Harmful Algae 87 (2019) 101624

Contents lists available at ScienceDirect

Harmful Algae

journal homepage: www.elsevier.com/locate/hal

Estimating the economic costs of algal blooms in the Canadian Lake Erie Basin

Robert B. Smith[a,*], Brad Bass[b], David Sawyer[c], David Depew[d], Susan B. Watson[e]

[a] Midsummer Analytics, 397 Third Avenue, Ottawa, Ontario, K1S 2K6, Canada
[b] Great Lakes Harmful Pollutants Section, Environment and Climate Change Canada, Toronto, Canada
[c] EnviroEconomics Inc., Ottawa, Canada
[d] Watershed Hydrology and Ecology Research Division, Environment and Climate Change Canada, Burlington, Canada
[e] Department of Biology, University of Waterloo, Waterloo, Canada

ARTICLE INFO

Keywords:
Blooms
Cladophora
Cyanobacteria
Economic cost
Ecosystem
Valuation
HABs
Health
Lake Erie
Microcystis
Monte Carlo analysis

ABSTRACT

Over the past two decades there has been a re-emergence of regular harmful algal blooms in Lake Erie due to increasing phosphorus loading, mainly from non-point agricultural sources. The Canadian and United States governments have jointly agreed to reduce phosphorus loadings to the lake in order to control the extent and severity of the blooms. Citizens on both sides of the border face a number of economic costs, both market and non-market, as a result of the blooms. This study values these costs for the Canadian portion of the Lake Erie basin economy using standard economic approaches that are widely applied within the world of cost-benefit analysis. The results suggest that algal blooms will impose equivalent annual costs equal to $272 million in 2015 prices over a 30-year period if left unchecked. The largest market costs will be imposed on the tourism industry ($110 million in equivalent annual costs) and the largest non-market costs will be borne by recreational users and those who place inherent value on the lake's quality ($115 million in equivalent annual costs). Management action to reduce phosphorus loadings is found to be justified on economic grounds if the 30-year net present value of the reduction program is less than $1294 million (2015 Canadian dollars).

1. Introduction

In 1972, Canada and the United States of America signed the Great Lakes Water Quality Agreement (GLWQA) to address, in part, the algal blooms that were particularly severe in Lake Erie at the time. Through binational nutrient reduction efforts, the blooms on Lake Erie, the smallest and most heavily impacted of the Great Lakes, were significantly diminished between the 1970s and the 1990s.

Over the past two decades there has been a re-emergence of regular harmful algal blooms (HABs) in Lake Erie. The periodic outbreaks of the 1990s have been replaced by annual outbreaks of extensive, summer-long planktonic blooms dominated by toxic and non-toxic cyanobacteria, particularly in the lake's western basin (Steffen et al., 2014; Watson et al., 2016). The term "harmful algal blooms" is used in this study to refer to any mass growth of planktonic or benthic algae, which may be dominated by cyanobacteria or eukaryotic algal taxa (*e.g.*, Watson et al., 2015; Watson and Boyer, 2015).

Excess phosphorus (P), mainly from agricultural non-point sources, has been identified as one of the key drivers of planktonic HABs in Lake Erie, and several recent papers have developed empirically-based response curves relating P loading to the size of the cyanobacterial blooms in the western basin of the lake (Michalak et al., 2013; Steffen et al., 2014).

The concern with HABs has several dimensions. As noted above, most of the summer planktonic blooms in Lake Erie are dominated by cyanobacteria ("blue–green algae"), some of which produce toxins, such as hepatoxic microcystins, that can be harmful (to the point of lethality) to humans, livestock, pets, birds, fish and other wildlife. Dense cyanobacterial blooms (cHABs) dominated by species of *Microcystis* and other potentially toxic cyanobacteria (*e.g.,* species of *Planktothrix*, *Dolichospermum*) now develop annually in the shallow, warm western basin and more intermittent outbreaks also occur along the shorelines of the deeper central and eastern basins (Hoagland and Scatasta, 2006; Steffen et al., 2014; Wynne and Stumpf, 2015; Watson

Abbreviations: cHAB, cyanobacterial harmful algal bloom; HAB, harmful algal bloom; HNAB, harmful and nuisance algal bloom; GLWQA, Great Lakes Water Quality Agreement; NOAA, National Oceanic and Atmospheric Administration; NPV, net present value; WQL, water quality ladder

* Corresponding author.
E-mail address: rob@midsummer.ca (R.B. Smith).

https://doi.org/10.1016/j.hal.2019.101624
Received 5 November 2018; Received in revised form 3 June 2019; Accepted 5 June 2019
Available online 24 June 2019
1568-9883/

et al., 2016; Miller et al., 2017).

Non-toxic “nuisance” HABs that foul the shoreline of the eastern basin of Lake Erie (and other areas of the Great Lakes) are also a major issue. Expansive blooms of the benthic filamentous green algae *Cladophora* sp. (mainly comprising *Cladophora glomerata*) occur each summer and foul recreational beaches and shorelines with dense, rotting algal mats, clog municipal and industrial water intakes, impair water quality and inshore habitat and pose microbial health risks to wildlife and humans (International Joint Commission, 2014). The bacterial degradation of beached *Cladophora* generates foul odours from the production of methyl sulphides and several faecal-smelling volatile organic compounds (Watson, 2004).

Together, the Lake Erie cHABs and *Cladophora* blooms, termed harmful and nuisance algal blooms (HNABs), can have significant socioeconomic impacts. Though very few studies have attempted to assess the impacts of HNABs on the Canadian economy, several studies consider the costs of such blooms to the United States (U.S.) and other economies (Anderson et al., 2000; Dodds et al., 2009; Krysel et al., 2003).

Dodds et al. (2009) assessed the annual costs of eutrophication in U.S. fresh water systems using an EGS approach based on a sample of water bodies from 13 nutrient regions in the U.S. They estimated nutrient concentrations from one body of water to another and assumed that all the lakes in their study were hypereutrophic in the summer. Their study assessed annual costs in four categories (Table 1).

Hoagland and Scatasta (2006) focused on the economic costs of hazardous (but not nuisance) coastal blooms in the U.S. and European Union. Steffensen (2008) focused on estimating the actual costs of managing algal blooms in Australia. As with the current study, both had difficulties in obtaining data and assumptions were required for estimating many of the costs (Tables 2 and 3).

Though direct comparisons of the results of the earlier studies with those here are not possible, as each of the studies applies to a different region with different assumptions and different populations, their results nonetheless provide some context for comparison. This is taken up further in the discussion of results in Section 4.

To assess and quantify the economic impacts of HNABs on Lake Erie, this study examined changes in the flows of Lake Erie’s ecological goods and services (EGS) due to HNABs for the Canadian side of the lake (Fig. 1). The lake provides a number of essential goods and services to industries and residents living in the Canadian basin: water for drinking, irrigation and industrial use; fish for commercial catch; recreation; and many cultural benefits. The cost categories considered in the study and the valuation approach used for each are presented in Table 4.

The principal objectives of this study were to identify the flows of EGS from Lake Erie impacted by HNABS, quantify the impacts of HNABs on these flows and, finally, to place an economic value on the changes in the flows (Fig. 2). Starting from a welfare economics standpoint, economic costs were estimated using a variety of approaches that combined cost estimates collected directly from impacted industries, results from other peer-reviewed studies and the professional judgement based on the authors’ knowledge of HNABs and their impacts on Lake Erie’s ecology and economy. The study did not include impacts on employment or other macroeconomic variables.

Table 1
Costs of eutrophication in United States’ freshwater systems.
Source: Dodds et al. (2009).

Cost category	Annual costs (billion U.S. 2007 dollars*)
Recreation and angling	0.37 – 1.16
Property values on the lake	0.3 – 2.8
Drinking water costs for bottled water	0.813
Loss of biodiversity	0.044
Total	1.527 – 4.817

* Base-year assumed as it is not reported by the Dodds et al.

Table 2
Costs of algal blooms in the United States.
Source: Hoagland and Scatasta (2006).

Cost category	Annual costs	
	United States	European Union
	(million 2005 U.S. dollars)	
Commercial fisheries	38	147
Public health	37	11
Recreation and tourism	4	637
Coastal monitoring and management	3	18
Total	82	813

Table 3
Management costs of algal blooms in Australia.
Source: Steffensen (2008).

Cost category	Annual Costs (million 1999 Australian dollars)
Joint Management costs	9
Urban extractive users	35
Rural extractive users	30
Non–extractive users	76-136
Total	180-240

Costs associated with changes in the flows of EGS from the lake to the “Lake Erie basin economy” were estimated over a 30-year timeframe. As discussed in Section 2.2, the Lake Erie basin economy is not a standard economic geography for which official economic or demographic statistics are published by government agencies, so it was necessary to define it specifically for the purposes of the study.

Future costs were discounted to their present value using a social discount rate, a measure of the time value of income, or the degree to which income today is preferred to income in the future. Social discount rates are generally lower than market or private discount rates because they reflect both public and private time preferences. A discount rate of 3% was chosen for this study, with an upper and lower bound of 7% and 0%. These are the rates used by Environment and Climate Change Canada for regulatory impact analyses (Y. Bourassa, personal communication). As a comparison, the 30-year discount rate used by the United States Office of Management and Budget is 3.4% (Office of Management and Budget, 1992).

The study focused specifically on the economic costs of algal blooms to the Canadian portion of the Lake Erie basin economy, using 2015 as the base-year, and included economic activities impacted by these blooms in the business, government and household sectors. When considered from the perspective of direct users of the lake’s EGS, the main economic units of interest on the Canadian side of the lake are households, tourism businesses, drinking water treatment plants and commercial fishers.

Both households and tourism operators make significant use of the lake’s recreational and cultural benefits. Drinking water plants make use of the lake’s water and commercial fishers of its renowned yellow perch and walleye stocks.

Though the dominant land use in the area around the lake is agriculture, very few farms actually draw water directly from the lake. Many farms benefit from the lake’s assumed capacity to receive fertilizers and other agricultural chemicals that run off their fields. However, as noted above, the overuse of this capacity is the primary driver of the lake’s HNAB problem. In principle, the farms could face increased costs in the future if action were taken by governments to limit the amount of P and other material that farms release to the lake. Estimating these costs was out of scope for this study, as the focus was on the costs HNABS impose on the economy, not on the costs of controlling them.

