A global scan of how the issue of nutrient loading and harmful algal blooms is being addressed by governments, non-governmental organizations, and volunteers

Étienne Foulon, Alain N. Rousseau, Glenn Benoy and Rebecca L. North

ABSTRACT

Harmful algal blooms (HABs) in aquatic ecosystems are of concern worldwide. This review deals with how jurisdictions around the world are addressing this water quality issue to inform recommendations regarding nutrient loading and HABs in Missisquoi Bay-Lake Champlain and Lake Memphremagog; transboundary lakes located in the USA and Canada that suffer from symptoms of eutrophication. A global scan of the literature resulted in the consideration of 12 case studies of large water bodies within large watersheds, excluding in-lake geoengineering approaches. Although all of the systems experience excessive nutrient loading, they vary in two key ways: sources of nutrients and manifestations of eutrophication ranging from HABs, to limited recreational uses, to the additional complexity of internal loadings and fish kills, up to drinking water shutdowns. The case studies were analyzed with respect to four categories of approaches, namely: (i) regulatory; (ii) incentive-based; (iii) risk mitigation; and (iv) outreach, engagement, and educational. We found that the management frameworks are based on integrated watershed management planning and national standards. National water quality standards, however, are not stringent enough to prevent HABs. Overall, identified case studies did not successfully remediate HABs, they simply managed them.

Key words | approach, incentive, regulatory, rehabilitation, remediation, risk mitigation

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INTRODUCTION

Algal blooms can happen in water bodies when there is an overabundance of nutrients (phosphorus – P, and nitrogen – N) and/or conducive environmental conditions (high water temperatures, intermittent high light intensities, stable conditions – usually; Watson *et al.* 2015). Blooms are a naturally occurring phenomenon resulting from the gradual accumulation of nutrients and organic matter from watersheds associated with sufficient light for photosynthesis (Anderson *et al.* 2019). Excess nutrients, however, may also originate from human-induced activities, such as agriculture (mostly from surface and subsurface water movement from fertilized soils and faulty manure storage), industrial and municipal wastewater treatment plants, leaky home septic systems, run-off from lawns, and even atmospheric depositions. Hence, humans have exacerbated the natural frequency, extent, location, and potential toxicity of algal blooms. Toxic algal blooms, referred to as harmful algal blooms (HABs), are of particular relevance to humans because of their risks to public health. HABs occur in freshwater systems often as a result of cyanobacteria such as *Microcystis*. Red tides or brownish blooms occur in brackish waters often as a result of harmful phytoplankton such as dinoflagellates of the genus *Alexandrium*

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and *Karenia*. HABs can produce dangerous toxins that may sicken or kill people and animals, create dead zones in the water (depleted in oxygen), raise treatment costs for drinking water (or provoke shutdowns), and impact industries that depend on clean water (EPA 2018a).

HABs are a worldwide issue. In the USA, all 50 states are impacted by either or both cyanobacterial and/or golden HABs (formed from single-cell *Prymnesium parvum* that may cause fish kills when blooming). The United States Environmental Protection Agency (USEPA) estimates that HABs and eutrophication cost the U.S. economy 2.2–4.6 billion dollars a year (Hudnell 2010). They are responsible for the state of emergency declared in Florida in 2016 and for the half a million Ohioans left without drinking water for a week in 2014. In Canada, algal blooms are not uncommon, but tracking them across over a million lakes and countless water bodies is tricky. Although the issue may not be so new (Reynolds & Walsby 1975), 'the rise of slime' (Jackson 2008) is more often associated with HABs. All large inland water bodies that form an arc across Canada on the edge of the Canadian Shield, Lake Champlain, Lake Ontario, Lake Erie, Lake of the Woods, and Lake Winnipeg, experience big blooms. Smaller blooms arise in all Canadian provinces. In Quebec, between 2004 and 2010, the number of reported visible blooms increased from 24 to 150 (Pick 2016). Reporting programs, phosphorus management strategies, as well as human exposure guidelines for some algal toxins, continue to be developed and released in an increasing number of jurisdictions (Pick 2016). In Europe, eutrophication, mostly linked to nitrates, is also widespread and even warrants a 369 multi-lake survey of cyanotoxins [e.g., 137 lakes sampled by Mantzouki *et al.* (2018)] requiring coordinating researchers from 27 different countries. In China, an increasing number of HAB events have been recorded in the last two decades in coastal waters (Yu *et al.* 2018). Since 2000, large-scale HABs appeared, such as dinoflagellates and haptophyte red tides in the East and South China Seas, respectively, and pelagophyte brown tides in the Bohai Sea. These emerging blooms have, since the 1970s, become more diversified and shifted from diatoms to harmful flagellates (Yu *et al.* 2018). Eutrophication of most inland lakes and reservoirs in China also threatens the regional ecological environment and water security. It has restricted the development of society and economy. In past decades, algal blooms have been observed in Lake Chao (Yang *et al.* 2010; Jiang *et al.* 2014), Lake Dianchi, and Lake Taihu (Huang *et al.* 2015; Qin *et al.* 2015). The rapidly accelerating pace of eutrophication in lakes across China has forced the government to set ambitious lake restoration goals (Qin *et al.* 2010).

The watersheds of Lake Memphremagog and Lake Champlain span two countries (Canada and the USA), one province (Québec), and two states (Vermont and New York). Due to excessive nutrient loading, sections of Lake Champlain and Lake Memphremagog have been experiencing symptoms of eutrophication for many years. In particular, the binational northeastern portion of Lake Champlain, Missisquoi Bay suffers from severe HABs on a regular basis. The most significant development regarding nutrient loading and HABs in Lake Champlain and Lake Memphremagog has been the approval of phosphorus Total Maximum Daily Loads (TMDLs) by the USEPA in 2016 and 2017, respectively, for the Vermont portion of the lakes. Despite these past efforts, the lakes continue to experience degraded water quality and frequent and severe HABs. Consequently, the governments of Canada and the United States issued a reference to the International Joint Commission (IJC) in 2017 to make recommendations on how best to strengthen existing activities being undertaken by the province of Quebec and the states of Vermont and New York. This review informs the development of recommendations that are meant to restore and protect these transboundary lakes, but it is also applicable to other lakes in North America and around the world that suffer from HABs. It summarizes and builds upon case studies of nutrient loads and HABs management in six countries – Australia, Canada, China, France, Switzerland, and the USA – and 12 different jurisdictions around the world before presenting key findings to inform potential HABs management strategies for Lake Memphremagog and Lake Champlain. Case studies were selected to include a variety of jurisdictional contexts, geographical and social settings that would enable some generalizing about the frameworks, approaches, and processes implemented by government agencies and departments, academic institutions, and non-governmental organizations (NGOs) to tackle nutrient loading and HABs.

The next three sections of this paper introduce: (i) the specific methodology underlying this review including how the case studies were analyzed with respect to four categories of implemented approaches, (ii) results pertaining to the case studies specifically, and (iii) a discussion section building on case studies supplemented by a separate review focusing on key findings identified within the literature.

MATERIAL AND METHODOLOGY

The goal of this review was to identify potential HABs management strategies for Lake Memphremagog and Lake Champlain by answering the following research question: 'How are nutrient loadings and HABs addressed across the world and how might these experiences inform the restoration and protection of lakes Champlain and Memphremagog?'. It focused on the frameworks, approaches, and processes implemented by government agencies and departments, academic institutions, and NGOs – both within countries and in transboundary contexts. 'Frameworks' refers to the overall picture of the program that is being used. 'Approaches' refers to the mechanisms used to deliver the program, whether they are through research agendas, regulatory and policy advances, implementation initiatives (combination of programs, financial incentives, technological fixes, societal behavioral changes, etc.), as well as outreach and engagement activities. 'Processes' refers to whether assessment or performance indicators and metrics are in place to track the progress through a positive feedback loop.

