Optimization of Nutrient Reduction Measures Targeting Agricultural and Urban Sources Around Lake Erie

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Abstract

Excessive nutrient loading to Lake Erie (LE) has been identified as a major threat to the ecosystems and human populations in and around LE. Governments across the Canada-US border have established phosphorus loading reductions, including targeting the Western and Central LE basin. In this work, we present an optimization model for the Canadian side of Lake Erie (LE) that determines the required abatement level of total phosphorus (TP), targeting agricultural activities and additional investments in end-of-pipe technologies in wastewater treatment plants across the Canadian LE watersheds, such that a target reduction in P concentration level is achieved at the lowest cost. The hydrological model used in this study considers the interdependence among six regions: St. Claire River and Lake, the Detroit River, and the Western, Central and Eastern Basins of LE.

Preliminary results show that a drop of 1 ppb in P concentration for the Western and Central Basins would cost 440 million CAD and involves reducing TP loads by 40 tonnes in the Lake St. Claire region, 150 tonnes on the Detroit River, 115 tonnes on the Western Basin, and around 300 tonnes in the Central Basin. The model also shows a positive externality for the Eastern Basin as it would decrease its P concentration by 0.5 ppb.

The newly developed integrated impact assessment model will be very informative for policymakers to determine the most cost-effective way to abate TP emissions into LE.

1 Introduction

1.1 Nutrient pollution at Lake Erie

Nutrient export from agriculture and urban sources has been identified as a major threat to the water quality of the Great Lakes (GL). In particular, total phosphorus (TP) loads have contributed to the eutrophication of the lakes and the outbreaks of harmful algal blooms, affecting most prominently Lake Erie (LE) [1].

In response to these quality changes, governments on both sides of the border have adopted TP target reductions for LE. 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 [2]. Targets include a 40% reduction of TP-loads with respect to 2008 levels for the central basin of Lake Erie, and a 40% reduction in spring loadings for priority tributary rivers to the western and central basins.

A key question is not only which types of measures and sectors should receive priority, but also where in the LE watershed should these measures be implemented to achieve TP reduction targets at the lowest cost possible. Any attempt to answer the latter question should account for the hydrological interdependence among the sub-watersheds making up the LE basin, as improvements upstream of the lake may be more cost-effective than downstream.

1.2 Hydrological dependence of Lake Erie basins

Mass balance models provide a description of a system in terms of inputs, outputs and accumulation of mass flows. Nutrient balance in the Great Lakes has helped determine the Total Phosphorus (TP) loading targets for its lakes and most prominently to LE where excessive nutrient loadings have become a major issue [3].
We use the mass balance equation proposed by Bocaniov [4] were the LE basin is divided into 6 hydrological regions (Saint Claire River (SCR), Lake Saint Clair (LSC), Detroit River (DR), Western Basin (WB), Central Basin (CB), and Eastern Basin (EB)) whose TP mass balance dependency is described by equation 1.

This model relates watershed TP loads (l_r) in $\left[10^3 \text{ t/year}\right]$ to P concentration (z_r) in $\left[\mu\text{g/L}\right]$ or [ppb] under the assumption that the hydrological system has reached steady state, i.e., its transient components have become negligible. A drawback of this assumption is the model does not say how long it takes for a change in loading to be reflected in a change in concentration of the water bodies; however, it has the advantage of depicting the long-term impact of such change.

The steady-state mass balance equation for the regions of LE is the following:

$$\underbrace{\begin{bmatrix} z_{\mathrm{SCR}} \\ z_{\mathrm{LSC}} \\ z_{\mathrm{DR}} \\ z_{\mathrm{WB}} \\ z_{\mathrm{CB}} \\ z_{\mathrm{EB}} \end{bmatrix}}_{z} = \underbrace{\begin{bmatrix} 6.25 & 0 & 0 & 0 & 0 & 0 \\ 4.92 & 4.92 & 0 & 0 & 0 & 0 \\ 4.90 & 4.90 & 6.05 & 0 & 0 & 0 \\ 2.51 & 2.51 & 3.10 & 3.10 & 0 & 0 \\ 0.73 & 0.73 & 0.90 & 0.90 & 1.48 & 0 \\ 0.36 & 0.36 & 0.44 & 0.44 & 0.73 & 1.30 \end{bmatrix}}_{S} \underbrace{\begin{bmatrix} l_{\mathrm{SRC}} \\ l_{\mathrm{LSC}} \\ l_{\mathrm{DR}} \\ l_{\mathrm{WB}} \\ l_{\mathrm{CB}} \\ l_{\mathrm{EB}} \end{bmatrix}}_{l} \tag{1}$$

therefore, the P concentration of the water bodies is described by $z = S \cdot l$.

