importance of manure as a fertilizer, to be seen more as a valuable resource, and less as waste to be disposed of (CAAAQ, 2008).

The concept of animal units has also been abandoned due to very wide disparities in animal feed, making it difficult to use averages to assess phosphorus concentrations in manure (CAAAQ, 2008). Calculations to assess application requirements are now based on the degree of phosphorus saturation in the soil rather than total concentration (richness), allowing for consideration of differences among soil types or among soils in the same category under different conditions. To this end, abacuses to determine maximum phosphorus deposits per hectare have been developed to replace calculations based on animal units per hectare, and because this approach is considered more effective in preventing eutrophication of waterways (CAAAQ, 2008).

In 2002, as part of the launch of the National Water Policy, the RRPOA was replaced by the *Agricultural Operations Regulation* (REA), which introduced requirements for phosphorus saturation thresholds for agricultural soils, restrictions on animal access to waterways beginning in 2005, mandatory ban of increasing crop areas in watersheds that are overly saturated with phosphorus, requirements to spread manure using a low ramp, and the recovery of waste water from dairy farms (Gouvernement du Québec, 2004).

Managing soil phosphorus concentrations

The problem of phosphorus oversaturation in agricultural soils was addressed through implementation of the REA, which governs the management, method and quantity of fertilizers (phosphorus) applied to fields.

Since 2010, the REA has required the tabling of a phosphorus report. The phosphorus report is an inventory of phosphorus loadings, produced or imported, and the ability of soils to receive these loadings in accordance with maximum annual phosphorus deposits provided by the REA. It checks the balance between phosphorus inputs and maximum depositional capacity, to prevent surplus water from entering waterways and altering their quality, notably by abetting the proliferation of blue-green algae" (MELCC, 2019b). The REA always requires the yearly presentation of a report on the equilibrium of phosphorus and the maintenance of that equilibrium. Therefore, the operator must have enough acreage to manage the fertilizing materials according to the guidelines set out in Appendix I of the REA.

Agri-Environmental Fertilization Plans (PAEF) have also been developed to help restore the soil's equilibrium and ensure that the quantities of fertilizers applied do not exceed plant needs. It is important to note that the abacuses more or less consider the plant's needs. They allow significant inputs into poor soils to enrich them, and lower inputs in rich or saturated soils to reduce phosphorus content.

PAEF determine, for each parcel in an agricultural operation and each annual growing season (maximum of 5 years), the crop grown and the spreading limits for fertilizers (MDDELCC, 2017). If the soil of a cultivated parcel exceeds one of the saturation thresholds listed in Appendix I of the REA, the fertilization recommendations listed in the PAEF for a livestock or manure spreading site stipulate that the concentration must be lowered and maintained below the prescribed thresholds.

The PAEF and phosphorus reports are prepared by agronomists hired by the agricultural producers concerned. Compliance with these provisions is monitored by the MELCC's regional branches. Data on the phosphorus reports released in 2016, as well as data on water quality in the bay watershed's agricultural zones, indicate that more work remains to be done to reduce phosphorus saturation rates in soils and ultimately the amount of phosphorus that is released into streams and Missisquoi Bay. Despite compliance, the support capacity has been significantly exceeded.

Phosphorus (P) mass balances and dynamic simulation of P inputs, storage and exports have been the subject of several studies in Vermont (Cassell et al., 1998, 2001, 2002; Meals et al., 2008a, 2008b). A clear finding of these studies was that the long-term goal of reducing phosphorus loads into Missisquoi Bay can only be achieved by addressing the imbalance between imports and exports in the agricultural sector and, where appropriate, in the urban environment as well (Jokela et al., 2002). At the dairy farm level, for example, mass balances established by Vermont researchers have shown that between 20% and 40% of the phosphorus imported (fertilizers, feed, etc.) leaves the farm in the form of milk, meat or other products (Anderson and Magdoff, 2000). Over time, the concentration of P increases in soils and deposition zones in water bodies, generating increasing P flows. For example, in the Québec portion of the Pike River's watershed, soil richness and input reports were shown to be significantly correlated, contributing to more than 85% of the spatial variability in phosphorus flows (Deslandes et al., 2002a, 2002b). Already more than 15 years ago, one third of the soils in a sub-basin in the same study area had saturation rates above the 10% vulnerability threshold for phosphorus loss (Michaud et al., 2002a, 2002b).

This finding does not diminish the importance of agricultural practices regarding the conservation and anti-erosive development of lands and waterways. Their benefits have been demonstrated in the Missisquoi Bay watershed, as elsewhere in the northeastern United States. However, in North America, long-term monitoring of the effects of these "traditional" beneficial management practices on control of P runoff, erosion and particulate loads has shown that P trapping sites become long-term sources of soluble phosphorus (Dodd and Sharpley, 2016). Clearly, the main implication of long-term P mass balance studies and the effectiveness of runoff and erosion control on P mobilization is that achieving P target loads in the Missisquoi Bay watershed is compromised without rebalancing the phosphorus mass balance.

Systems for separating solid fractions (90% of P) and manure liquids, for example, are widely used in Europe and have also proven to be effective in Québec hog farms (Godbout et al., 2006). The liquid fraction, relatively low in P but high in nitrogen, can then be applied to the field, while limiting soil enrichment in P and preventing P losses in the waterway. This "low P" manure is particularly beneficial in the organic grain sector, where soil is vulnerable to P over-enrichment due to continued use of farm fertilizers. With respect to the recoverable solid fraction (90% P; Godbout et al., 2006), high nutrient richness and low humidity make it easier to apply on more distant fields, or off-farm, after it has been dried, composted or granulated.

Supporting larger livestock operations, for example, in separate management of the solid and liquid phases of manure, is a two-pronged approach in preventing the long-term eutrophication of Missisquoi Bay. On the one hand, the availability of P-depleted manure will contribute to limiting long-term phosphorus enrichment in the watershed. As well, the cleaned-up solid fractions could replace phosphate mineral fertilizer inputs, lowering the overall P supply in the watershed.

Managing phosphorus levels in organic fertilizers at the source also involves reducing mineral phosphorus added to feeds by using enzymes in some livestock production to better assimilate phosphorus in cereals (e.g., phytase). Feed assessments would confirm whether the nutrition of livestock located in this watershed is benefiting from this option.

The MRC Brome-Missisquoi in Québec has mandated the *Institut de recherche et de développement en agroenvironnement* (IRDA) to adapt the Phosphorus Exports Diagnostic Tool to the needs of the MRC in terms of management and control of runoff water on its territory. This spatial reference tool makes it possible to estimate and visualize surface runoff, erosion and phosphorus transfer rates by surface area. The main risk areas were thus located for the entire Brome-Missisquoi RCM.

Also, the OBVBM commissioned IRDA to carry out in the basin of Rock River a scenario analysis aimed at reducing phosphorus loads by 40% using the *GEODEP* tool. The results of the analysis will be used to prioritize the interventions according to the gains and to make representations to the governmental authorities for the implementation of the actions. IRDA analyzed the entire watershed of Rock River for scenario modeling. However, the benefits/costs component was only implemented for the Québec portion of the watershed.

Four objectives guided the selection of alternative management practices modeled for the Québec portion of the watershed:

1. Reduction of erosion rates in corn and soybean crops through residue cultivation and cover crops
2. The superficial incorporation of farm manure in the application
3. Development of riparian zones to watercourses
4. Protecting areas that are flooded or excessively vulnerable to erosion

The project was funded by the LCBP under the Support to Pollution Prevention and Habitat Preservation component.

4.5.2 Farm Support Programs

The main support programs for agricultural producers in Québec are the Canadian Agricultural Income Stabilization (PCSRA) Program, the Farm Income Stabilization Insurance Program (ASRA), the Crop Insurance Program, used to address natural risks and the Farm Property Tax Credit Program. These programs are managed by the *Fédération Agricole du Québec* (FADQ). Spending on these programs ranges from $500 million to $1 billion annually. They have increased by almost 250% between the early 1980s and 2008 in response to various factors, e.g., property tax increases, climate events, etc., (CAAAQ, 2008). The ASRA is by far the Québec Government's largest financial assistance program. Supply-managed productions, which already enjoy special protection from foreign competition, are not eligible for this program (CAAAQ, 2008). Four non-supply-managed commodities (grain corn, feeder veal, pork and piglets) share the majority (about 65%) of the money spent on these various support programs in Québec (CAAAQ, 2008).

Since 2008, compliance or the protection of riparian buffers and the prohibition of increasing cropping areas in certain municipalities targeted by the REA have been implemented under the ASRA and crop insurance programs (Auditor General of Québec, 2012).

Prime-Vert Program

The Prime-Vert Program is managed by the MAPAQ and co-funded by the federal and provincial governments under various agricultural partnerships. Originally designed to support agricultural producers in establishing sealed storage structures, this program has provided funding to producers since 2002 to reduce non-point source pollution by supporting agri-environmental practices (BMPs). For example, farms can get the help they need to: manage animal access to waterways; develop riparian buffer and windbreak; install erosion protection structures in fields or along waterways; adopt farm practices that conserve soil and water. The Prime-Vert program is essential for the fight against non-point source pollution in Québec.

The 2018-2023 version of the Prime-Vert introduces new features such as funding for cover crops and intercropping, which rapidly became very successful with more than 350 applications received by MAPAQ (covering at least 10,000 ha) for the Montérégie in 2018. The new Prime-Vert program also considers the maintenance of riparian plantings that it has funded, which is a benefit and incentive for establishing these works. The amount available to producers has also increased from $30,000 to $40,000.

The 2018-2023 MAPAQ Prime-Vert program offers three funding streams:

Stream 1: Agri-environmental intervention by a farm, which funds among other things other agri-environmental developments (windbreak hedge, extended riparian strips, etc.) and soil conservation practises and structures (erosion control works, cover crops, etc.)

Stream 2: Regional or inter-regional agri-environment approach, which supports actions related to agri-environmental issues identified in the Montérégie by MAPAQ and local partners:

- Degradation of soils due to monoculture, inappropriate rotations and poor agricultural practices,
- Intensive use of pesticides that pose a serious risk to the environment and to health in field crops as well as in horticultural production, particularly in southern parts of the Montérégie,
- Stream pollution and degradation of water quality caused, in part, by agricultural inputs and soil loss in intensive cropping areas within watersheds, including the Rock River watershed,
- Biodiversity loss in intensive agricultural areas including the Missisquoi Bay watershed.

Stream 3: Support for development and transfer of agri-environmental knowledge, which provides assistance to experimental development, technological adaptation and transfer of agri-environmental knowledge, dissemination of agri-environmental information, and individual farm business support for testing implementation of proven BMPs (cover crops, fall cereal planting) on a maximum test area of 5 hectares.

Although this program meets the expectations of the 490 agricultural producers in the watershed, a significant decrease in grant applications was noted between the 2009-2013 and 2013-2018 periods, from 64% to 18% of the total participation rate.

The Prime-Vert Program has made it possible to carry out watershed projects such as removal of animals from waterways, soil conservation works (drains, rainwater inlets, filter trenches, etc.), cover crops, planting of shrub and windbreak hedge, storage infrastructure for manure, and purchase of equipment to reduce pesticide use. Training on the direct seeding method and other soil conservation practises has also been offered to agricultural producers, many of whom have purchased equipment to make the transition to these practices (Mimeault and Simoneau, 2010).