Colquhoun *et al.* (2014) presented the definitions of different types of review. Using those definitions, our review can be viewed as the interface between scoping reviews and realist reviews. Indeed, in our review, as in a scoping review, the scope is rather broad, requires knowledge synthesis and is aimed at mapping key concepts and approaches related to the explanatory research question. On the other hand, our review deals with a wicked problem requiring building upon existing relevant case studies to provide solutions and paths forward to a complex water quality issue, which is closer to a realist review.

As such, the review left out smaller lakes and watersheds where simple 'technical band aids' (i.e., PhosLock) seemed to be the standard approach. Second, given that regulations in Canada and in the USA are historically rooted in water quality standards established quite some time ago to curb point sources of pollution, we discarded any material that dealt with the implementation of strategies to resolve these issues – first implementations only. For example, we left aside material for Lake Victoria in Africa or four of the five largest freshwater lakes in China (i.e., Poyang, Dongting, Taihu, and Chao lakes). Finally, though phosphorus is typically the limiting nutrient to algal growth in most temperate freshwater systems, nitrogen is often the limiting nutrient in marine systems (Paerl 2009; Paerl *et al.* 2011; Paerl 2017; Higgins *et al.* 2018). As both are afflicted by symptoms of eutrophication, it was deemed relevant to examine case studies dealing with coastal HABs to increase the diversity of approaches used that very well could be relevant/adapted to dealing with freshwater HABs.

Given this scope, a rapid review of the global literature (primary literature, peer-reviewed reports and books, legislative materials, countries and states strategies, government bodies – including watershed-based organizations – online material) allowed identifying 12 case studies relevant to the issue at hand (totaling more than 1,000 scanned references). These were selected after systematically searching for information in different databases (i) Google Scholar, (ii) Scopus, as well as (iii) Google Search Engine, (iv) Government bodies' websites, and (v) watershed-based organizations sites for gray literature. Selection criteria included similarity of issues with Lake Memphremagog and Lake Champlain, diversity and quantity of available documents as well as an expert opinion.

The identified 12 case studies (301 references out of 1,000) represent jurisdictions around the world, depicted in Figure 1, that have various dominant nutrient sources and face different issues ranging from HABs, to limited recreational uses, to the additional complexity of internal loadings and fish kills, up to drinking water shutdowns. Second, as per the methodology of the realist review, we synthesized the variety of approaches used into four (4) categories, namely: (i) regulatory; (ii) incentive-based; (iii) risk mitigation; and (iv) outreach, engagement, and educational activities. This framework allowed us to map key approaches used to manage the problem of nutrient loads and HABs while the following questions were used

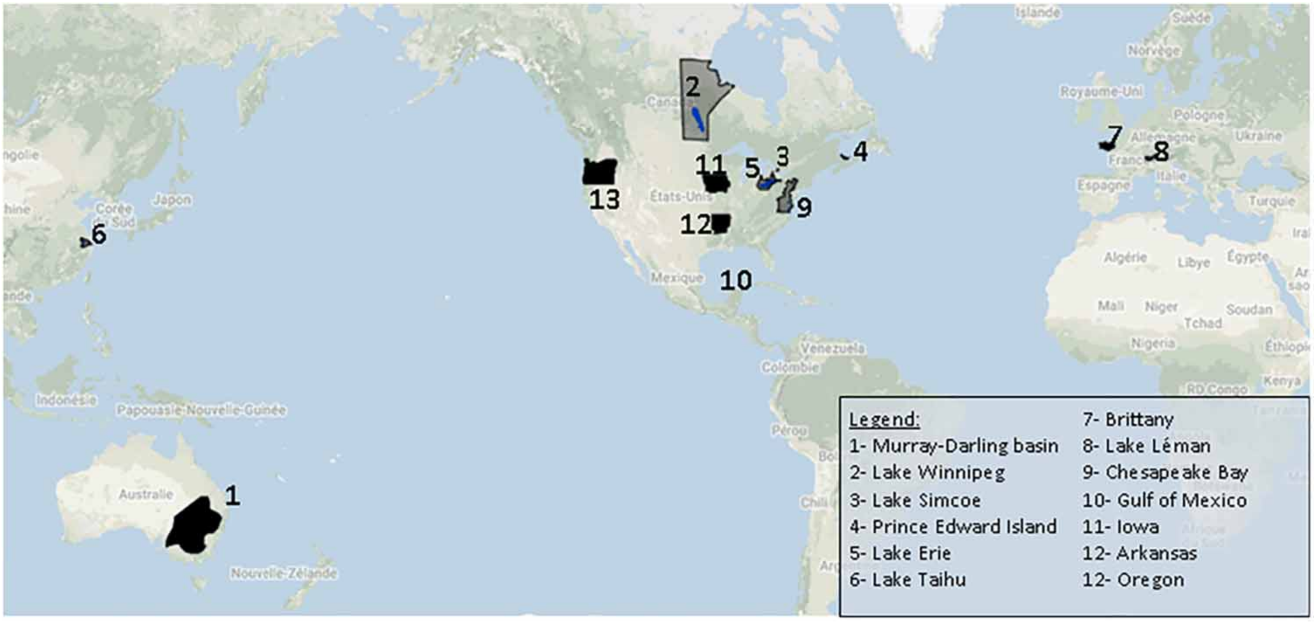

Figure 1 | Case study localizations, drawn with GoogleMyMaps™.

to guide our analysis of existing solutions and path forwards:

- When was the problem noticed? What research was done to determine whether the problem needed to be addressed?
- Which mitigation approach(es) was (were) used to address the problem?
- How were these approach(es) decided on? How long have these approach(es) been used?
- Have they been successful? How was 'success' determined?

The outcome of our analyses became our key findings which were refined through a third step, a separate supplementary review (107 references), ensuring enough cases were captured and allowing us to discuss our findings under five unifying themes covering: (i) the importance of jurisdictions' specificities in defining approaches, (ii) engaging with all stakeholders and building trust, (iii) rethinking best management practices (BMPs), (iv) monitoring and enforcing to ensure performance, and (v) the need for good governance and leadership. Throughout the result and discussion sections, the readers should keep in mind that all the references used were not provided due to obvious length constraints but are available upon request from the corresponding author. Overall 408 documents (301 + 107) were consulted to compile this review; the breakdown is provided in Appendix 1.

NUTRIENTS AND HABS MANAGEMENT STRATEGIES

Approaches used to address nutrient loads and HABs

Overall strategies applied in the case studies generally rely upon the same framework using a set of similar interdependent approaches rather than a single approach to address nutrient and HAB management issues. The different sets of approaches namely, regulatory approaches, incentive-based approaches; risk mitigation approaches and outreach, engagement, and educational activities, are being used simultaneously in all case studies.

