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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)

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A mass balance model is presented that links the total phosphorus concentration in lakes to the water residence time, R_w (lake volume divided by the annual water inflow) and the total phosphorus residence time, R_p (average standing stock of lake total phosphorous divided by the external annual total phosphorus input). Following a change in the external load, the lake total phosphorus concentration asymptotically approaches a new value that depends on the R_p:R_w ratio, with the rate of approach controlled by R_p. We applied this approach to a recent reanalysis of the water and total phosphorus budgets of the Lake Erie system of the Laurentian Great Lakes for the 2003-2016 period. We generated load–response relationships and response matrices that relate the steady state total phosphorus concentrations to external total phosphorus loads, for the whole Lake Erie system and for the individual basins (Lake St. Clair, western basin, central basin, eastern basin) and connecting channels (St. Clair River, Detroit River). These relationships and matrices provide a simple but robust framework to gauge the potential response of total phosphorus concentrations to total phosphorus load reductions, such as the 40% reduction proposed for Lake Erie under the Canada-United States Great Lakes Water Quality Agreement. The mass balance analysis further highlights the importance of inter-basin total phosphorus transfers. For example, around 70% of the total phosphorus concentration in the eastern basin is contributed by inflow from the central basin. Consequently, total phosphorus load abatements in watersheds upstream of the eastern basin, rather than in the direct watershed itself, will have the greatest impact on the eastern basin's concentration. Overall, our results illustrate how simple mass balance calculations can provide useful guidance to efforts to manage phosphorus enrichment of lakes.

Keywords: model, eutrophication, residence time

Introduction

Mass balance phosphorus (P) models have a long tradition in assessing and mitigating cultural eutrophication of lakes, including the Laurentian Great Lakes (Vollenweider, 1975; Burns et al.,

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1976; Chapra, 1977; Chapra and Robertson, 1977; Chapra and Sonzogni, 1979; Yaksich et al., 1985; Chapra and Dolan, 2012; Katsev, 2017). In the 1970s, mass-balance modeling informed the formulation of total P (TP) loading targets in the lower Great Lakes, especially Lake Erie (IJC, 1978; Table S-1; Supplementary material available online on publisher's website. note that tables and figures indicated with letter "S" are in the Supporting Information). The proposed TP target load for Lake Erie at that time was 11,000 MTA (MTA: Metric Tons per Annum), a reduction of 55% from the 1976 load, with an expected lowering of the open-lake spring concentrations to 15, 10, and 10 µg P l^{-1} for the Lake's western, central, and eastern basins, respectively (Table S-1). The new target load was achieved relatively quickly with significant improvements in water quality from the mid-1980s to mid-1990s.

Since the late 1990s, the return of harmful algal blooms and expanding hypoxia in Lake Erie have prompted calls for even stricter controls on the external P loads (IJC, 2012; GLWQA, 2016; Mohamed et al., 2019). This led to revised phosphorus loadings reduction targets that include a further 40% reduction in TP loads from the 2008 levels for the tributaries discharging in the western and central basins while the loading reduction target for the watershed of the eastern basin is still under consideration. The expected offshore spring TP concentrations are 12, 6, and 6 µg P l^{-1} for the western, central, and eastern basins, respectively (EPA, 2015). The establishment of new loading targets was guided by the GLWQA Nutrients Annex (Annex 4) multi-modeling efforts (Scavia et al., 2016) that combined the outputs from mass balance (Chapra et al., 2016), statistical (Bertani et al., 2016; Stumpf et al., 2016) and dynamic (e.g. Bocaniov et al., 2016; Rucinski et al., 2016) models.

The water residence time (R_w), here defined as a lake's volume divided by the yearly water input, is a key predictor of the in-lake TP retention efficiency (Vollenweider, 1975; Hejzlar et al., 2006; Maavara et al., 2015; Bocaniov and Scavia, 2018). Similarly, the TP residence time (R_p), defined as the standing stock of TP in the lake's water column divided by the yearly external TP supply, to R_w ratio (i.e. R_p:R_w) is known to be closely related to the trophic state of lakes (Janus and Vollenweider, 1984). Here, we apply a balance modeling approach based on the relative magnitudes of R_p and R_w to the TP cycling in the Lake St. Clair–Lake Erie (LSC-LE) system.