MAPAQ provided technical and financial support for several initiatives in the Missisquoi Bay watershed between 2007 and 2019, totalling more than $1.6 million, including the *Lisière Verte* program (2007-2010), the Missisquoi Bay ZIPP project (2009-2013), the ruisseau Morpions ZIPP project (2010-2014) and the OBVBM'S *Interventions ciblées sur le contrôle des eaux de ruissellement et la conservation des sols dans la MRC Brome-Missisquoi* (2016-2019). The latter project was funded by the Prime-Vert (regional approach) program, the MRC Brome-Missisquoi, OBVBM and Environment and Climate Change Canada's EcoAction program.

As part of this targeted project on storm-water control and soil conservation in the MRC Brome-Missisquoi, OBVBM and the MRC are working together to reduce the impact of runoff from agricultural lands in areas most vulnerable to erosion and in watersheds where stream maintenance work is taking place. Since 2016, targeted agricultural producers have received assistance from OBV/MRC agronomists to implement measures to reduce nutrient inputs into waterways. Cover-cropping practices expanded riparian buffers development and hydro-agricultural structures are highly recommended.

Several stakeholders interviewed observed significant changes in the "mindset" regarding the environmental protection of agricultural areas. The bay watershed would be "fertile ground" for innovative projects considering some strong interest from agricultural producers and advisors (OBVBM interviews, 2019). Some improvements are noticeable in water quality analyses weighted to the flows. However, loads are still excessive and nonpoint source management remains a major challenge in the Missisquoi Bay watershed.

4.5.3 Québec Water Strategy 2018-2030

In 2018, the Québec government unveiled the Québec Water Strategy 2018-2030 (Water Strategy), which replaces the 2002 National Water Policy (Gouvernement du Québec, 2018). The Water Strategy will be implemented through three successive action plans with the first Action Plan 2018-2023 representing investments of over $550 million.

The Water Policy's seven priorities are:

- Ensure public access to quality water,
- Protect and restore aquatic environments,
- Better prevent and manage water-related risks,
- Harness the economic potential of water,
- Promote sustainable water use,
- Acquire and share the best knowledge on water,
- Ensure and strengthen integrated water resources management.

The priorities and objectives for the Missisquoi Bay issue are Priority 1 with Objectives 3 and 4. With respect to Objective 3, which aims to bring the wastewater infrastructure up to standard, certain measures are aimed at ensuring better control of discharges and promoting the upgrade of residential wastewater treatment facilities. Objective 4, meanwhile, is the continuation of the agro-environmental shift through actions taken in the following areas: controlling sources of contamination of surface water, repairing animal waste storage facilities and improving the efficiency of riparian buffers. As well, Priority 7, which seeks to ensure and strengthen integrated water resources management, includes a measure to support the Québec-Vermont-New York cooperation for the integrated management of Lake Champlain, Lake Memphrémagog and the Richelieu River.

The Water Strategy's Action Plan 2018-2023 includes 63 measures administered by eleven government agencies and organizations whose key actions include: improving water-related risks prevention and management, including for flood events ($53 million); conserving and restoring aquatic environments ($32 million); ensuring access to quality water in adequate quantities, including through the program for the enhanced protection of drinking water sources ($34 million) (Gouv. du Québec, 2018). Monitoring of the Water Strategy is carried out by the MELCC; each year, a progress report must be published, and a mid-term report is in the works. The Water Strategy aims to foster greater coherence in water management responses.

As part of the Québec Water Strategy 2, the Program for Greater Protection of Sources of Drinking Water (PPASEP) supports municipalities implementing the Drinking Water Protection Regulation. The PPASEP is administered by the MELCC and it has two components: The first component will help municipalities that need to perform vulnerability analysis of their drinking water sources, while the second will help municipalities to financially compensate for lost revenues suffered by agricultural producers due to certain restrictions imposed by the Pesticide Management Code (MDDELCC, 2018e). The municipality of Bedford, which has its source of drinking water in Missisquoi Bay, is in the process of conducting the vulnerability analysis.

4.6 Recommendations from Experts

In Québec, the OBVBM consulted more than 65 persons from different agencies, research center and universities as well as municipal and agricultural stakeholders to gather their views and recommendations. A questionnaire was developed for each of the person consulted. Some provided written responses, but most were met in interviews from October 2018 to January 2019. Governance, financing programs and current regulations were discussed, and several solutions were discussed to reduce nutrient inputs to Lake Champlain. A comprehensive synthesis of the views expressed was completed and QC SCAG assessed the most relevant interview sections for the IJC mandate.

The personalized questionnaires approach gives rather qualitative results and does not make it possible to quantify or present statistics. However, opinions reflecting a certain consensus or raised by several persons served as a basis for the development of the recommendations of the QC SCAG are listed here.

Phosphorus and nutrients

Representatives of the scientific community agree that phosphorus is the preferred approach to reduce eutrophication in a body of water and related symptoms such as cyanobacteria efflorescence.

In order to limit the production of intensive crops in degraded areas, financial incentives have been invoked by many to promote the transition to cereal and fodder crops. Revised fertilizer requirements have been questioned many times (NMP/P-Balance Sheet) for these control tools to achieve water quality restoration goals. The support and financial support of agricultural producers, the cross-compliance and the compensation for ecological goods and services rendered, should, for many, be the subject of in-depth reflection in order to propose models that would be better suited to the needs of farmers. Market development to support grain and forage production to reduce corn/soybean production was also recommended. Financial support should be provided by several stakeholders to municipalities to upgrade sewage treatment works and reduce their overflows.

Policy and Governance

Most people consulted mentioned the importance of the renewal of the agreement between the Government of Québec and the State of Vermont that came to an end in December 2016 regarding phosphorus reduction at Missisquoi Bay in order to have an official commitment from both governments. To ensure that the objectives of this agreement are achieved, a budget envelope commensurate with the objectives has been strongly recommended, as well as the establishment of a binational agency or a committee of experts dedicated to evaluating and recommending the actions and solutions to be prioritized for the reduction of phosphorus inputs to Missisquoi Bay. In order to follow the progress of the objectives, an annual report should be presented to each of the bodies concerned and to the stakeholders in the field.

From a regional point of view, the delineation of constraint zones in the Regional County Municipality development plans could make it possible to regulate certain uses of the territory in the identified degraded areas. The protection of natural environments and wetlands was also a consensus. In terms of regulation, there have been several enforcement and monitoring shortcomings due to the lack of staff in the departments and the lack of financial resources of the municipalities as is the case with the Shoreline and floodplains Protection Policy that is generally poorly respected.

Cyanobacteria and public health

There is little information available on water bodies affected by cyanobacteria in Québec. The ministry no longer produces an annual report since 2016 and the follow-up is done by volunteers. The beach owners and municipalities do not sufficiently display the information transmitted by the Ministry of Health on follow-up instructions when a water body is affected by cyanobacteria. The fact that the MELCC no longer systematically samples recurrent water bodies, such as Missisquoi Bay, suggests that there are no longer any problems. For many, there is a risk of normalization of the situation. This would have a negative effect on the implementation of action to reduce nutrient inputs. For many stakeholders, the government should require beach owners and municipalities to inform citizens and visitors of the health risks.

In Vermont, as part of the literature review, the LCBP met with watershed professionals to discuss Lake Champlain's water quality and cyanobacteria management. These experts ranged in affiliation from small watershed groups and local municipal officials to regulatory personnel within state and federal governments. These informal, semi-structured interviews were guided by a series of standard questions on water quality and cyanobacteria in the Lake Champlain Basin (Appendix 1). Principally, these conversations focused on programs, factors, and efforts that had been successful and unsuccessful at addressing nutrient loading and cyanobacteria in Lake Champlain, and recommendations for future efforts, given level or increased funding. US Interviews were conducted in December 2018 and January 2019 and were typically around an hour in length. Our initial interviews were with CSAG members; subsequent interviews were solicited with watershed professionals suggested by CSAG members.

Responses from US interviewees were thematically grouped into loose categories: policy, regulation, and the distribution of funds; high-priority phosphorus contributions and potential solutions; and education, outreach, and watershed-scale collaboration. For each of these categories, we listed interviewees' mentions of the following topics: successful programs, projects, and factors; unsuccessful programs, projects, and factors; and recommendations. These responses are listed in Table 6 and discussed in more detail below.

Table 6. US Interviewee responses categorized by theme. The number in parentheses after each point represents the number of interviewees who mentioned the topic. Topics with fewer than two mentions are not listed.

	Successful programs, projects, and factors	Unsuccessful programs, projects, and factors	Recommendations
Policy, Regulation, and Distribution of Funds	• Vermont's Act 64 and associated regulatory changes (4), and in particular the new Required Agricultural Practices (4)	• Current system for distributing clean water funding (5) • Vermont's Act 64 and associated regulatory changes (2) • Organization of clean water programs make it difficult for individuals to see their own role (2)	• Keep current funding steady, and evaluate success (4) • Administer a new system for more efficiently distributing funding (4) • Give more power to watershed groups (4) • Decrease administrative and reporting requirements for clean water grants (4) • Increase funding for research (3) • Devote some funding to costly pilot projects (3) • Address aging infrastructure (2) • Consider climate change when making policy decisions (2)
High-Priority Phosphorus Contributions and Potential Solutions	*None mentioned*	• Current focus on crisis response rather than on proactive actions (2)	• Focus dollars on highest phosphorus contributors (6) • Address legacy phosphorus in Lake Champlain sediment (5) • Provide more support to farmers (4), possibly by overhauling the milk pricing structure (4) • Implement

			stormwater BMPs (4) • Prioritize nature-based water quality solutions (3) • Implement a cap-and-trade system for phosphorus (2) • Restore riparian corridors (2)
Education, Outreach, and Watershed-Scale Collaboration	• Existing education and outreach programs (5) • Lake Champlain long-term monitoring program (4) • Concept that water quality improvement is a shared stakeholder responsibility (4) • Collaboration between New York, Vermont, and Québec (4) • Citizen cyanobacteria monitoring (2) • Clean water advocacy groups (2)	• Lack of ownership of water quality problems, and reduced interjurisdictional collaboration (2)	• Encourage more clean water stakeholder "buy-in" (4) • Facilitate more watershed-scale collaboration (4) • More education and outreach, particularly to underserved communities and groups (2)

Respondents were split on the topic of Act 64, Vermont's Clean Water Act. The Required Agricultural Practices (RAPs) set forth by the act were viewed favorably; and the Act more generally received positive mentions from federal and state employees. While some observed that while the Act's 2015 passage may still be too recent to have had measurable positive impacts, it "has the potential to be successful." However, respondents from local governments and watershed nonprofits looked on the Act and related legislation less favorably, noting that while the tactical basin planning process may result in useful information, the process is difficult for stakeholders to understand and engage with, and that Act 64 may put an unfair share of responsibility on municipalities rather than the Vermont Agency of Natural Resources.

Interestingly, one perspective was that while the designation of the town's Rugg Brook and Stevens Brook subwatersheds as "stormwater impaired" was a difficult issue to address, it spurred action on the part of the town and had an ultimately positive impact. These waterbodies received impaired designation on Vermont's 2006 303(d) list (Vermont Department of Environmental Conservation 2009b, 2009a), and were granted approved TMDLs for stormwater in 2009 by the USEPA; the attention to water quality impairment caused by these stormwater designations appeared to prompt increased interest from stakeholders in water quality more generally.