Regulatory approaches

Regulatory approaches often set the scene for other approaches to be implemented. They require standards to be met, targets to be respected, potential ensuing sets of sanctions and fines for non-compliance. They require certain actions to be taken (or not taken) by users and do not provide incentives (financial or otherwise) for polluters. Examples include bans on specific agricultural practices such as applying fertilizer on snow or frozen soils or when the top two inches of soils are saturated from precipitation. Wetland no-net loss policies are another example generally associated with an offset system or mechanism based on a trading ratio (2–3 areal units of wetland restored to 1 areal unit of wetland lost) in case of unavoidable impact to a wetland. Nutrient reduction targets have been included in the regulatory approaches because they imply strategies, or a set of agreed upon priorities for all parties involved (including inter-state/province, state/province-country, and/or international memorandum of understanding). Also, in the USA, these targets can be defined through a total maximum daily load program (TMDL) resulting from the listing of a water body as impaired under listing 303(d) of the Clean Water Act (CWA). Septic system control and stormwater management regulatory approaches entail the design of a specific strategy to address HABs or nutrient mitigation measures within existing programs. This includes the obligation to incorporate low impact technologies during urban developments, imposing more stringent treatment/abatement requirements to sensitive areas, watersheds, or wastewater treatment plants (WTP), or requiring retrofitting when renovations are carried out or properties are sold. Finally, numerical nutrient criteria development is simply the setting of nutrient water quality standards (WQSs for phosphorus, nitrogen, and chlorophyll-a) to protect and regulate specific uses of water (drinking, recreational, wildlife), stretches of rivers, or even rivers as a whole. WQSs describe the desired condition of a water body and the means by which that condition will be protected or achieved. To summarize, regulatory approaches, as described in Table 2, include: (i) Ban on specific nutrient applications; (ii) Numerical nutrient criteria development; (iii) Wastewater management – relative to limiting nutrients exportation and WTP regulations in sensitive areas (or not); (iv) Setting enforceable reduction targets (including TMDLs); (v) Stormwater management.

Incentive-based approaches

Some of the approaches used to manage nutrient loads and HABs include incentives to promote the implementation of BMPs. Land retirement projects compensate landowners for 'retiring' sensitive areas relative to their contribution to water quality degradation. Offset programs and more generally water quality trading (WQT) promote trades (mostly Point Source to Non-Point Source – NPS) between pollutant source treatments as a way to make a voluntary and surplus pollutant reduction at a lower cost. Note that these programs are often associated with zero export policies. Conservation auctions work as reverse auctions where bidders (often farmers or private landowners) submit bids indicating the incentive they are willing to accept to implement a management practice (Packman & Boxall 2010). BMP insurance, also called 'green insurance' allows farmers to try management practices risk-free (Mitchell & Hennessy 2003), paying indemnities for actual losses (Baerenklau 2005), while yield insurance can offer premium rebates if farmers implement specific BMPs. Based on the same principle, governing bodies may offer tax credits as incentives to implement BMPs or conservation strategies, or levy pollution-related taxes to incentivize pollution-reducing approaches. Sometimes, payments/incentives are proportional to the actual measured performance or to the level of environmental benefits arising from a technical approach. All these incentives are mostly financial whether they use direct payments, loans or subsidies, or indirect financial gain by eventually increasing yields. Stewardship certification programs use indirect approaches. They rely on a willingness to improve the environment, on peer pressure (when a program has been implemented by your neighbors, you are more inclined to implement it yourself), and of course on market value increase. The ensuing certificates acknowledge the conservation efforts made to tackle nutrients and/or HABs issues. To summarize, incentive-based approaches, as described in Table 3, include: (i) BMPs insurance and insurance promoted BMPs; (ii) Conservation auctions; (iii) Land retirement projects; (iv) Performance payments or incentives related to conservation or BMPs; (v) Stewardship certification; (vi) Taxes, fees, or surcharges; (vii) WQT (including offset programs).

Risk mitigation approaches

In engineering, risk mitigation can be described as the process of developing options and actions to enhance opportunities and reduce threats (Mitre 2008). The environmental definition narrows it down to threats to human health and the environment (U.S. EPA 2017). This also includes tracking the identified risks. As such, algae surveillance programs allow tracking the most sensitive areas. They enable testing for toxins when algal blooms occur and increase the chance for releasing health advisories in time. Early warning systems (EWSs) based on satellite data are the current ultimate risk monitoring tools as they help narrow field testing and designing management strategies (not limited to HABs). However, other EWSs are based on a network of monitoring stations and water use restrictions relative to the crossing of water quality thresholds. Environmental pollution liability insurance is a risk mitigation approach as it ensures that a company going bankrupt will not prevent compensation or reparation (Zhou & Bi 2019). At the same time, it incentivizes polluters to invest in risk reduction and prevention measures through lower premiums (Feng *et al.* 2014a, 2014b). Note that this approach is currently in use only in China. Farm-based nutrient management plans ensure farmers have the tools and knowledge required to limit nutrient run-off to rivers and lakes. This particular approach is closely related to both education and incentive-based approaches. Drinking water protection plans increase protection and thus decrease risk, which is assessed as the product of the probability of pollution occurrence and severity of consequences. To summarize, risk mitigation approaches, as described in Table 4, include: (i) Algae surveillance program; (ii) Drinking water protection plans; (iii) Farm-based nutrient management plans; (iv) Cyanotoxins testing; (v) EWSs.

Outreach, engagement, and educational activities

Government bodies, local, as well as watershed-based, authorities, and NGOs can help users understand the consequences of their behavior and identify opportunities to improve nutrient management sustainability through outreach, engagement, and educational activities. These are present at all levels and for topics related to managing nutrients and HAB-induced pollution. Approaches include informational reports, guidance documents, and websites to inform about the issues at hand. They encompass outreach activities, educational programs, and media mobilization to help modify users' behaviors. They require technical seminars and conferences, public hearings, and coordination efforts to foster a sense of responsibility and improve stakeholders' engagement. The environmental farm plan represents a good example of an educational program targeting farmers. It consists of a voluntary assessment, by the farmer, of a farm operation's environmental strengths and areas of concern. In Ontario, Canada, it increases farmers' environmental awareness in as many as 23 different areas on their farms (OMAFRA 2016). Often, this program is a funding prerequisite for setting BMPs, going back to the incentive-based approach and illustrating how they are entwined. To summarize, outreach, engagement, and educational approaches include: (i) BMP guidance documents (for citizens, farmers, municipalities, water suppliers); (ii) Educational programs (including sensitization activities); (iii) Community engagement activities; (iv) Technical seminar and conferences; (v) Opinion surveys.

Overview of case studies

The identified case studies provide a sense of the different types of approaches available to manage nutrient loads and HABs environmental issues in a variety of geographical and social settings. Tables 1–4 highlight issues faced across case studies, as well as key regulatory, incentive-based, and risk mitigation approaches used to address these issues. All case studies also employ outreach, engagement, and educational activities to educate and give advice to stakeholders, to influence their behavior, and to promote programs and disseminate good practices. It is noteworthy that the content conveyed in Tables 1–4 is based on our interpretation of the information available in several, sometimes not as clear as we would have liked, documents pertaining to each case study. Thus, the content describes to the best of our knowledge the characteristics of each case study.

Although Prince Edward Island (PEI), Canada, is not directly concerned with freshwater HABs (only eight recorded occurrences in the last 12 years), it was included

Table 1 | Issues related to nutrient loads and HABs addressed across case studies

				Addressed issues				
Country	**State/ Prov**	**Management Area**	**Dominant nutrient source**	**HABs**	**Limited recreation**	**Internal loading**	**Massive fish kills**	**Drinking supply shutdown**
Australia	Multi	Murray–Darling basin	Agriculture	•	•		•	•[a]
Canada	MB	Lake Winnipeg	Multiple/upstream jurisdictions	•	•	•	•	[b]
Canada	ON	Lake Simcoe	Agriculture/atmosphere/urban	•	•	•		
Canada	PEI	Prince Edward Island	Agriculture				•[c]	
Canada-USA		Lake Erie	Agriculture–urban	•	•	•	•	•
China		Lake Tahiu	Agriculture–urban	•	•	•		•
France		Brittany	Agriculture	•	•		•	
France-Switzerland		Lake Léman	Natural/WWTP outlet	•	•[d]			
USA	MD-VA	Chesapeake Bay	Agriculture/urban	•	•	•	•	
USA		Gulf of Mexico	Agriculture	•	•	•	•	
USA	IA	State of Iowa	Agriculture/WWTP	•			•	•
USA	AR	State of Arkansas	Agriculture/urban	•	•		•	
USA	OR	State of Oregon	Multiple	•	•			•[e]

WWTP stands for wastewater treatment plant.
[a]Drinking water supply shutdowns for the Murray–Darling basin are also linked to extreme low flow conditions.
[b]Lake Winnipeg is not used as a source of drinking water.
[c]Not a common issue (51 fish kills over 1962–2017), but still addressed because they were mainly (72%) caused by pesticides.
[d]Currently very limited impact, but historically prevalent.
[e]To our knowledge, no drinking water shutdown happened yet. Still, the problem is addressed at the state level given that all warning signs are on.

