Estimating the Total Economic Costs of Nutrient Emission Reduction Policies to Halt Eutrophication in the Great Lakes

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Key Points:

- Excessive nutrient loadings into the Great Lakes (GL), resulting in eutrophication and increasingly frequent outbreaks of harmful algal blooms, have sparked government-promoted reductions of total phosphorus (TP) emissions from point and non-point sources in and around the GL.
- A new hydro-economic model is developed to guide policy and decision-making to achieve TP emission reduction targets in the least-cost way for the GL and Canadian economy, using economic optimization and accounting for trade flows between economic activities inside and outside the GL basin.
- The estimated least-cost way to reduce TP emissions by 40% in all GL amounts to a total annual cost of three billion Canadian dollars or 0.15% of Canada's GDP. The cost structure changes substantially as policy targets become more stringent, increasing the share of indirect costs, affecting not only the economic activities around the GL, but the economy of Canada as a whole due to the tightly interwoven economic structure.

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Abstract

The Great Lakes (GL) in North America are among the largest freshwater resources on this planet facing serious eutrophication problems as a result of excessive nutrient loadings due to population and economic growth. More than a third of Canada's GDP is generated in and around the GL. Hence, the economic interests affected by pollution and pollution control are high. New policies to reduce pollution are often insufficiently informed due to the lack of integrated models and methods that provide decision-makers insight into the direct and indirect economic impacts of their policies. This study fills this knowledge gap and estimates the impacts of different total phosphorus (TP) restriction policy scenarios across the GL. A first of its kind multi-regional hydro-economic model is built for the Canadian GL, extended to include TP emissions from point and non-point sources. This optimization model is furthermore extended with a pollution abatement cost function that allows sectors to also take technical measures to meet the imposed pollution reduction targets. The latter is a promising new avenue for extending existing hydro-economic input-output modeling frameworks. The results show decision-makers the least cost-way to achieve different TP emission reduction targets. The estimated least-cost way to reduce TP emissions by 40% in all GL amounts to a total annual cost of three billion Canadian dollars or 0.15% of Canada's GDP. The cost structure changes substantially as policy targets become more stringent, increasing the share of indirect costs and affecting not only the economic activities around the GL, but the economy of Canada as a whole due to the tightly interwoven economic structure.

1 Introduction

Policymakers' demand for integrated hydro-economic assessments and evaluations, addressing emerging water security challenges, has grown exponentially over the past decades. This has led to the development of various forms of integrated and hybrid hydro-economic modelling tools, often highly dependent on the specific context for which they are designed. The latter makes it difficult to transfer existing model structures from one area (country, state, province, basin or watershed) to the other. Economists have therefore searched for economic data and model structures that are more generally applicable for water resources management around the world, like the modelling framework developed in the Global Trade Analysis Project (Calzadilla, Rehdanz, & Tol, 2011a) or the use of multi-regional input-output (MRIO) analyses to study the linkages between economic activity and water use (Bogra, Bakshi, & Mathur, 2016; Cazcarro, Duarte, & Sánchez Chóliz, 2013; Guo & Shen, 2015; Ridoutt, Hadjikakou, Nolan, & Bryan, 2018). Although most integrated hydro-economic models can be classified as hydrological river basin simulation models including an economic optimization component (Brouwer & Hofkes, 2008; Harou et al., 2009), there has been a surge in the reliance on macro-economic optimization models including hydrological and environmental components to be able to address both the direct and indirect economic consequences of changes in large-scale water infrastructure, use and management (Berrittella, Hoekstra, Rehdanz, Roson, & Tol, 2007; Calzadilla, Rehdanz, & Tol, 2011b; Dellink, Brouwer, Linderhof, & Stone, 2011; Kahsay et al., 2019; Kahsay, Kuik, Brouwer, & van der Zaag, 2015; Ponce, Bosello, & Giupponi, 2012; Strzepek, Yohe, Tol, & Rosegrant, 2008). Typically, these models make use of well-established economic accounting systems, such as the System of National Accounts (SNA) and their environmental extensions, such as the System of Environmental-Economic Accounting (SEEA), to calibrate and validate the economic structure pertaining to a specific geographical area. One of the main challenges when using these macro-economic models to account for water flows is the geo-referencing of economic activities and their water use (Brouwer, Schenau, & Van Der Veeren, 2005), including trade-flows between basins, to adequately assess spatial spillover effects of exogenously or endogenously induced change in water availability and water use. Economic-environmental studies usually follow the administrative boundaries of countries or states (Garcia, Rushforth, Ruddell, & Mejia, 2020; Lenzen, 2009; Ruddell, Adams, Rushforth, & Tidwell, 2014; Soligno, Malik, & Lenzen, 2019), because this is the scale at which available data are presented. However, significant progress has been made using Geographical Information Systems (GIS) to spatially tailor these macro-economic models to river basins and watersheds (Garcia-Hernandez & Brouwer, 2020).

In this study, we focus on the macro-economic modelling of the joint production of '*goods*' and '*bads*' in the Great Lakes Basin (GLB), one of the largest freshwater resources in the world, where approximately half of the Canada-United States (US) trade takes place (Kavic, 2016) and 37 million people live and work (Environment and Climate Change Canada and the U.S. Environmental Protection Agency, 2017). Economic growth has led to serious degradation of water quality, in particular due to the emission of nutrients from urban and rural sources, resulting in increasing eutrophication and outbreaks of harmful algal blooms (Carpenter, 2008; Cornwell et al., 2015; McKindles, Frenken, McKay, & Bullerjahn, 2020; Michalak et al., 2013; Watson et al., 2016), jeopardizing water security and compromising the long-term sustainability of the social and economic activities in the GLB (Isely, Isely, Hause, & Steinman, 2018; Smith, Bass, Sawyer, Depew, & Watson, 2019). In view of the fact that the economic activities in the GLB are highly interdependent and connected to other regions across the country and internationally (Garcia-Hernandez & Brouwer, 2020), changes in one activity to reduce the emission of nutrients are expected to impact other activities inside and outside the GLB. In order to be able to better understand the interconnectivity of these various water-dependent activities in the economy as a whole and assess the wider direct and indirect economic impacts of nutrient reduction policies, an appropriate multi-regional macro-economic modelling framework is required. Historically, phosphorous has been considered the limiting nutrient in freshwater ecosystems (Schindler, 1977; Schindler, Fee, & Ruszczynski, 1978; Smith & Schindler, 2009). The US and Canada have discussed and implemented water quality agreements for the GLB going back to the 1970's, focusing in particular on total phosphorous (TP) emission reductions into the lakes. However, an integrated decision-support tool, addressing both environmental and economic concerns simultaneously, is missing.

In order to address this knowledge gap and identify how current and future TP-reduction targets can be achieved in a cost-effective way across point and non-point sources around the different lakes, minimizing their impact on the GLB and Canadian economy, a multi-regional macro-economic input-output (MRIO) model for the Canadian side of the GLB is developed. This model includes TP emission loads for both point and non-point pollution sources, such as agriculture, utilities (wastewater treatment plants), and manufacturing. The model building brings together detailed geo-referenced economic and environmental data from Statistics Canada, Environment and Climate Change Canada, Canada's National Pollutant Release Inventory and the Ontario Ministry of Agriculture, Food and Rural Affairs. Besides presenting the first integrated GLB hydro-economic model to estimate the direct and indirect costs of imposing TP emission reduction targets on emitting sectors located on the Canadian side of the GLB, new in this study is also the modelling of trade relationships within the GLB and between the GLB and the rest of the province Ontario and Canada. The modelling results shed light on the economic interdependencies within the GLB and between the GLB and the rest of the country, and the crucial role the GLB plays as a driver behind economic growth, both as a source for economic production and a sink for the negative byproducts of this production.

2 The Canadian Great Lakes Basin

The GLB is a region of significant importance for Canada and the US in terms of water resources, biodiversity, economy, and population. It contains almost 20 percent of the world's fresh surface waters and sustains about 4,000 species of plants and animals, making it the most diverse ecoregion in North America (Brinker, Garvey, & Jones, 2018; Comer et al., 2003). In terms of economic value, Ontario in Canada and the 8 US states that share the GL account for 38 percent of Canada's GDP (Statistics Canada, 2019b) and 27 percent of that of the US (Bureau of Economic Analysis, 2019), amounting to a joint GDP of 5.9 trillion US dollars in 2018 prices. Over the past 5 decades, population and economic growth have compromised the GLB's longer term sustainability, mainly due to the emission of a wide range of pollutants over land (e.g., agricultural runoff) and directly into the water (e.g., residential and industrial wastewater), including heavy metals and nutrients. The increase in TP-loads entering the lakes has resulted in increasing eutrophication and frequent outbreaks of harmful algal blooms, especially in Lake Erie and Lake Ontario (Cornwell et al., 2015; Del Giudice, Zhou, Sinha, & Michalak, 2018; Michalak et al., 2013; Rowland et al., 2020; Watson et al., 2016).

In response to these environmental challenges, the first Canada-US Great Lakes Water Quality Agreement was signed in 1972 and updated in 2012 in order to restore and protect the chemical, physical and biological integrity of the water of the GL (Environment and Climate Change Canada, 2019a). Actions contemplate several restoration strategies for each of the lakes, conservation of the habitat and biodiversity of native species, and the development of science-based TP policy targets to reduce excessive nutrient loadings and toxic and nuisance algal blooms. Policies aimed at nutrient reductions have produced significant improvements in the ecosystems of the GLB over the past decades. However, eutrophication problems arose again in the 2000's, and especially Lake Erie remains in a poor condition due to excessive TP-loads from agricultural and urban sources (Michalak et al., 2013; Watson et al., 2016).