In a recent publication, the authors re-analyzed data from 2003 to 2016 to produce average, steady state water and TP budgets for the LSC-LE system (Bocaniov et al., 2023). Here, we use these revised budgets to relate the average water column TP concentrations of the segments of the system to the corresponding external TP loads via the average water and TP residence times. We then illustrate how the approach can be used to produce first-order estimates of expected changes in TP concentrations in response to sustained changes in external TP loads along the LSC-LE continuum. While applied here to a specific lake system, the approach is general and can be applied to other aquatic systems once their water and TP budgets are known.

Total phosphorus mass balance model

The simplest formulation of the mass balance of TP in a lake (or a lake basin) is given by the following ordinary differential equation:

$$V\frac{dc}{dt} = Qc_i - Qc - kcV \tag{1}$$

where V is the volume of the lake, Q is the combined volumetric water inflow to the lake, c_i is the flow-weighted TP input concentration considering all the input pathways to the lake, c is the average TP concentration in the lake's water column, t is time, and k is the net in-lake TP loss rate coefficient in units of inverse time.

The key assumptions in Equation 1 are: (1) the lake can be treated as a well-mixed reservoir; (2) V is time-invariant, (3) the combined in-lake loss of TP (e.g. through sediment burial and water extraction) can be treated as a simple first-order process. Note that c_i is obtained by summing all the external TP loads and then dividing by the total water inflow, Q. In that way, input pathways not associated with advective water inflow (e.g. atmospheric deposition and diffusive exchanges) are taken into account.

Following Sonzogni et al. (1976), Equation 1 can be re-arranged to:

$$dc + \left(\frac{Q + kV}{V}\right) c\, dt = \frac{Q}{V} c_i\, dt \tag{2}$$

which can be further simplified by introducing the water (R_w) and TP (R_p) residence times, defined as follows (Sonzogni et al., 1976):

$$R_w = \frac{V}{Q} \tag{3}$$

and

$$R_p = \frac{V}{Q + kV} \tag{4}$$

hence yielding:

$$dc + \frac{1}{R_p} c\, dt = \frac{1}{R_w} c_i\, dt \tag{5}$$

Solving Equation 5 for the in-lake concentration *c* results in:

$$c = \frac{R_p}{R_w} c_i - \left(c_i \frac{R_p}{R_w} - c_o \right) e^{-t/R_p} \tag{6}$$

where the initial concentration at $t = 0$ is $c = c_o$. With increasing time *t*, the second term on the right-hand side of Equation (6) exponentially decays away and the concentration asymptotically approaches the new steady state value:

$$c_\infty = \frac{R_p}{R_w} c_i \tag{7}$$

Equation 7 shows that, under steady state conditions, the expected water column concentration scales linearly with the flow-weighted input concentration c_i, while the R_p:R_w ratio acts as the proportionality constant. Note that if TP behaves as a conservative constituent, R_p:R_w = 1 and the steady state concentration converges to $= c_i$. Thus, the deviation of R_p:R_w from unity is a measure of the non-conservative behavior of TP in a lake. In case of net in-lake removal of TP from the water column, R_p:R_w < 1. The latter is usually the case with phosphorus being removed through burial in the lake's bottom sediment. In more exceptional cases, R_p:R_w > 1, for example, when bottom sediment resuspension or shoreline erosion causes a net in-lake addition of TP to the water column. In such a situation, the rate coefficient *k* in Equation 1 would be negative.

The exponential term in Equation 6 controls the time-dependent evolution of the TP concentration following a step change in the input concentration c_i. For a steady-state water budget (i.e. a constant *Q*), a change in c_i causes a proportional change in the external loading (i.e. $Q \cdot c_i$). Thus, R_p represents the characteristic response time of the lake's TP cycle to a change in the external TP loading. The time required to reach a given concentration value *c* following a change in external loading is given by:

$$t = -\ln\left(\frac{c_\infty - c}{c_\infty - c_o}\right) \cdot R_p \tag{8}$$

It is important to note that predictions based on the above model assume that the in-lake processes affecting the TP concentration are not changing over time, that is, the rate parameter *k* remains constant.

Lake St. Clair-Lake Erie system

Physiography

The Lake St. Clair – Lake Erie (LSC-LE) system is an integral part of the Laurentian Great Lakes system shared between Canada and United States (Fig. 1). At the upstream end, Lake Huron water flows into the St. Clair River that discharges into Lake St. Clair. Water subsequently exits Lake St. Clair via the Detroit River that, in turn, flows into Lake Erie's western basin. Within Lake Erie, net water movement is eastward, from the western basin to the central basin and then to the eastern basin. Outflow from Lake Erie into Lake Ontario is principally via the Niagara River with a much smaller fraction leaving through the Welland Canal.