Table 2 | Regulatory approaches used across case studies

	Regulatory approaches					
Management area	**Setting reduction targets[a]**	**Stormwater management**	**Wastewater management**	**Ban on winter manure spreading**	**Wetland no-net loss policy**	**Numeric nutrient criteria[b]**
Murray–Darling basin	•	•				•
Lake Winnipeg Manitoba	•		•	•	•	•
Lake Simcoe	•	•	•		•	•
Prince Edward Island	•				•	
Lake Erie	•	•	•	•		•
Lake Taihu	•[b]	•	•		•	•[b]
Brittany	•	•	•	•	•	•
Lake Léman	•	•	•	•	•	•
Chesapeake Bay watershed	•	•	•	•	[c]	
Gulf of Mexico Arkansas	•	•	•			
Iowa	•	•	•	•		
State of Oregon	•			•		

[a]This issue is discussed, but we cannot ascertain that reduction targets are required by law.
[b]Typically what this means is that the jurisdiction has defined N/P numerical criteria for at least one class of water. With that logic, jurisdiction that uses N/P criteria based on a reduction program (including through TMDLs) do not fit in that category. Implementation details for the whole USA can be found at https://www.epa.gov/nutrient-policy-data/state-progress-toward-developing-numeric-nutrient-water-quality-criteria. One can note that Florida, Minnesota, Missouri, North Carolina, and Oregon are using Chlorophyll-a concentrations as a standard that can be used to determine if waters are impaired due to nitrogen and phosphorus pollution. China has a 10 mg/L limit for Nitrate (N-NO_3^-) for both drinking water and surface water standards, but no numerical criteria for phosphorus.
[c]Although the whole watershed does not have a no-net loss wetland policy, at least Virginia and Maryland do.

Table 3 | Incentive-based approaches used across case studies

Management area	Incentive-based approaches						
	Land retirement	Stewardship certification	Water quality trading	Performance incentives	Insurance promoted BMPs	Conservation auctions	Taxes, fees, or surcharges
Murray–Darling basin	•	•	•			•	•
Lake Winnipeg Manitoba	•	•		[a]		•	
Lake Simcoe	•	•	•	•			•
Prince Edward Island	•	•			•		•
Lake Erie	•	•	•	•			•
Lake Tahiu	•	•	•	•	•		•
Brittany	•	•					•
Lake Léman	•[b]						•
Chesapeake Bay watershed	•	•	•	•	•		•
Gulf of Mexico Arkansas	•	•	•	•			•
Iowa	•	•	•	•	•[c]	•	•
State of Oregon	•	•	•	•			

[a]Performance incentives are part of the recommendations made to municipalities applying for the lake friendly certification (https://p2infohouse.org/ref/54/53080.pdf), but we cannot ascertain that these approaches are already available in the Lake Winnipeg watershed.
[b]Lake Léman does not have a Land retirement project but uses a very active biological agriculture transformation policy promoting high-standard BMPs.
[c]Pilot program offered in four states in 2003 and currently offered by BMP CHALLENGE TM.

Table 4 | Risk mitigation approaches across case studies

Management area	Risk mitigation approaches				
	Nutrient management plan (farm)	Drinking water protection plans[a]	Early warning system	Algae surveillance program	Cyanotoxin testing[b]
Murray–Darling basin	•	[c]	•	•	•
Lake Winnipeg Manitoba	•	•		•	•
Lake Simcoe	•	•		•	
Prince Edward Island	•	•			•[d]
Lake Erie	•	•	•	•	•
Lake Taihu	[a]				•
Brittany	•	•		•	•
Lake Léman	•	•	•	•	
Chesapeake Bay watershed	•	•	•	•	•
Gulf of Mexico	N.A.	N.A.	•	•	•
Arkansas	•	•			
Iowa	•	•		•	•
State of Oregon	•	•		•	•

[a]Many of those plans are prepared on a voluntary basis.
[b]These refer to the testing of microcystins even if in the USA, some states (Minnesota, Ohio, Oregon, and Vermont) have implemented guidelines for anatoxins, cylindrospermopsins, and saxitoxins (details can be found at https://www.epa.gov/nutrient-policy-data/guidelines-and-recommendations).
[c]No specific drinking water protection plan identified; however, groundwater generic protection exists and surface water is managed in a whole basin plan.
[d]In shellfish only.

in the case studies because water quality is heavily impacted by nutrients: out of 75 monitoring stations from across Canada examined by Environment Canada (2011), two of the three stations in PEI rivers had the highest levels and increasing trends of total nitrogen and nitrate–nitrite concentrations. Indeed, the province is the kingdom of potato farming where nitrogen is used as a fertilizer and contaminates all sources of water including groundwater (Jiang & Somers 2009; Paradis *et al.* 2016), which is the sole drinking water supply of the province.

Some of the selected case studies involve multiple jurisdictions (provinces, states, and countries) and lack a binding agreement; the following paragraphs introduce those that were used to inform regulatory approaches presented in Table 2. The Murray–Darling Basin is not detailed below because the Algal Management Strategy (Murray-Darling Basin Ministerial Council 1994) defines every involved jurisdiction's role and sets agreed upon targets.

The Lake Winnipeg Basin is a vast watershed that covers parts of two countries (Canada and the USA), four provinces (Alberta, Saskatchewan, Manitoba, Ontario) and four states (North Dakota, South Dakota, Minnesota, Montana). The nutrient pollution problem and solution are both inter-provincial and international in scope and involve multiple jurisdictions, but the Province of Manitoba has the primary responsibility for decisions related to water quality management of Lake Winnipeg, as the lake is located entirely within the province. Given the differences and the number of jurisdictions involved, Table 2 presents information for the province of Manitoba (ECCC 2019).

Lake Erie is the smallest of the Laurentian Great Lakes and its watershed (i.e., of its shore solely) covers parts of two countries (Canada and USA), one province (Ontario), and five states (Indiana, Michigan, Ohio, Pennsylvania, New York). Under the 2012 Great Lakes Water Quality Agreement (GLWQA), the governments of Canada and the USA agreed 'to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes basin ecosystem'. In 2011, they released the Lake Erie Binational Nutrient Management Strategy outlining the agreed-upon actions to reduce excessive phosphorus loading and eutrophication. In 2018, to meet binational phosphorus reduction targets adopted in 2016, Canada and the USA released action plans for reducing phosphorus loadings. Although these strategies and management plans are not strictly speaking binding, they informed our summary (Table 2). To the best of our knowledge, we verified the legal status of each piece of information within the countries regulations.