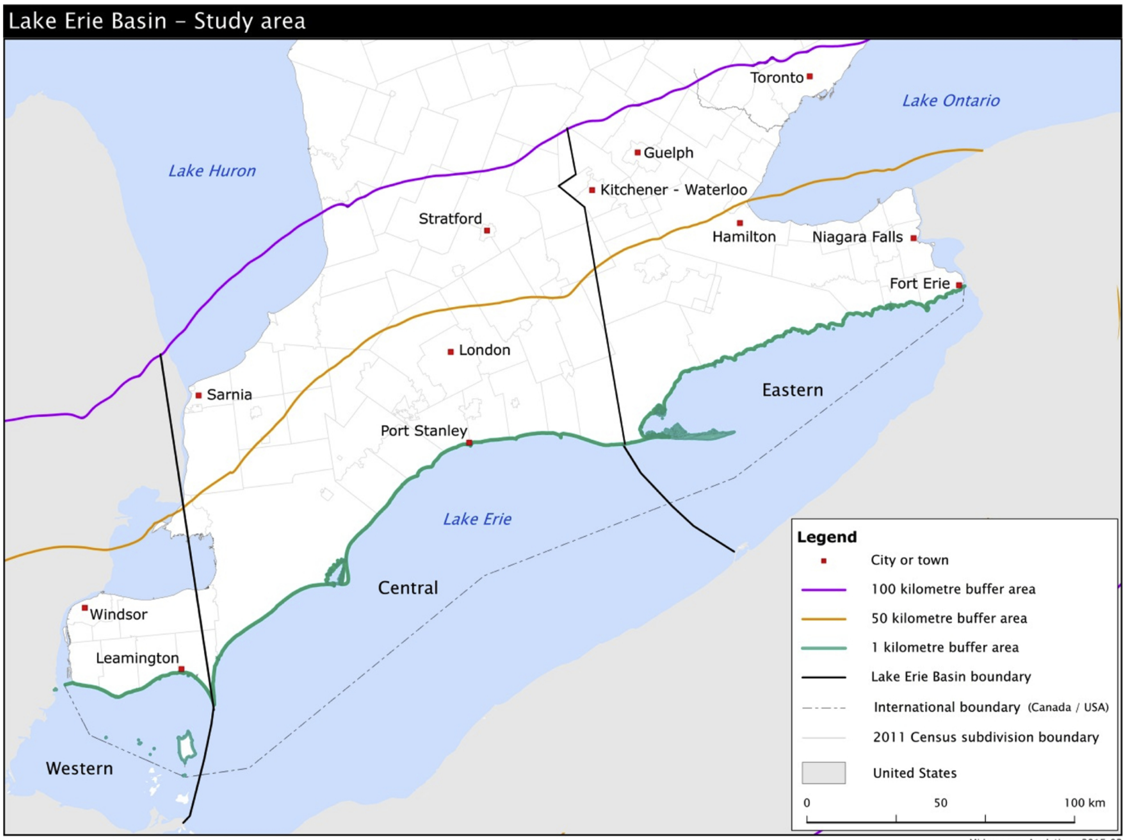

Fig. 1. Geographic Boundaries of the Basins and Economy of Lake Erie. The three basins are ecologically defined boundaries. The coloured lines indicate the three buffer areas from the lakeshore used for the economic analysis. Source: Current study.

Canadian industries do not figure strongly among users of Lake Erie's goods or services. Only two small facilities (both in the food processing industry) drew water from the lake in 2015, both in relatively small quantities. Previously, a large coal-fired electric power station at Nanticoke was a major user of the lake's water, but the station was mothballed in 2013 as part of the Government of Ontario's phase-out of coal-fired power generation. Another large facility (an oil refinery) operates in Nanticoke and, although it is licensed to withdraw water from the lake, there is no record that it did so in 2015 or previously.

Table 4
Cost categories considered in this study.

Cost category	Impacts	Valuation approach
Commercial fishing	Reduced value added in the commercial fishing industry due to reduced flows or quality of freshwater fish and/or increased costs to harvest fish	● Reductions in value added triggered at each step in the WQL ● Size of reductions (as a percentage of baseline value added) based on authors' judgement
Water consumers	Increased capital and operating costs for water treatment plants and industrial water users due to reduced raw water quality	● Increased capital and operating costs triggered when water quality reaches 5.4 on the WQL (*not swimmable, but good habitat for fish and wildlife)* ● Increased costs based on financial data collected directly from drinking water treatment plant operators
Recreational users	Reduced utility due to diminished enjoyment from beach activities, fishing, boating, birdwatching and hunting	● Reduced utility triggered as follows: for beach activities, when water quality falls below 7 on the WQL (*swimmable*); for fishing, when water quality falls below 5.4 on the WQL ((*not swimmable, but good habitat for fish and wildlife)*; for boating, birdwatching and hunting, when water quality falls below 4.3 on the WQL (*satisfactory habitat for some fish and wildlife)* ● Utility losses estimated using a generic benefits-transfer model (Johnston and Thomassin, 2010)
Non-users	Reduced utility due to diminished well-being associated with knowledge of the lake's degraded condition	● Reduced utility triggered at each step in the WQL ● Utility losses estimated using a generic benefits-transfer model (Johnston and Thomassin, 2010)
Tourism	Reduced value added in the tourism sector (hotels, restaurants, travel) due to lost business as a result of reduced numbers of visitors to the lake	● Reductions in value added triggered at each step in the WQL ● Size of reductions (as a percentage of baseline value added) based on authors' judgement
Property owners	Reduced wealth (lowered property values) due to the lake's degraded condition	● Reductions in property value triggered at each step in the WQL ● Size of reductions (as a percentage of baseline property values) based on authors' judgement
Health	Reduced utility and increased health care costs due to increased individual morbidity/mortality	● Not modelled due to lack of data

Fig. 2. Study approach. HNAB intensities were projected over the 30-year study timeframe for each of three scenarios for the control of P loadings to Lake Erie. Bloom intensities were linked with the Resources for the Future Water Quality Ladder (Vaughan, 1986) to trigger costs in the various cost categories considered. Annual costs were estimated over the study timeframe and discounted to present values.

Several large municipal drinking water treatment plants drew important quantities of water from the lake in 2015; a few small, private plants also withdrew water, though in relatively small amounts. In addition, a few golf courses used the lake's water, again in relatively small amounts.

All EGS provided by the lake were, in principle, within scope for the study and all those found to be of economic significance are included in the results presented here. The seven cost categories investigated in the study (Table 4) reflect the users of the lake's EGS discussed in the preceding paragraphs.

In some cases, economic markets do not price goods and services that can have very high societal benefits – such as clean water and air – because they are so-called "public goods", freely available to all. Economists recognize that public goods increase social benefits, or welfare and have developed a branch of the discipline called welfare economics in which, among other things, the value of these "free" goods is studied. Although some EGS, such as, food, timber, minerals and fossil fuels, are priced by the market, many others fall into the category of public goods.

2. Methods

2.1. Introduction

This study used a damage-assessment approach, linking changes in the extent, frequency, duration and type of algal blooms to changes in the flows of Lake Erie's EGS. Changes to EGS flows trigger changes in the economic benefits realized by beneficiaries. Damage assessment is an extension of cost-benefit analysis and is routinely applied in the assessment of ecological damages.

To estimate the costs of the changes in the flows of Lake Erie's EGS associated with HNABs, it was necessary to define the linkages between the Lake Erie basin economy and these flows. This required:

- a definition of the Lake Erie basin economy
- definitions of scenarios for the control of P loadings to the lake, and
- projections of HNAB intensities in each of the lake's basins.

Each of these is discussed further in the remainder of this section. The approach to estimating the economic value of the changes in the flows of the lake's EGS is discussed in the following section.

2.2. Defining the Lake Erie economy

While a great deal of economic activity occurs on and around Lake Erie, in a statistical sense the "Lake Erie basin economy" does not exist. Statistics Canada (the official statistical agency of the Canadian government) compiles and publishes statistics at the national, provincial and, in some cases, sub-provincial levels. None of the administrative regions used by the agency to publish its statistics reflects the boundaries of Lake Erie's flow of EGS. The Lake Erie basin economy was therefore defined formally for the purposes of this study as all activity taking place and individuals living within a certain distance of the lakeshore and making direct use of the lake's EGS. This approach allowed for unique geographical regions to be used in estimating the impacts on different beneficiaries. For example, the boundary of the "economy" relevant to the impacts of HNABs on residential property values was defined as that within one km of the lakeshore. In contrast, the economy used to study the impact imposed on recreational users was defined to extend 50 km from the lakeshore.

In total, three buffer areas were used to define the different economies for the purposes of the study: 0–1 km, 0–50 km and 0–100 km. These areas were further divided by perpendicular lines extending northward from the lakeshore to reflect the fact that Lake Erie itself is divided into western, central and eastern ecological basins (Fig. 1). These areas were also used as the basis for obtaining special tabulations of demographic and economic statistics from Statistics Canada required for input into the costing models.

2.3. Defining HNAB control scenarios

Three scenarios for controlling HNABs through the control of P loadings were used to estimate the impacts of policy measures to preserve the lake's EGS: i) a "stable lake" scenario – where the conditions of the lake were assumed not to deteriorate or improve beyond the "current" state of affairs, using 2015 as the base-year[1] ; ii) a "business-as-usual" scenario – where no policy measures to control P loadings are taken and the lake gradually worsens over time to eventually reach a stable, significantly degraded state in 2030; and iii) a "policy intervention" scenario – where policy measures to control P loadings are assumed to be taken beginning in 2020, with the lake continuing to worsen until then, followed by gradual improvements afterward to reach a stable and substantially improved state by 2025 for cHABs and 2030 for *Cladophora*. Note that specific policy measures were not considered in this study; the control scenarios simply assumed that such measures (*e.g.*, farmers adopting new management practices for P) were either taken, or not, and the lake's quality either improved, or worsened, as a result. The ecological conditions of the lake under the three scenarios were defined by extrapolation from the baseline conditions (Higgins et al., 2005a,b; Depew et al., 2011; Wynne and Stumpf, 2015), as discussed next.

2.4. Projecting HNAB intensities

As noted above, Lake Erie is split into three ecologically distinct basins and the types of blooms that affect each basin differ. The western and, to a lesser extent, central basins are affected by cHABs dominated by species of *Microcystis*, *Dolichospermum* and *Aphanizomenon*. The eastern basin, in contrast, has few cHABs but is severely impacted by the filamentous algae *Cladophora*.

The baseline ecological conditions of cHABs on Lake Erie were defined using a satellite assessment of blooms conducted by the U.S. National Oceanic and Atmospheric Administration (NOAA) for harmful blooms (Wynne and Stumpf, 2015). The definition of baseline conditions for nuisance algae (*Cladophora*) was more difficult due to a lack of suitable data.

[1] It should be noted that the stable lake scenario is not considered ecologically plausible. It was included in the study to provide a basis of comparison for the other two scenarios, both of which reflect plausible future paths for the lake.

2.5. Projecting cHAB intensities

NOAA has tracked cHABs in Lake Erie, which are dominated by *Microcystis,* on an approximately weekly basis using satellite imagery since 2009. Data from the resulting NOAA database were used to project cHABs over the study's 30-year timeframe. Data on the areal coverage and intensity of cHABs in each of the lake's three basins for each 10-day period during the bloom season (June–October) for the years 2009 to 2014 were obtained with the permission of the NOAA scientific authority (R. Stumpf, personal communication). These years reflect the full variation seen in blooms in recent years and were, therefore, taken as representative of the baseline (2015) conditions of blooms on the lake. The minimum, maximum and average bloom conditions seen during this period were calculated using NOAA data.