Although the St. Clair River and Detroit River are called rivers, they are actually fast-flowing connecting channels. The St. Clair River (64 km long and 9-21 m deep) and the Detroit River (51 km long and 6-15 m deep) have very short hydraulic residence times of less than one day (Table 1). Lake St. Clair is relatively large and shallow (area 1114 km^2; mean depth 4 m) with a relatively short water residence time (~ 10 days; Bocaniov et al., 2019). By contrast, Lake Erie is huge (area 25,654 km^2; Table 1) and consists of a sequence of three major basins: the relatively shallow western basin (mean depth 8.5 m; volume 27.8 km^3), the central basin (mean depth 19.7 m; volume 318.7 km^3), and the deepest eastern basin (mean depth 25.5 m; volume:

159.3 km^3). The three basins together contain about 505.8 km^3 of water and the entire LSC-LE system 511.2 km^3 (Table 1).

Water and total phosphorus budgets

The authors recently re-evaluated the water and TP budgets for the six segments of the LSC-LE system, that is, St. Clair River, Lake St. Clair, Detroit River plus the three basins of Lake Erie (Bocaniov et al., 2023). They produced multi-year averaged annual water and TP budgets for the period 2003-2016. Figure 2 and Tables 1 and S-2 summarize the relevant features of the budgets, with additional details in Table S-3, including the mean annual TP concentrations in the six segments of the LSC-LE system.

Most water inflow to the LSC-LE system is from Lake Huron (159.1 km^3 yr^{-1}; Fig. 2). Surface inflow and groundwater discharge from the entire LSC-LE watershed plus on-lake precipitation together account for about 53.2 km^3 yr^{-1}. The outflow to Lake Ontario is 187.2 km^3 yr^{-1}, 12% lower than the total inflow to the LSC-LE system because of evaporation and other water losses, in particular consumptive usage. Equation 1 does not explicitly represent these loss terms. When fitting the steady state TP model to the observed TP concentrations in the various segments of the LSC-LE system, the impact of water losses other than the downstream outflow from the segment is therefore folded in the segment-specific apparent rate coefficients k.

For each segment of the LSC-LE system, the average annual values of the water volume and