1.3 Agriculture Abatement

Abatement measures in agriculture and its associated cost curve are taken from the optimal implementation of Best Management Practices (BMPs) across the Grand River watershed [5]. In this study, authors allow the selection of different BMPs, including input nutrient reduction; cover crops; buffer strips; and wetland restoration, such that a target phosphorus reduction is achieved at the outlet of the watershed.
The optimal financial cost curve obtained shows (Figure 1) that a quadratic equation provides a good fit to describe the cost in [10^6 CAD/year] as a function of the TP loads that are reduced to Lake Erie (x) in metric tons per year:

$$\mathrm{cost}(x) = 4.65 - \left(3.2 \times 10^{-1}\right)x + \left(4.0 \times 10^{-3}\right)x^2. \tag{2}$$

However this cost curve is associated to a given cropland area. Since we want to transfer this equation to other regions of different area, we need to adjust it by introducing the effect of area size. Assuming the cost is inversely proportional to area size, (i.e., cost $\propto$ 1/area) would make a same load reduction costlier on a smaller area region and cheaper on a larger area. Therefore, we adjust the abatement cost curve as follows:

$$\mathrm{newcost}(x, a) = \frac{a_0}{a}\mathrm{cost}(x), \tag{3}$$

where a is the area of the region and a_0 the baseline area of the Grand River watershed. Equation 3 is the one we use on the optimization models.

1.4 Wastewater Treatment Plants

There are 116 wastewater treatment plants (WWTPs) located in the watersheds that drain to Lake Erie (Figure 2). Abatement measures on these plants aim at

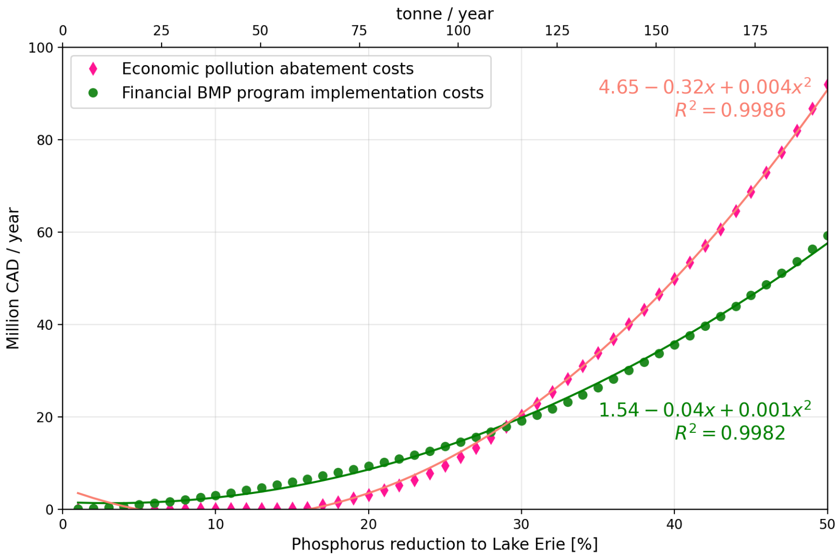

Figure 1: Abatement economic cost curve (shown in red).

Table 1: Areas of the Lake Erie model

Region	Name	Area km^2	%
SCR	Saint Claire River	0	0
LSC	Lake Saint Claire	10,573	44.2
DR	Detroit River	540	2.3
WB	Western Basin	673	2.8
CB	Central Basin	2,970	12.4
EB	Eastern Basin	9,184	38.4
	Sum	**23,941**	**100**

reducing phosphorus concentration on the discharge water. This can be achieved by installing a filter at the outlet of the plant that removes excessive phosphorus.

We assume the annual prorated cost of installing and maintaining a filter to decrease the amount of TP in the discharge water is proportional to the treatment volumes or capacity of the plants. We further assume the filter captures a percentage of the TP concentration on the treated water.