The 10-day *minima* and *maxima* seen between 2009 and 2014 were used as the end-points for, respectively, the policy intervention and business-as-usual control scenarios. In other words, the best conditions seen between 2009 and 2014 for any given 10-day period in the bloom season were taken as the best conditions that could be assumed achievable, on average, for that same 10-day period with policy interventions to control P loadings to the lake (that is, under the policy intervention scenario). Likewise, the worst conditions seen between 2009 and 2014 (a timeframe that included the record-breaking 2011 *Microcystis* bloom) were taken to be the worst conditions, on average, that would exist on the lake if no actions were taken to control P (that is, under the business-as-usual scenario). Using these assumptions, baseline conditions data were projected to create a 30-year time series of cHAB extent and concentrations on the lake under the two control scenarios.

A 30-year cHAB bloom intensity index series (2015–2045) was then developed summarizing the data on bloom extent and concentration into an index from 0 (no bloom) to 1 (full coverage of high-intensity bloom) for each 10-day period and basin. This index was then related to step changes in the well-known Resources for the Future water quality ladder (WQL) (Vaughan, 1986; Fig. 3), with 0 in the index corresponding to 0 on the WQL and 1 in the index corresponding to 10 on the WQL. The index, so linked with the WQL, became the basis for assuming changes in the flows of EGS from Lake Erie. Linking the index to the WQL allowed for use of the results of a model of household willingness to pay for freshwater EGS (such as recreation) developed by Johnston and Thomassin (2010).

2.6. Projecting *Cladophora* intensities

The process for defining baseline conditions was based on the authors' own research experience with *Cladophora*, static maps of submerged aquatic vegetation and anecdotal assessments for nuisance blooms (G. Hudgin, personal communication).

The approach to projecting the intensity of *Cladophora* blooms

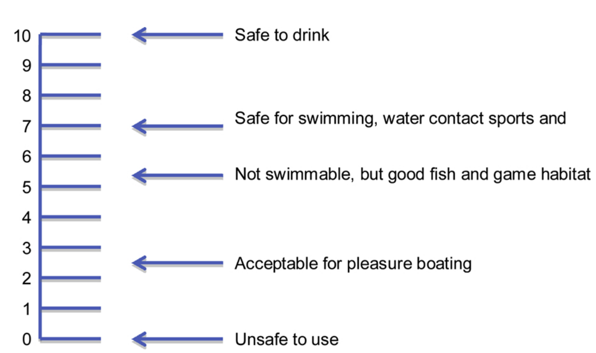

Fig. 3. The Resources for the Future Water Quality Ladder. This illustrates the step changes in water quality that were used in the economic assessment. Source: Adapted from Vaughan (1986).

differed considerably from that for cHABs because of data limitations, differences in the drivers of *Cladophora* blooms and the fact that *Cladophora* is a concern mainly in the lake's eastern basin.

A baseline map of the extent and intensity of *Cladophora* in submerged aquatic vegetation in the Great Lakes was obtained from Michigan Tech Research Institute (2019). The map was built from an aggregation of satellite imagery from 2010 and 2011. Based on evidence from this map and other studies (Higgins et al., 2005b; Depew et al., 2011), *Cladophora* was taken to have colonized most of the hard substrate in the eastern basin by 2015. It was further assumed that this level of colonization was sufficient to considerably impair recreational service flows in the basin due to wash-up of *Cladophora* mats on beaches. Since production of *Cladophora* is limited by P and light availability (Higgins et al., 2005a,b), it was also assumed that the increased P loading to the eastern basin would worsen the impairment in the business-as-usual scenario. Although increased turbidity associated with increased P loading from non-point sources will likely increase the light limitation status of *Cladophora*, possibly leading to reductions in the area of substrate colonized (*e.g.*, Valipour et al., 2016), a relaxation of P limitation would likely result in multiple cohorts of *Cladophora* production, leading to an increase in shore fouling.

Although studies and models exist relating *Cladophora* growth to inputs of P and other growth factors (Auer and Canale, 1982; Parker and Maberly, 2000; Higgins, 2005; Malkin et al., 2008), predicting future levels of *Cladophora* remains an area of research beyond the scope of this study. Instead, authors' assumptions based on direct knowledge and discussions with a regional environmental health manager (G. Hudgin, personal communication) regarding the current extent of *Cladophora* and its likely evolution were used to project the intensity of *Cladophora* blooms over the study's 30-year timeframe.

A *Cladophora* bloom intensity index similar to the cHAB index described above was created based on assumed levels of impairment to flows of EGS in the eastern basin now and in the future. This index was tied to the WQL in the same manner as described above for the cHAB index.

The starting point for the *Cladophora* index was to assume that: i) 50% of days are unsuitable for swimming on eastern basin beaches under baseline (2015) conditions due to wash-up of *Cladophora*; ii) other recreational uses[2] are also impaired but at lower levels[3] ; iii) if the lake worsens (business-as-usual scenario), swimming will no longer be possible on eastern basin beaches affected by *Cladophora* by 2030 and other activities will fall to levels where they are only possible about half of the time[4] and iv) if actions are taken to control P, wash-up becomes less of a problem (policy intervention scenario) and all recreational activities become possible most of the time 10 years after the actions are commenced.[5]

The baseline *Cladophora* index was derived by multiplying the number of recreationists[6] undertaking each recreational activity in the

[2] Sport fishing, boating, wildlife viewing and sport hunting.

[3] Specifically, under baseline conditions, 10% of days were assumed to be unsuitable for sport fishing, boating and hunting and 25% of days were assumed to be unsuitable for birding. The greater share of days assumed impaired for birding reflects the assumption that aesthetic conditions of the lake's nearshore area have a greater impact on birdwatchers than on fishers, boaters and hunters.

[4] Specifically, 50% of days are assumed to be unsuitable for fishing, boating and birdwatching and 25% of days for hunting under business-as-usual conditions by 2030. Hunters' utility is assumed to be the least sensitive to losses from *Cladophora* fouling because their experience is assumed to less sensitive to aesthetic factors and because, unlike boating and fishing, hunting does not necessarily involve direct contact with fouled waters.

[5] Specifically, 10% of days were assumed to be unsuitable for swimming and 5% of days for other activities by 2030 under the policy intervention scenario.

[6] Estimated by multiplying the population living within 50 km of the eastern basin shoreline by the proportion of the population undertaking each activity as reported in the *Canadian Nature Survey* (Federal, Provincial and Territorial Governments of Canada, 2014).

Table 5
Summary of key control-scenario time periods.
Source: Current study.

Scenario	Base-year	Management of P loadings begins	Period while lake is worsening	Period while lake is improving	Period while lake is stable and condition relative to base-year
Business-as-usual	2015	n/a	2016–2029	n/a	2030–2045 Degraded relative to base year
Policy intervention	2015	2020	2016–2020	2021–2025 for cHABs 2021–2030 for Cladophora	2026–2045 for cHABS 2031–2045 for Cladophora Improved relative to base year

eastern basin (normalized from 0 to 1) by the percentage of days assumed to be impaired for that activity and summing across activities, resulting in a baseline index varying from 0 to 1, with 0 implying no impairment for any activity 1 implying full impairment for all activities.

To create the 30-year *Cladophora* index time series required for each of the two bloom control scenarios, it was assumed that the eastern basin would require 15 years to reach its fully impaired end-point under the business-as-usual scenario and 10 years to reach its less-impaired end-point under the policy intervention scenario (with policy interventions assumed to begin in 2020). The baseline index values were used as the starting point for the two *Cladophora* index time series, with the normalized shares of the recreationists undertaking each activity assumed not to change over time and the degree of impairment assumed to evolve linearly to their assumed endpoints in each scenario over the time frames just noted.

These time frames – 15 years to full impairment and 10 years to improvement – are consistent with observations of *Cladophora* response to changes in P loadings from wastewater treatment plant discharges (Neil and Jackson, 1982; Painter and McCabe, 1987; Parker and Maberly, 2000). It is recognized that *Cladophora* may respond more slowly to changes in P loadings from diffuse sources, however, so these time frames may be optimistic. A linear extrapolation was used to estimate annual changes in the index between the baseline conditions and the end-points. Table 5 summarizes the key time periods in the two control scenarios.

3. Approach to estimating the costs of HNABs

The approach to estimating the economic costs of the differing control scenarios was conceptually straightforward, though considerable challenges were met in its implementation due to data shortcomings. The approach was based on estimating incremental economic costs, consistent with cost-benefit analysis, or more generally, welfare economics. The analysis included the value of non-market EGS such as general environmental quality and recreational experiences. Consistent with standard cost-benefit analysis, inflation was not considered in the analysis and a real (that is, inflation-adjusted) discount rate was used to express all costs in present values. Estimates of economic impacts on beneficiaries not directly affected by HNABs were not considered in the study.

The EGS impacted under each control scenario were defined using the authors' assessment of the relationship between algal blooms and flows of EGS. In keeping with a welfare economics approach, all flows were considered rather than just those observable in the market.

A simple model of the Lake Erie basin economy was developed to project changes in the value of EGS over time under the different scenarios based on assumptions about baseline economic activity and growth. Damage functions – mathematical relationships describing the damage to an ecological good or service caused by HNABs – were embedded within this model to estimate the costs associated with algal bloom scenarios. All key variables were structured as probability density functions and built into an uncertainty analysis using Monte Carlo techniques. Generally, variables whose values were allowed to vary in the Monte Carlo analysis were assumed to be normally distributed, though Poisson distributions were used where observed *minima* and *maxima* suggested data were skewed around the mean. For constants (such as the discount rate), a variance of 30% on either side of the value was used.

The application of the costing approach varied between cost categories (Table 4). Given the scarcity of data relating to HNABs and their costs, considerable reliance on authors' judgement could not be avoided in defining parameters in some categories (*e.g.*, assumed losses for commercial fishing at various points on the WQL). That this introduces a degree of arbitrariness to some estimates is acknowledged. The study team was intentionally built from a combination of economists and ecologists – the former with many years of combined experience valuing EGS and the latter with many years of combined experienced studying Lake Erie HNABs – and its decisions were taken collaboratively in order to mitigate the impact of this arbitrariness on the study's results.

Considerable use was made of the Johnston and Thomassin (2010) model of household willingness to pay for freshwater EGS. This is a generic "benefits-transfer" model summarizing the results of a meta-analysis of several dozen studies designed to elicit how Canadians and Americans value changes in freshwater quality in specific settings. Benefits transfer refers to the fact that the model transfers findings (that is, "benefits") from sites similar to but not necessarily the same as the study site (in this case, Lake Erie).[7] This obviously introduces a degree of inaccuracy in the results, as benefits accruing at one site will not necessarily accrue similarly at other sites. Johnston and Thomassin's approach of analyzing the results of a range of studies moderates this loss of accuracy to some extent (though it should be noted that only two of the studies analyzed were Canadian, limiting the degree to which their meta-analysis reduces the inaccuracies of benefits transfer in the Canadian context).