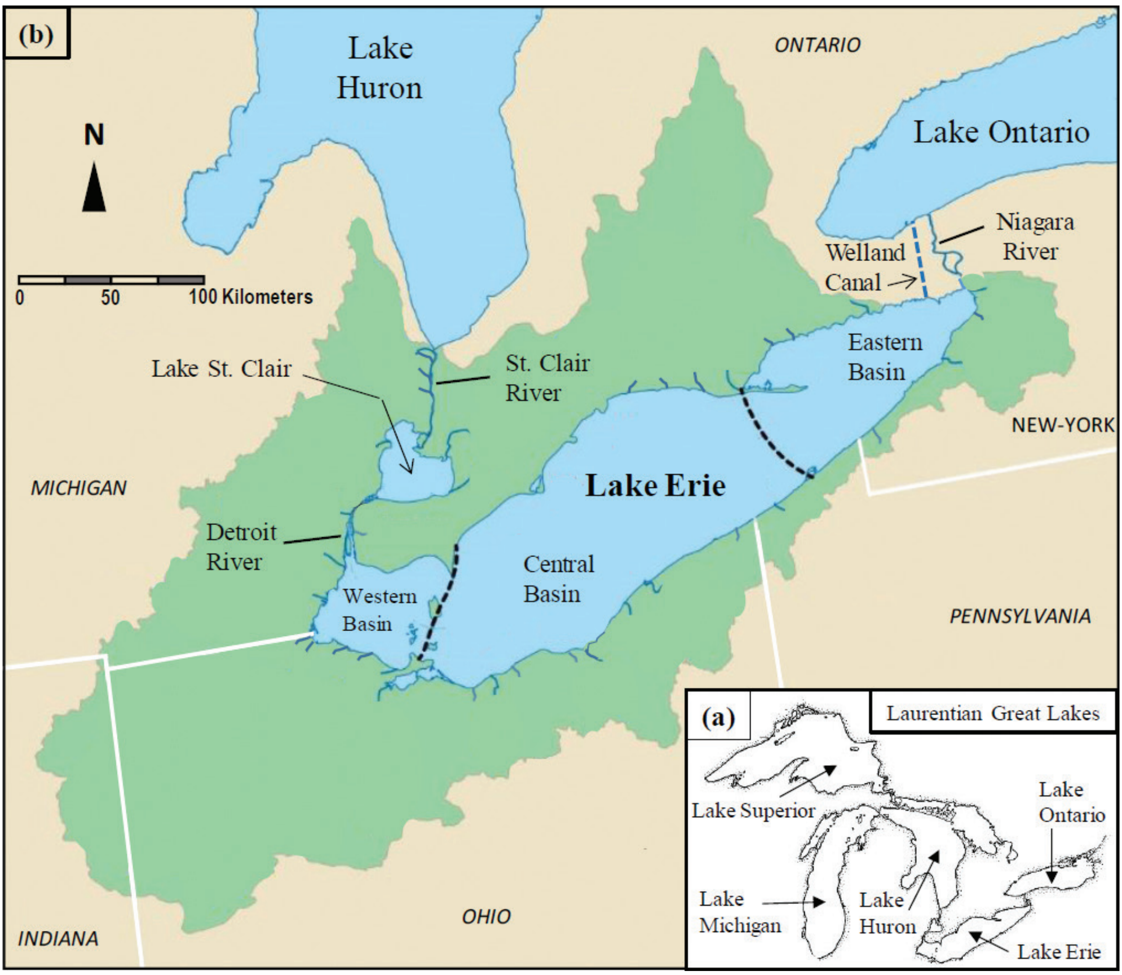

Figure 1. (a) Map of the Laurentian Great Lakes of North America; (b) Map of the Lake St. Clair - Lake Erie (LSC-LE) system. Area in green indicates the boundaries of the LSC-LE watershed area.

Table 1. For each segment of the Lake St. Clair–Lake Erie system the table provides: the average water volume (V), the annual water inflow (Water INflow) and outflow (Water OUTflow), the water residence time (R_w), the mean annual total phosphorus (TP) concentration ([TP] segment) and standing stock of TP (TP Stock), the total TP loading (TP Load), the TP residence time (R_p), the input TP concentration ([TP] inflow), and the R_p:R_w ratio. All values are averages for the 2003-2016 period (Bocaniov et al., 2023).

Segment	V*	Water INflow	Water OUTflow	R_w	[TP] segment	TP Stock	TP Load	R_p	[TP] inflow	R_p:R_w
	km^3	km^3 yr^{-1}	km^3 yr^{-1}	day	mg m^{-3}	MT	MTA	day	mg m^{-3}	-
St. Clair River	~0.4	160.0	160.0	0.88	12.94	~5	2070	0.88	12.94	1.00
Lake St. Clair	4.6	165.5	164.5	10.15	14.95	69	3034	8.27	18.34	0.815
Detroit River	~0.4	165.2	165.2	0.83	18.84	~7	3112	0.83	18.84	1.00
Lake Erie, including:	505.8	-	-	953	-	5012[a]		312		0.33
- Western Basin	27.8	177.1	173.9	57	19.42	540[b]	6260	31	35.36	0.55
- Central Basin	318.7	195.6	180.4	595	10.39	3311[c]	6730	180	34.52	0.30
- Eastern Basin	159.3	193.1	187.2	301	7.29	1161[d]	4183	101	21.66	0.34
LSC-LE System	511.2	212.3	187.2	-	-	5093	11,712	-	-	-

Note: * Based on mean water levels over 2003 to 2016 period: 175.95 (Lake St. Clair) and 174.16 (Lake Erie) meters above International Great Lakes Datum (1985).
[a] mean stock: 5012 MTA, spring stock: 6328 MTA, summer stock: 3699 MTA;
[b] mean stock: 540 MTA, spring stock: 643 MTA, summer stock: 437 MTA;
[c] mean stock: 3311 MTA, spring stock: 4153 MTA, summer stock: 2473 MTA;
[d] mean stock: 1161 MTA, spring stock: 1532 MTA, summer stock: 789 MTA.

total water inflow were used to calculate the water residence time (R_w, Equation 3). For a given segment of the LSC-LE system, the total water inflow includes the inflow from the upstream segment, the direct surface and groundwater discharge from the segment's own watershed, and the amount of precipitation received by that segment. Next, the TP residence time, R_p, in each of the segments was obtained by fitting Equation 7 to the mean annual water column TP concentration using the known values of R_w and c_i, and adjusting the value of k. Once R_w and R_p are defined for each segment, then they can be used in estimates of TP concentrations (Tables S-4 and S-5).