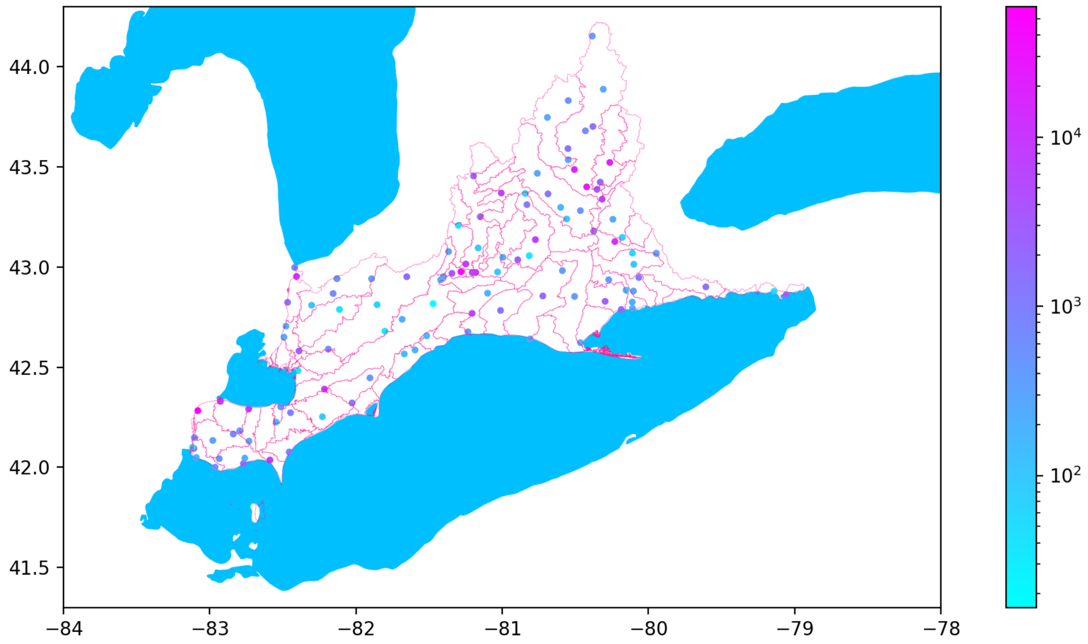

Figure 2: WWTPs located in Lake Erie watersheds, annual discharge (2018) in legend.

2 Methods

2.1 Model I

The model determines the abatement level in agriculture on each region of Lake Erie and whether to install a filter on each WWTPs located in these regions, such that a target P concentration reduction on the water bodies is achieved.

It assumes the area-adjusted abatement cost curve of the Grand River watershed (equation 3) also describes the cost of similar abatement measures on the other watersheds that drain to Lake Erie. Another assumption of the model is that all the WWTPs located on these watersheds have the capacity to install a filter to reduce P concentration on their discharge volumes.

The decision variables are the following:

- $x \in \mathbb{R}^{\mathrm{R}}$ is the TP abatement in agriculture in units $\left[\frac{\mathrm{t}}{\mathrm{year}}\right]$.
- $w \in \mathbb{R}^{\mathrm{I}}$ indicates whether WWTP i installs the filter $(w_i = 1)$ or not $(w_i = 0)$ $\left[\mathrm{unitless}\right]$.

The optimization model is

$$\min_{x,w} \quad x^{\mathrm{T}}Ax + b^{\mathrm{T}}w \tag{4}$$

s.t.

$$Sx + Ww \geq z_{\mathrm{Target}} \tag{5}$$
$$x \geq 0 \tag{6}$$
$$w_i \in \{0,1\} \quad \forall i, \tag{7}$$

and its parameters are

- A diagonal matrix of size $R \times R$ containing the quadratic terms of the cost function in equation 2 in [CAD year/t^2].
- S is the system matrix of equation 1 in [10^{-15} year/L].
- z_{Target} is the target concentration reduction in [ppb].
- $b_i = m + \frac{1}{T}\sum_{\tau=0}^{T} C_\tau (1+i)^{-\tau}$ is the annual maintenance and annual prorated net present value of the investment of installing the filter on WWTP i for a period of one year considering a filter lifetime of T years in [CAD / year].
- L is an indicator matrix of size $R \times I$ whose elements $l_{r,i} = 1$ if WWTP i is located in region r and zero otherwise [unitless].
- F is a diagonal matrix of size $I \times I$ whose diagonal elements $f_{i,i}$ are the TP decrease on the discharge of WWTP i in [t/year].