Interviewees were asked about where they saw opportunities for policy, research, and implementation improvement. When given a scenario of level funding, several of those interviewed suggested keeping current water quality appropriations steady, and evaluating success. This was true particularly of those state and federal employees who had been involved in crafting Act 64, Vermont's Clean Water Act, who requested that more time be given to determine success of initiatives that have recently gone underway.

Interviewees had fewer responses when asked to list examples of programs and efforts that had been unsuccessful in addressing water quality and cyanobacteria in Lake Champlain. The most major topic, shared by five interviewees, was that the current structure of dispersing water quality funding is inefficient and could be made more effective. However, the specifics of views on this topic varied substantially: several interviewees argued that too great a proportion of total funding goes to administrative support and reporting costs, and that more resources should go to implementation rather than research and monitoring, while others suggested that funds be distributed based on water quality outcomes – that is, pounds of phosphorus reduction. High-Priority Phosphorus Contributions and Potential Solutions

Several interviewees mentioned the importance of optimizing the distribution of increased funds. Some suggested that an increase in funding go to the Agency of Natural Resources to be administered; there is already significant challenge in issuing funds in a timely and efficient manner, so up to a third of any increased funds should go to fund staff to facilitate grant projects around the state. However, other interviewees, mostly from municipalities and watershed groups, disagreed, suggesting that the federal and state governments attempt to be more closely aligned with local nonprofits, and stretch funding by removing the barriers that these organizations have to cross, such as the time-consuming process of applying for grants rather than receiving steady funding, and the significant amount of reporting paperwork. Another suggestion was to decentralize state government to better support municipalities: specifically, moving up to 80% of the ANR's Montpelier staff to underserved communities throughout the Vermont. These differing views illustrate the clear division in perceptions of priorities and challenges between state and federal employees who craft and promote the current regulatory framework, and the municipal staff and watershed groups who conduct on-the-ground implementation work in response.

The most common suggestions for the use of increased funding were to target high priority phosphorus sources, and to prioritize education and outreach efforts. Regarding high priority phosphorus areas, responses were varied, but many centered on agriculture. Several mentioned the importance of encouraging the state, municipalities, and watershed groups to buy out farms in critical phosphorus source areas, particularly in the Lake Carmi watershed; while agriculture is seen as a fundamental part of the watershed's landscape, farming is the largest contributor of phosphorus to Lake Champlain and must be addressed. Providing support and incentives to farmers to transition away from high-impact crops like corn and dairy may be a relatively simple way of decreasing agricultural phosphorus. Funds for farmer education, subsidies for equipment purchases and best management practices (BMPs) installation, and easier access to personalized nutrient management plans were mentioned as possible ways to support farmers.

Another suggestion was an overhaul of the federal milk pricing structure. Most milk prices paid to farmers are set monthly, according to Federal Milk Marketing Orders, based on a combination of market-determined dairy prices and estimated production costs, yields, and location (MacDonald, Cessna, and Mosheim 2016). Milk production has shifted to larger farms, and these larger farms can earn much more per unit of milk than smaller operations, giving them a strong incentive to further expand; these farm size increases caused milk production costs to decrease for larger farmers between 1998 and 2012, and as a result milk prices have been reduced (MacDonald, Cessna, and Mosheim 2016). In 2010, the median national dairy herd size was 900 cows, up from 80 in 1987 (MacDonald, Cessna, and Mosheim 2016); in Vermont, the average herd size is 125 cows, an increase from 60 in 1990 (Parsons 2010). These descriptive statistics are not directly comparable, but they suggest that while Vermont's dairy herds have nearly doubled in size, they are still much smaller than the industrial-scale dairy herds nationwide. Vermont's dairy industry has been described as "in crisis" (Heintz, April 2018), and the pressure for farmers to aggregate larger herds on the same farm parcel increases the environmental impact of dairy production. Dramatic surges in volatility of milk prices have negatively impacted farmers (Bolotova 2016), and eliminating or overhauling the federal milk pricing scheme has been a topic of research and discussion for several decades (Manchester and Blayney 1997; McNew 1999).

While addressing the most challenging nutrient and cyanobacteria areas on Lake Champlain is crucial, several interviewees also noted the importance of protecting and conserving intact, well-preserved areas. Protecting and maintaining natural resources maximizes their water quality value, shifting focus to "nature-based" solutions rather than relying entirely on technological innovation to fix ongoing problems.

Technology was a recommendation for several of those interviewed: increased funding would allow for the installation and testing of new, costly systems to remove phosphorus and increase water quality. Some pilot project possibilities included phosphorus treatment train installations; purchase and implementation of enhanced treatment units (ETUs), used in place of traditional septic systems to remove more nitrogen and phosphorus; and addressing of high phosphorus legacy sediments in the Lake. In particular, respondents suggested implementing pilot projects to highlight the value of ecosystem services and considering applying successful pilot projects on a larger scale – for example, implementing the treatment train project on a larger scale, perhaps at the mouth of the Rock River.

4.6.1 Education, Outreach, and Basin-Scale Collaboration

A major theme throughout the interviews was the importance of basin-scale collaboration in the Lake Champlain Basin. Several of those interviewed noted the value of collaboration between the United States and Canada, and suggested that successful regulations – be they from Vermont, New York, or Québec – be implemented in other jurisdictions as well. Respondents emphasized the need for communication and collaboration with Québec, and suggested a common informatics and planning process for the basin, and that New York and Québec might consider adopting Vermont's Municipal Roads General Permit system.

Most interviewees noted their recognition of the importance of data collection and research. Many listed the Lake Champlain Monitoring Program as an example of a program that has been successful in addressing water quality and cyanobacteria. This bi-state program, begun in 1990, provides long term data on many of Lake Champlain's water quality parameters, including total and dissolved phosphorus. It has provided scientific basis for several regulatory and policy actions in the basin. Respondents noted that in addition to the strength of the data collected by the long-term monitoring program, the citizen cyanobacteria monitoring program coordinated by VTDEC and the Lake Champlain Committee has given stakeholders an opportunity to learn more about water quality and get involved in research on the Lake.

Education and outreach were topics with significant support from interviewees. Activities that encourage stakeholder engagement and public participation were particularly well-regarded, including LCBP's teacher trainer program (Champlain Basin Education Initiative) and Boat Launch Steward program (while these stewards are principally intended to focus on invasive species prevention, they have interactions with many users of high-traffic boat launches on the Lake, and often discuss phosphorus and cyanobacteria with concerned stakeholders). Several respondents mentioned the importance and challenge of reaching new audiences; television, radio, and new social media avenues like Facebook and Twitter were raised as opportunities. Thinking generationally – involving younger stakeholders in the Lake's management – was a topic of major discussion as well.

One final commonality between interviews was the importance of personal responsibility and long-range thinking. The state of Lake Champlain and, more specifically, Missisquoi Bay, is the result of hundreds of years of human land use, and several respondents noted that the TMDL's 20-year timeframe will likely not be adequate to complete clean-up effort. Stakeholders in the basin need to better understand the timescale required for major changes in water quality, and

Overall, most of those interviewed observed that while the management of phosphorus and cyanobacteria is substantial challenge, particularly need to be educated on their personal impacts and responsibilities. in a complex, diverse, multi-jurisdictional system like Lake Champlain, progress is being made in several sectors. The importance of prioritizing high-impact phosphorus sources, continuing to collect high quality data to inform policy, and providing education, outreach, and support to stakeholders is clear.

5 Recommendations for Reduction of Nutrient Loading and Cyanobacteria Blooms in Missisquoi Bay

Missisquoi Bay has long been degraded by excessive phosphorus inputs from the Bay watershed, and has one of the highest in-lake phosphorus concentrations of any segment of Lake Champlain (Lake Champlain Basin Program 2018). While the drainage area to Missisquoi Bay makes up only 15% of the lake's total watershed, it contributes about 23% of the total phosphorus load to the lake. The effects of this disproportionately high phosphorus loading from the Bay watershed are compounded by the Bay's shallowness and limited connectivity to the rest of the lake. The resulting excessive phosphorus levels threaten Missisquoi Bay's ecosystem, public drinking water supply, and recreational opportunities.

Despite progress made by the governments of Québec and the State of Vermont (the Parties) in the Missisquoi Bay watershed through the implementation of urban and agricultural remediation measures, the phosphorus concentration target of 0.025 mg/L was not reached by December 30, 2016, when the Agreement between the Parties concerning phosphorus reduction in Missisquoi Bay expired.

As noted in numerous sections of this report, climate change poses a significant ongoing stressor upon the quality of Missisquoi Bay waters. While the recommendations presented below address water quality specifically, an overriding recommendation is that the Governments of Canada and the United States, as well as those of Québec and Vermont, implement meaningful controls on carbon emissions. If left unchecked, continued warming and related hydrologic impacts will increasingly undermine the achievement of our water quality goals.

The management recommendations below are provided to the Canadian and United States federal governments and their partners with the goal of reducing nutrient inputs to the Missisquoi Bay and the frequency and severity of cyanobacteria blooms in this lake segment.

These recommendations are based on the Québec and US reports of the IJC's Champlain Science Advisory Group (CSAG) and other water quality and policy experts in the region, including participants in a facilitated technical workshop in May 2019.

The following recommendations acknowledge several underlying factors critical to understanding nutrient loading and cyanobacteria blooms in Missisquoi Bay, not the least of which are climate change impacts:

- The land use history of the watershed affects the distribution, condition, connectivity, and nutrient storage potential of forests and wetlands,
- The Missisquoi Bay watershed has a land to water ratio of about 40:1, which is relatively high compared to 18:1 for the Lake Champlain and less than 3.5:1 for the Great Lakes watersheds,
- Climate change, and the associated potential increase in temperature and extreme event impacts, may likely result in more nutrient loading and more frequent cyanobacteria blooms, and
- Nutrients from agricultural sources within the Missisquoi Bay watershed have been identified as the leading cause of impairment. (Smeltzer and Simoneau 2008; U.S. EPA 2016b)

Priority recommendations

1. Create and coordinate a Bi-national Phosphorus Reduction Task Force to strengthen cooperation and accountability between the Parties in order to achieve mutually agreed goals

Although many of the recommendations in this report needs to be addressed by higher levels of government, several should be addressed within the Action Plan to be developed by the Missisquoi Bay Phosphorus Reduction Task Force.