The mean water column TP concentrations are the arithmetic averages of the concentrations measured in April (spring) and August (summer) as part of the regular U.S. monitoring programs. The offshore spring and summer TP concentrations in the three basins of Lake Erie vary significantly, however (Table S-3). Spring concentrations are typically higher than summer values with, on average, relatively smaller differences in the western basin (47%: 23.1 ±12.9 versus 15.7 ±6.2 µg P l^{-1}), higher in the central basin (67%; 13.0 ±3.6 versus 7.8 ±1.7 µg P l^{-1}), and highest in the eastern basin (92%; 9.6 ±2.1 versus 5.0 ±0.8 µg l^{-1}). For each of the three basins, empirical correlations between the spring and summer TP concentrations and the mean TP concentration were derived from the 2003-2016 data (Table S-6). These were used to derive individual load-response curves for the mean, spring, and summer TP concentrations.

Results and discussion

Water and Total Phosphorus residence times

The water residence times (R_w) range from less than 1 day for the St. Clair River and Detroit River to about 10 days for Lake

St. Clair, and 953 days (2.61 years) for Lake Erie (Table 1). Large differences exist between Lake Erie's basins, however: 57 days for the western basin, 595 days for the central basin, and 301 days for the eastern basin. The TP residence times (R_p) are indistinguishable from R_w for the fast-flowing connecting channels (St. Clair River and Detroit River). By contrast, in the lake segments the R_p values are systematically shorter than the corresponding R_w values: R_p ranges from 8 days for Lake St. Clair to 312 days for Lake Erie, with 31, 180, and 101 days for the western, central, and eastern basins, respectively (Table 1). Hence, whereas the R_p:R_w ratios of the connecting channels approach unity, R_p:R_w < 1 for the lake segments: 0.82 and 0.33 for Lake St. Clair and Lake Erie, and 0.55, 0.34, and 0.30 for the western, eastern, and central basins, respectively.

Interannual variability

Prior to assessing the interannual variability of R_w and R_p, it is helpful to define the variability in the annual water and TP loads using the coefficient of variation (CV), that is, the ratio of the standard deviation to the mean, with CV values usually expressed in relative terms (as a percentage). On average, we find that the variation in TP loads is almost three times larger than for water loads. For example, average CVs for the three basins of Lake Erie were 6.1% and 17.2% for the water and TP loads, respectively (Table S-2).

The residence times are based on the water and TP budgets averaged over the 2003-2016 period (Figure 2). As such, they represent the long-term, steady-state R_p and R_w values that reproduce the 14-year averaged annual TP concentrations in the various segments of the LSC-LE system. In any given segment, however, the annual TP concentration varies from year to year due to inevitable fluctuations in water flows, TP inputs, and in-lake removal rates, as well as non-steady state conditions. To delineate the level of interannual variability that can be expected, the annual TP concentrations observed each year (from 2003 to 2016) in the four lake segments are plotted in Figure 3 against the model-derived steady state concentrations. The results show that the observed annual TP concentrations lie roughly within factors of ±2 μg P l^{-1} of the model values.