In 2018, the Canada-Ontario Lake Erie Action Plan was adopted which outlines the targets set by the Government of Canada to reduce the TP-loads into Lake Erie (Environment and Climate Change Canada and the Ontario Ministry of the Environment and Climate Change, 2018). Targets include a 40 percent reduction of TP-loads with respect to 2008 levels for the central basin of Lake Erie, and a 40 percent reduction in spring loadings for priority tributary rivers to the western and central basin. For the eastern Lake Erie basin, a precautionary approach was adopted and target reductions are still under review, but also for this part it is clear that actions to reduce TP-loads will have to be taken. We build on these existing water quality agreements and policy targets to assess the expected economic implications of different TP emission reduction scenarios for each of the GL separately and the GLB as a whole using the newly developed integrated MRIO model.

3 Baseline and policy scenarios

TP emission reduction scenarios are based on the aforementioned 2012 Water Quality Agreement between Canada and the US, in particular the most recent 2018 Lake Erie Action Plan. Four scenarios are developed, each targeting a particular geography and/or sector in the GLB. All scenarios assume that there is no new technological innovation readily available that can be implemented, implying that economic sectors continue to use current technologies and hence their pollution level per unit of output stays the same during the period of analysis, which is the baseline year 2016. Information about historic TP emissions were collected from the NPRI and calculated for manufacturing and WWTPs to determine whether any trends are detectable in these sectors. Although both sectors experienced a decrease in TP release over the period 2006 to 2010, their TP releases have remained approximately constant during the following years until and including our baseline year 2016. This is presented in the Supplementary Information, including a comparison with other information sources to assess the accuracy and reliability of the baseline data used in the MRIO Since not much variation in TP emission levels has occurred in the last 5 years nor in the next 3 years (2017-2019), we consider the emission intensities for the baseline year 2016 representative of the emission levels observed over the past decade. Under each scenario, the most recent available (2016) pollution intensity levels of each economic sector along each lake are taken as the baseline and the imposed TP emission reduction is expressed as a percentage reduction from these sector and lake-specific baseline values. For each scenario, the results of a percent emission reduction are presented up to a maximum of 50 percent. The four scenarios are summarized in Table 1.

Scenario A involves the reduction of TP loads to water bodies coming from all P-emitting sectors located inside the Canadian GLB, i.e. agriculture, manufacturing and utilities (wastewater treatment plants). The different P-emitting subsectors considered under manufacturing are listed in Table 2. These sectors emit more than 1 tonne of TP per year. This scenario evaluates the direct and indirect economic consequences of a policy intervention where the GLB is targeted as a single unit. The direct cost consists of the value-added loss in the P-emitting industries that are targeted in the policy scenario to reduce their TP emission levels, whereas the indirect costs consist of the value-added loss in the remaining (i.e., not directly targeted) industries. The outcome reflects the least-cost way of achieving different TP emission reduction levels for the GLB as a whole, i.e. how the impact on GDP can be minimized by prioritizing emission reductions in P-emitting economic activities across all four lakes.

Scenario B consists of four lake-specific emission reduction policy interventions, one for each lake in the GLB. Under this scenario, all the lake-specific P-emitting sectors are restricted relative to their baseline TP emission intensity. This scenario is stricter than Scenario A because this time each lake has to meet the same percentage TP emission reduction target instead of reducing TP-levels for the GLB as a whole. This allows us to identify which economic sectors should be targeted along each lake to achieve the TP emission reduction in the least-cost way for each lake separately.

Scenario C evaluates the effect of sector-specific TP emission reductions in the GLB for the P-emitting sectors agriculture (crop and animal production) and manufacturing (P-emitting subsectors are shown in Table 2). This scenario assesses the economic effects of targeted sector policies in the Canadian GLB.

Finally, scenario D evaluates the economic costs of TP emission reductions targeting non-point sources (agriculture) in Lake Erie and point source pollution (manufacturing) in Lake Ontario. Lake Erie is the agricultural heart of the GLB. Most agricultural activities in the GLB take place in the watersheds draining into Lake Erie, while manufacturing mainly takes place around Lake Ontario where most of the GLB's and the province's GDP is generated (75% and 68%, respectively).

4 Methodology

4.1 Multi-Regional Input-Output model

The economic data to construct the multi-regional input-output (MRIO) model is taken from the most recent 2016 Supply and Use tables of Canada and Ontario at the 'detailed' level (Statistics Canada, 2019c). These tables divide the economy into 240 industries and 492 commodities. P-emitting sectors are identified and singled out from these tables and the remaining non-emitting sectors are aggregated at the North American Industry Classification System 'summary' level (Statistics Canada, 2019a). The resulting Supply and Use tables contain 31 industries, from which the provincial IO table is created using a fixed commodity sales structure, which assumes that sales of products have a specific consumption structure irrespective of the producing industry. This type of construction is the standard way to calculate IO tables from Supply and Use tables (Miller & Blair, 2009).

The MRIO table is developed for the GLB by disaggregating the provincial IO table of Ontario following the drainage sub-basin boundaries of the Great Lakes for Lake Superior, Huron, Erie, and Ontario, and creating a fifth region to account for the remainder of Ontario province, labeled RoP ('rest of the province'). This disaggregation procedure uses jobs by industry and population at the level of census subdivisions (575 geographic units for the province of Ontario) to geographically identify the location of economic activities (production and consumption), and aggregates them to sub-basin regions based on the area of the census subdivisions that falls inside the drainage regions of the Great Lakes. This provides an initial estimation of production output and consumption by sub-basin, which is then further finetuned using average distances between regions, a distance-decay consumption function, and a downscaling technique called the Flegg Location Quotient (FLQ) (Jahn, 2017). The disaggregated MRIO table is then coupled with the remaining provinces of Canada and another region is created for the rest of the Canadian economy, labeled 'RoC' ('rest of Canada'). The inter-regional inter-industry trade flows within the province Ontario are calculated using the FLQ method, whereas the inter-regional final consumption trade flows are calculated using the distance-decay consumption function. Both methods are presented in Garcia-Hernandez and Brouwer (2020). As a final step, linear programming is used to ensure consistency between the Canada-GLB MRIO and the original Canadian and provincial IO tables. Trade flows between the Canadian regions are shown in Table 3. The novelty of the MRIO presented in this study compared to Garcia-Hernandez and Brouwer (2020) is the inclusion of the rest of Canada (RoC) as a separate region.

An economic optimization model is developed that allocates TP emission reductions across sectors and lakes such that an imposed reduction target is achieved while minimizing the loss of value added or GDP (Garcia-Hernandez & Brouwer, 2020) with respect to the baseline situation and satisfying a set of restrictions related to the intermediate consumption. The model is specified as follows:

$$\underset{\boldsymbol{x}}{\text{Min}}(\boldsymbol{x}-\boldsymbol{x}_0)^T\boldsymbol{\Lambda}\,(\boldsymbol{x}-\boldsymbol{x}_0) \tag{1}$$

s.t.

$$\boldsymbol{x} = \boldsymbol{A}\,\boldsymbol{x} + \boldsymbol{f} \tag{2}$$

$$\boldsymbol{\rho}^T\boldsymbol{x} \leq P_0 - \Delta P \tag{3}$$

$$\boldsymbol{f}_{min} \leq \boldsymbol{f} \leq \boldsymbol{f}_0. \tag{4}$$

Bold variables or parameters represent block or partitioned vectors or matrices containing the information of each region in the model. For example, the output, the TP emission intensity vectors and the matrix of technical coefficients are defined in terms of the regional sub-components as follows:

$$\boldsymbol{x} = \begin{pmatrix} \boldsymbol{x}_1 \\ \vdots \\ \boldsymbol{x}_R \end{pmatrix}, \quad \boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_{11} & \cdots & \boldsymbol{A}_{1R} \\ \vdots & \ddots & \vdots \\ \boldsymbol{A}_{R1} & \cdots & \boldsymbol{A}_{RR} \end{pmatrix}, \quad \boldsymbol{\rho} = \begin{pmatrix} \boldsymbol{\rho}_1 \\ \vdots \\ \boldsymbol{\rho}_R \end{pmatrix}. \tag{5}$$

The remaining variables or parameters of the model are defined in the same manner. The control variable $\boldsymbol{x}$ is a new gross output vector, $\boldsymbol{x}_0$ the baseline output vector, and the matrix $\boldsymbol{\Lambda}$ in the objective function (1) is defined as $\boldsymbol{\Lambda} = \text{diag}(\boldsymbol{v}^*) * \text{diag}(\boldsymbol{v}^*)$, where $\boldsymbol{v}^*$ is the vector of coefficients representing the value-added per dollar of output, such that the value-added is $\boldsymbol{v} = \text{diag}(\boldsymbol{v}^*)\boldsymbol{x}.$ Therefore, the objective function becomes Min $(\boldsymbol{v} - \boldsymbol{v}_0)^T(\boldsymbol{v} - \boldsymbol{v}_0)$. A quadratic form is selected because it avoids over-penalizing industries with relatively low output. The further the output of an industry is from its baseline value, the higher the cost of decreasing gross output on that industry. Because of the nonlinear objective function, the model may generate a sequence of solutions for different emission reductions that follows a nonlinear trajectory. Allowing for non-linear solutions in the economic optimization procedure is a significant step forwards given the linearity of existing IO models.