Although the Agreement between the Government of Québec and the Government of the State of Vermont concerning phosphorus reduction in Missisquoi Bay expired in December 2016, the principles outlined within that MOU should continue to guide the Parties.

a. Agree to maintain the 0.025 mg/L annual average concentration target

b. Create a permanent binational Missisquoi Bay Phosphorus Reduction Task Force as a standing subcommittee of the Lake Champlain Steering Committee, to be tasked with reviewing, developing and assisting in the implementation of actions to reach the above target. This committee will work with partners to develop a binational Action plan to reduce phosphorus loads within a defined timetable. The bi-national Action Plan should include requirements of applicable water quality management plans, and the Committee should provide input in the development of future iterations of these plans. This group would be responsible for defining and assisting in the implementation of measures, and support tracking and monitoring progress through performance indicators

c. The Missisquoi Bay Phosphorus Reduction Task Force will work to ensure consistent transboundary data collection procedures, standardized data quality assurance, and multilingual public access and communication pertaining to phosphorus data, with the goals of unifying scientific methods in the Missisquoi Bay watershed and of carrying one unified message to the public on status and progress

d. The Missisquoi Bay Phosphorus Reduction Task Force will report annually to the Lake Champlain Steering Committee, the OBVBM Board of Directors and to the Public on progress toward achieving these goals. The Action Plan will include an accountability element in which the annual report will provide a summary of achievement of the goals outlined within the Action Plan

e. The State and Provincial governments of Vermont and Québec, as well as the federal governments of the United States and Canada, should provide the necessary sustained funding to achieve clean water goals referenced above

2. **Develop a binational mass balance analysis for phosphorus imports and exports in the Missisquoi Bay watershed**

Understanding the amount of phosphorus that is brought into the Missisquoi Bay basin from external sources (imported phosphorus), how phosphorus is cycled through the Missisquoi Bay basin ecosystem, and how much phosphorus is exported, either out of the Bay and into the rest of Lake Champlain or out of the watershed by human activity will be critical to addressing the frequency of cyanobacterial blooms in the long-term. A binational phosphorus mass-balance model that addresses movement of phosphorus throughout the Missisquoi Bay basin ecosystem will help to inform management decisions and measure progress toward achieving management goals for the Bay.

a. Develop a binational mass balance model for phosphorus in the Missisquoi Bay watershed, and advance transboundary work that addresses total phosphorus inputs, exports, and storage at the sub-watershed, industry, and land-use sector scales

b. Develop and implement a strategy to reduce importation of phosphorus to manage the balance of phosphorus imports and exports in the watershed

3. **Reduce phosphorus application to land in the Missisquoi Bay watershed**

While a majority of the phosphorus loading into Missisquoi Bay is from agricultural sources, it is important to consider sources of phosphorus across all land uses in the Missisquoi Basin.

The 2016 Vermont phosphorus TMDL for Missisquoi Bay estimates that a 64.3% reduction in total phosphorus load is needed to meet the TMDL allocation for the Missisquoi Bay segment

In many cases, the nitrogen-to-phosphorus ratio in fertilizers is lower than necessary for most crops. Consequently, to achieve minimum nitrogen application rates, phosphorus is over-applied to agricultural soils, over-enriching them with phosphorus. This phosphorus can then move downstream into Missisquoi Bay during runoff events.

Approximately 33% of the soils analyzed in the Pike River watershed municipalities had saturation rates above the vulnerability threshold of 10% for phosphorus loss (Agrosol 2002), illustrating the role of legacy soil phosphorus.

To reduce these impacts and limit soil enrichment, resource managers and agricultural producers must reduce phosphorus inputs at their source.

a. Reduce nutrient inputs by considering the actual phosphorus needs of plants and adapt agronomic recommendations to focus on the capacity of soils to support phosphorus

b. Implement soil management and conservation practices that reduce legacy soil phosphorus, particularly in critical source areas, and develop protocols for long-term, sustainable management of soil phosphorus

c. In Québec, revise the “charts of maximum annual deposits” outlined in Québec regulations to reduce the maximum applications authorized by the Agricultural Operations Regulation chart

d. Remove the inherent risk of reducing phosphorus inputs through a financial compensation program to offset potential yield losses

e. Investigate processes and markets for reclaimed phosphorus and develop innovative solutions to commodify phosphorus into products and export from the watershed

4. Increase the proportion of crop systems that contribute less phosphorus

Agriculture is important to the regional economy, community, and sense of place for the residents of the Missisquoi Bay region of Québec and Vermont. Management actions focused on agricultural interventions in this Basin should recognize and acknowledge the importance of these social factors. However, agriculture also is the single greatest source of phosphorus and sediment to Missisquoi Bay, and significant efforts need to be taken to reduce the pollutant loads from agriculture into the Bay if the frequency of harmful cyanobacterial blooms is to be reduced in the future.

The Missisquoi Bay watershed has experienced a significant increase in annual corn and soybean crops, to the detriment of grasslands and small-grain crops over the past 30 years. Inadequate erosion protection provided by soy stubble and corn silage, as well as the relative importance of the area of corn tilled in the fall, means that a significant proportion of land in the watershed is left bare in late fall and subject to runoff and erosion in winter and spring. As well, these crops do not provide a window for the summer application of farm fertilizers, while pre-seeding or post-harvest applications have an increased risk of soil compaction and runoff emissions.

Providing financial incentives to producers in the watershed to transition to crops and agricultural methods that contribute less phosphorus is critical.

a. Support programs that promote conversion to perennial forage (grassland) areas for livestock operations, particularly in fields that are vulnerable to erosion

b. Encourage cropping system transition from corn and soy to small grain and other crops that provide soil and water quality benefits, and provide financial support to develop new markets for these crops. This may include development of high-quality hay and grain markets, and re-examining the impacts of subsidy programs such as those dealing with ethanol

c. Increase the acreage of spring and fall cereal crops that will improve soil health and reduce erosion

d. Plant cover crops in the annual cultivation of corn silage, soybeans, spring grains, and other annual crops

e. Promote management of crop residue in spring instead of fall to reduce risk of soil erosion, such as spring stubble plowing and direct seeding

5. Increase the protection and enhancement of floodplains, wetlands, and forest and ensure their reconnection for nutrient storage

Resource managers have begun to explore "green" or nature-based solutions to aid in the reduction of pollutant loads to Lake Champlain. Nature-based solutions can offer less expensive options for mitigating pollutant loads and provide numerous co-benefits, such as thermal cooling, flood mitigation, and habitat improvement for aquatic and riparian species, that are not typically available through traditional nutrient management practices.

Many natural features on the landscape that historically served these purposes have been removed or modified by humans for various purposes: the building of dams, straightening and dredging of rivers, and removal of riparian vegetation and forests have substantially altered the hydrology of the Missisquoi Bay watershed. Restoring these natural features, such as wetlands, floodplains and forests, can reduce erosive impacts of severe storm events and capture sediment, nutrients, and other pollutants before they are delivered to Missisquoi Bay.

a. Actively pursue the protection and restoration of properly functioning waterways by promoting and restoring the dynamic equilibrium and geomorphic function of rivers and streams

b. Expand programs to retire and conserve lands, and acknowledge co-benefits of land conservation, such as flood mitigation, increased wildlife habitat, and new recreational opportunities

c. Promote nature-inspired techniques like constructed wetlands to complement nature-based solutions like floodplain reconnection and riparian buffer plantings

d. Provide financial and technical incentives for the strategic implementation of perennial nature-based or nature-inspired solutions, including incentivized forestry practices and progress-based payments

6. Engage with public stakeholders to commit to clean water and healthy ecosystem goals

Many of the recommendations contained within this report require regulatory interventions or funding from government agencies or ministries to support research toward optimizing resource dollars to achieve water quality goals. The stakeholders who live and work in the Missisquoi Bay watershed and greater Lake Champlain region can work toward accomplishing important milestones within the management plan for the bay and the lake. Public outreach programs can elevate conversations around protection of the lake and practices that people can do on their own land or in their daily lives to promote and improve the health of Lake Champlain. These stakeholders also can hold their elected officials accountable to water quality goals for Lake Champlain.

Cross-border communication among stakeholder groups is critical toward a common understanding of the management goals and needs for Lake Champlain. Programs that support and augment local education of lake issues and management practices will help increase the support for improvement of the water quality of Missisquoi Bay and greater Lake Champlain.

a. Encourage stakeholder engagement and commitment to clean water and healthy ecosystem goals. This can be achieved in part by expanding existing water quality education and outreach in the Lake Champlain Basin, particularly to underserved communities and groups, and encouraging citizen science and service-learning opportunities

b. Facilitate more watershed-scale cooperation and collaborative educational and engagement opportunities between potential partners, including the United States and Canada, Vermont, New York, and Québec, and among local municipalities, watershed groups, and higher education institutions

c. The Missisquoi Bay Phosphorus Reduction Task Force will develop opportunities for communicating information to stakeholder groups, including a website and media presence, to receive and respond to stakeholder inquiries. Communication should include coverage of the temporal lag times between watershed practice implementation and water quality responses in receiving waters

Additional recommendations by theme

Agriculture

a. In Vermont, communicate accurate and timely weather forecasts to the agricultural community to encourage smart fertilizer use and manure application as Agro Météo in Québec

b. Strengthen the regulatory framework for livestock farms to apply, store, and export manure, and adapt manure spreading equipment to encourage fertilizer incorporation into soil

c. Prioritize implementation of management practices toward critical source areas to reduce contributions of bioavailable phosphorus from these sources

d. Promote increased soil health and crop productivity due to BMP implementation to the agricultural community

e. Continue to widely implement and incentivize BMPs shown to be most effective. The State of Vermont and the Province of Québec should consider sustained and, where feasible, new funding for BMP implementation.

f. Develop a process for progress payments to compensate farmers for achieving interim milestones toward water quality improvements on their lands

Regulation and Funding

While substantial federal, state, provincial, and local resources have been devoted to improving water quality in Missisquoi Bay, work remains to be done. Harmonizing management goals and successful policy across the border may allow for jurisdictions to collaborate on new regulatory initiatives and help to combat the perception that governments and stakeholders in other jurisdictions are not doing enough to address Missisquoi Bay's water quality challenges.

Funding for clean water funding is finite. Given this, limited resources should be focused on areas, practices, and techniques that will achieve the greatest amount of phosphorus reduction for each dollar invested. There may also be opportunities to optimize the process for achieving clean water goals by evaluating the efficiency of federal, state, and local agencies' staffing and funding levels and organization.

a. Regulations across the watershed should work toward achievement of common transboundary standards within the regulatory framework of the respective jurisdictions. This includes regulations to be applied to particular land use sectors, including developed, forested, and agricultural land, and strategic enforcement initiatives

b. Expand incentive programs to increase implementation of best management practices with alternative funding streams, including incremental progress-linked payments and alternative tax programs that apply to multiple land uses across the basin, including developed, forested, and agricultural land

c. Finite management resources should be applied to achieve the greatest return on investment toward management goals. The efficiency of the current systems in place for distributing federal, state, and other funds to nutrient reduction programs should be evaluated, with consideration of staffing levels and organization at federal, state, and local levels

d. Some resources should be invested in exploration of high-cost, potentially high-risk pilot projects that could yield high phosphorus reductions per dollar invested

Research

Support for research into our understanding of the ecological processes of the Missisquoi Bay system is critical to achieving water quality goals for Missisquoi Bay and the greater Lake Champlain basin. Improved knowledge of efficacies of important best management practices, new or relatively untested management practices, and research into our understanding of ecological systems and processes is critical toward optimizing future management resources to achieve water quality goals.

a. Increase funding for nutrient reduction research applicable to management in the Lake Champlain Basin, and focus this funding and research on the evolution of critical source areas and the highest phosphorus contributing sectors

b. Continue to support research that improves understanding of different forms of phosphorus bioavailability in Missisquoi Bay and strengthens understanding of in-lake nitrogen-phosphorus dynamics

Developed Areas

While agriculture is the largest contributor of phosphorus to Lake Champlain by land use, other human activities are major factors as well. Support for nutrient management from these land use sectors is essential to realizing the water quality goals in Missisquoi Bay.