The Lake Léman watershed covers 8,000 km^2 across two countries (25% in France and 85% in Switzerland) and 555 municipalities (CIPEL 2010). The lake is fed (among other sources) by the Rhone River, which drains an area of 98,000 km^2 with more than 90% located in France. Phosphorus loadings from the Rhone represent 95% of the total phosphorus entering the lake (Quetin 2007). The International Commission for the Protection of the Leman's waters (The *Commission internationale pour la protection des eaux du Léman contre la pollution*, CIPEL) released the 2011–2020 binational strategy in 2010 (CIPEL 2010). Given the history of France and Switzerland not following through on the CIPEL's recommendations at the same time, we decided not to rely on the strategy to fill in Table 2. Rather each jurisdiction's legislation was scanned when possible. Indeed, since 1968, the CIPEL has been advocating for regulating the use of phosphates in laundry detergent. This resulted in a ban of phosphates in laundry detergents in 1986 in Switzerland and in 2007 in France.

Chesapeake Bay is the largest estuary in the USA. Its watershed includes the District of Columbia as well as parts of six states: Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia. This area encompasses 13.6 million people and nutrients come from a range of point and NPSs, including WWTPs, industrial facilities, agricultural fields, lawns, and atmospheric deposits (EPA 2011). On 29 December 2010, the U.S. Environmental Protection Agency established the Chesapeake Bay Total Maximum Daily Load [TMDL; (EPA 2015a)]. This TMDL applies to the entire 64,000 squared-mile watershed; however, it is sub-divided into 92 smaller TMDLs across the six states and the District of Columbia. As TMDLs are legally binding, they informed our summary (Table 2).

The Gulf of Mexico contributing area begins at the Mississippi River delta and contributing watersheds drain much of the USA and a tiny portion of Canada. This includes 31 states, from Montana to Pennsylvania and extending southward along the Mississippi River. Most of the nitrogen input comes from major farming states in the Mississippi River valley, including Minnesota, Iowa, Illinois, Wisconsin, Missouri, Tennessee, Arkansas, Mississippi, and Louisiana (Bruckner 2018). Despite the existence of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (Hypoxia Task Force, HTF), demonstrating the need for cooperative action by grouping together 12 states, five federal agencies, and a representative for tribes, the U.S. EPA does not plan to take the lead and implement a legally binding TMDL for the whole contributing area. For the moment, it allows states to stay in the lead. Besides, the HTF agreed on an interim target of a 20% nutrient load reduction by the year 2025 as a milestone toward reducing the hypoxic zone to less than 5,000 km^2 by 2035 (EPA 2015b). However, this task force does not have legislative power and each state must develop its own strategy and regulations. Given the extent of the Gulf of Mexico/Mississippi River watershed, and given the goal of this review (informing freshwater nutrients loads and HABs management), we decided to fill in Table 2 for two states only, Iowa and Arkansas.

DISCUSSION OF LESSONS LEARNED

Analyzing the 12 case studies reveals several lessons in effective nutrient loads and HABs management that can be grouped into five themes: (i) importance of jurisdictions' specificities in defining approaches; (ii) engaging with all stakeholders and building trust; (iii) re-thinking BMPs; (iv) monitoring and enforcing to ensure performance; and (v) need for good governance and leadership.

Approaches and their specificities

Tables 1–4 clearly illustrate the overall homogeneity in the management strategies applied in the reviewed case studies. Each element, however, of the regulatory, incentive-based, and risk mitigation approaches are applied in a different manner within each jurisdiction. This observation warrants the following remark; we considered that every specific element of the approaches identified should be the subject of a distinct systematic literature review to make recommendations tailored to the Lake Memphremagog and Missisquoi Bay-Lake Champlain areas.

As examples and insights into the previous remark, we looked into two elements taken from the categories of approaches presented in Tables 2 and 3. First, regarding numerical nutrient criteria, the EPA has been recommending their adoption for 14 different ecoregions since January 2000 (EPA 2019). Today, a greater number of states have adopted numerical criteria for response variables such as chlorophyll-a, rather than N or P, using scientifically defensible approaches different than that proposed in the U.S. EPA's guidelines. For the binational Lake Winnipeg watershed (ECCC 2018), water quality guidelines are different for the lake (Total P: 0.05 mg/L; Total N: 0.75 mg/L) and rivers. There are different total phosphorus guidelines for the major rivers and seasons (e.g., Saskatchewan River: 0.088 mg/L for open-water periods and 0.028 mg/L for ice-covered months; Red River: 0.102 mg/L, open water; Winnipeg: 0.012 mg/L, open water) as well as for total nitrogen (Saskatchewan: 0.838 mg/L for open-water periods and 0.761 mg/L for ice-covered months; Red: 1.4 mg/L; Winnipeg: 0.44 mg/L). The nitrogen guidelines were modified for these site-specific guidelines from the previous 1 mg/L limit applied at all sites because neither Manitoba nor the Canadian Council of Ministers of the Environment (CCME) has a guideline. The quality status is also computed differently for the lake and rivers. The lake quality is perceived to be good when seasonally weighted average concentrations are at or below the guidelines. The river quality status is considered good if less than 10% of samples are above the objective; water quality is fair if the objective is exceeded 10–50% of the time; it is poor otherwise (ECCC 2018). Battling with numerical criteria, officials at the Iowa Department of Natural Resources have decided not to set numerical standards for the state's recreational lakes (Payne 2019). Proposed standards would have needed to be met 75% of the time (Total N: 0.9 mg/L; Total P: 0.035 mg/L). The refusal is based on the fact that too many streams and lakes in the state would not meet numerical criteria, thus, diluting available funds instead of reducing nutrients in prioritized areas as proposed and implemented by the Iowa Nutrient Reduction Strategy (Iowa Department of Agriculture and Land Stewardship *et al.* 2013). On the other side of the Atlantic, nitrogen quality standards are set at 11.3 mg/L in France and should be met 90% of the time (Arrêté du 25 janvier 2010 relatif aux méthodes et critères d'évaluation de l'état écologique, de l'état chimique et du potentiel écologique des eaux de surface pris en application des articles R. 212-10, R. 212-11 et R. 212-18 du code de l'environnement. *Decree of 25 January 2010 on the methods and criteria for assessing the ecological status, the chemical status, and ecological potential of surface waters adopted pursuant to Articles R.212-10, R.212-11, and R.212-18 of the Environmental Code.*). In this review, all the selected jurisdictions are using stewardship certification programs, but their field of applications and requirements vary. In Ontario, PEI, and the Lake Erie watershed, nutrient providers can be certified through the 4R Nutrient Stewardship Certification Program to encourage the implementation of a series of BMPs related to using the Right source of nutrients at the Right rate and Right time in the Right place (4R Certification Program 2017a, 2017b). At the same time, forest and tree farm certifications are, respectively, offered in Oregon (Oregon Department of Forestry 2010) and Arkansas (Arkansas Forestry Association 2019) while Lake friendly certification is offered to municipalities around Lake Winnipeg (Lake Friendly undated).

Engaging with all stakeholders and building trust

It is widely recognized that the success of environmental management strategies is partially based on mobilizing all stakeholders around key issues and building trust around the proposed strategy. This is even truer in the case of integrated watershed management and it is still a recurring theme identified in the case studies.

Because of the historical development of WQT in the Lake Simcoe Region Conservation Authority (LSRCA), it was recognized from the beginning that the Lake Simcoe Phosphorus Offset Program (LSPOP) would require widespread consensus and endorsement of project outcomes (XCG consultants 2014). The program steering committee was composed of the LSRCA, its partner municipalities, and individuals and groups with whom the LSRCA routinely works on watershed environmental issues. It also included representation from the agricultural sector, the land development and building industry, the Chippewas of Georgina Island First Nation, as well as the watershed municipalities and government ministries. A pilot offset project working group was formed with York Region who agreed to participate as the pilot municipality. In addition to the stakeholder engagement, a public outreach and consultation aspect of the LSPOP was established that included three major components: (i) Stakeholder Soundings – a survey of watershed stakeholders; (ii) four community workshops designed to engage the public-at-large; and (iii) the Citizen's Guide to Phosphorus Offsetting – a guide aimed at the general public describing the concept and details of phosphorus offsetting. The consultation process provided the project team with good insight into public perceptions and helped the program achieve stakeholder acceptance and endorsement (for example, 89% of farmers would recommend that other watersheds undertake a similar program (O'Grady 2011, 2013).