Johnston and Thomassin's model may be used to estimate willingness-to-pay separately for recreational users and "non-users" (that is, those who value a site's existence even if they do not use it) for changes in water quality for a variety of different site types, including freshwater lakes. A number of location-specific "toggle" variables in the model allowed construction of estimates that were oriented to Lake Erie and the water quality changes predicted by the cHAB and *Cladophora* intensity indexes used in this study. The model was further localized for use here using household income data specific to each Lake Erie basin obtained on request from Statistics Canada and changes from baseline water quality measured by the cHAB and *Cladophora* intensity indexes. Table 6 shows the baseline willingness-to-pay values derived from the Johnston and Thomassin model for use in this study.

A Monte Carlo analysis was used to frame the uncertainty around the cost estimates. Key variables, defined using probability density functions, included the discount rate, the bloom intensity indexes, population forecasts, income forecasts and willingness to pay for changes in water quality. The uncertainties around these variables were accounted for by the Monte Carlo simulation (10,000 iterations for each

[7] Findings are referred to as "benefits" because it is often (though not always) the case in the valuation of EGS that the benefits of those goods and services are of interest. In the present case, it is not the benefits, but the costs of losing those benefits, that is of interest.

Table 6
Per-household willingness-to-pay for baseline water quality, by type of user and basin.
Source: Authors' estimates based on Johnston and Thomassin, 2010.

	Willingness-to-pay for beach, boating, and birdwatching	Willingness-to-pay for hunting and fishing	Willingness-to-pay, non-users
Western	11.70	14.80	35.84
Central	28.99	32.20	50.29
Eastern	8.38	10.60	35.84

model run) using the simulation mean and the 20th and 80th percentiles. All costs were calculated as 30-year NPV of the stream of future costs estimated for each scenario.

3.1. Loss in commercial fishing value added

Though no evidence that commercial fishing was impacted by the baseline bloom levels was found, it was assumed that future increases in the frequency and intensity of HNABs would result in reductions in fish catches and also, therefore, the value added of the commercial fishing industry (value added is the industry-level equivalent of gross domestic product). Value added represents the returns to the human capital (fishers), produced capital (*e.g.*, fishing boats) and natural capital (the lake's stocks of commercially important fish stocks) employed in the industry. More specifically, it represents the income that flows to the owners of these capital stocks: fishers (wages), boat-owners (profits) and the government (license fees; quota payments)[8] . In welfare economic terms, this income represents the benefit associated with commercial fishing and any loss in income due to HNABs can, thus, be seen to be the (welfare) economic cost imposed on the owners of these capital stocks.

The WQL was used to link assumed changes in commercial fishing value added in the basin to changes in water quality. Table 7 shows the losses in value added assumed to occur at different steps in the WQL. In the absence of evidence on which to base these losses, they were established according to the authors' judgement. The factors considered in establishing them are discussed further in Section 4.2.5.

Formally, the 30-year NPV of the change in annual commercial fishing value added is estimated as follows:

$$\Delta VA^{CF} = \sum_{b=1}^{3}\sum_{n=1}^{30}\frac{(VA^{CF}_{b,0}(1+\rho)^n(LF_{b,n})}{(1+i)^n}$$

where,

ΔVA^{CF} is the change in the 30-year NPV of the annual changes in Lake Erie commercial fishing value added

$VA^{CF}_{b,0}$ is the base-year value of commercial fishing value added in Lake Erie basin b (western, central, eastern) as reported in Table 8

ρ is a constant representing annual commercial fishery value added growth derived from historical value added data for the industry as published by Statistics Canada (2019) and adapted for use here[9]

n is time (from year 1–30)

$LF_{b,n}$ is a factor representing the loss in value added (in percent) in basin b and year n derived by linking the HNAB intensity index for basin b and year n with the assumed value added losses reported in Table 7, and

i is the discount rate.

Table 7
Assumed relation between WQL step changes and commercial fishing value added losses.
Source: Current study.

Change in WQL value	Assumed loss in value added (%)
7.0 to 5.4	0
< 5.4 to 4.3	20
< 4.3 to 2.5	30
< 2.5	50

3.2. Increased capital and operating costs for water consumers

Increased capital and operating costs were considered for the following categories of water consumers: farms, manufacturing plants, golf courses and municipal/private drinking water treatment plants. The names of the facilities operating in these industries that were active users of lake water in 2015 were obtained the Ontario Ministry of the Environment and Climate Change (2019) *Permit to Take Water Database*.[10] Of these users, costs imposed by HNABs were found to be material only for municipal drinking water treatment plants and manufacturing plants.

For municipal drinking water treatment plants, evidence gathered through a survey of plant operators indicated that increased operating and capital costs due to HNABs had already been seen by 2015 and that these costs would increase if blooms were to worsen in the future (Section 4.2.6 discusses this further). Consistent with benefit-cost analysis, the increased capital costs up to 2015 were considered sunk and not further considered. The increased operating costs in 2015 were taken as the baseline costs imposed by HNABs.

Table 9 presents the baseline HNAB-related costs and the incremental costs (operating and capital) assumed to be triggered for drinking water treatment plants if blooms worsen. The costs are based

[8] The flow of income to natural capital is referred to by economists as resource rent. In Canada, ownership of most *in situ* natural resources rests with the Crown (represented usually by a provincial government). Governments, as the resource owners, have the legal right to collect resource rent, which they do through various means: royalty payments, resource extraction fees, license fees and so on. It is often the case, however, that governments do not collect all possible resource rent, choosing to leave some to resource extractors (businesses) to encourage them to enter what can be a risky part of the economy. In other cases, there is little or no rent to collect, as unrestricted entry into common property resource exploitation drives resource prices to the point where extractors earn a return only just sufficient to keep them from deploying their labor and capital elsewhere; any effort to collect rent from them would result in their abandonment of the industry. This is known as rent dissipation and it is common in many fisheries around the world. Whether rent is dissipated in the Lake Erie commercial fishery is not known, but even if it were this would not affect the results of this study. Returns to labor and produced capital are clearly positive in the industry and, therefore, HNABs can have welfare impacts by reducing those incomes. A useful introduction to the concept of resource rent and its implications for economic and natural resource policy in Canada is found in Anderson (1985).

[9] Value added of the Lake Erie commercial fishery was estimated by multiplying Statistics Canada's estimated total value added for the fishing, hunting and trapping industry in the province of Ontario by the Lake Erie share of Ontario's commercial fish catch (Great Lakes Fishery Committee, 2019). Any contribution of commercial hunting and trapping to this value added was considered small enough to be ignored, as these activities are not widely pursued in the province.

[10] Companies or organizations extracting more than 50 m^3 of water per day from the lake must, with a few exceptions, obtain a permit from the Ministry and are listed in this database. All agricultural, manufacturing, commercial and municipal users of lake water were assumed to require at least 50 m^3/day and, therefore, to be found in this database.

Table 8
Baseline commercial fishing value added, by basin.
Source: Current study.

	Lower bound	Central estimate	Upper bound million 2015 dollars
Western	6.10	6.47	6.83
Central	11.65	12.35	13.06
Eastern	0.95	1.00	1.06

on data collected through the survey of plant operators noted above. They are broken into costs that are considered fixed (that is, independent of plant size) and those that are considered to vary with plant size. Operating costs are found in both the fixed and variable categories; capital costs are only variable.

To estimate the 30-year NPV of costs imposed on the plants by HNABs, it was assumed that the baseline fixed and variable operating costs would continue until conditions on the lake, as measured by the cHAB and *Cladophora* intensity indexes, fell to 5.4 on the WQL (*not swimmable but good habitat for fish and wildlife*). This decline triggers the incremental fixed operating and incremental variable operating and capital costs reported in Table 9 are triggered. Once triggered, the additional operating costs are assumed to continue until water quality improves or, if it does not, until the end of the study period. Capital expenditures are only triggered once, on the assumption that the assets in question will have lifetimes of several decades.

Formally, the 30-year NPV of increased costs due to HNABs for drinking water treatment plants is estimated as follows:[11]

$$\Delta C^{DWPT}_{west,\,central} = \sum_{p=1}^{3}\sum_{n=1}^{30}\frac{(FC_0^{w,c} + FC_n^{w,c}) + (VC_0^{(op)w,c} + VC_n^{(op)w,c})(DC_p) + (VC_n^{(cap)w,c})(DC_p)}{(1+i)^n}$$

$$\Delta C^{DWPT}_{east} = \sum_{p=1}^{9}\sum_{n=1}^{30}\frac{(FC_0^{e} + FC_n^{e}) + (VC_0^{(op)e} + VC_n^{(op)e})(DC_p) + (VC_n^{(cap)e})(DC_p)}{(1+i)^n}$$

where,

$\Delta C^{DWPT}_{west,\,central}$ is the change in the 30-year NPV of increased costs due to HNABs for drinking water treatment plants in the western and central basins

ΔC^{DWPT}_{east} is the change in the 30-year NPV of increased costs due to *Cladophora* for drinking water treatment plants in the eastern basin

$FC_0^{w,c}$ is the baseline fixed operating costs due to HNABs for plants in the western and central basins and FC_0^{e} is the same thing for the eastern basin (Table 9)

$FC_n^{w,c}$ is the fixed operating costs due to HNABs for plants in the western and central basins in year n

FC_n^{e} is the fixed operating costs due to *Cladophora* for plants in the eastern basin (Table 9)

$VC_0^{(op)w,c}$ is the baseline variable operating costs due to HNABs for plants in the western and central basins and $VC_0^{(op)e}$ is the same thing for the eastern basin (Table 9)

$VC_n^{(op)w,c}$ is the variable operating costs due to HNABs for plants in the western and central basins in year n and $VC_n^{(op)e}$ is the same thing for the eastern basin (Table 9)

DC_p is a factor (plant design capacity) used to scale variable costs for drinking water treatment plant p

$(VC_n^{(cap)w,c}$ is the variable capital costs due to HNABs for plants in the western and central basins in year n and $(VC_n^{(cap)e}$ is the same thing for the eastern basin (Table 9)

n is time (from year 1–30), and

i is the discount rate.

For manufacturing facilities (two small food processing plants), estimates of increased operating costs under the control scenarios were obtained directly through telephone interviews with plant operators. A 30-year time series of these costs, which were provided by the operators under the provision they would be kept confidential, was discounted to a present value for inclusion in this study.

3.3. Loss in household utility from recreation

Lake Erie is the site for a range of recreational activities that algal blooms have the potential to negatively impact; including, boating, fishing, swimming, hunting and wildlife viewing. At the core of these activities is enjoyment of the experience, which is strongly related to environmental quality; specifically, in the case of this study, to the presence of HNABs on Lake Erie.

HNABs can impact the enjoyment of these activities in a variety of ways. Beach goers, boaters, sport fishers and hunters in the western and central basins, where *Microcystis* blooms are the main concern, may see the quality of their experiences lowered because of the unsightliness of the blooms (which colour the water a murky green), the odour and worry over the possible health consequences of exposure to cyanobacterial toxins, either by direct contact while swimming, waterskiing, *etc.* or by ingestion through consumption of contaminated water, sport fish or waterfowl.[12] Wildlife viewers may have little to worry about in terms of toxin exposure but could still see the quality of their experiences lowered by the unsightliness of the blooms.