Per unit of area, developed land contributes an equivalent phosphorus load to agricultural land. Impervious surfaces, such as parking lots and rooftops, quickly shed stormwater during rain events, releasing phosphorus and other pollutants into tributaries and Missisquoi Bay. Green stormwater infrastructure practices have been used with success to slow the flow of stormwater, allowing the stormwater to infiltrate into the ground, decreasing the load of phosphorus and additional pollutants to waterways.

Substantial progress has been made in wastewater management, but there is still work to be done. Since the 1980s, the Québec government has used an approach based on effluent discharge objectives (EDOs), which are calculated according to surface water quality criteria, characteristics of the host environment, and environmental uses; the MELCC has developed more stringent standards for phosphorus discharges from wastewater treatment facilities, including new requirements specified in the remediation certifications, reducing the maximum allowable concentration to 0.3 mg/L since January 1, 2017. In Vermont, stricter wastewater treatment facility phosphorus load allocations were established as part of the 2016 Lake Champlain TMDL update.

a. Stormwater management research and innovative implementation opportunities should be integrated into municipal and regional planning efforts to reduce inflows to combined sewer systems and support implementation of green stormwater infrastructure practices to reduce overland storm flows. Development opportunities that protect or restore water quality should be encouraged through regulatory tools
b. Regulations governing state or provincial, municipal, and privately-owned infrastructure (including individual and commercial septic systems) should be updated and enforced to ensure compliance,
c. Funding opportunities should be identified to support major infrastructure assessments and upgrades to water pollution control facilities to continue to achieve phosphorus discharge requirements

Phosphorus legacy sediment in Missisquoi Bay

A significant portion of annual sediment and phosphorus loads accumulates at the bottom of Missisquoi Bay, creating a latent load of phosphorus and other contaminants. This problem is exacerbated by the fact that sediments accumulate more than they are released by the waters to the outflow. Indeed, 42% of phosphorus loads are eventually moved to the water column, while 58% accumulate in sediments. (HydroQual Inc., 1999)

Reduction of the frequency and severity of cyanobacterial blooms in Missisquoi Bay cannot be achieved without first reducing the amount of phosphorus delivered to the Bay from the watershed (external loading) but eventually the amount of phosphorus cycling into the water column from the sediment (internal loading) will need to be addressed.

a. Use internal phosphorus cycling models to facilitate investigation of management techniques for phosphorus removal or inactivation from Missisquoi Bay sediment, in consideration of the known hydrodynamics of the bay and movement of water through the Alburgh-Swanton causeway

6 List of References

ACBVLB, 2019. Premiers résultats de la qualité de l'eau au lac Bromont, 8 juillet 2019. Communiqué. Jean-Baptiste Wart, Président de l'Action conservation du bassin versant du lac Bromont.

Act 76: An Act relating to the provision of water quality services. 2019.

Act 250: Land Use and Development Law. 1970.

Agrosol, 2002. Édition spéciale : baie Missisquoi, Revue de l'Institut de Recherche et de Développement en Agroenvironnement. Décembre 2002, vol 13 no 2. 148 p.

Blais, S., 2002. La problématique des cyanobactéries (algues bleu-vert) à la baie Missisquoi en 2001, Sylvie. Blais, Revue Agrosol, IRDA. Décembre 2002, vol. 13, no 2, pp. 103 à 110.

______, S, 2014. État de situation sur les cyanobactéries à la baie Missisquoi de 2000 à 2008 en lien avec les seuils provisoires pour les eaux récréatives, Québec, Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, Direction du suivi de l'état de l'environnement, ISBN 978-2-550-71485-9 (PDF), 44 p. + 13 ann.

Bolotova, Y.V. 2016. "An Analysis of Milk Pricing in the United States Dairy Industry." Agribusiness 33 (2): 194–208.

Boluwade, CA. and C. Madramootoo, 2015. Determining the influence of land use change and soil heterogeneities on discharge, sediment and phosphorus. Journal of Environmental Informatics 25-2:126-135.

Boudreau, 2017. Les projets pilotes de restauration de lacs : un bilan. MDDELCC. Boyer, G., M. Watzin, A. Shambaugh, M. Satchwell, B. Rosen, T. Mihuc, 2004. The occurrence of cyanobacterial toxins in Lake Champlain. in Lake Champlain: Partnership and Research in the New Millenium, pp 241-257.

Bowling, L., S. Blais, M. Sinotte, 2015. Heterogeneous spatial and temporal cyanobacterial distributions in Missisquoi Bay, Lake Champlain: an analysis of a 9 year data set. Journal of Great Lakes Research 41: 164-179.

CAAAQ, 2008. Agriculture et agroalimentaire : assurer et bâtir l'avenir Propositions pour une agriculture durable et en santé Rapport de la Commission sur l'avenir de l'agriculture et de l'agroalimentaire québécois. Jean Pronovost, président Mario Dumais, commissaire Pascale Tremblay, agr., commissaire Suzanne Dion, secrétaire générale Yvon Boudreau, collaboration spéciale et rédaction. Remis à Québec, le 31 janvier 2008 Monsieur Laurent Lessard Ministre de l'Agriculture, des Pêcheries et de l'Alimentation.

CBVBM, 2004a. Profils historiques du bassin versant de la baie Missisquoi. Portrait du bassin versant de la baie Missisquoi. Corporation bassin versant Baie Missisquoi. 100 p. + cartes et tableaux.

CEHQ, 2013. Suivi hydrologique de différentes stations hydrométriques. En ligne : https://www.cehq.gouv.qc.ca/suivihydro/default.asp. Consulté en 2013.

CEHQ, 2015. Atlas hydroclimatique du Québec méridional – Impact des changements climatiques sur les régimes de crue, d'étiage et d'hydraulicité à l'horizon 2050. Québec, 2015, 81 p.

CICBM, 2003. Comité interministériel de concertation sur la baie Missisquoi – Région Montérégie. Plan d'action 2003-2009 sur la réduction du phosphore. Baie Missisquoi, Octobre 2003.

Chapman, M., and J. Duggan. 2015. "The Transition Towards the 2016 Lake Champlain TMDL: A Survey of Select Water Quality Litigation from Vermont 2003-2015." Vermont Journal of Environmental Law 17 (1): 629–650.

Charles Eichacker. 2016. "Monmouth Selectmen Support Treatment of Cochnewagon Lake to Control Algae Blooms." Centralmaine.Com, 2016. https://www.centralmaine.com/2016/05/29/monmouth-selectmen-support-treatment-of-cochnewagon-lake-to-control-algae-blooms/.

City of Rockland, ME. 2002. "City of Rockland, 2002 Comprehensive Plan, Chapter 3." http://www.rocklandme.govoffice3.com/vertical/sites/%7BDE9EDD66-EFF4-4A6B-8A58-AA91254C1584%7D/uploads/Ch._3_-_Natural_Resources.pdf.

Class A Special (A-S) Fresh Surface Waters. 1972. https://www.epa.gov/sites/production/files/2014-12/documents/nywqs-section1.pdf.
Class AA Fresh Surface Waters. 1972. https://www.epa.gov/sites/production/files/2014-12/documents/nywqs-section1.pdf.
Class B Fresh Surface Waters. 1972.
Class C Fresh Surface Waters. 1972. https://www.epa.gov/sites/production/files/2014-12/documents/nywqs-section1.pdf.
CMI (Commission Mixte Internationale), 2005. Impacts transfrontaliers du pont-jetée de la baie Missisquoi et du projet de construction d'un nouveau pont sur la baie Missisquoi, Rapport aux Gouvernements des Etats-Unis et du Canada, Commission mixte internationale Canada et Etats-Unis.
CMI, 2012. Rapport final à la Commission mixte internationale. Groupe d'étude international sur la baie Missisquoi. Membres du Groupe d'étude : Erik Beck (coprésident) États-Unis, Eric van Bochove (coprésident) Canada, Eric Smeltzer Vermont, Daniel Leblanc, Québec
Connor, Jody N., and Michael R. Martin. 1989. “An Assessment of Sediment Phosphorus Inactivation, Kezar Lake, New Hampshire.” Water Resources Bulletin 25 (4): 845–53.
Conservation Law Foundation v. Environmental Protection Agency. 2008.
Cooke, D. 2005. Restoration and Management of Lakes and Reservoirs, Third Edition. CRC Press. https://doi.org/10.1201/9781420032109.
Covabar. 2015. Plan directeur de l’eau - Portrait du bassin versant de la Rivière Richelieu et de la zone Saint-Laurent. Beloeil : Comité de concertation et de valorisation du bassin de la rivière Richelieu, 278 p.
CT Institute of Water Resources. 2008. “Connecticut Institute of Water Resources Annual Technical Report FY 2008.”
Davis, T., D. Berry, G. Boyer, C. Gobler, 2009. The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of microcystis during cyanobacteria blooms. Harmful Algae 8-5: 715-725.
DEH, 2018. Limites des bassins versants du Québec. UDH 15 Février 2018. Données géomatiques.
Direction de l’expertise hydrique, 2018b. Document d’accompagnement de l’Atlas hydroclimatique du Québec méridional. Québec, ministère du Développement durable, de l’Environnement et de la Lutte contre les changements climatiques, 2018, 34 p.
Dillon, John. 2018. Act 250’s “Next 50 Years”: Commission Looks at Future of Vt. Development Review Law. Colchester, Vermont. https://www.vpr.org/post/act-250s-next-50-years-commission-looks-future-vt-development-review-law#stream/0.
Deslandes, J., I. Beaudin, A. R. Michaud, F. Bonn and C. A. Madramootoo. 2006. Influence of landscape and cropping system on phosphorus mobility within the Pike River watershed of Southwestern Québec. Canadian Water Resources Journal 32(1): 21-42. Janvier.
Doering, P., C. Oviatt, B. Nowicki, E. Klos, L. Reed, 1995. Phosphorus and nitrogen limitation of primary production in a simulated estuarine gradient. Marine Ecology Progress Series 124: 271-287.
Dodds, W., W. Bouska, J. Eitzmann, T. Pilger, K. Pitts, A., Riley, J. Schloesser, D. Thornbrugh, 2009. Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. Environmental Science & Technology 43-1: 12-19.
Douglas, James H. 2003. Clean and Clear Water Action Plan. Vermont, USA. https://web.archive.org/web/20081120122609/http://governor.vt.cdc.nicusa.com/sites/gov/files/speeches/clean-and-clear-water.html.
———. 2004. Governor’s State of the State Message, Journal of the Joint Assembly of the State of Vermont Adjourned Session. Montpelier, Vermont, USA. http://www.leg.state.vt.us/docs/legdoc.cfm?URL=/docs/2004/journal/ja040106.htm.
Duy, T.N., Lam, P.K.S., Shaw, G.R. et Connell, D.W., 2000. Toxicology and risk assessment of freshwater cyanobacterial (blue-green algal) toxins in water, Rev Environ Contam Toxicology, 163: 113-186.

Enright, P. AND C.A. Madramootoo. 2004. Phosphorus losses in surface runoff and subsurface drainage waters on two agricultural fields in Québec. In Proceedings of the Eighth International Drainage Symposium, Sacramento, California, March 21, 2004. St. Joseph, MI: American Society of Agricultural Engineers.

Entrevues OBVBM, 2019. Entrevues réalisées dans le cadre du mandat de la CMI sur la qualité de l'eau de la baie Missisquoi. OBVBM, Bedford.