The public can of course be involved and sensitized beyond the scope of specific projects as Nature Alberta has been demonstrating for more than 15 years (Nature Alberta 2013). Indeed, shoreline advisors provide a personalized experience for each individual property outlining BMP suggestions and the results of the consultation, along with additional resources to support property management decisions to benefit their property and the lake. It is noteworthy Nature Alberta has added a shoreline naturalization incentive to encourage lakefront property owners to naturalize their shorelines (Alberta 2016).

In addition to community involvement and stakeholder consultations, using data to illustrate environmental conditions and explaining future evolution and mitigation measures can help to build trust. Sharing data and enabling public access helps promote transparency. More specific tools can also be mobilized. For example, in Ontario, the South Nation Conservation promoted controlled tile drainage (CTD) using cost–benefit analysis (Kitchen & Kitchen 2017; OSCIA 2017; South Nation Ontario 2017). A computerized tool helped producers predict crop yield benefits from CTD (available from: https://demo.gatewaygeomatics.com/ctd/) versus conventionally drained systems under varying weather conditions for their individual properties. This educational approach could effectively improve CTD application and the tool has even been advertised using video clips and workshops, organized by a trio of Conservation Authorities. Indeed, according to one of the lead researchers on CTD (D.R. Lapen, Agriculture and Agri-Food Canada, May 2019), the farming community is more aware and the uptake rate better than ever; suggesting it takes time to change drainage practices.

A third approach of trust building may require more bottom-up approaches. Indeed, the majority of approaches identified in the literature review rely on top-down approaches; they are generally developed and proposed by a higher level (often governmental agencies) and passed down along the hierarchy for final implementation by the users. These approaches have little input from the public or end-users and can be a hindrance for public participation at the regional scale (Rollason *et al.* 2018). Bottom-up approaches are initiated by local, state, and grass-root organizations (e.g., farmers associations, industrial groups, NGOs, watershed groups, lakeshore residents) and refined to reflect regional, national, and international (when and if they do reach this level) concerns. These kind of approaches are often less costly and enjoy a great deal of success (at least in their implementation), because they are locally developed and more easily trusted. Examples include the Alternative Land Use Services program. This pilot project took place from 2006 to 2009 in Blanshard, Manitoba (Allen 2015). The program reflects the concept that farmers and ranchers can use their land in an alternative way to produce ecosystem services that benefit Canadians. It first offered payment for wetland services to landowners and, though short-lived, proved effective (Mann *et al.* 2014). It was so effective in fact, that developed ALUSs are now offering services across Canada in six provinces (Alberta, Manitoba, Ontario, P.E.I, Québec, and Saskatchewan). It is the first Canadian province-wide application of payments for ecosystem services (PES; Kolinjivadi *et al.* 2019). In the USA, the CWA enforceable objective [CWA, 101(a), United States Code, Vol. 33, 125 1(a)] states 'The objective of the Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters'. One could say that the development of indices of biological integrity at the local then state level (Hawkins 2006; MPCA 2015, 2018; Rehn *et al.* 2015; Kuhn *et al.* 2018; U.S. EPA 2019) was, although unplanned, also an application of bottom-up approaches. Mariam (2001) argues that the bottom-up approach has also been used by the USEPA to set standards for drinking water under the authority of the Safe Drinking Water Act (SDWA). These standards specify zero risk from carcinogens in drinking water as a non-enforceable health goal. However, because this goal cannot be achieved at any cost, the standards establish legally enforceable limits set as close as possible to ensure zero risk, taking into account cost and technical feasibility. The goal must also be based on a trade-off between what the public would be willing to accept *vis-à-vis* losses in economic benefits (Mariam 2001).

Thinking BMPs through

The observation is clear, BMPs' efficacy is questioned. They have been used to manage nutrient loads for several decades in the USA (Osgood 2017) and other developed countries. Yet, there are very few success stories of restoring eutrophic lakes (where watershed size is large, i.e., <10-times lake surface area; in comparison, the Lake Champlain watershed is 17 times larger than the Lake – 1,269 km^2, Lake Memphremagog has the same ratio). Their cost-effectiveness is also questioned, especially when compared with in-lake technical measures to control algae (Welch & Jacoby 2001; Wagner 2017) or phosphorus loads (Huser *et al.* 2016), including internal loading. Certain types of BMPs, such as nutrient management, seem more efficient than others (e.g., buffer strips or cover crops) in decreasing nutrient (especially phosphorus) loads (Liu *et al.* 2016). In cases where BMPs are inadequate as the sole restoration measure, in-lake technical solutions and wetland restoration can be used as supplemental strategies (Liu *et al.* 2016; Osgood 2017) or, when source control is not an option, as an alternative (Huser *et al.* 2016; Wagner 2017). The following paragraphs offer some insights related to the possible re-thinking of BMPs.

It is concerning that BMPs are still not adopted by most farmers (varying from 30 to 80% depending on location and type of BMP). Hence, farmers and landowners adoption behavior is a widely studied topic whether it is in the USA in western Lake Erie (Zhang *et al.* 2016), Ontario (Weber 2017), Australia (Pannell *et al.* 2006), or even worldwide (Liu *et al.* 2018). This topic still requires some research and the role of social media diffusion of information has been highlighted as a potential mean of increasing adoption (Liu *et al.* 2018). One of the reasons why BMPs are not adopted is that farmers and landowners are rather risk-adverse. This interesting avenue was explored with BMP insurance. This type of insurance guarantees economic losses endured due to the application of a BMP. A test-strip without BMP serves as the control parcel (USDA 2003). Often, a 5% deductible exists; beyond a loss of more than 5%, losses are refunded to the policy holders (Maulsby 2001). Apart from high transaction costs imposed by private insurance companies (Harris Palm-Forster & Swinton 2012), BMP insurance has potential (Mitchell 2004; Harris Palm-Forster *et al.* 2014).

Conservation procurement auctions are another type of market-based BMP adoption strategy. In these auctions, farmers/landowners submit bids for implementing BMPs; the bids are ranked and funded based on cost-effectiveness (Smith *et al.* 2009). Auctions are attractive and increasingly used because competitive bidding is expected to increase the cost-effectiveness of nature conservation programs (Dijk *et al.* 2018; Rolfe *et al.* 2018). In practice, participation rates of conservation procurement auctions are often low, even lower than with broader agri-environmental and PES schemes (Haynes *et al.* 2007; Defrancesco *et al.* 2008; Mettepenningen *et al.* 2011; Taylor & Van Grieken 2015; Rolfe *et al.* 2017). The decision to participate in a conservation tender involves three simultaneous decisions: (i) whether to change a management practice; (ii) whether to be involved in a public or private program with contractual obligations; and (iii) how to set a price or bid (Rolfe *et al.* 2018). Also, there are a number of factors that affect each stage of the decision process with some, such as landholder attitudes and risk considerations, relevant to all three.

The auctions can bring about a paradigm shift as it could allow targeting high-priority areas with cost-efficient measures relative to conservation results (Greenhalgh 2010; Smith *et al.* 2012; Harris Palm-Forster 2015). Instead of incentivizing a procurement of means, payments could be made to incentivize results (Kerr *et al.* 2016). The innovative institutional designs that could go beyond the traditional government programs and do more to reward outcomes and not just actions, introduced by Kerr *et al.* (2016), are corroborated by the Delta Institute which proposes to shift towards pay for performance programs (Fisher *et al.* 2016) and by the USDA which proposed similar programs (NRCS 2017). Besides, this could supplement the trending PES schemes (MAPAQ 2005) and be coupled with progress payments such as in Finland where specific BMPs are required the years following enrollment in the conservation program to keep increasing payments coming (MAPAQ 2005).