Restriction (2) equates production and final consumption where the vector $\boldsymbol{f}$ is the new final demand level determined by the model. Restriction (3) ensures that P-emissions from the different emitting sectors do not exceed the target set by the policy scenario. The vector $\boldsymbol{\rho}$ is the vector of emission coefficients whose entries are $\rho_i = P_0^i / x_0^i$, where P_0^i is the baseline TP emissions to water in Tons per year from sector i and x_0^i is the baseline gross output in dollars per year of sector i. $P_0 = \sum_i P_0^i$ is the baseline amount of emissions reaching a water body in Tons/year, and $\Delta P \geq 0$ is the target reduction. Restriction (4) establishes bounds on the new final demand level, where $\boldsymbol{f}_{min}$ is the minimal supply that must be met and $\boldsymbol{f}_0$ is the baseline value. The Supplementary Information contains a slightly more detailed description of the economic optimization procedure as well as an extension to account for the inclusion of technical pollution abatement measures in the model. This last feature is implemented in section 5.3 Sensitivity Analysis.

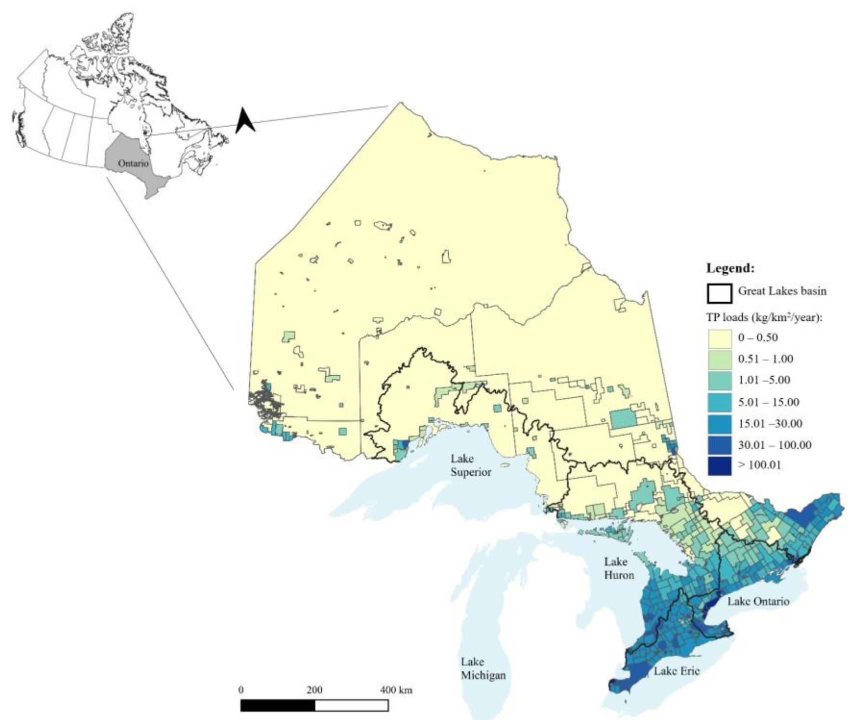


Figure 1. Total Phosphorus emissions to water for 2016 (kg km^{-2} year $^{-1}$) from point and non-point sources in Ontario at census subdivision level. The hydrological boundaries delimiting emissions reaching the Great Lakes for Lake Ontario, Lake Erie, Lake Huron and Lake Superior are shown in black. Data sources: the maps of Canada's provinces and census subdivisions are based on Statistics Canada (Statistics Canada, 2017). The map of the Great Lakes and corresponding basins are based on U.S. Geological Survey (USGS, 2014).

4.2 Point and non-point source phosphorus emissions

Figure 1 shows the estimated TP emission levels that reach a water body in the Great Lakes originating from different point and non-point sources across the different census subdivisions in Ontario. Data about TP releases to water bodies by point source sectors, in particular manufacturing and wastewater treatment facilities (see Table 2), are obtained from the National Pollutant Release Inventory (NPRI) (Environment and Climate Change Canada, 2019b). The NPRI is a database containing mandatory self-reported releases, disposals, and transfers of substances by facilities with at least 10 fulltime workers. The facilities are identified by the subsector they belong to, allowing us to relate the release data to the subsectors in the MRIO model. Emission levels for smaller facilities than those reporting to the NPRI are calculated based on jobs data per sector across the province of Ontario from Statistics Canada. Manufacturing facilities in the NPRI are allocated to the watersheds making up the GLB using their geographical coordinates. The detailed estimation procedure is presented in the Supplementary Information to this paper.

Reporting wastewater treatment plants (WWTPs) in the NPRI (13% of all WWTPs in Ontario) are cross-referenced with the Wastewater Systems Effluent Regulations (WSER) database (Environment and Climate Change Canada, 2019c) to obtain the TP concentration on the effluent, taking the TP releases (Ton/year) from the NPRI and effluent (m^3) from the WSER. The emission levels of the non-reporting WWTPs are subsequently obtained using the median concentration level of the reporting plants located in the same city or municipality boundary and the effluent volumes reported in the WSER. Then, the total releases are the sum of the releases from the reporting and the non-reporting WWTPs. Here too, the detailed estimation procedure is presented in the Supplementary Information.

Finally, using the Statistics Canada census consolidated sub-divisions (CCSD) as underlying lowest spatial resolution units, information was collected on farmland area size from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) for 2016 (Table 4). The Ministry collects data regularly to complement the provincial Agricultural Census, which takes place every 5 years. Total phosphorus loads and runoff from croplands and pastures are calculated using the coefficients of average loading by land use taken from Kim et al. (2017), as shown in Table 5, multiplied by the area of farmland in each CCSD to account for the proportion that reaches a water body that either directly or indirectly drains into one of the Great Lakes. The estimation procedure is further clarified in the Supplementary Information, including a comparison with other information sources to assess the accuracy of our estimation. The estimated runoff from agricultural land is lower than the value reported for example in Robertson et al. (2019) for the Great Lakes, largely because we do not account for important TP loading processes, including for example the contribution of groundwater and legacies (e.g. Plach et al., 2018; Van Staden et al., 2021). However, the estimate is of the same order of magnitude and correctly identifies this sector as the largest contributor of TP in Lake Erie. The calculation of region-specific TP emission coefficients for both point and non-point sources of pollution allows the optimization model to identify spatially differentiated solutions to reduce the baseline emission levels from manufacturing, municipal wastewater treatment plants, croplands and livestock pastures.

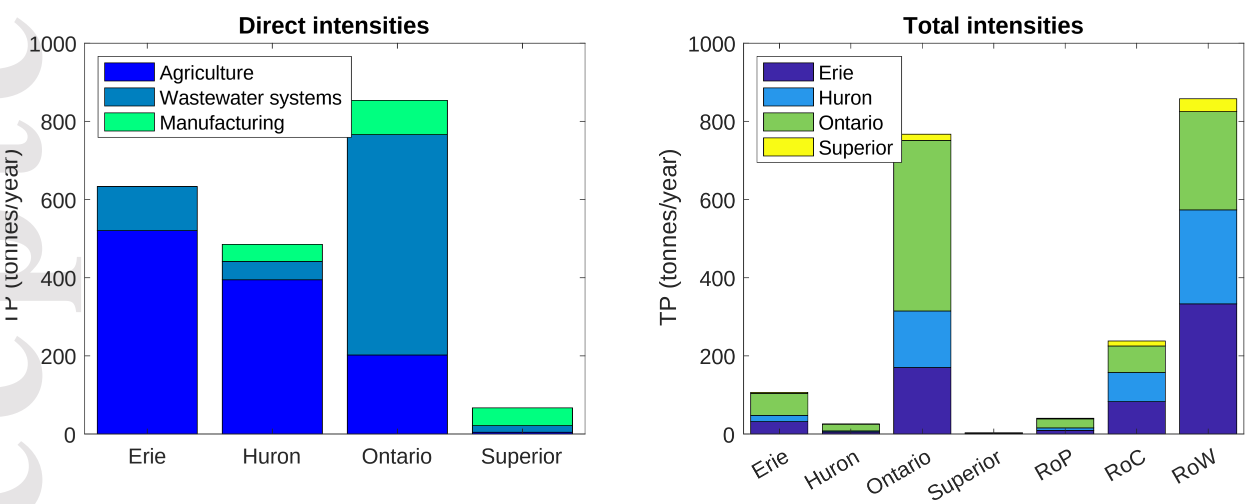


Figure 2. Direct and total direct and indirect Total Phosphorus emission intensities into the Great Lakes.

5 Results

5.1 Total phosphorous emission intensities across the Great Lakes

In a first step, the baseline TP emission intensity of economic activities in and around the GLB were estimated, distinguishing between direct and total TP emission intensity (Figure 2). Whereas direct intensities represent the TP emissions going directly into the lakes, total emission intensities (also called total direct and indirect intensities) reflect the emissions induced by final consumption, i.e. the TP-footprint of the different consumer regions, including the different lake regions, the rest of the province (RoP), the rest of Canada (RoC) and the rest of the world (RoW). The total intensities are therefore not equal to the sum of the presented direct intensity (the left-hand side of Figure 2) and a separate indirect intensity component. The total intensity (the right-hand side of Figure 2) shows for each Great Lake the destination of its production output and associated TP release, whereas the direct intensity shows which sectors are responsible for which share of the total release of TP going into each Great Lake. For more details about the calculation procedure, see the Supplementary Information. The direct intensities by sector and lake in Figure 2 show that agriculture is the main direct contributor to TP emissions in Lake Erie (82%) and Lake Huron (81%). Wastewater treatment plants (WWTPs), processing both residential and industrial wastewater, are the main TP source in Lake Ontario (66%) and the RoP (51%), and the second largest contributor in Lake Superior (25%), Lake Erie (18%) and Lake Huron (10%). Manufacturing is the largest source of TP emissions to water in Lake Superior (67%).