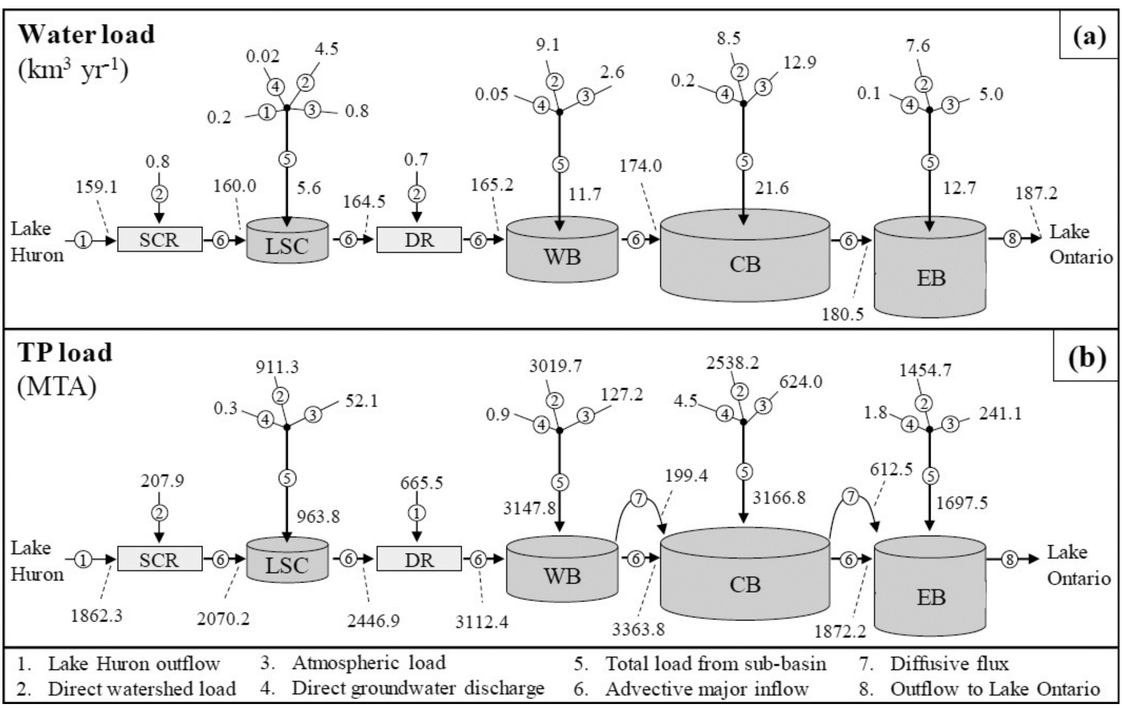

Figure 2. Lake St. Clair – Lake Erie System water (a) and total phosphorus (TP; b) annual budgets averaged over the 2003-2016 period. MTA: metric tonnes per annum. All values from Bocaniov et al. (2023). See Table S-2 for more detailed information on loads.

This range of interannual variability provides a first rough estimate of the uncertainty associated with the predictions of the steady state TP model.

Load-response curves

The load-response curves in Figure 4 show the model-predicted steady state TP concentrations in the three basins of Lake Erie for TP loads ranging from 20% to 120% of the average 2003-2016 TP loads. In the calculations, the TP loads are varied but the water budget is assumed to remain unchanged (Figure 2a). Furthermore, the same relative change in TP load is imposed simultaneously to the inflow from Lake Huron and the direct watershed surface discharges while keeping the TP loads associated with atmospheric deposition and groundwater input the same as in the 2003-2016 average TP budget (Figure 2b). In addition to the load-response curves for the mean annual open water TP concentrations, Figure 4 also shows the load-response curves for the spring and summer concentrations derived using their empirical linear correlations to the annual mean concentrations given in Table S-6.

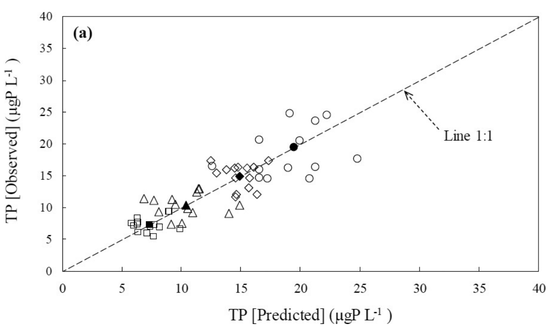

Figure 3. Annual TP concentrations observed each year between 2003 and 2016 in the four lake segments (Lake St. Clair and the three basins of Lake Erie) plotted against the model-derived steady state TP concentrations. Open symbols indicate single-year values while the solid symbols are the 2003-2016 average values. One outlier for the year 2009 in the western basin has been removed from the graph because of heavy wave-induced resuspension during a storm at the time of sampling (April 2009). Lake St. Clair: diamonds; western basin: circles; central basin: triangles; eastern basin: squares.

Based on the load-response curves, if the external TP load to Lake Erie is brought down by 40% from the 2008 baseline of 11,000 MTA, then the spring offshore TP concentrations would drop to 13.1, 7.8, and 5.9 μg P l^{-1} for the western, central, and eastern basin, respectively (Figure 4b). For comparison, the corresponding average 2003-2016 concentrations are 23.1, 13.0, and 9.6 μg P l^{-1} (Table S-1). These predicted post-load reduction spring TP concentrations are comparable to the previously expected concentrations in the three basins of 12, 6, and 6 μg P l^{-1} following a 40% TP load reduction (EPA, 2015).