Ensuring performance

As illustrated in the BMP section, ensuring performance is paramount to the success of nutrient and HABs management. It also conditions the public trust in and support of these programs. Case studies have shown that ensuring performance can be achieved in one of three ways. First, regulations need to be enforced. Second, monitoring programs (data collection) should be designed carefully and attention should be given to their time span. Third, monitoring should not be limited to data collection and adaptive management and should be implemented to ensure long-term performances. These three elements are highlighted through the following insightful examples.

Since experiencing a record bloom in 2011 and since the 2014 drinking water crisis in Toledo, Ohio (Smith *et al.* 2015a), data have not shown improvements over Lake Erie. This may have helped the publicized initiative granting Lake Erie the same legal Rights as people to sue polluters by referendum in March 2019 (Daley 2019). Voluntary programs are not working (Bunch 2018), regulation for NPS pollution is needed (Lucas County 2015), as is enforcement of the CWA (Coleman 2016). However, it was not until March 2018 that Ohio declared western Lake Erie impaired (EPA 2018b) under section 303(d) of the CWA, thus preventing, according to the EPA, the application of a TMDL. Still, since 2018, no TMDL planning has been released and this despite a similar experience around Chesapeake Bay. Indeed, states struggled for decades to make voluntary, incentive-based approaches work. Their efforts were overwhelmed by the impacts of population growth and agricultural production. In 2010, all six states in the Chesapeake Bay area asked the EPA to establish a TMDL. This is enforceable, contrary to voluntary measures, thus allowing the EPA to impose backstop measures such as requiring additional reductions from point sources and withholding federal grant money if states miss interim milestones. The Chesapeake TMDL has had measurable effects on nitrogen, phosphorus, and sediment loads (Scavia 2017), and the Bay is slowly getting healthier, although the recovery is still 'fragile'(Blankenship 2018).

At the same time, Lake Erie faces unintended consequences of conservation practices. The early 2000s were marked with a step-change increase in riverine soluble reactive phosphorus (SRP) loads. These elevated loads were sustained between 2002 and 2014. The increase was attributed to increased SRP delivery for 65% (likely due to changes in tillage practices combined with increased hydrological connectivity between fields and streams) while higher runoff accounted for the other 35% (Jarvie *et al.* 2017). In the meantime, watershed TP budgets declined, attributable to various BMPs. Among those, land management practices were widely adopted: tillage was reduced to minimize erosion and particulate P loss, and tile drainage was increased to improve profits. Research shows that these land management practices, designed to reduce erosion and particulate P transport, may have conversely contributed to the increased SRP loads (Kleinman *et al.* 2003; Kleinman & Sharpley 2003; Smith *et al.* 2015a, 2015b; Bullerjahn *et al.* 2016), illustrating both the critical need for long-term monitoring and adaptive management. Denmark and the Netherlands learned the same lesson regarding long-term monitoring. Between 1970 and 2007, lake restoration was conducted in more than 90 lakes using bioremediation (SØNdergaard *et al.* 2007; Søndergaard *et al.* 2017). These involved fish removal and stocking, but also zebra mussel (*Dreissena polymorpha)* introductions, as an aid to increasing transparency by filtering seston particles. Despite improvements in Secchi disk depths, decreases (over 50% change relative to the initial summer concentrations) in chlorophyll-a, total phosphorus, and nitrogen concentrations in the first few years – the strongest effects did not appear until 4–6 years after the start of fish removal – for more than half the lakes. The long-term effects of restoration initiatives indicate a return to the turbid state after 10 years (SØNdergaard *et al.* 2007). Fish removal for all lakes varied from 1 year to more than 10 years; however, repeated fish removal or supplementation with physio-chemical measures may still be an effective option (Jeppesen *et al.* 2012). Most Denmark and Netherland lakes were shallow and eutrophic and do not compare directly to Lakes Champlain or Memphremagog, but this case illustrates rather clearly the critical importance of direct long-term monitoring of technical management practices.

Apart from physico-chemical data, other elements need to be monitored. Effective management is also about tracking the progress made in implementing strategies. This element, along with a willingness to apply adaptive management, appears clearly in all the consulted case studies. In the Lake Léman watershed, plan implementation is well designed, quickly understandable, and can be summarized through visual aids. Indeed, a so-called Tableau de bord distinguishes the ecological state of the lake on one side and reviews scheduled actions and their progress on the other (https://www.cipel.org/le-leman/tableau-bord/). In the Gulf of Mexico, a satellite-based HAB EWS closely monitors and analyses operational bulletins (Davis *et al.* 2013; Kavanaugh *et al.* 2013). Operational bulletins are produced twice a week during active bloom events and provide information about the possible presence or confirmed identification of new blooms, in addition to monitoring existing blooms and providing forecasts of the spatial bloom extents, movement, and intensifying conditions (National Ocean Service 2018). The bulletins also report daily coastal respiratory irritation forecasts (http://tidesandcurrents.noaa.gov/hab). Since data on utilization of the product is extremely important for guiding improvements, efforts are made to evaluate utilization and usefulness of bulletins. During years 2004–2008, weekly bulletin utilization was consistently greater than 83% (Kavanaugh *et al.* 2013), particularly for bulletins labeled as 'high priority', demonstrating that the priority categories successfully indicate the importance of their content to subscribers. East Florida hosts the least number of bulletin subscribers. However, during the 2007–2008 bloom, a high proportion of bulletins were confirmed as utilized, indicating that bulletins are helpful to subscribers involved in response to both frequent and rare bloom events.

Between 2008 and 2011, the Chesapeake Bay Program (CBP) was best characterized as a trial and error process of adaptation in which learning was serendipitous, rather than an explicit objective (National Research Council 2011). This statement is applicable to all presented case studies. Effective adaptive management requires the assessment of uncertainties relevant to decision-making and the recognition than even the most well-thought plan should be modified based on what is learned through voluntarily designed management tests.

Governance and leadership

Without clear governance and strong leadership, the key elements presented above would be moot. Clear governance ensures that each stakeholder, no matter the level, knows exactly their place and role. Leadership ensures actions are taken, even in the context of integrated resource management where inertia is massive. Approaches to strengthen governance and leadership go beyond the topic of this literature review and would probably need considering environmental management strategies as a whole to get useful insights. In this report, however, it is possible to point out one example per each case study, illustrate their importance, and highlight the vital need for voluntarily strengthening them. The following paragraphs detail the case studies for which governance or leadership has not yet been discussed.

The Murray–Darling River basin is managed across four states and a territory, covering one million square kilometers, equivalent to 14% of the country's total area (MDBA 2010; Bellamy 2013). In 1992, the Darling River suffered one of the world's largest toxic algal blooms, over 1,000 km. It became the catalyst needed to prompt the state and federal governments to enact the Murray–Darling algal management strategy in 1994 (Murray-Darling Basin Ministerial Council 1994). The key to this strategy was the development of catchment and regional management plans. It highlighted what can be achieved when federal and state governments agree on an approach to address a significant problem, which has implications for more than one state. Everyone's role was clearly defined, from the basin commission to the commonwealth, state, and local governments, and ultimately to the individuals. Yet, mega blooms occurred in 2007, 2009, 2010, 2016, and 2018. Following the bloom of 2009, the New South Wales Office of Water developed the River Murray algal bloom management strategy. It clearly stated that the Murray Regional Algal Contingency Plan (RACC) performed its functions well and responded effectively to the bloom, but still made a recommendation for more effective future management (Ryan *et al.* 2009). However, now trust has been lost. These plans and overall well-managed governance (at least in the beginning) did not prevent the massive fish kills of January 2019 in the lower Darling Basin. These may have been caused or rendered worse due to water basin plans sharing water beyond ecological flows, worsening blooms, and causing fish kills.