The total direct and indirect TP intensities on the right-hand-side of Figure 2 show that international exports to the RoW and final demand in Lake Ontario are the main drivers behind TP emissions in the GLB. Examining the TP-footprint in Lake Erie shows that it is largely driven by final consumption elsewhere, i.e. in the RoW (52%), Lake Ontario (27%) and the RoC (13%). Only 5 percent is related to final demand in and around Lake Erie self. This first assessment of TP emission intensities already indicates that imposing emission reductions may have far-reaching consequences for existing trade flows inside and especially outside the GLB.

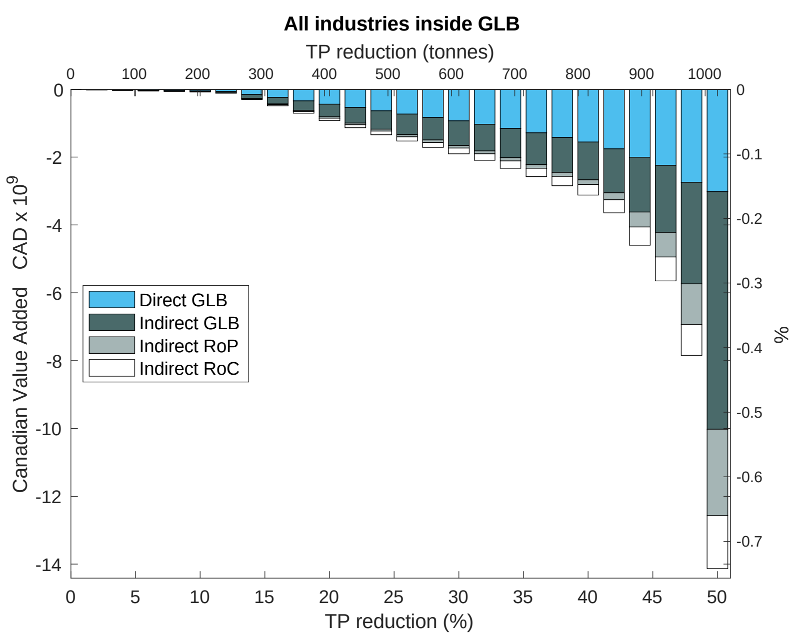
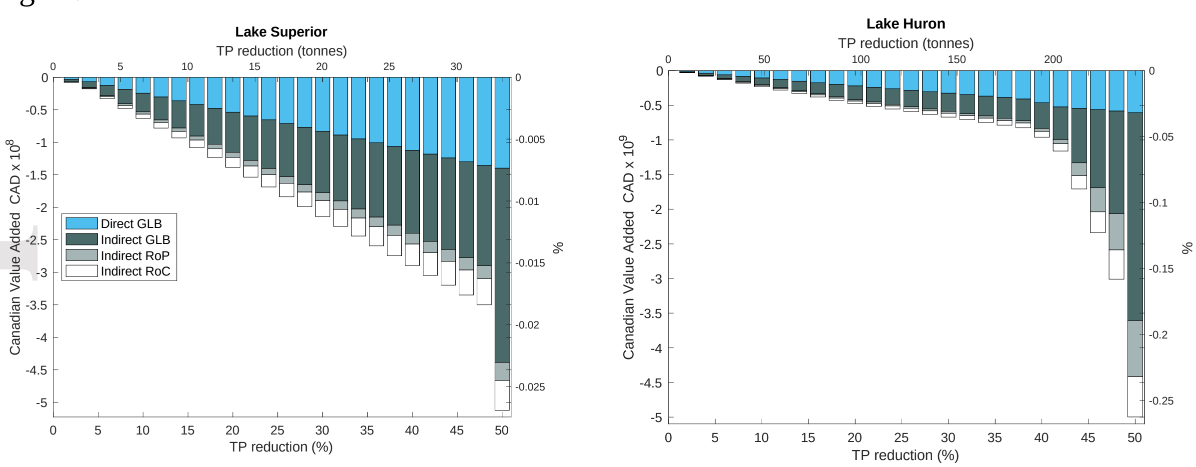


Figure 3. Canadian value added loss by type of economic cost under scenario A.

5.2 The total economic costs of TP emission reduction scenarios

Under scenario A, the TP emission reduction produces increasing total and marginal economic costs (Figure 3) to the Canadian economy. The pollution reduction costs show an exponential increase when reducing TP emission levels up to 50 percent in the GLB. The costs are initially relatively low up to a 10-15 percent emission reduction, but increase sharply at higher pollution reduction levels. Reducing emission levels further after 35 percent results in substantially higher economic costs. It is important to point out that the costs of initial TP emission reductions in the Great Lakes seem negligible in Figure 3. Note, however, that the vertical axis measures the loss in GDP for Canada as a whole, which was close to 1.9 trillion Canadian dollars (CAD). Even a very small reduction in Canada's GDP in 2016 of say 0.01 percent (invisible in Figure 3) implies a total cost of almost 190 million CAD per year. The loss of value added (GDP) when reducing TP emission levels by 20 percent across the GLB is 0.18 percent for the province of Ontario and 0.05 percent for Canada as a whole. This is equivalent to 943 million CAD annually. This loss of value added increases to 2.8 percent and 0.75 percent for Ontario and Canada, respectively at a 50 percent policy target. The corresponding unit value added loss ranges from 0.25 to 14.2 million CAD per tonne of TP reduced in the GL, where the higher marginal costs correspond to more binding restrictions on emission levels. The cost structure changes too depending on the imposed policy target. The direct costs account for more than 60 percent of the total costs when starting to reduce P emission levels into water and their share gradually decreases to 20 percent when approaching the highest TP-reduction target of 50 percent. As expected, this indicates that indirect costs play an increasingly important role when TP-reduction targets increase and become more stringent.



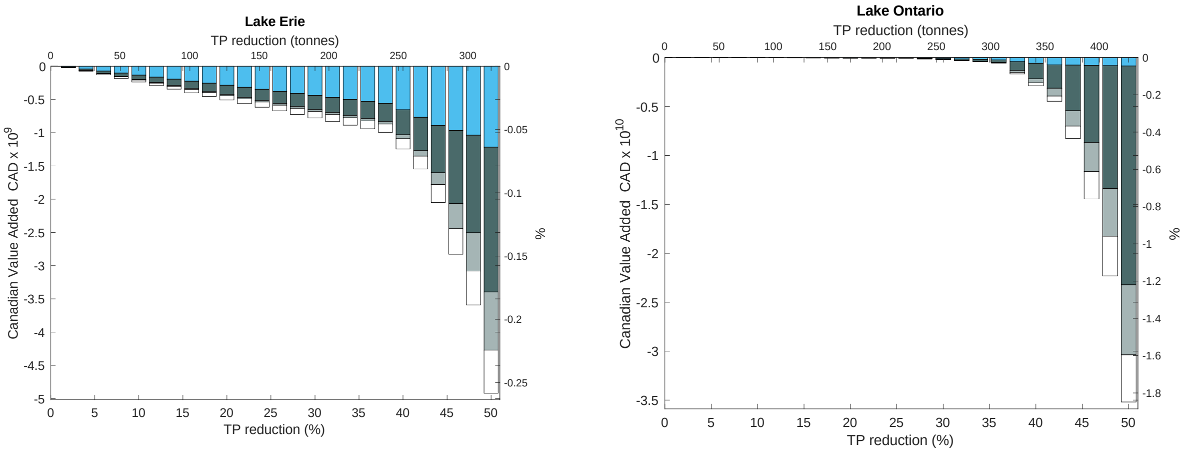


Figure 4. Canadian value added loss by type of economic cost under scenario B.

The economic impacts of implementing scenario B (Figure 4) differ orders of magnitude across the four lakes. This can be seen along the vertical axis on the left hand side of each figure, which is in hundreds of millions CAD for Lake Superior (10^8), billions (10^9) CAD for Lake Erie and Lake Huron and tens of billions CAD (10^{10}) for Lake Ontario. The highest economic costs of TP emission reductions are found in Lake Ontario, where the total costs go up to 1.8 percent of Canada's GDP when aiming to limit TP emissions by 50 percent. This is much lower for Lake Erie and Lake Huron (0.25%) and for Lake Superior (0.025%). Note that the absolute reduction of TP loadings into the GL also differs between the four lakes. This can be seen on the horizontal axis at the top of the figures, and affects the marginal costs of pollution abatement.

Most economic losses to improve water quality are hence incurred in the most densely populated Lake Ontario region, followed by Lake Erie and Lake Huron. The economic costs in Lake Ontario seem to reach a tipping point at a 25 percent reduction target when costs cannot be absorbed by the region only any longer and propagate rapidly elsewhere due to the large regional trade flows as shown in Table 3. The cost estimations between Lake Erie and Lake Huron are very similar in view of the important contribution of the primary sectors, i.e. agriculture in Lake Erie and mining in Lake Huron, to provincial output. The absolute reduction in TP emission levels is higher in Lake Erie though than in Lake Huron, as can be seen from their top axis. The pollution abatement cost curves in Figure 4 for these two lakes are linear up to an emission reduction level of almost 40 percent, and become non-linear thereafter. Overall over the initial linear cost trajectory of both lakes, about 55 percent of the total costs are direct and 45 percent indirect, but this changes considerably when more pollution is reduced and ultimately 75 percent of the total costs consist of indirect costs. The economic costs in Lake Superior under scenario B are linear and maintain more or less the same cost structure (40% direct, 60% indirect) irrespective of the emission reduction target. This linear trend in cost indicates that moderate reductions do not have a major impact on the Canadian economy due to the trade flow structure of the Lake Superior economy as shown in Table 3. Trade flows between Lake Superior and the other regions are relatively low, reflecting limited connectivity. The costs for Lake Superior are smallest of all four lakes, but also eliminate the smallest amount of TP loads into the lake in absolute terms.