2.2 Model II

This model has the same variables and parameters as Model I but has an additional parameter, α, which expresses the relative weight or importance of concentration reductions on each region of the model. The objective function of Model I is introduced here as a constraint, and the phosphorus concentration constraint of Model I is introduced as the objective function.
The optimization model is

$$\max_{x,w} \quad \alpha^{\mathrm{T}}\big(Sx + Ww\big) \tag{8}$$

s.t.

$$x^{\mathrm{T}}Ax + b^{\mathrm{T}}w \leq \text{budget} \tag{9}$$
$$x \geq 0 \tag{10}$$
$$w_i \in \{0,1\} \quad \forall i. \tag{11}$$

3 Scenarios

Since excessive nutrient loading is most outstanding at the Western and Central Lake Erie basins, we create scenarios that set phosphorus reduction targets at these basins individually and jointly which are solved using model I:

- **Scenario A1**. Phosphorus concentration target reduction for the Western basin:
$$z_{\text{Target}} = [0, 0, 0, 1, 0, 0]^{\text{T}} \text{ in [ppb]}.$$
- **Scenario A2**. Phosphorus concentration target reduction for the Central basin:
$$z_{\text{Target}} = [0, 0, 0, 0, 1, 0]^{\text{T}} \text{ in [ppb]}.$$
- **Scenario A3**. Phosphorus concentration target reduction for the Western and Central basins:
$$z_{\text{Target}} = [0, 0, 0, 1, 1, 0]^{\text{T}} \text{ in [ppb]}.$$

As a separate set of experiments, we create **Scenario B** to test the optimal allocation of abatement measures to reduce the concentration assuming a given budget of 50, 100, 150,. . . , 500 million CAD annually. Since we are interested in reductions at the Western and Central basins, we set the weights of these basins to be 100 times that of the other regions:

$$\alpha_{\text{WB}} = \alpha_{\text{CB}} = 100\ \alpha_r, \text{ with } \alpha_r = 1 \text{ for all } r \in \big\{\text{SCR, LSC, DR, EB}\big\}.$$

4 Results

Scenario A1 shows the optimal total load reduction is 367 t/year, of which about 33% or 122 t/year comes from abatement measures in agriculture and the rest (around 245 t/year) come from implementing measures at WWTPs. The total cost of this program is 36 millions per year. Table 2 shows the optimal solution.

The lion's share of load reductions (63%) take place on areas that drain to Lake Saint Clair, followed by those at Detroit River (25%). It is noteworthy that load reductions at the basin that is directly targeted, the Western basin, only account for 12% of all load reductions. The optimal number of filters to install on WWTPs is 64.

Achieving the nutrient target on this scenario, a 1 ppb TP drop in concentration on the Western Basin, requires taking measures upstream and produces a positive externality on the downstream basins. The Central and Eastern Basins achieve a nutrient reduction without implementing any measure there.

Table 2: Optimal solution for Scenario A1

Region	Agr. abate.	WWTP abate.	Allocation	P reduction	WWTP
	t/year	t/year	%	z [ppb]	filters
SCR	0	0	0	0	0
LSC	68	164	63	1.14	51
DR	26	66	25	1.7	4
WB	28	15	12	1	9
CB	0	0	0	0.3	0
EB	0	0	0	0.14	0
Sum	122	245	100	4.28	64

For Scenario A2, a total load reduction of 987 t/year is needed to achieve the target of reducing 1 ppb TP on the Central Basin. Agriculture abatement measures account for 729 t/year or about 74% of the total, and WWTP measures account for 258 t/year or the remaining 26%.
The total cost of all abatement measures for this scenario is 414 million per year, which is a significant increase from the previos scenario. However, a common feature of both scenarios is the implementation of upstream measures: approximately 70% of the TP reduction effort takes place upstream in this scenario.

Table 3: Optimal solution for Scenario A2

Region	Agr. abate.	WWTP abate.	Allocation	P reduction	WWTP
	t/year	t/year	%	z [ppb]	filters
SCR	0	0	0	0	0
LSC	243	164	41	2	51
DR	91	66	16	2.9	4
WB	99	15	12	1.8	9
CB	296	13	31	1	10
EB	0	0	0	0.5	0
Sum	729	258	100	8.2	74

The results for Scenario A3 are identical to those of Scenario A2. The reason is that the optimal solution of Scenario A2 involves taking measures upstream that achieve a 1.8 ppb drop in the Western basin, which is higher than the target of 1 ppb imposed in Scenario A3. Since this result is not trivial and depends upon the parameters of the model, we decided to keep this scenario separate.