EPA. 1980. "Lake Restoration in Cobbossee Watershed." Capsule Report EPA-625/2-80-027.

———. 2001. "Section 319 Success Stories Volume III: Successful Implementation of the Clean Water Acts Section 319 Nonpoint Source Pollution Program." https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20004UJH.txt.

EXXEP, 2004. Gestion de la qualité de l'eau à la baie Missisquoi : Regard sur les solutions. Document préparé pour la Corporation bassin versant baie Missisquoi par EXXEP Environnement.136 pages + 1 annexe.

Facey, Douglas E., J. Ellen Marsden, Timothy B. Mihuc, and Eric A. Howe. 2012. "Lake Champlain 2010: A Summary of Recent Research and Monitoring Initiatives." Journal of Great Lakes Research 38: 1–5. https://doi.org/10.1016/j.jglr.2011.12.001.

FALLU & ROY, 2015.Restauration de lacs: Où en sommes-nous?.

Fast, Arlo W., Victor A. Dorr, and Robert J. Rosen. 1975. "A Submerged Hypolimnion Aerator." Water Resources Research 11 (2): 287–93. https://doi.org/10.1029/WR011i002p00287.

Federal Water Pollution Control Act. 1978. Washington D.C., United States of America.

Fortin, N., V. Munoz-Ramos, D. Bird, B. Levesque, L. Qhyte, C. Greer, 2015. Toxic cyanobacterial bloom triggers in Missisquoi Bay, Lake Champlain, as determined by next generation sequencing and quantitative PCR. Life 5-2: 1346-1380.

Francy, D., J. Graham, E. Stelzer, C. Ecker, A. Brady, P. Struffolino, K. Loftin, 2015. Water quality, cyanobacteria, and environmental factors and their relations to microcystin concentrations for use in predictive models at Ohio Lake Erie and Inland Lake recreational sites, 2013-14. U.S. Geological Survey Scientific Investigations Report.

Giles, C., P. Isles, T. Manley, Y. Xu, G. Druschel, A. Schroth, 2016. The mobility of phosphorus, iron, and manganese through the sediment-water continuum of a shallow eutrophic freshwater lake under stratified and mixed water-column conditions. Biogeochemistry 127: 15-34.

Giroux, M., Enright, P., Vézina, L., Royer, R. ET Berrouard, A., 2002. Concentrations et charges d'azote et de phosphore perdues dans les drains souterrains selon les cultures et les modes de fertilisation. Québec, Institut de recherche et de développement en agroenvironnement. 33 p

Gobler, C., J. Burkholder, T. Davis, M. Harke, T. Johengen, C. Stow, D. Van de Waal, 2016. The dual role of nitrogen supply in controlling the growth and toxicity of cyanobacterial blooms. Harmful Algae 54: 87-97.

Governor's Press Office. 2017. "Governor Proposes $65M Investment to Combat Algal Blooms That Threaten Recreational Use of Lakes as Well as Drinking Water State's Water Quality Rapid Response Team to Convene Regional HABs Forums, Develop Community-Specific Action Plans and Cutting-Edge." Albany, New York. https://www.governor.ny.gov/news/governor-cuomo-unveils-12th-proposal-2018-state-state-protecting-new-yorks-lakes-harmful-algal.

———. 2018. "Action Plans for Twelve Priority Waterbodies Identify Contributing Factors and Provide Strategies to Reduce Pollution Sources Lessons Learned from Regional HABs Summits Include Innovative Solutions That Can Be Replicated in Waterbodies Across the State." Albany, New York. https://www.governor.ny.gov/news/governor-cuomo-announces-action-plans-combat-harmful-algal-blooms.

Gouvernement du Québec, 2018. Communiqué de presse, Stratégie québécoise de l'eau 2018-2030 - L'eau, source de richesse et de fierté pour tous. Laval, le 27 juin 2018. En ligne : http://mddelcc.gouv.qc.ca/infuseur/communique.asp?no=4023

______, 2004. Règlement sur les exploitations agricoles. Chapitre Q-2, r. 26. En ligne : http://legisquebec.gouv.qc.ca/fr/ShowDoc/cr/Q-2,%20r.%2026

_____, 2002a. Entente entre le gouvernement du Québec et le gouvernement de l'État du Vermont concernant la réduction du phosphore dans la baie Missisquoi.

Hart, E., N. Gotelli, R. Gorney, M. Watzin, 2013. Population dynamics of harmful algal blooms in Lake Champlain: a tale of two phases. PeerJ PrePrints.

Hébert, S. et D. Blais, 2017. Territoire et qualité de l'eau : développement de modèles prédictifs, Québec, Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, Direction générale du suivi de l'état de l'environnement et Direction de l'expertise en biodiversité, ISBN 978-2-550-77770-0 (PDF), 30 p.

Hébert, C., 2018. La Ville de Bedford investit 1,8 M$ dans ses infrastructures. L'Avenir et des Rivières, Le 25 janvier 2018. En ligne : https://www.laveniretdesrivieres.com/ville-de-bedford-investit-18-m-infrastructures/

Healy, Denis, and Kenneth Kulp. 1995. "Water-Quality Characteristics Of Selected Public Recreational Lakes And Ponds in Connecticut." 1995. https://pubs.usgs.gov/wri/1995/4098/report.pdf.

Hegman, W., D. Wang, C. Borer, 1999. Estimation of Lake Champlain Basin-Wide Phosphorus Export. Lake Champlain Basin Program Technical Report 31.

Hyenstrand, P., P. Blomqvist et A. Petterson (1998) Factors determining cyanobacterial success in aquatic systems - a literature review. Archiv für Hydrobiologie Special Issues of Advanced Limnology 51: 41-62.

Huser, Brian J., Sara Egemose, Harvey Harper, Michael Hupfer, Henning Jensen, Keith M. Pilgrim, Kasper Reitzel, Emil Rydin, and Martyn Futter. 2016. "Longevity and Effectiveness of Aluminum Addition to Reduce Sediment Phosphorus Release and Restore Lake Water Quality." Water Research, Special Issue on Geo-engineering to Manage Eutrophication in Lakes, 97 (June): 122–32. https://doi.org/10.1016/j.watres.2015.06.051.

ISQ, 2018. Institut de la statistique du Québec, Estimations de la population et Statistique Canada, Estimations de la population. Adapté par l'Institut de la statistique du Québec. 13-02-2018.

Isles, Peter D F. 2016. "A Multiscale Analysis of the Factors Controlling Nutrient Dynamics and Cyanobacteria Blooms in Lake Champlain." University of Vermont.

Isles, P., C. Giles, T. Gearhart, Y. Xu, G. Drushcel, A. Schroth, 2015. Dynamic internal drivers of a historically severe cyanobacteria bloom in Lake Champlain revealed through comprehensive monmonitoring. Journal of Great Lakes Research 41-3: 818-829.

Isles, P., D. Rizzo, Y. Xu, A. Schroth, 2017. Modeling the drivers of interannual variability in cyanobacterial bloom severity using self-organizing maps and high-frequency data. Inland Waters 7-3: 333-347.

Jamieson, A., C.A. Madramootoo et P. Enright, 2003. Phosphorus losses in surface and subsurface runoff from a snowmelt event on an agricultural field in Quebec. Canadian biosystems engineering, vol 45, p. 1.1-1.7.

Koerting, Katrina. 2018. "Waramaug Task Force Turns Lake from Green to Clean." NewsTimes. August 18, 2018. https://www.newstimes.com/local/article/Waramaug-Task-Force-turns-lake-from-green-to-clean-13164381.php.

Koliba, C., A. Zia, A. Schroth, A. Bomblies, J. Van Houten, D. Rizzo, 2016. The Lake Champlain Basin as a complex adaptive system: insights from the Research on Adaptation to Climate Change (RACC) Project. Vermont Journal of Environmental Law 17-4: 533-563.

Kortmann, Robert W. 1994. "Lake Waramaug 1975–1993 … What We've Learned." Lake and Reservoir Management 9 (1): 65–71. https://doi.org/10.1080/07438149409354727.

Kortmann, Robert W. 2010. "Long-Term Restoration Project Synopsis." Ecosystem Consulting Service, Inc.

Lake Champlain Basin Atlas. 2018. http://atlas.lcbp.org

Lake Champlain Basin Program. 2018. “2018 State of the Lake and Indicators Report.” Grand Isle, VT: Lake Champlain Basin Program.
Lake Champlain Basin Program. 2005. “State of the Lake: Lake Champlain in 2005 – A Snapshot for Citizens.” Grand Isle, VT: Lake Champlain Basin Program.
Lake Champlain Basin Study. 1979. “Shaping the Future of Lake Champlain: The Final Report of the Lake Champlain Basin Study.” Burlington, VT, USA: New England River Basins Commission.
Lake Waramaug Association. 2018. “Lake Waramaug Association, Inc. 101st Annual Membership Meeting Minutes.” http://www.waramaugassoc.org/June2018Minutes.pdf.
———. n.d. “Lake Waramaug Association - Meeting Minutes.” Accessed January 9, 2019. http://www.waramaugassoc.org/minutes.html#June15
Lake Waramaug Task Force. n.d. “About —.” Accessed January 24, 2019. https://www.lakewaramaug.org/about/.
———. n.d. “In-Lake Restoration Systems and Other Task Force Facilities.” https://www.lakewaramaug.org/science/.
Langendoen, R., A. Simon, L. Klimetz, N. Bankhead, M. Ursic, 2012. Quantifying sediment loadings from streambank erosion in selected agricultural watersheds draining to Lake Champlain. Lake Champlain Basin Program Technical Report 72.
Levesque, B. ET AL., 2014. Prospective study of acute health effects in relation to exposure to cyanobacteria. Publié dans Science of the Total Environment 466-467 (2014) 397-403.
Levine, S.N., A. LINI, M.L. Ostrofsky, L. Bunting, H. Burgess, P. R. Leavitt, D. Reuter, A. Lami, ET P. Guilizzoni. 2012. The eutrophication of Lake Champlain’s northeastern Arm: Insights from paleolimnological analyses. J. Great Lakes Res. vol. 38 (suppl. 1), p. 35–48. doi:10.1016/j.jglr.2011.07.007.
Lewtas, Kimberly, Michael Paterson, Henry David Paterson, and Dimple Roy. 2015. “Manitoba Prairie Lakes: Eutrophication and in-Lake Remediation Treatments Literature Review.”
Limnotech, 2012. Development of a Phosphorus Mass Balance Model for Missisquoi Bay. Lake Champlain Basin Program Technical Report 65.
MacDonald, J.M., J. Cessna, and R. Mosheim. 2016. “Changing Structure, Financial Risks, and Government Policy for the U.S. Dairy Industry.” 205. U.S. Department of Agriculture, Economic Research Service.
Maine DEP. 2001. “Sebasticook Lake Total Maximum (Annual) Load.” DEPLW 2000-110. https://www.maine.gov/dep/water/monitoring/tmdl/2001/tmdlsebrep.pdf.
———. 2011. “Nonpoint Source Management Program 2010 Annual Report.” DEPLW-1205. https://www.maine.gov/dep/water/grants/319-documents/reports/2010/2010%20Annual%20Report.pdf.
Manley, T.O., K.L. Hunkins, J.H. Saylor, G.S. Miller, P.L. Manley, 1999. Aspects of Summertime and Wintertime Hydrodynamics of Lake Champlain. in Lake Champlain in Transition: From Research MaToward Restoration. American Geophysical Union, Washington, DC.
Manley, T.O., Z. Perzan, L. Herdman, T. Chen, 2018. Missisquoi Bay Circulation Dynamics and 3D Hydrodynamic Modeling of the Restricted Arm of Lake Champlain- A Question of Water Quality and Causeways. Poster presented at Lake Champlain Research Conference, Burlington, VT January 2018.
Manchester, A.C., and D.P. Blayney. 1997. “The Structure of Dairy Markets: Past, Present, and Future.” 757. United States Department of Agriculture Economic Research Service.
Marsden, J.E., R. Langdon, 2012. The history and future of Lake Champlain’s fishes and fisheries. Journal of Great Lakes Research 38:19-34.
MAPAQ, 2019a. Programme de crédit de taxes foncières agricoles. En ligne : https://www.mapaq.gouv.qc.ca/fr/Productions/taxes/conditionsdadmissibilite/Pages/conditionsdadmissibilite.aspx