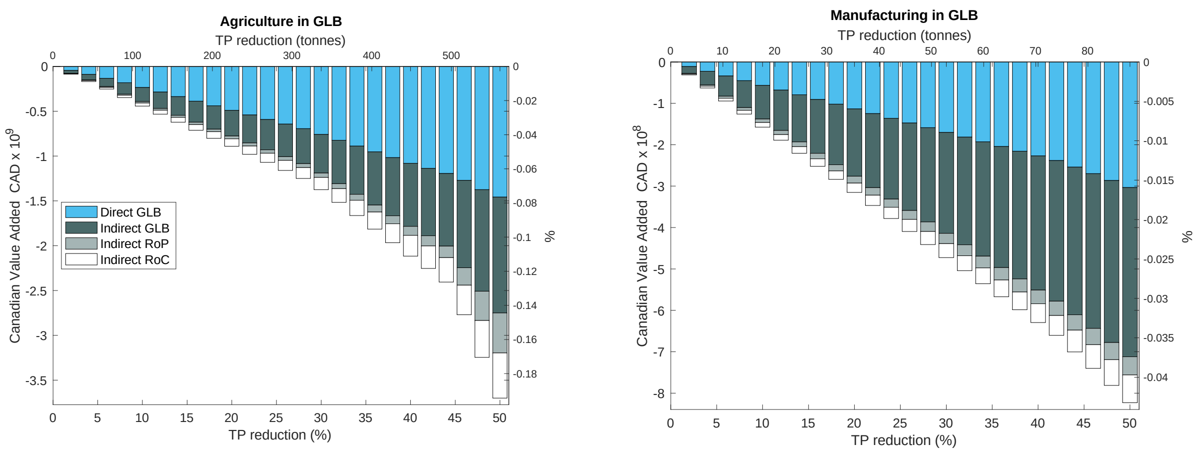


Figure 5. Canadian value added loss by type of economic cost under scenario C.

After inspection of the most cost-sensitive lake-regions in the GLB under scenario B, scenario C investigates in which sector it is most costly to reduce TP emissions (Figure 5). As in Figure 4, the scales on the two vertical axes in Figure 5 and the top axis representing the TP-reduction in absolute terms differ for agriculture as a non-point source of TP and manufacturing as a point source. Baseline TP emission levels are orders of magnitude larger in agriculture than in manufacturing. The total economic costs are also much higher in agriculture than in manufacturing. The total costs increase to up to 0.20 percent of national GDP for a 50 percent emission reduction in agriculture compared to 0.045 percent in manufacturing. The economic costs show more of a non-linear trend for agriculture than for manufacturing. Due to the lower baseline emission level in manufacturing, the marginal abatement cost of TP is much higher in manufacturing than in agriculture, up to a factor 2 for higher emission reduction policy targets. This implies that it is much cheaper to start eliminating TP-loads originating from agriculture than from manufacturing. The share of indirect costs is higher and more stable in manufacturing (around 65%) than in agriculture (49-61%), meaning that a reduction in TP emission levels not only affects the manufacturing industry in the GLB, but also other sectors in the GLB, the economy of the province Ontario and Canada as a whole.

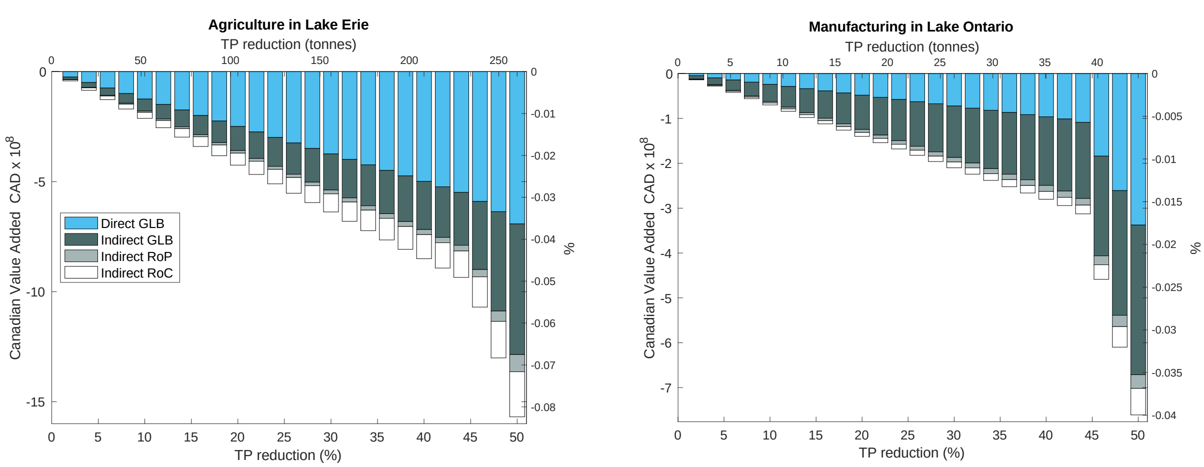


Figure 6. Canadian value added loss by type of economic cost under scenario D.

The effects of the same scenario implemented in Lake Erie for agriculture and manufacturing in Lake Ontario under scenario D show some slight differences (Figure 6). Although the total economic costs on the vertical scales are more comparable, they remain substantially higher for agriculture in Lake Erie than for manufacturing in Lake Ontario. Reducing the emission of TP into Lake Erie from agricultural activities by 40 percent results in a total economic cost of CAD 0.85 billion or a loss of 0.11 percent of Ontario's GDP in 2016. A similar reduction of 40 percent in Lake Ontario in manufacturing comes at a cost of CAD 0.28 billion (0.035% of provincial GDP). Most of these costs in agriculture in Lake Erie are direct costs (57%), while indirect costs prevail in manufacturing in Ontario (68%). As under scenario C, the marginal costs are much higher in manufacturing (CAD 8-17 million/tonne TP) than in agriculture (CAD 4-6 million/tonne TP). Contrary to scenario C, the total economic costs seem slightly more linear for agriculture in Lake Erie and more non-linear for manufacturing in Lake Ontario, especially after 45 percent of the TP loadings into the lakes have been eliminated. Although targeting agriculture in Lake Erie has comparable costs to targeting manufacturing in Lake Ontario, the former entails reducing a much larger absolute amount of TP and should be given priority over targeting the manufacturing sector in Lake Ontario.

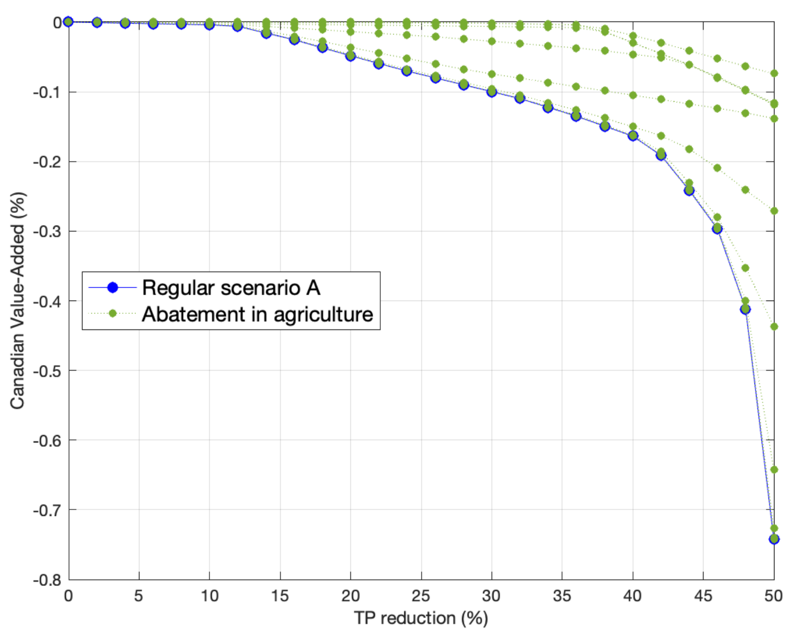


Figure 7. Scenario A (blue line) with the possibility to adopt pollution abatement measures at different costs in agriculture in the Great Lakes Basin (green lines).

5.3 Sensitivity analysis

An alternative and possibly more cost-effective manner to reduce pollution levels is through the adoption of pollution abatement measures. Pollution abatement technologies are not included in IO models, and this is one of their major drawbacks when aiming to analyze the economic impacts of pollution abatement policies. Accounting for pollution abatement measures would require production functions to be more flexible than the fixed technical coefficients in IO models and define appropriate marginal rates of substitution between input factors. This is typically the case in computable general equilibrium models where such measures can then be accounted for by including, for example, a separate pollution abatement sector based on the marginal costs of pollution abatement measures (Dellink et al., 2011). Typically, these costs increase disproportionally with respect to the amount of pollution reduced, reflecting that it becomes increasingly expensive to eliminate the last units of pollution. To assess the possible impact of sector-specific technological measures to reduce pollution levels, we extended the optimization model by including an abatement cost function. More details about the extension of the economic optimization procedure to include these abatement costs are provided in the Supplementary Information.