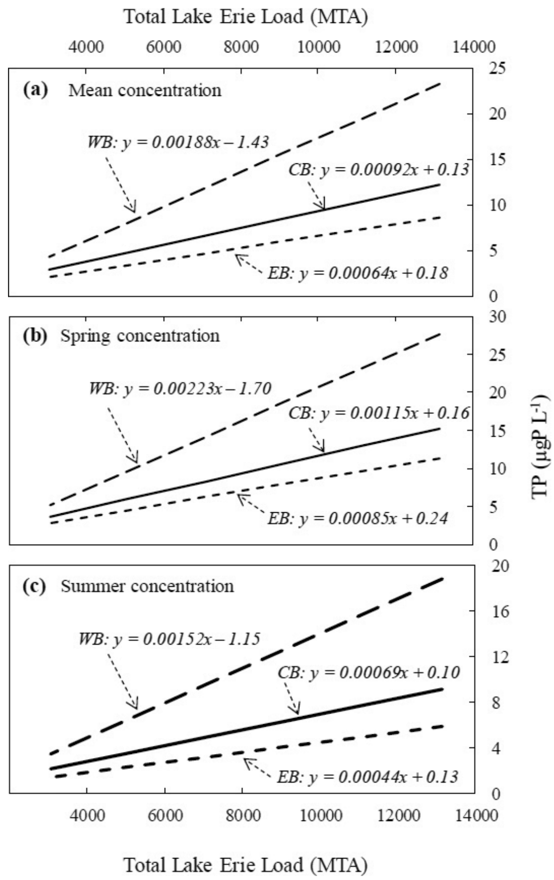

Figure 4. (a-c) Load-response curves with the corresponding regression equations for the mean annual (a), spring (b) and summer (c) TP concentrations of the three basins of Lake Erie plotted versus the total TP load to Lake Erie. See text for detailed explanation.

The load-response curves that relate the basin-specific TP concentrations to the total external TP loading (Figure 4) can also be used to predict other water quality indicators that are in turn related to the TP concentrations (Figures S-1 and S-2). For example, the summer phytoplankton biomass (Chlorophyll-a, Chl-a) in Lake Erie and other Laurentian Great Lakes has previously been correlated to the spring TP concentrations, with the latter being correlated to summer water

Table 2. Steady state response matrix for the Lake St. Clair – Lake Erie continuum for the 2003-2016 period. The values indicate the increase (decrease) in TP concentration (μg P l^{-1}) in each segment (row) for an increase (decrease) of 1000 MTA TP load from Lake Huron (LH), the segment's watershed, and the watershed of any upstream segment (columns). SCR: St. Clair River; LSC: Lake St. Clair; DR: Detroit River; WB: Western Basin; CB: central basing; EB: Eastern Basin.

	Loading						
	LH	SCR	LSC	DR	WB	CB	EB
Response							
St. Clair River (SCR)	6.2525	6.2525					
Lake St. Clair (LSC)	4.9245	4.9245	4.9245				
Detroit River (DR)	4.9035	4.9035	4.9035	6.0535			
Western Basin (WB)	2.5170	2.5170	2.5170	3.1073	3.1073		
Central Basin (CB)	0.7321	0.7321	0.7321	0.9038	0.9038	1.4838	
Eastern Basin (EB)	0.3620	0.3620	0.3620	0.4469	0.4469	0.7322	1.3063

Table 3. Steady state response matrix for the Lake St. Clair – Lake Erie continuum for the 2003- 2016 period. The values indicate the contributions to the mean annual TP concentration (μg P l^{-1}) in each segment (row) of the TP inflow from Lake Huron and those of the TP watershed load plus TP atmospheric deposition to the segment itself and any upstream segment. Abbreviations are the same as in Table 2.

	Total load (watershed plus atmospheric)							Total concentration
	LH	SCR	LSC	DR	WB	CB	EB	
Response								
St. Clair River (SCR)	11.64	1.30						12.94
Lake St. Clair (LSC)	9.17	1.02	4.75					14.94
Detroit River (DR)	9.14	1.02	4.72	4.03				18.91
Western Basin (WB)	4.68	0.53	2.43	2.07	9.78			19.49
Central Basin (CB)	1.37	0.15	0.71	0.60	2.84	4.70		10.37
Eastern Basin (EB)	0.68	0.07	0.35	0.30	1.41	2.32	2.21	7.34

Table 4. Steady state response matrix for the Lake St. Clair – Lake Erie continuum for the 2003- 2016 period. The values indicate the contributions to the mean annual TP concentration (μg P l^{-1}) in each segment (row) of the TP inflow from Lake Huron and those of the TP watershed load plus TP atmospheric deposition of the segment itself and any upstream segment. Abbreviations are the same as in Table 2.