In the eastern basin, where *Cladophora* is the main concern, toxin exposure is not an issue (though rotting masses of *Cladophora* can harbour pathogenic bacteria[13]). However, the impact of *Cladophora* on the aesthetic value of recreational experiences is, arguably, worse than that of *Microcystis.* Not only are *Cladophora* mats unsightly when they wash up on beaches, but they are also foul smelling and unpleasant to walk through. An environmental health manager consulted for this study (G. Hudgin, personal communication) related that his staff sometimes have difficulty launching their small survey boats from the beach because of the thickness of the floating mats.

The approach used to value changes in the flows of the lake's recreational services was based on the Johnston and Thomassin model (see above). More specifically, the 30-year NPV of losses in utility due to reduced recreational service flows was estimated as follows:

$$\Delta U^{rec} = \sum_{n=1}^{30}\frac{(-1)\left(\sum_{b=1}^{3}\sum_{j=1}^{5}(WTP_{bj}^{rec})(p_{bj})(hh_b)\right)}{(1+i)^n}$$

where,

ΔU^{rec} = the 30-year NPV of losses in recreational user utility in the Lake Erie basin economy due to HNABs

WTP_{bj}^{rec} is recreational-user willingness to pay for recreational activity j (beach going; boating; sport fishing; wildlife viewing and hunting) for discrete water quality improvements by households within 50 km of the shoreline in Lake Erie basin b (Fig. 1) based on the Johnston and Thomassin model (see Table 6 for the baseline levels of this willingness-to-pay)

p_{bj} is the participation rate of households living within 50 km of the basin b shoreline in recreational activity j (beach going; boating; sport fishing; wildlife viewing and hunting) based on data from the *Canadian Nature Survey* (Federal, Provincial and Territorial Governments of

[11] For simplicity of presentation, the distinction between large and medium plants in the western and central basin found in the data in Table 9 is not reflected in these equations.

[12] Relatively few studies have been done to determine the degree to which the liver toxin microcystin accumulates in fish tissue and the conclusions of existing studies are somewhat conflicting. Some conclude the risk to human health from consumption of contaminated fish is low (Adamovsky et al., 2007; Dyble et al., 2011) while others suggest that it may be serious (Freitas de Magalhaes et al., 2001; Papadimitriou et al., 2009; Poste et al., 2011).

[13] For example, the bacteria *Shigella*, known to cause digestive tract illness, may be found in *Cladophora* mats in the Great Lakes (Ishii et al., 2006).

Table 9
Fixed and variable HNAB-related water treatment plant costs, by basin and plant size.
Source: Authors' estimates based on data collected by survey from water treatment plant operators.

	Western and central basins		Eastern Basin
	Large plants (> 111,200 m^3/day)	Medium plants (< 111,200 m^3/day)	
	Fixed HNAB-related costs[a] (dollars per plant)		
Baseline annual fixed operating costs imposed by HNABs	6000	6355	6,710
Incremental annual fixed operating costs triggered if HNABs worsen beyond baseline conditions	3600	3620	3,640
	Variable HNAB-related costs[b] (dollars per m^3 of rated plant capacity)		
Baseline annual variable operating costs imposed by HNABs	0.44	8.99	17.54
Incremental annual variable operating costs triggered if HNABs worsen beyond baseline conditions	1.44	2.51	3.57
Incremental variable capital costs triggered if HNABs worsen beyond baseline costs	32	33	32.89

[a] Fixed costs are those for monitoring water quality and additional cleaning of intake pipes related to HNABs.
[b] Variable costs are those for treating raw water related to HNABs.

Canada, 2014)

hh_b is the number of households living within 50 km of the Lake Erie basin b shoreline based on data obtained on request from Statistics Canada

n is time (from year 1–30), and

i is the discount rate.

It should be noted that Johnston and Thomassin's model allows estimation of household willingness to pay for *improvements* in water quality. This willingness to pay can, in turn, be taken to reflect the utility (welfare) that households derive from such improvements on the presumption that they would not pay for them otherwise. Since this study required an estimate of the loss in utility associated with *declines* in water quality due to HNABs, the assumption was made that the negative of willingness to pay estimated according to Johnston and Thomassin's model was a reasonable estimate of utility losses.

3.4. Loss in utility for non-user households

Utility losses associated with HNABs can be experienced even by individuals who do not use Lake Erie directly but derive well-being from the lake nonetheless. Lake Erie is part of an ecosystem of globally recognized significance – the Laurentian Great Lakes - the largest body of freshwater in the world. Like all of the Great Lakes, it is a source of inspiration, recreation and discovery for millions of people. The lake has played an important role in the heritage of many cultures, shaping historical settlement and development patterns long before and after the arrival of Europeans in North America. The lake's name and the names of many cities, counties, tributaries and landmarks along its shore have Native American or immigrant origins. Its moderating effect on the local climate influences human culture, outdoor activities, agriculture and the health of adjacent ecosystems.

The literature demonstrating that individuals experience losses in utility when features of the natural environment they care about are degraded is large (see, for example, Ferrer-i-Carbonell and Gowdy, 2007; Grinde and Patil, 2009; Ferreira et al., 2013; Ambrey et al., 2014; Tsurumi et al., 2018). That such losses would occur is perhaps obvious when the individual interacts with directly with the natural feature in question. It occurs, however, even in cases where the individual does not directly use the feature and may never intend to. The simple knowledge that something of value is threatened is enough to cause a loss in utility for many non-users. Evidence that these losses are real is demonstrated by the expressed willingness of non-users to pay for initiatives to improve the quality of a degraded environment. Given this, the effects of HNABs on Lake Erie would certainly fall into the category of environmental degradation that would be expected to lead to utility losses for non-users. The model developed by Johnston and Thomassin was used to estimate the loss of utility for non-users.

Similarly to recreational utility losses, the 30-year NPV of losses in non-user utility due to reduced cultural service flows was estimated as follows:

$$\Delta U^{non} = \sum_{n=1}^{30} \frac{(-1)(\sum_{b=1}^{3} (WTP_b^{non})(hh_b))}{(1+i)^n}$$

where,

ΔU^{non} = the 30-year NPV of losses in non-user utility in the Lake Erie basin economy due to HNABs

WTP_b^{non} is non-user willingness to pay for discrete water quality improvements by households within 50 km of the shoreline of Lake Erie basin b (Fig. 1) based on the Johnston and Thomassin model (see Table 6 for the baseline levels of this willingness-to-pay), and

hh_b is the number of households living within 50 km of the Lake Erie basin b shoreline based on data obtained on request from Statistics Canada

n is time (from year 1–30), and

i is the discount rate.

As discussed in Section 4, non-user utility losses found following the above approach are quite large in all control scenarios.

3.5. Lost tourism value added

Lake Erie is a popular tourist destination for those who live locally and for visitors from further afield. The lake is known for its sandy beaches and warm water, its world-class sport fisheries and its proximity to other popular tourist destinations, including Niagara Falls. For all of these reasons, the lake helps support a large local tourism industry.

To determine the portion of Ontario's tourism value added attributable to the Lake Erie basin economy, it was assumed that all tourism activities in the 0–50 km buffer around the lakeshore constituted the "Lake Erie basin tourism industry". It was further assumed that tourism value added is directly proportional to tourism employment, which allowed use of employment data for the 0–50 km buffer around each of Lake Erie's three basins (obtained on request from Statistics Canada) to allocate total tourism value added for the province of Ontario to Lake Erie. To do this, total 2011 tourism employment in each Lake Erie basin (within the 50 km buffer) was divided by Statistics Canada's estimate of tourism employment at the provincial level (Statistics Canada, 2014). Multiplying this share by 2012 tourism value added for Ontario (Ontario Ministry of Tourism, Culture and Sport, 2019) provided a reasonable estimate of 2012 tourism value added for each Lake Erie basin. Using this method, tourism added value in the Lake Erie basin economy was estimated to be about $2.7 billion in 2012, or 20% of Ontario's 2012 tourism value added of $12.2 billion.

To create the 30-year (2015–2045) time series of tourism value added required for the study, 2012 tourism value added in each basin was assumed to grow at the same annual rate as tourism employment in the basin grew between 2001 and 2011 in the 0–50 km buffer. Employment data were obtained on request from Statistics Canada.

To model the possible future impacts on tourism, it was assumed that if conditions on the lake worsen to the point where the cHAB and *Cladophora* intensity indexes reach values equivalent to 5.4 on the WQL (not swimmable but good habitat for fish and wildlife) and 4.3 (habitat suitable for some fish and wildlife) respectively, the annual value added of the tourism industry would decline by 1%. Further declines to the subsequent levels in the WQL lead first to an additional loss of 2% of value added, for a total of 3%, and finally to an additional 2% loss for a total annual value-added loss of 5% under the worst conditions assumed for this study. Thus, at worst, it is assumed that 95% of current Canadian Lake Erie basin tourism value added is maintained in all control scenarios. In other words, even if Lake Erie were degraded by algal blooms to the point where it would support next to no recreational activity, the assumed impact on tourism was assumed to be small. While arguably not realistic and subject to considerable uncertainty, this conservative approach was intentionally chosen to ensure the resulting estimates did not overstate the impact of HNABs on tourism. Nonetheless, the estimated costs to tourism were the largest of the cost categories studied.

3.6. Loss of wealth for property owners

Many studies have shown that the value of property located along water bodies is influenced by the quality of the adjacent water body. Clean water is more aesthetically pleasing than contaminated water and waterfront property has significantly greater value with increased quality (Krysel et al., 2003; Dodds et al., 2009). Waterfront properties in the United Kingdom, for example, have been found to be worth 10–40% more than equivalent non-waterfront properties (Wood and Handley, 1999). These effects have been found to apply at distances of up to 1.2 km from the shoreline (Dornbusch et al., 1973), but generally fall off quickly with distance from the shoreline.

Many people live along the Canadian shore of Lake Erie, some only on a seasonal basis (cottagers) and others year-round. According to data obtained on request from Statistics Canada, some 24,270 residential properties are found within 1 km of the lake's Canadian shoreline, with an average value of $242,000 in 2011 (Table 10). It was assumed therefore that the values of all these properties are influenced to the same extent by the presence of HNABs. The values of properties further than 1 km from the shoreline were assumed not to be affected by HNABs.

Though the literature on the relationship between housing values and environmental quality is large, there is little information available discussing the link between housing value and HNABs specifically. One study (Ara et al., 2006) dealing with Lake Erie was found, though it focused on fecal coliform counts and Secchi depth disk[14] readings as water quality measures rather than HNABs.