______,2019b. Programme Prime-Vert. Enligne: https://www.mapaq.gouv.qc.ca/fr/Productions/md/programmesliste/agroenvironnement/Pages/Prime-Vert.aspx
_____, 2019c. En ligne: https://www.mapaq.gouv.qc.ca/fr/Transformation/md/programmesliste/developpementindustrietransformation/Pages/ProgrammeServicesConseils.aspx
______, 2018c. Données du programme Prime-Vert pour le bassin versant de la baie Missisquoi entre 2013 et 2018. G. Poisson et L. Lemieux, MAPAQ, Mai 2018
MDDEP, 2009. Bulletin no 1, Suivi de l'action 1.4 du Plan d'intervention gouvernemental sur les algues bleu-vert 2007-2017 Atelier – Projets pilotes de restauration des lacs. En ligne : http://www.environnement.gouv.qc.ca/eau/algues-bv/bulletin/atelier1.pdf
MDDELCC, 2017. Guide de référence du Règlement sur les exploitations agricoles. 2017. 185 pages. [En ligne]. http://www.mddelcc.gouv.qc.ca/milieuagricole/guide-reference-REA.pdf
MELCC, 2019b. Bilan de phosphore. En ligne :
http://www.environnement.gouv.qc.ca/milieu_agri/agricole/phosphore/bilan.htm
Martin, T. 2015. "The Vermont Clean Water Act: Water Quality Protection, Land Use, and the Legacy of Tropical Storm Irene." Vermont Journal of Environmental Law 17 (1): 688–709.
McCarthy, M, W. Gardner, M. Lehmann, A. Guidon, D. Bird, 2016. Benthic nitrogen regeneration, fixation, and denitrification in a temperate eutrophic lake: effects on the nitrogen budget and cyanobacteria blooms. Limnology and Oceanography 61-4: 1-19.
McNew, K. 1999. "Milking the Sacred Cow: A Case for Eliminating the Federal Dairy Program." Policy Analysis, no. 362: 1–16.
Mendelsohn, D., C. Swanson, T. Isaji, 1997. Hydrodynamic Modeling of Missisquoi Bay in Lake Champlain. Vermont Agency of Natural Resources.
Meringolo, Dominic. 2016. "Proactive Management of HAB's Using In-Lake Phosphorus Inactivation Technologies." May 27.
Michaud, A., J. Deslandes ET I. Beaudin, 2006. Modélisation de l'hydrologie et des dynamiques de pollution diffuse dans le bassin-versant de la Rivière aux Brochets à l'aide du modèle SWAT. Rapport final. Aubert Michaud, chercheur, Ph. D., Julie Deslandes, géographe, M. Sc., Isabelle Beaudin, géographe, M. Sc., Institut de recherche et de développement en agroenvironnement, 2006
Michaud, A.R., I. Beaudin, J. Deslandes, F. Bonn et C. A. Madramootoo. 2007. SWAT-predicted influence of different landscape and cropping systems alterations on phosphorus mobility within the Pike River watershed of South-western Quebec. 2007. Canadian journal of soil science 87(3) 329-344. Mai.
Michaud, A.R., Lauzier, R., et M.R. Laverdière. 2004. Temporal and spatial variability in non-point source phosphorus in relation to agricultural production and terrestrial indicators. In: T. O. Manley, P. L. Manley and T.B. Mihuc ed., Lake Champlain: partnerships and research in the new millennium. Kluwer academic/plenum pub. New York NY. Pp. 97-121
Mimeault Martin et Marc Simoneau, 2010. Suivi environnemental des eaux du bassin versant de la baie Missisquoi, Séance d'information de la Commission mixte internationale à Saint-Armand, Québec le 13 octobre 2010. Non publié
MRC Brome-Missisquoi (Municipalité régionale de comté de Brome-Missisquoi), 2013. Schéma d'aménagement révisé deuxième remplacement, amendé par le projet de règlement 06-1013 (Projet de règlement). [En ligne : http://www.mrcbm.qc.ca/fr/docu_reglement.php]
Moore, J. 2016. Tile Drainage and Phosphorus Losses from Agricultural Land. Lake Champlain Basin Program Technical Report Number 83.
Morgan, T.J., E. Moye, Eric Smeltzer, and V. Garrison. 1984. "Lake Morey Diagnostic-Feasibility Study. Final Report." Vermont Department of Water Resources and Environmental Engineering. https://anrweb.vt.gov/PubDocs/DEC/WSMD/Lakes/Docs/lp_moreyfinalreport.pdf.

Morrisey, L. and D. Rizzo, 2010. Quantifying sediment loading due to stream bank erosion in impaired and attainment watersheds in Chittenden County, VT using advanced GIS and remote sensing technologies.

NALMS, 1990. “Lake and Reservoir Restoration Guidance Manual, Second Ed..Pdf.”

Nabout, J.C., B. da Silva Rocha, F.M. Carneiro, C.L. Sant’Anna, 2013. How many species of cyanobacteria are there? Using a discovery curve to predict the species number. Biodiversity and Conservation 22-12: 2907-2918.

Narrative Water Quality Standards. 1972. https://www.epa.gov/sites/production/files/2014-12/documents/nywqs-section1.pdf.

New York Department of Environmental Conservation. 2018. Lake Champlain Waterbody Inventory/Priority Waterbodies List. https://www.dec.ny.gov/docs/water_pdf/wichamplchamplain.pdf.

Nürnberg, Gertrud K. 2007. “Lake Responses to Long-Term Hypolimnetic Withdrawal Treatments.” Lake and Reservoir Management 23 (4): 388–409. https://doi.org/10.1080/07438140709354026.

Nürnberg, Gertrud K., Rosemary Hartley, and Edward Davis. 1987. “Hypolimnetic Withdrawal in Two North American Lakes with Anoxic Phosphorus Release from the Sediment.” Water Research 21 (8): 923–28. https://doi.org/10.1016/S0043-1354(87)80009-X.

NYSDEC. 2017a. “Irondequoit Bay 2016 Lake Classification and Inventory Survey.” https://www.dec.ny.gov/docs/water_pdf/lci16rptirondbay.pdf.

———. 2017b. “Lake Waccabuc 2017 CSLAP Report.”

NYSFOLA. 2009. Diet for a Small Lake: The Expanded Guide to New York State Lake and Watershed Management. 2nd ed. New York State Federation of Lake Associations, Inc. https://www.dec.ny.gov/docs/water_pdf/dietlakech7.pdf.

OBVBM, 2015. Plan directeur de l’eau du bassin versant de la baie Missisquoi. OBVBM, Bedford

Omernik, J. M. (1987), Ecoregions of the Conterminous United States. Annals of the Association of American Geographers, 77: 118-125. doi:10.1111/j.1467-8306. 1987.tb00149.

Osswald, J., S. Rellan, A. Gago, V. Vasconcelos, 2007. Toxicology and detection methods of the alkaloid neurotoxin produced by cyanobacteria, anatoxin-a. Environment International 33-8:1070-1089.

Patoine, Michel. 2017. Charges de phosphore, d’azote et de matières en suspension à l’embouchure des rivières du Québec – 2009 à 2012 [En ligne]. Québec : Ministère du Développement durable, de l’Environnement et de la Lutte contre les changements climatiques, Direction générale du suivi de l’état de l’environnement, 25 p.

Paulin, 2017. Rapport d'étape saison 2017, Projet pilote de traitement des cyanobactéries par ultrason, Association du lac Tomcod. En ligne : https://www.associationdulactomcod.org/resources/rapport%20d'%C3%A9tape%20cyano%202017.pdf

______, 2018. Rapport d'étape saison 2018, Projet pilote de traitement des cyanobactéries par ultrason, Association du lac Tomcod. En ligne : https://www.associationdulactomcod.org/resources/rapport%20d'%C3%A9tape%20cyano%202018.pdf

Parsons, B. 2010. “Vermont’s Dairy Sector: Is There a Sustainable Future for the 800 Lb. Gorilla?” 4. Burlington, VT, USA: University of Vermont Center for Rural Studies.

Pearce, A., D. Rizzo, M. Watzin, G. Drushcel, 2013. Unraveling associations between cyanobacteria blooms and in-lake environmental condiditons in Missisquoi Bay, Lake Champlain, USA, using a modified self-organizing map. Environmental Science & Technology 47-24: 14267-14274.

Potter, F., R. Sims, T. Alexander, B. Sylvester, R. Godfrey, J. Wood, 2008.The Missisquoi Areawide Plan.

Purcell & Taylor, P.C. 1981. “Final Report on Restoration Efforts Nutting Lake Restoration Program Billerica, Massachusetts.”

Reservoir Environmental Management. 2018. “Model Simulations of Mixing Technologies to Reduce Cyanobacteria in Lake Carmi.”

https://dec.vermont.gov/sites/dec/files/documents/VDEC_LakeCarmiPhase2FinalReport_2018-08-24_Revised_2018-10-22.pdf.

Robert, C., 2008. Résultats de cyanobactéries et cyanotoxines à sept stations de production d'eau potable (2004-2006), Québec, Ministère du Développement durable, de l'Environnement et des Parcs, 23 pages et 2 annexes.

Robert, C., H. Tremblay et C. Deblois, 2004. Cyanobactéries et cyanotoxines au Québec : suivi à six stations de production d'eau potable (2001-2003), Québec, Ministère du Développement durable, de l'Environnement et des Parcs, envirodoq : ENV/2005/0099, 58 p. et 3 ann.

Rosen, B., A. Shambaugh, L. Ferber, F. Smith, M. Watzin, C. Eliopoulos, P. Stangel, 2001. Evaluation of potential blue-green algal toxins in Lake Champlain, Summer 2000. Lake Champlain Basin Program Technical Report 39.

Roy, A. 2016. Résultats du projet pilote de restauration du lac à l'Anguille, volet 2 : expérimentation d'un marais filtrant pour réduire les apports de phosphore au lac. Groupe AIM inc., Rimouski (Québec) Canada. 50 p. et annexes. ISBN 978-2-9815799-1

Sansone, Andrew. 2016. "Irondequoit Bay 2015 Monitoring Report."

———. 2018. "Irondequoit Bay Monitoring Summary 2016-17."

Scheinert, S., A. Zia, J. He, R. Kujawa, C. Koliba, 2014. Value of water quality and public willingness to pay for water quality policy and project implementation. Research on Adaptation to Climate Change in the Lake Champlain Basin and Vermont's Waterways (RACC). Vermont EPSCoR.