To illustrate the effect of including pollution abatement measures, we re-run scenario A where agriculture as the largest emitter of TP in the GLB is allowed to adopt pollution abatement measures, called Best Management Practices (BMPs), as another mechanism to reduce TP runoff into the Great Lakes. The maximum abatement potential is set arbitrary in this sensitivity analysis to equal 50% of the baseline emission level. For the cost and effectiveness of BMPs in the agricultural watersheds surrounding the GL we make use of the overview provided by Macrae et al (2021). We vary the average unit cost of pollution abatement in agriculture in the sensitivity analysis, starting from CAD 10 thousand per tonne of TP removal, i.e. the most cost-effective BMP identified in Macrae et al. (2021), and increasing the cost subsequently each time by a factor 10 to see up to which point no abatement measures are selected anymore by the model because it is less costly to reduce the sector's gross output. The results are presented in Figure 7.

The green lines represent pollution abatement measures in agriculture in general and refer to no specific BMP measure in particular, except that they are provided at increasing starting costs, as outlined before. They show that also pollution abatement costs in agriculture increase disproportionally as more TP is removed from agricultural land until they intersect or overlap with the cost of cutting crop and livestock production to reduce the emission of TP. As expected, allowing for the inclusion of technical abatement measures can reduce the total economic costs of pollution control for Canada as a whole substantially, up to a factor 7 in this specific illustration. It is important to point out that we do not account in the sensitivity analysis for the incentive payments needed to realize the necessary behavioral changes of farmers to adopt BMPs. Relatively few studies have examined the factors influencing Canadian farmers' adoption of BMPs (Haiyan Liu & Brouwer, in press). Although the 2016 baseline TP emission level from agricultural land includes TP releases under existing BMP subsidy programs, additional BMP adoption in the cost-effectiveness analysis is purely driven by economic rationality where BMP adoption to reduce TP emissions is prioritized over the reduction of agricultural crop and livestock production as long as the costs of the former are smaller than the costs of the latter.

6 Discussion

The newly developed MRIO model and economic optimization procedure for the GLB permit identification of the least-cost way to reduce TP emission levels across sectors and lakes. The non-linear economic optimization procedure and the inclusion of pollution abatement measures in the sensitivity analysis allow us to account for two major drawbacks of IO models compared to computable general equilibrium models, i.e. its linearity and fixed technical coefficients. This is a significant step forwards, both from a methodological point of view and to support future policy and decision-making with respect to nutrient reduction strategies across the GL. The GLB are responsible for a significant portion of Canada's GDP and hence the trade-offs between the vested economic interests affected when aiming to improve the water quality of the GL as foreseen in Ontario's Great Lakes Strategy are sizeable. A key novelty of the MRIO design is furthermore that it allows us to take the economic effects of pollution control policy into consideration in a consistent and coherent way at different scales, i.e. individual lake, the basin as a whole, the province and the country as a whole.

The results from the scenario analysis show that the more flexibility there is in reducing existing emission levels across lakes and sectors, the lower on average the pollution reduction costs. Pursuing a policy of emission reductions across the entire GLB, irrespective of the TP-emitting sector or the particular drainage region where TP releases take place, as under scenario A, results in the lowest average costs in terms of dollars per tonne of TP reduced. In contrast, narrowing down the regions and sectors results in higher economic costs, as shown for example under scenario's B and C. Marginal emission reduction costs differ across sectors and regions due to differences in economic productivity, emission intensity coefficients, and connectivity of sectors and regions to the wider provincial and national economy. Having a larger pool of sectors and regions to choose from when imposing TP emission reduction targets and having the regions and sectors allocate the permitted emission allowances based on region and sector-specific productivity characteristics allows for more cost-effective outcome configurations. For example, imposing a 40 percent TP emission reduction across all GL, including Lake Erie as foreseen in existing policy regulations, results in a total economic cost of CAD 3.11 billion for the GLB as a whole under scenario A and 5.36 billion under scenario B. The size of the indirect costs involved and hence the economic spinoff effects across the province and Canada as a whole also differs under both scenarios for this policy target. While they are more or less half of the total costs under scenario A, they vary between 50 and 80 percent under scenario B. The extent to which policy interventions generate such spinoff effects is expected to be an important additional consideration when selecting nutrient reduction strategies. Hence, presenting the direct and indirect costs associated with different emission reduction policy targets for the GLB, as we do with the help of this new integrated hydro-economic model, is considered paramount to inform decision-making.

Contrary to the lake-specific emission coefficients for point sources in manufacturing and wastewater treatment, it was a challenge to define lake-specific runoff coefficients for agriculture as the largest non-point source of TP emissions in the GLB based on the limited available data and information. Developing a more encompassing nutrient accounting system to support decision-making at the relevant GL basin-scale, including TP-flows between lakes and atmospheric deposition, is an important future research direction. At the same time, estimating the impact of the TP emission reductions on the Great Lakes' water quality using a more comprehensive environmental model that takes into account soil characteristics, historic atmospheric conditions, chemical interactions and other mass transport processes affecting TP from its source to the receiving water body is another important step to be able to also assess the benefits of the associated water quality improvements. From the model exercise it became clear that the costs of pollution abatement are an order of magnitude larger in manufacturing than in agriculture. This ranking is not expected to change or to be reversed when accounting for the uncertainties surrounding diffuse pollution sources such as TP-runoff from agricultural land and atmospheric deposition. As a result, agriculture was much more targeted as a sector to achieve the imposed TP emission reductions in the economic optimization procedure. The total costs for the agricultural sector are therefore also much higher than for manufacturing when developing sectoral policies as under scenario C or D. An important question in future decision-making may be how fair or acceptable such a burden on agriculture will be perceived.

Noteworthy here is also that the value added generated by utilities, in particular wastewater treatment as a public municipality service, is relatively low and the economic costs for this sector are therefore expected to be an underestimation. Reducing emissions from this point source typically involves upgrading of treatment facilities, which demands large capital investments that are currently not factored into this version of the hydro-economic model for the GLB. These investment costs are expected to increase the economic costs for this sector significantly. The impact of technical pollution abatement measures as another mechanism to cope with emissions is exemplified for agriculture in the sensitivity analysis. This exercise showed that introducing abatement measures in agriculture may substantially offset the total economic costs of pollution control. These technological changes improve the productivity of economic activities and lower the TP emission levels per unit of output. Our results suggest that investments in clean technology may be preferred to more drastic measures such as reducing production. The inclusion of pollution abatement measures in the P-emitting sectors is hindered by the lack of data and information that relate investments in new treatment technologies to decreases in TP emissions reaching the GL water bodies to evaluate their cost-effectiveness, and will be an important next step to further develop the optimization model. (Duchin & Levine, 2011). Interesting is also the use of alternative economic policy instruments to curb the emission of TP into the GL, as for example explored in Liu et al. (2020) by imposing a tax on the price of fertilizer to achieve a 40 percent reduction in western Lake Erie on the US side.

7 Conclusions

Located in the economic heart of the Canadian economy, the GL provide a wide variety of ecosystem goods and services, especially as a sink for the negative by-products of a wide variety of socio-economic activities, in particular the emission of total phosphorous. The economic damage costs of these externalities have been estimated at CAD 270 million per year for the Canadian side of Lake Erie under a business as usual scenario (R. B. Smith et al., 2019). Comparing these estimated damage costs with the predicted economic pollution reduction costs with the new developed MRIO model for the GLB allows us to assess what an economic optimum pollution level would be. In principle, this can be done for every lake if data and information about the social costs of eutrophication would be available for each lake. This is unfortunately currently not the case.

Zooming in on Lake Erie given the 2018 Canada-Ontario Lake Erie Action Plan aiming to reduce TP emission levels by 40 percent provides interesting insight into how economically efficient this policy target is based on the predicted economic costs for the province of Ontario as a whole. The estimated direct and indirect costs of a 40 percent TP emission reduction in Lake Erie under scenario B (CAD 1.24 billion) are almost a factor 5 higher than the estimated avoided damage costs in the literature. Targeting agriculture only as the largest emitter of TP in Lake Erie under scenario D (CAD 0.85 billion) suggests that the estimated economic costs are a factor three higher than these avoided damage costs.

Examining the pollution reduction cost curve in Figure 4 for Lake Erie shows that the break-even point where the pollution reduction costs equal the avoided damage costs is found somewhere between a 10 to 15 percent TP emission reduction. This is considerably lower than the proposed 40 percent emission reduction, suggesting that the proposed policy target in the Lake Erie Action Plan may be hard to justify from an economic point of view on the Canadian side based on our current level of knowledge and understanding using this new integrated hydro-economic model. However, investments in clean technology and BMPs may significantly reduce the economic burden of achieving such an emission target.

Paramount in reducing the growing frequency of harmful algal blooms (HABs) in the GL is the inclusion of the US side of the Great Lakes in a comprehensive international integrated assessment of the costs and benefits of TP emission reduction strategies to combat the negative impacts of eutrophication and HABs on the people, communities and economic activities around the GLB. This is in line with ongoing research efforts in the US on integrated assessment modelling for water to assess the social costs of water pollution, summarized in a special issue in Land Economics in 2020 (Keiser et al., 2020). Given the high share of TP-runoff into the GL on the US side (Environment and Climate Change Canada and the U.S. Environmental Protection Agency, 2017; Kim et al., 2017; Maccoux, Dove, Backus, & Dolan, 2016; Robertson et al., 2019), attempting to solve this transboundary environmental challenge unilaterally is expected to be an uphill battle.