In the absence of evidence to guide estimation of the loss in property value with 1 km of the lakeshore due to HNABs, conservative assumptions were made about the loss in value associated with each step change in the WQL. When the cHAB and *Cladophora* intensity indexes reach levels equivalent to 5.4 on the WQL (*not swimmable but good habitat for fish and wildlife*), a 2% loss in property values is assumed. Further declines to 4.3 (*satisfactory habitat for some fish and wildlife*) and 2.5 (*suitable only for boating*) on the WQ lead to additional 2% losses in property value, for a total loss of 6% under the worst conditions

[14] Secchi depth is a measure of water clarity. It is likely correlated with the presence of algal blooms on Lake Erie but there are a number of other factors that affect Secchi depth as well.

Table 10
Number and baseline value of dwellings within 1 km of the Lake Erie shoreline. Source: Statistics Canada.

Basin	Number of Housing Properties	Average Value of Housing Properties (thousand 2011 dollars)	Total value of Housing Properties (million 2011 dollars)
Western	6,680	243	1624
Central	3,575	233	835
Eastern	14,015	244	3417
Total	**24,270**	**242**	5875

Note: Totals may not equal sum of their parts due to rounding.

foreseen.

Given the significant impacts of HNABs on Lake Erie's water quality and ample evidence of links between water quality and property values, these are considered to be conservative assumptions that likely underestimate the influence of HNABs on Lake Erie property values.

3.7. Human health costs

Considering data from both Canada and the U.S., little evidence of human morbidity and no evidence of mortality due to cyanobacterial toxins on Lake Erie was found. In the State of Ohio, there were two probable and seven suspected cases of illness associated with Lake Erie HNABs in 2010 and no cases of any sort in either 2011 or 2012. No other state reported any cases during this period (Carmichael and Boyer, 2016) and no more recent data were available. Given the much larger population on the U.S. side of the lake, the number of illnesses, if any, on the Canadian side is likely to be very small. Commensurate with this, no known cases of morbidity have been publicly reported in Ontario (R. Copes, personal communication). For this reason, human health costs were assumed to be negligible for the purposes of the study.

4. Results

4.1. Total costs of algal blooms

HNABs are likely to impose substantial costs on the Lake Erie basin economy over the next 30 years under the business-as-usual scenario. A sizeable share of these costs could be avoided if policy actions were taken to control P loadings to the lake (Table 11). The central estimate of the 30-year NPV of total economic costs under the business-as-usual scenario is $5324 million, or $2850 million more than the central estimate of the costs under the policy intervention scenario. If the upper and lower bound estimates are used instead of the central estimates to calculate the difference between the business-as usual and policy intervention scenario costs, the difference could be as great as $4169 million ($5824 million less $1655 million) or as small as $1294 million ($4076 million less $2782 million).

An alternative approach to expressing the results is in terms of equivalent annual costs. This permits comparison of uneven streams of future costs by expressing them in terms of the constant-value streams that yield NPVs identical to those of the uneven cost streams. The equivalent annual cost of the business-as-usual scenario is found to be $272 million, or $145 million more than equivalent annual cost of the policy intervention scenario (Table 12). If the upper and lower bound estimates are used instead of the central estimates to determine the difference between the business-as usual and policy intervention scenario costs, this difference could be as great as $213 million ($297 million less $84 million) or as small as $66 million ($208 million less $142 million).

When compared with the results of the studies mentioned earlier, the findings here appear reasonable, bearing in mind that direct comparisons are not possible. Dodds et al. (2009) reported annual costs for

Table 11
Estimated economic costs of HNABs on the Lake Erie basin economy – 30-year NPV (3% discount rate).
Source: Current study.

Scenario	Lower bound	Central estimate	Upper bound
	million 2015 dollars		
Stable lake	1680	2788	3206
Business-as-usual scenario	4076	5324	5824
Policy intervention scenario	1655	2474	2782

Table 12
Estimated economic costs of HNABs on the Lake Erie basin economy – Equivalent annual cost.
Source: Current study.

Scenario	Lower bound	Central Estimate million 2015 dollars	Upper bound
Stable lake	86	142	164
Business-as-usual	208	272	297
Policy intervention	84	126	142

eutrophication in all U.S. freshwater systems of $1.5 billion to $4.8 billion (U.S. dollars[15]) (Table 1). This would be 7–20 times the upper bound of the equivalent annual costs of losses in the Canadian Lake Erie basin economy found here, taking exchange rates into consideration. Such a multiple would be expected given the difference in scope and economic context for the two studies.

Hoagland and Scatasta (2006), who considered hazardous (but not nuisance) algal blooms in the U.S. and the European Union and focused only on coastal blooms, found annual costs of just $82 million in the U.S. but $813 million in the European Union (2005 U.S. dollars) (Table 2). Hoagland and Scatasta's estimated recreation and tourism cost in the U.S. ($4 million) is particularly low. They note that it relies upon poor information. The estimated recreation and tourism impacts in the European Union ($637 million) are much more consistent with the results of the present study (see Section 4.2.1), as are the overall results for the European Union.

Steffensen's (2008) study of algal bloom management costs in Australian is the least relevant to the findings here, as management costs and costs imposed on users of EGS are very different things. Nonetheless, the fact that Steffensen finds annual management costs on the order of $200 million (1999 Australian dollars) would imply that the annual costs imposed on users must also be of that magnitude, or management actions would not be justified.

4.2. Costs by category

The central cost estimates for each control scenario are presented for each cost category in order of size in Table 13 based on the 30-year NPV for the business-as-usual case and in Table 14 based on equivalent annual cost. The costs imposed on the tourism industry (lost value added) and non-users (lost utility) are, by considerable margins, the largest costs associated with HNABs, regardless of the scenario.

4.2.1. Lost tourism value added

In the case of tourism, little evidence was found of HNAB-related impacts on the Lake Erie basin tourism economy up to 2015. Two studies of the economic impacts of the massive 2011 *Microcystis* bloom on the Ohio economy (Bingham et al., 2015 and International Joint Commission, 2014) both found little evidence of any impact on tourism. Both noted, however, the lack of data available to characterize the impacts, though both suggested that tourism could be impacted in the future if lake conditions were to worsen.

Further evidence that HNABs were not affecting tourism in the years prior to the study period is provided by employment data obtained on request from Statistics Canada. Between 2001 and 2011, tourism employment in the eastern and central basins increased at annual average rates of 2.2% and 2.7% respectively. The corresponding figure for western basin was −3.3%. It is not clear whether the decline in tourism employment in the western basin can be attributed to the increasing severity and frequency of cHABs in the western basin. The eastern basin faced an increasing problem with *Cladophora* blooms during this same period and no evidence of loss of tourism employment was seen there. Still, it is possible that the decline in western basin tourism employment was somehow related to cHABs, a point that deserves further study.

Based on the above evidence, the 2015 tourism impact of HNABs in the Lake Erie basin economy was assumed to be zero but the blooms were found to impose significant costs from 2016 to 2045 in both control scenarios. As noted in Section 3.5, future costs to tourism operators (in terms of reduced annual value added) were assumed to range between 1% and 5% depending on the severity of the bloom. Even these conservative assumptions add up unavoidably to large costs simply because the tourism industry is, itself, so large and because HNABs were projected to surpass the levels at which these losses would be triggered for much of the time in both scenarios. Under the business-as-usual scenario, the 30-year NPV of lost tourism value added is $2165 million (2015 Canadian dollars), or 41% of total scenario costs; under the policy intervention scenario, it is $550 million, or 22% of total costs (Table 13).[16] Given the range of assumptions required to arrive at these estimates, they are considered of below-average quality compared with the overall study results and should be interpreted with caution.

4.2.2. Losses in non-user utility

In the case of non-user loss of utility, all households within 100 km of Lake Erie's shore were assumed to suffer reductions in utility when the lake is degraded. Since some 2.6 million households are found in the area, the total economic cost is significant even if each household experiences only a modest utility loss.

Whichever scenario is considered, the results suggest that non-user households face very large costs. Under the business-as-usual scenario, the 30-year NPV of lost utility for non-users is $1849 million[17], or 35% of total scenario costs; under the policy intervention scenario it is $1357 million, or 55% of total costs (Table 13). This makes non-user utility losses either the highest or second highest (next to tourism) cost category depending on the scenario. The fact that non-user utility losses do not decline much from the business-as-usual to the policy intervention scenario is explained by the fact that 1) the baseline (2015) condition of the lake is assumed to be poor enough to trigger non-user utility losses; 2) the lake spends a number of years in a further degraded or gradually improving state even in the policy intervention scenario (Table 5) and 3) even once stabilized after policy interventions, the lake is not pristine and, therefore, non-user utility losses are assumed to continue despite improvements to the lake's condition.

4.2.3. Lost residential property value

Substantial costs in terms of lost property value are found in all control scenarios. This is in part because baseline conditions on the lake are assumed to be are sufficiently degraded to have an impact on 2015 property values, meaning that costs are imposed in most of the study period. It is also due to the large value of the housing asset that is at

[15] The base-year for the values in Dodds et al. is unclear but it can be assumed to be around 2007 given the publication year of 2009.

[16] As noted earlier, the stable lake scenario is not an ecologically meaningful scenario, so the results for it are not discussed here.

[17] All cost estimates in this section are expressed in 2015 Canadian dollars unless otherwise noted.

Table 13
Estimated economic impacts on the Lake Erie basin economy by category and scenario – 30-year NPV (3% discount rate).
Source: Current study.

Category	Stable Lake	Business-as-usual million 2015 dollars	Policy Intervention
Tourism	785	2165	550
Non-users	1452	1849	1357
Property owners	343	712	348
Recreational users	135	421	112
Commercial fishing	0	93	34
Water users	73	84	74
Human health	*Not measurable (likely negligible)*		

Table 14
Estimated economic impacts on the Lake Erie basin economy by category and scenario – Equivalent annual cost.
Source: Current study.

Category	Stable Lake	Business-as-usual million 2015 dollars	Policy Intervention
Tourism	40	110	28
Non-users	74	94	69
Property owners	17	36	18
Recreational users	7	21	6
Commercial fishing	0	5	2
Water users	4	4	4
Human health	*Not measurable (likely negligible)*		

risk. According to Statistics Canada (Table 10), the total value of homes along the lakeshore in 2011 was nearly $5.9 billion. Even with the conservative estimates of the loss in property value due to HNABs assumed here, such a large asset leads inevitably to significant costs. The estimated 30-year NPV of lost property values under the business-as-usual scenario was $712 million, while that under the policy intervention scenario was $348 million.

4.2.4. Losses in recreational user utility

Utility losses were considered for beach goers, sport fishers, boaters, hunters and wildlife viewers. All were found to experience only substantial losses. Total 30-year NPV losses in recreational utility were $421 million under the business-as-usual scenario and $112 million under the policy intervention scenario (Table 13). The breakdown of these costs by activity is shown in Table 15.

The baseline condition of the lake was considered poor enough to trigger utility losses for beach goers starting in 2015 in all control scenarios. Continual future losses are triggered for beach activities in the business-as-usual scenario, under which the total 30-year NPV of lost utility was estimated to be $230 million. In the policy intervention scenario, losses, which total $88 million, are triggered until the *Cladophora* intensity index reaches the swimmable level (2030), after which beach goers suffer no further utility losses (Table 15).