In the Lake Simcoe watershed, transport (erosion and atmospheric deposition of particulate P) of sediments represents a major contributor to eutrophication and is due to a high urbanization rate. Total phosphorus entering the Lake from atmospheric deposition has been estimated to account for 25–50% of total inputs (Winter *et al.* 2007; Ramkellawan *et al.* 2009; Brown *et al.* 2011) based on bulk atmospheric deposition data spanning 1990–2007. To combat high rates of soil erosion associated with urban development, construction-phase stormwater management (CPSWM) guidelines have been adopted to reduce the quantity of eroded soil entering streams and rivers. A literature review (Trenouth *et al.* 2013) of international guidelines and the science they are based on allowed calling for a revision of Ontario's guidelines. A new concept of Dust Response Units (DRUs) coupled with the wind erosion prediction system allowed identifying high-risk zones for atmospheric deposition (Weiss *et al.* 2013). Results of this analysis showed that 12 of 66 DRUs (i.e., 18% of all DRUs) contributed 85% of the total P input, allowing the implementation of control practices. Lake modelling exercises allow the assessment of BMP efficiency and apply scenario analyses to devise theoretically effective management strategies (Jin *et al.* 2013). These examples show how research can promote the adaptation of eutrophication and HABs management initiatives.

The combat against eutrophication in the binational Lake Léman has been led since 1960 by an inter-governmental agency – CIPEL – which was founded by Switzerland and France. It first aimed at coordinating their efforts to tackle the lake's pollution on a watershed basis including the lake itself, its tributaries, and their own surface and underground contributors (Rapin 1992). The commission managed research programs and communicated their results (Rapin & Gerdeaux 2013). It gave advice to both governments on pollution control measures and prepared the first elements needed for international regulations (for example, the ban on phosphates in laundry detergent or binational contracts such as river contracts). Forty years later, although still *en route* for complete restoration and being praised for dynamical management policy commitments, efforts are still needed to lower phosphorus concentrations under 0.015 mg/L to limit the risk of algae proliferation (CIPEL 2018).

Under the governance of the Chesapeake Monitoring Cooperative, a group of leading organizations is managing the integration of volunteer-based and non-traditional water quality and macroinvertebrate monitoring data into the CBP partnership (Alliance for the Chesapeake Bay 2018; Chesapeake Monitoring Cooperative 2018, 2019). The database now includes more than 66,000 water quality records as well as 921 benthic macroinvertebrate measurements over 122 rivers/streams sampled by 389 people representing 74 different organizations. This cooperative initiative ensures that data are used to inform watershed management decisions and efforts as well as proposing a comprehensive watershed stewardship program as part of the Alliance for Chesapeake Bay; mobilizing a total of 75,000 volunteers from over six states (Chesapeake Executive Council 1996). This type of initiative highlights the benefits of integrating volunteers in monitoring programs. In addition to providing outreach and education about lake water quality, it helps building trust, ensures performance, and can even provide data of the same quality as those generated by a research laboratory (Obrecht *et al.* 1998) under the right supervision.

The Department of Environmental Quality (DEQ) of Oregon developed its own strategy demonstrating how leadership and state policy development contributes to the better management of HABs. Between 2000 and 2010, due to the presence of HABs, more than 40 public health advisories were issued in Oregon (EPA 2016). Hence in 2010, the state started including waters with HAB health advisories in the 303(d) list of impaired waters, requiring, under the CWA, that a TMDL program be established. Given the likelihood that the number of water bodies in Oregon experiencing HABs is much larger, the DEQ developed recommendations for its strategy. The overall recommendations (EPA 2016) focused on both the CWA and the SDWA. They went from modifying current DEQ actions, including optional operation given available staff time, advocating for additional funding, and legislative or EPA support (Oregon DEQ 2011). As a result, for example, additional water quality criteria (Chl-a, DO) have been used as proxies to manage and/or monitor HABs, a variety of HAB-related activities are now regulated, source testing data are now used to prioritize field actions (including BMPs), and multi-level cooperation has greatly improved (with OHA in particular). All these examples illustrate the ramifications of state policy development as applied to the management of HABs.

CONCLUSION

Freshwater nutrient loads and HABs management are worldwide issues typically dealt with in large watersheds with frameworks based on integrated watershed management planning and national standards. Unfortunately, these standards are not stringent enough to prevent algae blooms. In the 408 documents compiled for this review, no actual success story or mention of a success story was found; there were only management stories of a more or less frequently recurring phenomenon. The review of 12 case studies analyzed the diversity of approaches used under four different themes: (i) key regulatory approaches; (ii) incentive-based; and (iii) risk mitigation approaches. All case studies also employ (iv) outreach, engagement, and educational activities to educate and give advice to stakeholders, to influence their behavior, and to promote programs and disseminate good practices. There is a need for a systematic review with respect to the elements of the approaches identified in order to make recommendations tailored to the Lake Memphremagog and Missisquoi Bay-Lake Champlain areas. Although BMPs have been used for decades throughout the world to manage NPS pollutions, these are questioned for their apparent lack of measurable outcome and cost-efficiency. This is especially true when cost–benefit analyses are used and may even increase the use of technical solutions over comprehensive approaches. Market-based strategies to offset pollution or promote targeted BMP adoption are becoming popular. Some even suggest that payments could be made to incentivize results, instead of incentivizing a procurement of means. Although climate change synergy will likely increase the frequency of HABs, it was already specifically mentioned or considered in all the reviewed management strategies. Here, we summarize the current state of knowledge of nutrient loading and implications for HABs. We propose solutions and paths forward to a wicked problem which should prove insightful for policy-makers and managers alike through the following findings. National water quality standards have not proved stringent enough to prevent HABs. Identified frameworks are all based on integrated watershed management and national standards. No actual success stories related to remediation of HABs were identified; they were simply management stories. The efficacy of NPS BMPs is questioned throughout the world due to insufficient evidence to determine whether they can mitigate HABs. Market-based strategies to offset pollution or promote targeted BMP adoption are becoming popular and resulting in cost-effective and efficient approaches. Cost–benefit analyses may increase the use of technical solutions over comprehensive approaches. At this point, there is not really a unique case study that could be applied to Lake Champlain and Lake Memphremagog. Specific elements of the approaches identified in this review and unifying themes, however, hold promises. This is why we advocate for conducting a systematic literature review with regard to those themes in order to develop recommendations tailored to the Lake Memphremagog and Missisquoi Bay-Lake Champlain areas.

At last, we would like to address the elephant-sized question in the room. Will climate change increase HABs frequency? Interactive effects of eutrophication and climate change on harmful cyanobacterial blooms are complex. Current knowledge and literature suggest these processes are likely to enhance the magnitude and frequency of HAB events. Changes in agricultural practices and management strategies will thus be key determinants. Climate change is currently considered in all the reviewed management strategies. This is rather good news given that Peeters *et al.* (2007), Wiedner *et al.* (2007), Paerl & Huisman (2008), Russell & Connell (2009), Smith & Schindler (2009a, 2009b), Tadonléké *et al.* (2009), Paerl *et al.* (2011), Winter *et al.* (2011), O'Neil *et al.* (2012), Anderson (2014), North *et al.* (2014), Taranu *et al.* (2015), Culbertson *et al.* (2016), Nürnberg & LaZerte (2016) certainly demonstrate that climate change synergy will likely increase HABs frequencies.

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