Results for **Scenario B** show the most effective budget allocation to reduce phosphorus concentration in Lake Erie also involves implementing abatement measures in croplands and WWTPs in areas that drain to Lake St. Clair as shown in Figure 3.
We notice decreasing marginal effects on nutrient reductions, meaning that for each additional dollar spent, its effectiveness gradually decreases. This is a consequence of having a quadratic cost function.

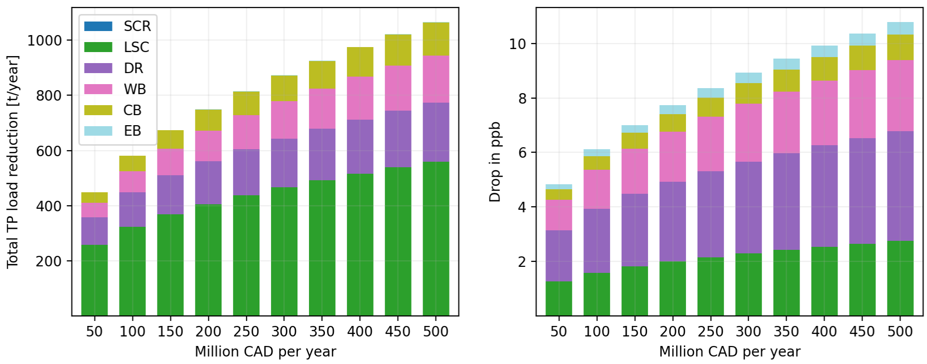

Figure 3: Results for Scenario B.

5 Conclusions

This work has shown the relevance of explicitly including the hydrological dependence among the Lake Erie (LE) basins when determining a program for nutrient reduction on localized regions. Upstream measures represent a more cost-effective solution to address nutrient mitigation at downstream areas.

Implementing abatement measures on the areas that drain to Lake St. Claire represent the most cost-effective way to reduce phosphorus concentration on the Western and Central Basins of LE. These measures would include investment in end-of-pipe filters for the WWTPs and the implementation of BMPs in agriculture.

Targeting the Central Basin requires a major effort in terms of load reductions and cost than targeting the Western Basin; however, as seen in the results of Scenario A, reducing phosphorus concentration on the Central Basin entails reducing the concentration on the upstream water bodies including the Western Basin.

Further improvements of the model include the inclusion of the US side of Lake Erie and allowing the model more investment options for WWTPs such as different types of phosphorus filters.

References

[1] S. B. Watson, C. Miller, G. Arhonditsis, G. L. Boyer, W. Carmichael, M. N. Charlton, R. Confesor, D. C. Depew, T. O. Höök, S. A. Ludsin, G. Matisoff, S. P. McElmurry, M. W. Murray, R. Peter Richards, Y. R. Rao, M. M. Steffen, and S. W. Wilhelm, "The re-eutrophication of lake erie: Harmful algal blooms and hypoxia," *Harmful Algae*, vol. 56, pp. 44–66, 2016.

[2] Environment and Climate Change Canada and the Ontario Ministry of the Environment and Climate Change, *Canada-Ontario Lake Erie action plan.* https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021WR030772, 2018.

[3] International Joint Commission, "Great lakes water quality agreement," 2012. https://www.canada.ca/en/environment-climate-change/services/great-lakes-protection/2012-water-quality-agreement.html.

[4] S. Bocaniov, D. Scavia, and P. Van Cappellen, "A mass-balance approach for predicting lake phosphorus concentrations as a function of external phosphorus loading: Application to the lake st. clair–lake erie system (canada–usa)," *Aquatic Ecosystem Health & Management*, vol. 26, no. 4, pp. 20–30, 2023.

[5] R. Brouwer, R. Pinto, J. Garcia-Hernandez, X. Li, M. Macrae, P. Rajsic, W. Yang, Y. Liu, M. Anderson, and L. Heyming, "Spatial optimization of nutrient reduction measures on agricultural land to improve water quality: A coupled modeling approach," *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, vol. 71, no. 3-4, pp. 329–353, 2023.