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Data

Authors will upload the results of the model to the public repository https://www.frdr-dfdr.ca/ upon acceptance of the paper

References

Berrittella, M., Hoekstra, A. Y., Rehdanz, K., Roson, R., & Tol, R. S. J. (2007). The economic impact of restricted water supply: A computable general equilibrium analysis. *Water Research*. https://doi.org/10.1016/j.watres.2007.01.010

Bogra, S., Bakshi, B. R., & Mathur, R. (2016). A Water-Withdrawal Input-Output Model of the Indian Economy. *Environmental Science and Technology*, *50*(3). https://doi.org/10.1021/acs.est.5b03492

Brinker, S. R., Garvey, M., & Jones, C. D. (2018). Climate change vulnerability assessment of species in the Ontario Great Lakes Basin. In *Ontario Ministry of Natural Resources and Forestry, Science and Research Branch*. https://doi.org/10.1017/CBO9781107415324.004

Brouwer, R., & Hofkes, M. (2008). Integrated hydro-economic modelling: Approaches, key issues and future research directions. *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2008.02.009

Brouwer, R., Schenau, S., & Van Der Veeren, R. (2005). Integrated river basin accounting in the Netherlands and the European Water Framework Directive. *Statistical Journal of the United Nations Economic Commission for Europe*. https://doi.org/10.3233/sju-2005-22202

Bureau of Economic Analysis. (2019). GDP by State. Retrieved November 1, 2019, from https://www.bea.gov/data/gdp/gdp-state

Calzadilla, A., Rehdanz, K., & Tol, R. S. J. (2011a). The GTAP-W model: accounting for water use in agriculture. *Kiel Working Paper No. 1745*.

Calzadilla, A., Rehdanz, K., & Tol, R. S. J. (2011b). Trade Liberalization and Climate Change: A Computable General Equilibrium Analysis of the Impacts on Global Agriculture. *Water*. https://doi.org/10.3390/w3020526

Carpenter, S. R. (2008). Phosphorus control is critical to mitigating eutrophication. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.0806112105

Cazcarro, I., Duarte, R., & Sánchez Chóliz, J. (2013). Multiregional input-output model for the evaluation of Spanish water flows. *Environmental Science and Technology*. https://doi.org/10.1021/es4019964

Comer, P., Faber-Langendoen, D., Evans, R., Gawler, S., Josse, C., Kittel, G., … Teague, J. (2003). Ecological Systems of the United States: A Working Classification of U.S. Terrestrial Systems. *Nature Serve: Ecological Systems of the United States: A Working Classification of U.S. Terrestrial Systems*. https://doi.org/10.1146/annurev.anthro.30.1.227

Cornwell, E. R., Goyette, J. O., Sorichetti, R. J., Allan, D. J., Kashian, D. R., Sibley, P. K., … Trick, C. G. (2015). Biological and chemical contaminants as drivers of change in the Great Lakes-St. Lawrence river basin. *Journal of Great Lakes Research*. https://doi.org/10.1016/j.jglr.2014.11.003

Del Giudice, D., Zhou, Y., Sinha, E., & Michalak, A. M. (2018). Long-Term Phosphorus Loading and Springtime Temperatures Explain Interannual Variability of Hypoxia in a Large Temperate Lake. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.7b04730

Dellink, R., Brouwer, R., Linderhof, V., & Stone, K. (2011). Bio-economic modeling of water quality improvements using a dynamic applied general equilibrium approach. *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2011.06.001

Duchin, F., & Levine, S. H. (2011). Sectors may use multiple technologies simultaneously: The rectangular choice-of-technology model with binding factor constraints. *Economic Systems Research*. https://doi.org/10.1080/09535314.2011.571238

Environment and Climate Change Canada. (2019a). Canada-US Great Lakes water quality agreement. Retrieved November 1, 2019, from https://www.canada.ca/en/environment-climate-change/services/great-lakes-protection/canada-united-states-water-quality-agreement.html

Environment and Climate Change Canada. (2019b). National Pollutant Release Inventory. Retrieved September 4, 2019, from https://www.canada.ca/en/services/environment/pollution-waste-management/national-pollutant-release-inventory.html

Environment and Climate Change Canada. (2019c). Wastewater Systems Effluent Regulations. Retrieved December 6, 2019, from https://www.canada.ca/en/environment-climate-change/services/wastewater/system-effluent-regulations-reporting.html

Environment and Climate Change Canada and the Ontario Ministry of the Environment and Climate Change. (2018). *Canada-Ontario Lake Erie Action Plan, Partnering on Achieving Phosphorus Reductions to Lake Erie from Canadian Sources*. Retrieved from https://www.canada.ca/content/dam/eccc/documents/pdf/great-lakes-protection/dap/action_plan.pdf

Environment and Climate Change Canada and the U.S. Environmental Protection Agency. (2017). *State of the Great Lakes 2017 Technical Report*. https://doi.org/Cat No. En161-3/1E- PDF. EPA 905- R- 17- 001

Garcia-Hernandez, J. A., & Brouwer, R. (2020). A multiregional input–output optimization model to assess impacts of water supply disruptions under climate change on the Great Lakes economy. *Economic Systems Research*. https://doi.org/10.1080/09535314.2020.1805414

Garcia, S., Rushforth, R., Ruddell, B. L., & Mejia, A. (2020). Full Domestic Supply Chains of Blue Virtual Water Flows Estimated for Major U.S. Cities. *Water Resources Research*, *56*(4), e2019WR026190. https://doi.org/10.1029/2019WR026190

Guo, S., & Shen, G. Q. (2015). Multiregional input-output model for china's farm land and water use. *Environmental Science and Technology*. https://doi.org/10.1021/es503637f

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., & Howitt, R. E. (2009). Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2009.06.037

Isely, P., Isely, E. S., Hause, C., & Steinman, A. D. (2018). A socioeconomic analysis of habitat restoration in the Muskegon Lake area of concern. *Journal of Great Lakes Research*. https://doi.org/10.1016/j.jglr.2017.12.002

Jahn, M. (2017). Extending the FLQ formula: a location quotient-based interregional input–output framework. *Regional Studies*. https://doi.org/10.1080/00343404.2016.1198471

Kahsay, T. N., Arjoon, D., Kuik, O., Brouwer, R., Tilmant, A., & van der Zaag, P. (2019). A hybrid partial and general equilibrium modeling approach to assess the hydro-economic impacts of large dams – The case of the Grand Ethiopian Renaissance Dam in the Eastern Nile River basin. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2019.03.007

Kahsay, T. N., Kuik, O., Brouwer, R., & van der Zaag, P. (2015). Estimation of the transboundary economic impacts of the Grand Ethiopia Renaissance Dam: A computable general equilibrium analysis. *Water Resources and Economics*. https://doi.org/10.1016/j.wre.2015.02.003

Kavic, R. (2016). *Connecting across borders: A special report on the Great Lakes and St. Lawrence Regional Economy*.

Keiser, D., Kling, C., Phaneuf, D. J., Keiser, D., Kling, C., & Phaneuf, D. J. (2020). Introduction to the Special Issue: Integrated Assessment Models and the Social Cost of Water Pollution Workshop. *Land Economics*, *96*(4), iii–iv. https://doi.org/10.3368/WPLE.96.4.III

Kim, D. K., Kaluskar, S., Mugalingam, S., Blukacz-Richards, A., Long, T., Morley, A., & Arhonditsis, G. B. (2017). A Bayesian approach for estimating phosphorus export and delivery rates with the SPAtially Referenced Regression On Watershed attributes (SPARROW) model. *Ecological Informatics*. https://doi.org/10.1016/j.ecoinf.2016.12.003

Lenzen, M. (2009). Understanding virtual water flows: A multiregion input-output case study of Victoria. *Water Resources Research*, *45*(9). https://doi.org/10.1029/2008WR007649

Liu, Haiyan, & Brouwer, R. (2022). Incentivizing the Future Adoption of Best Management Practices on Agricultural Land to Protect Water Resources: The Role of Past Participation and Experiences. *Ecological Economics*, *In press.*

Liu, Hongxing, Zhang, W., Irwin, E., Kast, J., Aloysius, N., Martin, J., & Kalcic, M. (2020). Best Management Practices and Nutrient Reduction: An Integrated Economic-Hydrologic Model of the Western Lake Erie Basin. *Land Economics*, *96*(4), 510–530. https://doi.org/10.3368/WPLE.96.4.510

Maccoux, M. J., Dove, A., Backus, S. M., & Dolan, D. M. (2016). Total and soluble reactive phosphorus loadings to Lake Erie: A detailed accounting by year, basin, country, and tributary. *Journal of Great Lakes Research*. https://doi.org/10.1016/j.jglr.2016.08.005

Macrae, M., Jarvie, H., Brouwer, R., Gunn, G., Reid, K., Joosse, P., … Zwonitzer, M. (2021). ..One size does not fit all: towards regional conservation practice guidance to reduce phosphorus loss risk in the lake erie watershed. *Journal of Environmental Quality*. https://doi.org/10.1002/jeq2.20218

McKindles, K., Frenken, T., McKay, R. M. L., & Bullerjahn, G. S. (2020). *Binational Efforts Addressing Cyanobacterial Harmful Algal Blooms in the Great Lakes*. https://doi.org/10.1007/698_2020_513

Michalak, A. M., Anderson, E. J., Beletsky, D., Boland, S., Bosch, N. S., Bridgeman, T. B., … Zagorski, M. A. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1216006110

Miller, R. E., & Blair, P. D. (2009). Input-output analysis: Foundations and extensions, second edition. In *Input-Output Analysis: Foundations and Extensions, Second Edition*. https://doi.org/10.1017/CBO9780511626982

Plach, J.M., Macrae, M.L., Ali, G.A., Brunke, R.R., English, M.C., Ferguson, G., Lam, W.V., Lozier, T.M., McKague, K., O'Halloran, I.P., Opolko, G., Van Esbroeck, C.J., 2018. Supply and transport limitations on phosphorus losses from agricultural fields in the Lower Great Lakes Region, Canada. Journal of Environmental Quality 47(1), 96–105.