Schuett, E., 2012. Blue-green algae kills thousands of fish in Missisquoi Bay. Montreal Gazette. August 27, 2012.

Shambaugh, Angela. 2016. "Cyanobacteria and Human Health Concerns on Lake Champlain." Vermont Journal of Environmental Law 17 (4): 516-32.

Shambaugh, A., S. Vose, B. O'Brien, L. Fisher, H. Campbell, 2017. Cyanobacteria Monitoring on Lake Champlain Summer 2016.

Simoneau, 2017B. Qualité de l'eau des tributaires de la baie Missisquoi : évolution 1979-2015 et portrait récent 2013-2015. Marc Simoneau, Direction générale du suivi de l'état de l'environnement (DGSEE), Direction de l'information sur les milieux aquatiques (DIMAQ).

Simoneau, 2018. Qualité de l'eau des tributaires de la baie Missisquoi : évolution temporelle 1999-2015 et portrait récent 2015-2017. Assemblée générale annuelle de l'Organisme de bassin versant de la baie Missisquoi– Saint-Armand, 18 juin 2018. Direction de l'information sur les milieux aquatiques (DIMAQ).

Smeltzer, E. and M. Simoneau, 2008. Phosphorus loading to Missisquoi Bay from sub-basins in Vermont and Québec, 2002-2005. Missisquoi Bay Phosphorus Reduction Task Force.

Shumlin, P. 2015. Governor's State of the State Message, Journal of the Joint Assembly of the State of Vermont Adjourned Session. Montpelier, Vermont, USA.

Sklenar, K., J. Westrick, D. Szlag, 2016. Managing cyanotoxins in drinking water: a technical guidance manual for drinking water professionals. American Water Works Association and Water Research Foundation.

Smeltzer, E. 1999. "Phosphorus Management in Lake Champlain." In Lake Champlain in Transition: From Research Toward Restoration, edited by T.O. Manley and P.L. Manley, 435–451. American Geophysical Union.

Smeltzer, E., A. Shambaugh, P. Stangel, 2012. Environmental change in Lake Champlain Revealed by Blong-Term Monitoring. Journal of Great Lakes Research 38: 6-18.

Smeltzer, E., F. Dunlap, and M. Simoneau. 2009. "Lake Champlain Phosphorus Concentrations and Loading Rates , 1990-2008." 57. Grand Isle, VT: Lake Champlain Basin Program.

Smeltzer, E., and S. Quinn. 1996. "A Phosphorus Budget, Model, and Load Reduction Strategy for Lake Champlain." Lake and Reservoir Management 12 (3): 381–393. https://doi.org/10.1080/07438149609354279.

Smeltzer, Eric. 1990. “A Successful Alum/Aluminate Treatment of Lake Morey, Vermont.” Lake and Reservoir Management 6 (1): 9–19. https://doi.org/10.1080/07438149009354691.
Smeltzer, Eric, Richard A. Kirn, and Steven Fiske. 1999. “Long-Term Water Quality and Biological Effects of Alum Treatment of Lake Morey, Vermont.” Lake and Reservoir Management 15 (3): 173–84. https://doi.org/10.1080/07438149909354115.
Smeltzer, Eric, and Edward B Swain. 1984. “Answering Lake Management Questions with Paleolimnology.” In Lake and Reservoir Management: Practical Applications, Proceedings of the Fourth Annual Conference and International Symposium of the North American Lake Management Society, October, 268–74.
Statistique Canada, 2006. Recensement de l'agriculture de 2006. Compilation effectuée par le Ministère du Développement durable, de l'Environnement et des Parcs. [En ligne : http://www.statcan.ca/francais/freepub/95-629-XIF/2007000/tables_menu_f.htm
TetraTech, 2015. Lake Champlain Basin SWAT Model Configuration, Calibration and Validation. TetraTech, Inc., Fairfax, VA.
Theriault, R., 2013. Identification des sources de nitrate et des facteurs contrôlant sa distribution dans les sols agricoles et les eaux souterraines des bassins versant Ewing et Walbridge (Montérégie Est), Institut national de recherche scientifique, Québec, 163 pp.
Thibeault, 2016. Le dragage des Trois-Lacs et autres projets pilotes de restauration des lacs. Karine Thibault, consultante en environnement, 2016. En ligne : http://www.grobec.org/pdf/projets/2016-09-16_Karine_Thibault.pdf
Thorne, P. and W. Schlesinger, 2017. Science Advisory Board Review of Lake Erie Nutrient Load Reduction Models and Targets.
Troy, A., D. Wang, D. Capen, J. O’Neil-Dunne, S. MacFaden, 2007. Updating the Lake Champlain Basin Land Use Data to Improve Prediction of Phosphorus Loading. https://www.uvm.edu/giee/pubpdfs/Troy_2007_Lake_Champlain_Basin_Program.pdf
U.S. Census Bureau 2010. “2010 Census: Vermont Profile.”
U.S. EPA 2016. “Phosphorus TMDLs for Vermont Segments of Lake Champlain.” June 2016.
Vaux, P. 2015. “Maine Lakes: Geographic & Morphometric Information.” Maine Dept. Environmental Protection, Maine Dept. Inland Fisheries & Wildlife, Maine Office of GIS, Augusta, Maine. http://www.gulfofmaine.org/kb/2.0/record.html?recordid=9680&save_record=1&.
Verhovek, Sam Howe. 1988. “Slow Death Of a Lake Is Stopped.” The New York Times, September 4, 1988, sec. N.Y. / Region. https://www.nytimes.com/1988/09/04/nyregion/slow-death-of-a-lake-is-stopped.html.
Vermont ANR. 2008. “Phosphorus TMDL for Lake Carmi.” October 2008. https://dec.vermont.gov/sites/dec/files/documents/WSMD_mapp_2009_Carmi%20P%20tmdl.pdf.
———. 2009. “Phosphorus Total Maximum Daily Load (TMDL) for Ticklenaked Pond.”
Vermont DEC. 2013. “Missisquoi Bay Basin Water Quality Management Plan.” http://dec.vermont.gov/sites/dec/files/documents/WSMD_mapp_BasinPlan_MissqBay_2013.pdf.
Vermont Department of Environmental Conservation. 2009a. “Total Maximum Daily Load to Address Biological Impairment in Rugg Brook (VT05-07), Franklin County, Vermont.” Boston, MA: United States Environmental Protection Agency - Region 1.
———. 2009b. “Total Maximum Daily Load to Address Biological Impairment in Stevens Brook (VT05-07), Franklin County, Vermont.” Boston, MA: United States Environmental Protection Agency - Region 1.
———. 2019. Clean Water Fund. https://dec.vermont.gov/watershed/cwi/cwf.
Vermont Department of Health, 2018. Drinking Water Guidance. http://www.healthvermont.gov/sites/default/files/documents/pdf/ENV_DW_Guidance.pdf

Vermont Department of Health, 2015. Cyanobacteria guidance for Vermont communities. http://www.healthvermont.gov/sites/default/files/documents/2016/12/ENV_RW_CyanobacteriaGuidance.pdf.

Vermont Natural Resources Board. 2019. What Are the 10 Criteria? https://nrb.vermont.gov/act250-permit/criteria.

Vermont State Treasurer's Office. 2007. "State of Vermont General Obligation Bonds." Montpelier, Vermont, USA: Vermont State Treasurer's Office.

———. 2015a. $115 Million in Bonds Successfully Sold by the State of Vermont. Montpelier, Vermont, USA: Vermont State Treasurer's Office. https://secure.vermont.gov/portal/government/article.php?news=5676.

———. 2015b. $115 Million in Bonds Successfully Sold by the State of Vermont. Montpelier, Vermont, USA: Vermont State Treasurer's Office. https://secure.vermont.gov/portal/government/article.php?news=5676.

VT DEC Watershed Management Division. n.d. "Lake Morey - Lake Score Card - Current Trends and Status." VT DEC Watershed Management Division - IWIS. Accessed March 5, 2019. https://anrweb.vt.gov/DEC/IWIS/ReportViewer3.aspx?Report=LakeScoreCard_Current_TrendsAndStatus&ViewParms=False&LakeID=MOREY.

Voigt, B., J. Lees, J. Erickson, 2015. An assessment of the economic value of clean water in Lake Champlain. Lake Champlain Basin Program Technical REport 81.

Water Resources Services, INc. 2018. "Morses Pond Annual Report: 2018." https://www.wellesleyma.gov/DocumentCenter/View/13648/Morses-Pond-2018-Annual-Report-PDF.

WATZIN, 2005. Ecosystem Indicators and an Environmental Scorecard. Lake Champlain Basin Program. Technical Report No.46. Prepared by Mary C. Watzin, Robyn L. Smyth, E. Alan Cassell, W. Cully Hession, Robert E. Manning, and Deane Wang Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT.

Way, Phelp's, and P O Box. 2005. "Comprehensive Plan for the Management of Morses Pond."

Wetzel, R, 2001. Limnology: Lake and River Ecosystems. 3rd Edition, Elsevier.

Winchell, M., D. Meals, S. Folle, J. Moore, D. Braun, C. DeLeo, K. Budreski, 2011. Identification of Critical Source Areas of Phosphorus Within the Vermont Sector of Missisquoi Bay Basin. Lake Champlain Basin Program Technical Report 63B.

Winchell, M., S. Folle, D. Meals, J. Moore, R. Srinivasan, E. Howe, 2015. Using SWAT for sub-field identification of phosphorus critical source areas in a saturation excess runoff region. Hydrological Sciences Journal 60:5 (844-862).

Winslow, M., 2016. A natural and human history of Lake Champlain. Vermont Journal of Environmental Law 17-4: 482-500.

Wironen, M., E. Bennett, J. Erickson, 2018. Phosphorus flows and legacy accumulation in an animal-dominated agricultural region from 1925 to 2012. Global Environmental Change 50: 88-99.

Wroth, L. Kinvin. 2012. "Six Flags over Champlain: Starting Points for a Comparative Analysis." Journal of Great Lakes Research 38 (SUPPL. 1): 167–175. https://doi.org/10.1016/j.jglr.2011.02.008.

Zilliges, Y., J.C. Kehr, S. Meissner, K. Ishida, S. Mikkat, M. Hagemann, A. Kaplan, T. Borner, E. Dittmann, M. Otto, 2011. The cyanobacterial hepatotoxin microcystin binds to proteins and increases the fitness of microcystis under oxidative stress conditions.PLoS ONE 6-3:1-11.

Appendix 1: Standard Questions for Expert Interviews

Before beginning the interview, Ellen provided an introduction to the project and an overview of the interview goals (supplementing the literature review with expert opinions from the watershed).

1. In your role, how often do you consider water quality and cyanobacteria?
    a. Is this consideration seasonal?
2. How much do you interface with stakeholders? How concerned are they with water quality and cyanobacteria?
3. Regarding water quality and cyanobacteria in the Lake, what are some programs and projects that you feel have been successful? Why?
4. What are some programs and projects that you feel have been unsuccessful? Why?
5. Where do you see opportunities for improvement?
    a. Given unlimited funding?
    b. Given a realistic increase in funding?
    c. Given no funding increase, how would you distribute resources?
6. Would you like to add anything as an anonymous Lake and watershed stakeholder?

Do you have any suggestions for further people to contact?