As for sport fishers, little evidence exists to suggest that the overall sport fishery on Lake Erie had been negatively affected by HNABs in the years leading up to 2015 in terms of the number of people fishing or their success in catching fish. Data from the Canadian and Ontario governments (Fisheries and Oceans Canada, 2019; H. Ball, personal communication) suggest that key Lake Erie recreational fishing parameters were within normal ranges for Ontario resident anglers in the time period 1995–2010, when HNABs were becoming increasingly problematic on the lake (Table 16).

Consistent with this, baseline (2015) conditions on the lake were found to impose only small losses in sport fisher utility using a WQL

Table 15
Estimated economic impacts on Lake Erie recreationists by activity – 30-year NPV (3% discount rate).
Source: Current study.

Activity	Stable Lake	Business-as-usual million 2015 dollars	Policy Intervention
Beach goers	99	230	88
Boating	< 1	69	4
Sport fishing	35	58	17
Wildlife viewing	< 1	52	3
Sport hunting	< 1	12	1

value of 5.4 (*not swimmable but good fish and game habitat*) to trigger losses. As blooms worsen in the business-as-usual scenario, both the cHAB and *Cladophora* intensity indexes fall below 5.4 on the WQL, leading to more substantial utility losses for sport fishers. The total 30-year NPV of sport fisher utility losses under the business-as-usual scenario was $58 million. Under the policy intervention scenario, index values were found rarely to be below 5.4 on WQL and sport fishing losses were consequently small ($17 million).

As for other recreationists (boaters, hunters and wildlife viewers), the value of 4.3 on the WQL (*satisfactory habitat for some fish and wildlife*) used to trigger utility losses in these activities resulted in no utility losses in 2015. This is consistent with findings from the 1996 and 2012 surveys of the importance of nature to Canadians that Ontarians' rates of participation in these activities were either stable or up significantly in the years leading up to the study period (Table 17).

As blooms worsen in the business-as-usual scenario, both the cHAB and *Cladophora* intensity indexes fall below 4.3 on the WQL, leading to substantial utility losses for boaters and wildlife viewers (which attract relatively large numbers of people) and smaller, but still important, losses for hunters. Under the policy intervention scenario, index values rarely fall below 4.3 on the WQL and losses for these activities all but disappear.

4.2.5. Losses in commercial fishing value added

The estimated 30-year NPV of value added losses in the commercial fishing industry is found to be $93 million under the business-as-usual scenario and $34 million under the policy intervention scenarios. These relatively low losses are due in part to the fact that baseline conditions on the lake were found not to impose measurable costs on commercial fishers. This is discussed further below. The relatively low costs are also a function of the fact that the industry itself is not large in economic terms. The total 2015 value added of the Lake Erie commercial fishing industry is estimated here to have been just under $20 million. In comparison, total value added in the Ontario economy in 2015 is estimated by Statistics Canada (2019) to have been about $706 billion.

In a major report on the state of Lake Erie, the International Joint Commission (2014) noted that the commercial fish harvest in 2011, a year when Lake Erie experienced one of the most serious HNAB events in its history, was above typical values, particularly when compared with harvests in the early 2000s.

Additional landed catch and value data obtained on request from Fisheries and Oceans Canada (R. Orok, personal communication)

Table 16
Lake Erie sport fishing – Trends in key parameters for Ontario resident anglers.
Source: Fisheries and Oceans Canada, 2019 and 2008; H. Ball, personal communication.

Parameter	1995	2000	2005	2010
Number of anglers	90,691	68,591	62,684	91,880
Number of angler-days	869,211	543,437	725,362	770,353
Catch (number of fish)	3,394,775	3,640,637	5,927,908	5,500,000
Catch per unit effort (fish/day)	3.91	6.70	8.17	7.14

Table 17
Overall Participation Rates of Ontario Residents in Lake-related Recreational Activities, 1996 and 2012.
Source: 2012 figures are from Federal, Provincial, and Territorial Governments of Canada (2014) and 1996 figures are from Environment Canada (1999) with authors' adjustments.

Year	Non-motorized water and beach activities	Recreational Fishing	Birding[a]	Motorized water-vehicle use	Hunting wild animals
	Share of the population taking part (%)				
1996	25	17	18	7	4
2012	42	21	19	22	5

[a] Birding was not an explicit category in the 1996, so the value for "wildlife viewing" from that report is reported here.

confirmed that harvests of most high-value commercial species[18] from Lake Erie in 2013 were at or above typical levels seen from 1994 to 2013 in terms of weight.

Analysis of value added data (Statistics Canada, 2019) for the commercial fishing industry further supports the conclusion that the industry's health was good up to 2015. Real (inflation-adjusted) value added for the Lake Erie fishery in 2013 was near or above its level seen since 1997. For this and the other reasons above, the assumption here was that the lake's baseline conditions did not impose any costs on commercial fishers.

Though no evidence of baseline impacts was found, evidence was found suggesting that two of the most important species in the fishery were evolving along with the changing ecological conditions of the lake and that fishers were beginning to see the effects of these changes.

According to data from the Great Lakes Fishery Commission (2014a,b), the share of the western basin (which is heavily impacted by cyanobacterial blooms) in overall yellow perch and walleye catches has been gradually declining since 2000. In the case of yellow perch, the catch has shifted mainly to the central basin but also significantly to the eastern basin. The walleye catch has shifted only to the central basin.

These shifts are consistent with the regional impacts of cyanobacterial blooms which have been greatest in the western basin. They are also consistent with the comment made by the Lake Erie Committee of the Great Lakes Fishery Commission (GLFC) in setting the 2012 total allowable catch levels for yellow perch: stocks of this species "generally appear to be healthier as one moves west to east across Lake Erie, consistent with environmental conditions (such as nutrient loads) of recent years" (Great Lakes Fishery Commission, 2012). The International Joint Commission (2014) has raised similar concerns, noting that impacts on commercially important fish species are likely if ecological conditions in the lake continue to deteriorate and cyanobacterial blooms become more common in the central and, even, eastern basins.

Anecdotal evidence (B. Locke, personal communication) suggests that commercial fishers were already experiencing some difficulty in catching their quotas by 2015, though, as noted above, they were still managing to do so without suffering apparent economic losses. First-hand reports from fishers indicated they were having to fish longer to meet quota and were finding their nets fouled by algal biomass.

These anecdotal reports, combined with the concerns expressed by the agencies the monitor the fishery, led to the conclusion here that the fishery had reached the point in 2015 where further declines in lake's quality would have an important impact on fishery value added. This, in turn, led to the assumptions noted earlier (Table 7) of 20%, 30% and 50% losses in value added as the lake's quality moved down the WQL steps. These losses are reflected in the 30-year NPV of lost value added to the fishery reported above. The significant difference in costs between the business-as-usual and policy intervention scenario is due to the fact that limiting P loadings to the lake keeps its condition in almost all cases above 4.3 on the WQL, thus limiting losses in the fishery to no more than 20% of value added.

[18] In order of 2013 value, the five most important commercial species are: yellow perch, walleye, white bass, rainbow smelt and white perch.

4.2.6. Costs imposed on water users

A variety of users withdraw water directly from the lake for their own use: farms, golf courses, industrial facilities and public/private drinking water facilities. For these, costs were found to be material only for municipal drinking water treatment plants.

Nearly all farms with licenses to extract water from Lake Erie operate along the shorelines of the western and central basins where *Microcystis* blooms dominate. Since the main concern for farms is clogging of intake pipes and *Microcystis* blooms do not present a major clogging threat (this is associated with *Cladophora* blooms), costs imposed on farms were found to be negligible.

Seven golf courses are licensed to withdraw water from Lake Erie. Of these, three are located in the western and central basins. Discussions with the operator of one these courses suggested that current and future costs due to HNABs are likely negligible. Costs were also assumed to be negligible for the four eastern-basin courses due to relatively small quantities of water involved, their intermittent need for water and the seasonal nature of the golf industry.

Only two small industrial operations, one a cannery and the other a fish processing plant, drew water from Lake Erie as of 2015. Their HNAB-related costs (the details of which were shared for the purposes of this study under a confidentiality agreement) were found to be small (30-year NPV of less than $1 million). A large thermal-electric power plant had, until its 2013 closure as part of the Government of Ontario's phase-out of coal-fired powerplants, been a major user of water in the lake's eastern basin. Presumably, it would have faced substantial HNAB-related costs had it continued operating. The remaining large industrial facility licensed to withdraw water from the lake (an eastern-basin refinery) has no record of actually using lake water even though it is permitted to do so.

As for drinking water treatment facilities, costs for the five small, private facilities licensed to withdraw water from the lake were considered negligible. Based on a survey sent to operators of the 12 municipally operated treatment plants[19], it was found that HNABs already impose costs in terms of increased operating expenses and that worsened conditions on the lake would result in further increases to operating expenses and the need for additional capital expenditures (R. Bouchard, personal communication; B. Fields, personal communication). The plant operators emphasized that they are currently capable of providing the required levels of treatment to ensure that drinking water sourced from Lake Erie is safe for Canadian consumers. This view was supported by Dr. Satish Deshpande of the Ontario Ministry of Environment and Climate Change (personal communication), who noted that Ontario government drinking water treatment protocols are sufficient to meet water quality standards. It was also reinforced by the fact that no instances of drinking water advisories issued as a result of algal blooms on Lake Erie could be found.

Plant operators did report occasional complaints from consumers related to taste and odour that may be attributable to algal blooms.

[19] Two responses covering three plants (25% response rate) were received. The plants covered were Essex County's Union water treatment plant (a large plant operating in the western basin) and Norfolk County's Port Dover and Port Rowan water treatment plants (smaller plants operating in the eastern basin).

Such complaints were reported to be readily dealt with by adjusting treatment parameters, primarily the use of granular activated carbon (R. Bouchard, personal communication).

Based on the costing data collected through the plant operator survey, the 30-year NPV of increased capital and operating costs for municipal drinking water treatment plants is found to be $83 million under the business-as-usual scenario and $74 million under the policy intervention scenario. The costs are similar because in both scenarios water quality drops below the point on the WQL (5.4 - *not swimmable but good habitat for fish and wildlife*) where we assumed that increased operating and capital costs are triggered. Note that increased capital costs were assumed to be made only once during the 30-year study timeframe. Operating costs were assumed to vary over the period depending on condition of the lake, explaining why costs are slightly lower in the policy intervention scenario.

5. Discussion

5.1. Implications of results

Overall, the cultural value of Lake Erie – its value for recreation, tourism and as an "environmental icon" of inherent value – is found to be its most important source of value and, therefore, the one that is most impacted by HNABs. Lake Erie is an internationally recognized icon that attracts and has meaning for many millions of people. Its degradation necessarily imposes costs on those individuals and the costs estimated in this study reflect this.

Based on the costs found, policy intervention to control P loadings to Lake Erie would be justified on economic grounds if the 30-year NPV of the control costs were less than $1294 million (the difference between the lower bound on business-as-usual costs and the upper bound on policy intervention costs; Table 11).