Ponce, R., Bosello, F., & Giupponi, C. (2012). Integrating Water Resources into Computable General Equilibrium Models - A Survey. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2160652

Ridoutt, B. G., Hadjikakou, M., Nolan, M., & Bryan, B. A. (2018). From Water-Use to Water-

Scarcity Footprinting in Environmentally Extended Input-Output Analysis. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.8b00416

Robertson, D. M., Saad, D. A., Benoy, G. A., Vouk, I., Schwarz, G. E., & Laitta, M. T. (2019). Phosphorus and Nitrogen Transport in the Binational Great Lakes Basin Estimated Using SPARROW Watershed Models. *Journal of the American Water Resources Association*. https://doi.org/10.1111/1752-1688.12792

Rowland, F. E., Stow, C. A., Johengen, T. H., Burtner, A. M., Palladino, D., Gossiaux, D. C., … Ruberg, S. (2020). Recent Patterns in Lake Erie Phosphorus and Chlorophyll a Concentrations in Response to Changing Loads. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.9b05326

Ruddell, B. L., Adams, E. A., Rushforth, R., & Tidwell, V. C. (2014). Embedded resource accounting for coupled natural-human systems: An application to water resource impacts of the western U.S. electrical energy trade. *Water Resources Research*, *50*(10), 7957–7972. https://doi.org/10.1002/2013WR014531

Schindler, D. W. (1977). Evolution of phosphorus limitation in lakes. *Science*. https://doi.org/10.1126/science.195.4275.260

Schindler, D. W., Fee, E. J., & Ruszczynski, T. (1978). Phosphorous input and its consequences for phytoplankton standing crop and production in the experimental lakes area and in similar lakes. *J. FISH. RES. BOARD CANADA*. https://doi.org/10.1139/f78-031

Smith, R. B., Bass, B., Sawyer, D., Depew, D., & Watson, S. B. (2019). Estimating the economic costs of algal blooms in the Canadian Lake Erie Basin. *Harmful Algae*. https://doi.org/10.1016/j.hal.2019.101624

Smith, V. H., & Schindler, D. W. (2009). Eutrophication science: where do we go from here? *Trends in Ecology and Evolution*. https://doi.org/10.1016/j.tree.2008.11.009

Soligno, I., Malik, A., & Lenzen, M. (2019). Socioeconomic Drivers of Global Blue Water Use. *Water Resources Research*, *55*(7), 5650–5664. https://doi.org/10.1029/2018WR024216

Statistics Canada. (2017). Boundary Files, Reference Guide Census year 2016.

Statistics Canada. (2019a). Archived - Gross Domestic Product by Industry. Retrieved December 5, 2019, from https://www.statcan.gc.ca/eng/statistical-programs/document/1303_D7_T9_V1

Statistics Canada. (2019b). Table 36-10-0402-01 Gross domestic product (GDP) at basic prices, by industry, provinces and territories (x 1,000,000). Retrieved September 1, 2019, from https://doi.org/10.25318/3610040201-eng

Statistics Canada. (2019c). Table 36-10-0478-01 Supply and use tables, detail level, provincial and territorial (x 1,000).

Strzepek, K. M., Yohe, G. W., Tol, R. S. J., & Rosegrant, M. W. (2008). The value of the high Aswan Dam to the Egyptian economy. *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2007.08.019

USGS. (2014). Great Lakes and Watersheds Shapefiles. Retrieved January 21, 2022, from https://www.sciencebase.gov/catalog/item/530f8a0ee4b0e7e46bd300dd

Van Staden, T.L., Van Meter, K.J., Basu, N.B., Parsons, C.T., Akbarzadeh, Z., Van Cappellen, P. Agricultural phosphorus surplus trajectories for Ontario, Canada (1961–2016), and erosional export risk. Sci. Total Environ. (in press).

Watson, S. B., Miller, C., Arhonditsis, G., Boyer, G. L., Carmichael, W., Charlton, M. N., … Wilhelm, S. W. (2016). The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful Algae*. https://doi.org/10.1016/j.hal.2016.04.010

Table 1. Total phosphorous emission reduction policy scenarios

		Geographical target	
		Great Lakes Basin as a whole	Specific sub-basins
Sectoral target	All TP emitting subsectors	**Scenario A** A. All sectors in the GLB as a whole: 2,046 t/year	**Scenario B** B1. All sectors in Lake Superior: 74 t/year B2. All sectors in Lake Huron: 485 t/year B3. All sectors in Lake Erie: 634 t/year B4. All sectors in Lake Ontario: 854 t/year
	Specific TP emitting sectors	**Scenario C** C1. Agriculture in the GLB: 1,122 t/year C2. Manufacturing in the GLB: 183 t/year	**Scenario D** D1. Agriculture in Lake Erie: 520 t/year D2. Manufacturing in Lake Ontario: 88 t/year

Note: The tonnes per year (t/year) in each scenario refer to the baseline emission levels of total phosphorous. The tonnes per year per lake under scenario B do not add up to 2,046 t/year for the Great Lakes basin as a whole due to rounding errors.

Table 2. Sector classification used for the MRIO model and their link to the emission reduction policy scenario's

P-emitting sub-sectors (≥ 1 Tonnes/year)		TP to GLB (tonnes/yr)	%	Sub-sectors included in scenario's					
				A	B1-B4	C1	C2	D1	D2
1	Crop production (excluding greenhouse, nursery and floriculture)	1,031	50.4	X	X	X		X	
2	Animal production (excluding aquaculture)	91	4.4	X	X	X		X	
3	Water, sewage and other systems (wastewater treatment plants)	740	36.2	X	X				
4	Grain and oilseed milling manufacturing	7.3	0.4	X	X		X		X
5	Pulp, paper and paperboard mills manufacturing	154	7.5	X	X		X		X
6	Basic chemical manufacturing	8	0.4	X	X		X		X
7	Other chemical product manufacturing	14.5	0.7	X	X		X		X
	Total	**2,046**	100.0						
P-emitting sub-sectors excluded due to low emissions (< 1 Tonnes/year)									
8	Gold and silver ore mining								
9	All other metal ore mining								
10	Iron and steel mills and ferro-alloy manufacturing								
11	Non-ferrous metal rolling, drawing, extruding and alloying manufacturing								
Non-P-emitting sectors									
12	Agriculture, forestry, fishing and hunting (non-P-emitting)								
13	Mining, quarrying, and oil and gas extraction (non-P-emitting)								
14	Utilities (excluding wastewater treatment plants)								
15	Construction								
16	Manufacturing (non-P-emitting)								
17	Wholesale trade								
18	Retail trade								
19	Transportation and warehousing								
20	Information and cultural industries								
21	Finance and insurance								
22	Real estate and rental and leasing								
23	Professional, scientific and technical services								
24	Management of companies and enterprises								
25	Admin. and support, waste management and remediation services								
26	Educational services								
27	Health care and social assistance								
28	Arts, entertainment and recreation								
29	Accommodation and food services								
30	Other services (excluding public administration)								
31	Public administration								

Note: X indicates that the P-emitting sub-sector is included in the policy scenario.

Table 3. Trade flows between the different Great Lakes, the rest of the province Ontario (RoP), the rest of Canada (RoC), and the rest of the World (RoW) (2016 Billion CAD)

		Destination							Total
		Sup.	Huron	Erie	Ont.	RoP	RoC	RoW	
Origin	Sup.	1.75	0.47	0.90	2.65	0.58	2.04	2.55	10.94
	Huron	0.40	29.12	9.46	53.46	4.75	5.41	5.52	108.12
	Erie	0.69	5.67	84.38	78.19	6.17	11.72	35.76	222.58
	Ont.	1.89	15.76	55.80	659.10	19.61	79.82	130.91	962.89
	RoP	0.71	3.90	9.41	49.84	41.12	7.10	8.49	120.57
	RoC	2.36	3.17	5.96	61.99	3.41	1,805.9	349.42	2,232.21
	RoW	0.38	0.72	17.53	118.68	1.83	373.87	0	513.01
Total		8.18	58.81	183.44	1,023.91	77.47	2,285.86	532.65	4,170.32

Table 4. Type, description and sources of total phosphorous (TP) data used in this study.

Data description			P source	Spatial resolution	Year	Source	Link
A. Administrative data							
1.	Census sub-divisions	Spatial unit for data collection dividing the GLB and Ontario into census sub-divisions (n = 575), corresponding to municipalities, or equivalent areas, used for statistical purposes.	NA	CSD	2016	SC	https://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2016-eng.cfm
B. P loads data							
2.	Agriculture	Land use in farmlands at the level of census consolidated subdivisions (CCSD) (n = 273).	diffuse	county & township	2016	OMAFRA	http://www.omafra.gov.on.ca
3.	Industry	Subsector code, emissions, releases, and coordinates of reporting facilities.	point	point	2016	ECCC	https://open.canada.ca/data/en/dataset/1fb7d8d4-7713-4ec6-b957-4a882a84fed3
4.	Wastewater	Effluents and city of location of each wastewater facility.	point	point	2016	ECCC	https://open.canada.ca/data/en/dataset/1fb7d8d4-7713-4ec6-b957-4a882a84fed3

Note: CSD – Census sub-divisions, ECCC - Environment Climate Change Canada, SC - Statistics Canada, OMAFRA – Ontario Ministry of Agriculture, Food and Rural Affairs.

Table 5. Total phosphorus loads from land use on farmlands to water.(Kim et al., 2017)

Land use	TP loads (Kg acre^{-1} yr^{-1})
Land with crops	0.137
Summer fallow land	0.291
Tame or seeded pasture	0.105
Natural land for pasture	0.105