As noted in the introduction, much of the current P loading to the lake comes from agricultural non-point surfaces. A variety of management options exist to reduce P loadings from the agricultural sector, including those aimed at:

- reducing overall application rates of chemical fertilizers
- changing the timing of application so that it does not coincide with the spring freshet
- encouraging use of land management practices that limit runoff; such as, natural buffers along in riparian zones found in farmland and low- or zero-tillage planting methods.

Beyond agriculture, urban areas also contribute to P loadings. The problem is again one of rainfall runoff and snowmelt, which can carry road salt, animal feces, leaf litter and lawn fertilizers containing P from urban areas creeks and rivers that feed the lake. Improved stormwater and wastewater management are the main opportunities for intervention. Possibilities include:

- optimization of wastewater plant operations
- additional filtration of wastewater plant effluents
- filtration of stormwater to remove large particles (*e.g.*, leaf matter)
- enhancement of infiltration of stormwater into soil through infiltration basins/trenches or use of permeable road surfaces
- construction of artificial wetlands or engineered holding ponds for stormwater retention.

Of course, such interventions would have the greatest impact if they were coordinated across jurisdictions and sectors. Loadings of P to Lake Erie come from both Canada and the U.S., with the latter being the larger source. They also come from both rural and urban areas and, in the latter case, from towns and cities of varying sizes and management capacities. In such a context, actions to control P on the part of Canada but not the U.S. or on the part of farmers but not municipalities, while not to be discouraged, are necessarily less effective than coordinated action on the part of all players.

In spite of the estimated savings associated with the policy intervention *versus* business-as-usual scenarios, HNABs are found here to impose considerable costs on the Lake Erie basin economy even when efforts are taken to control them. The assumption in the policy intervention scenario is that policy action, if taken, would not begin before 2020 and would require 5–10 years to have its full effect means that the lake worsens until 2020 in both the business-as-usual and policy intervention scenarios. Even the baseline HNAB levels used in this study impose significant costs on the economy, so the worsening conditions in both control scenarios to at least 2020 result in significant costs.

The business-as-usual and policy intervention scenarios not only differ in total costs but also in their allocation across categories. In the business-as-usual scenario, tourism and non-user impacts account for approximately two thirds of the costs. In the policy intervention scenario, the impact on tourism is reduced not only in absolute terms but also in terms of tourism's overall share of economic costs. In that scenario, the largest costs are found to be imposed on non-users, since even with policy intervention the lake remains degraded compared to is pristine state and non-users are assumed to continue to be willing to pay for further quality improvements. Nonetheless, non-users are still expected to see their utility losses reduced by 27% after policy intervention. The fact that reductions of greater than 50% are expected after invention in the costs imposed on all other users of the lake's EGS (except drinking water treatment plants), suggests that policy intervention is justified on economic grounds.

5.2. Quality of the estimates

Every effort was made to base the estimates on the best available scientific and economic data and methods. It is important to emphasize, that HNABs and in particular, their economic costs, remain only partially studied and understood. Thorough review of the economic literature for information regarding the costs of HNABs yielded few directly relevant studies. For these reasons, the cost estimates in this study are intentionally conservative and almost certainly represent a lower bound on the true economic cost imposed by HNABs on the Canadian Lake Erie basin economy.

Throughout the study, it was necessary to make assumptions regarding the values of key variables. Some cost categories required more assumptions than others. As a result, the accuracy of the estimates is not uniform across all categories. While a quantitative assessment of this accuracy is not possible, a qualitative assessment is provided in Table 18). In addition to these general comments, a few of the specific assumptions made in the study merit further discussion.

5.2.1. Recreational utility losses

The choice to use a 50 km buffer along the lakeshore to measure utility losses for recreationists was made to ensure that losses were measured only for recreational users who could reasonably be considered residents of the Canadian Lake Erie basin economy. These households were assumed to be naturally oriented toward Lake Erie for their Great Lake-based recreation. It is acknowledged, however, that lakes Ontario, St. Clair, Huron and many smaller freshwater lakes are also close-by for many Southern Ontario households, so opportunities for lake-based recreation are plentiful. The 50 km buffer likely includes households who spend some or all of their lake-based recreation time at lakes other than Lake Erie and for whom the lake's degraded condition imposes no actual recreational utility losses.[20] At the same time, there are likely many households outside of the 50 km buffer who spend some

[20] It is worth pointing out that HNABs are not an issue only on Lake Erie. They occur also on Lake St. Clair and, to a lesser extent, in lakes Huron and Ontario (Ontario Biodiversity Council, 2019).

Table 18
Assessment of cost estimate quality by category.
Source: Current study.

Cost category	Quality of cost estimate	Impact on overall costs	Comment
Commercial fishing	Below average	Low	No data were available to assess relation between HNABs and commercial fishing value added. The share of value added lost for each change in the lake's water quality was based on discussions with industry experts and assumptions.
Water users	Average	Low	Actual cost data were available for only a few users; assumptions were required about how these users represented others in the costing model.
Recreational users	Above average	Moderate	
Non-users	Above average	High	
Tourism	Below average	High	No data were available to assess the relation between HNABs and tourism value added. The share of value added lost for each change in the lake's water quality was based on discussions and assumptions.
Property Values	Average	High	
Human health	n/a	n/a	It was not possible to estimate the cost of HNABs in terms of human health impacts due to data limitations as these are not reported and were very small when reported in Ohio.

time on Lake Erie and whose utility losses would not be captured in the results here. Though it is impossible to know with certainty, the view taken in the study was that the use of a 50 km buffer resulted in a conservative estimate of recreational utility losses.

5.2.2. Residential property values

The assumption that the values of all residential properties within 1 km of the lake's shoreline are equally sensitive to the presence of HNABs is likely incorrect. In reality, there is likely a gradient in price influence, with property values right on the shoreline being highly sensitive to the presence of HNABs, those close to the shoreline but not right on it (say, within 250 m) being somewhat sensitive and those further away (beyond 1 km) showing little sensitivity. The impact of this assumption on the quality of the results is tempered somewhat by the fact that the highest value properties in the 1 km buffer used in the study are likely those right on the shoreline or very close to it. Those in the outer portion of this band are likely of lower value and, therefore, will have a relatively small effect on estimated total loss in property value.

The possibility of intermingling of property value losses with recreational utility losses is also acknowledged. People often choose to live near the shorelines of waterbodies because they are enthusiastic about recreational opportunities or simply because they enjoy being close to nature. Thus, many of the households for which property value losses have been estimated in the study would also be households that would suffer recreational or non-user utility losses. Since these households could also be assumed to be concerned about losses in property values, it is possible that some of their willingness to pay to improve water quality is motivated by concerns over such losses rather than losses in recreational or cultural services, in which case there could be double counting of the welfare losses here between the recreational, non-user and property value categories.

5.3. Sensitivity of the estimates

The cost estimates are sensitive to some degree to all the variables and assumptions used in the costing approach. Two variables deserve further discussion though, as the results are particularly sensitivity to them. These are the discount rate used in the NPV calculation and the size of the buffers used to define the Lake Erie basin economy.

As noted, a 3% discount rate was used in NPV calculations to ensure consistency with the approach used by Environment and Climate Change Canada in its own economic analyses and in alignment with federal government guidance on cost-benefit analyses (Treasury Board of Canada Secretariat, 2007). In its sensitivity analyses for regulatory assessments, Environment and Climate Change Canada assumes upper and lower discount rate bounds of 7% and 0% respectively. These same bounds were used in the Monte Carlo simulations in this study.

As noted, assumptions regarding the geographic scope of the Lake Erie basin economy were necessary, as no such "economy" is recognized in national statistics. Given the importance of population size in some of the cost estimates (for example, the estimate of utility losses for recreational users of the lake), the results are sensitive to the decision regarding the boundaries of the basin economy.

The choices to define the economy here using 1 km, 50 km and 100 km buffer areas along the lake's shoreline are obviously not the only ones that could have been made. For example, while the population living within 50 km of the lakeshore was assumed to represent the pool of "recreationists" in the Lake Erie basin economy, it is clear that some people will travel from further afield to enjoy the lake's recreational opportunities. Similarly, the estimates of utility losses for non-users could have been extended further than those living within 100 km of the lakeshore. The buffers were chosen to be conservative, however, so as not to exaggerate the estimated costs.

5.4. Opportunities for further research

While the results of this study show it is possible to derive estimates of the economic costs of HNABs to the Lake Erie basin economy, doing so is far from straightforward and requires a number of assumptions that limit overall quality. The results also show that the costs of Lake Erie HNABs are likely significant, consistent with the findings of other studies.

Major improvements in the quality of the estimates could be made by focusing research in four areas:

- measurement of the views of HNABs among tourists in the Lake Erie basin (whether they use the lake itself or not) and the impact of HNABs on the tourism experience, with the goal of quantifying changes in tourism visits associated with given changes in the lake's quality
- measurement of the views of HNABs among those directly using Lake Erie's recreational services (*e.g.*, beach goers and sport fishers) and the impact of HNABs on the recreational experience, with the goal of quantifying changes in recreational visits associated with given changes in the lake's quality
- measurement of the impact of HNABs on Lake Erie shoreline properties, and
- measurement of non-users' actual willingness to pay for improvements in Lake Erie's water quality.

6. Conclusions

Although algal blooms have been a recurring ecological and economic problem on Lake Erie for decades, this study was the first to estimate the costs of these blooms to the Canadian Lake Erie basin economy. The study went beyond a strict accounting of dollars spent in coping with algal blooms to include the loss of various EGS provided by the lake to both users and non-users alike. In order to estimate the costs, both existing (*e.g.*, WQL) and new (*e.g.*, bloom intensity indexes) tools were used.

The central estimate of the total 30-year NPV of doing nothing - the business-as-usual scenario - is approximately twice as high ($5324 million) as the costs if policy action is taken to reduce algal blooms ($2474 million). These figures range from a high of $5842 million to a low of $1655 million respectively. Policy action to control P loadings is found to be justified on economic grounds if the 30-year NPV of the costs of the actions is less than $1294 million, the difference between the lower bound on the business-as-usual costs and the upper bound on the policy intervention costs (Table 11). Despite the argument posed by Steinman et al. (2017) that severe freshwater ecosystem stress and recreational benefits can coexist due to resiliency of ecosystem services, there are likely to be ancillary benefits of controlling P beyond reducing algal blooms. Some of these would include reduced flows of other pollutants (notably nitrogen), improvements in the quality of water bodies flowing into or out of Lake Erie and investments in new infrastructure and management practices. Algal blooms may also have long-term ecological and economic impacts not accounted for in this analysis that would increase the value of reducing P loads to Lake Erie.

Declaration of interest

Smith and Sawyer carried out the work associated with this study while under a consultancy contract to Environment and Climate Change Canada. Bass served as scientific authority for that contract.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of contribution

The original research associated with this study was carried out by Smith and Sawyer. Bass assisted in development of the literature review and scenarios and provided data for model development. Depew provided information for the *Cladophora* scenarios and Watson contributed to the literature review and assisted in development of the model. All authors have approved the final article.[CG]

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