	Atmospheric deposition load							Total concentration
	LH	SCR	LSC	DR	WB	CB	EB	
Response								
St. Clair River (SCR)	-	-						
Lake St. Clair (LSC)	-	-	0.26					0.26
Detroit River (DR)	-	-	0.25	-				0.25
Western Basin (WB)	-	-	0.13	-	0.40			0.53
Central Basin (CB)	-	-	0.04	-	0.11	0.93		1.08
Eastern Basin (EB)	-	-	0.02	-	0.06	0.46	0.31	0.85

transparency (Secchi disc Depth: SD; Dove and Chapra, 2015; see Figures S-1a and S-1b). Similarly, the seasonal (May 1 – October 31) integrated phytoplankton primary production (PP) can be derived from the load-response curves by applying relationships between PP and TP reported for the lower Laurentian Great Lakes (Millard et al., 1996; Graham et al., 1996; see Figure S-1c). First-order estimates of annual fish community production (FP; Figure S-2a) and annual mean fish community standing biomass (FB; Figure S-2b) can also be obtained using global relationships with mean TP concentrations (Downing et al., 1990). While the empirical relationships for the water quality indicators yield relatively rough estimates, these may be useful in framing decisions. For example, the proposed 40% reduction in total Lake Erie TP load is predicted to decrease the summer Chl-a concentrations by 35 to 38% across Lake Erie, while seasonal PP would also drop by at least one third in the three basins (Table S-7). Additionally, we would predict substantial improvements in water clarity, with SD on average increasing by more than one meter (Table S-7). At the same time, fish community production and standing biomass could see a decrease by up to one fourth (Table S-7).

Response matrices

Model response matrices yield further insights into the sensitivity of the TP concentrations in the various segments of the LSC-LE system to the external TP loads (Tables 2 to 4). Following the approach proposed by Chapra and Sonzogni (1979), we computed the model-predicted increase (decrease) in the mean annual TP concentration in each of the segments resulting from an increase (decrease) of 1000 MTA of TP loading to the segment itself, as well as to the TP loading in the upstream segments plus that supplied from Lake Huron (Table 2). Thus, a 1000 MTA reduction of the TP inflow from Lake Huron is predicted to lower the mean annual TP concentration of Lake St. Clair and the western, central, and eastern basins of Lake Erie by 4.92, 2.52, 0.73, and 0.36 µg P l^{-1}, respectively. Similarly, a 1000 MTA reduction in TP load to the western basin would cause a lowering of the mean annual TP concentration of the western, central, and eastern basins by 3.11, 0.90, and 0.45 µg P l^{-1}, respectively. Results from our response matrix (Table 2) can further be used to develop a set of equations directly predicting mean offshore TP concentrations as a function of loads (Table S-8).

Alternatively, the importance of the hydrological connectivity along the LSC-LE continuum is illustrated by calculating how much of the mean annual TP concentration in a given segment can be attributed to the direct watershed TP inputs plus atmospheric deposition of that segment and how much originates from the TP loads of the upstream segments and from Lake Huron (Table 3). For example, according to Table 3, direct TP loading to the central basin contributes 4.70 µg P l^{-1} to the mean annual TP concentration in that basin, while the loads to the western basin and Lake Huron contribute 2.84 and 1.37 µg P l^{-1}, respectively.

For Lake St. Clair, of the mean annual TP concentration of 14.94 µg P l^{-1}, 68% (10.19 µg P l^{-1}) is supplied from upstream sources by the St. Clair River (Table 3). While upstream loading plays a relatively lower role in the western basin, it still represents about 50% (9.71 µg P l^{-1}) of the mean annual TP concentration in that basin (19.49 µg P l^{-1}). For the central and eastern basins, the upstream contributions represent 55 and even 70%, respectively. The TP loading from Lake Huron alone explains 61, 24, 13, and 9% of mean annual TP concentrations in Lake St. Clair and the western, central, and eastern basins, respectively (Table 3).

The TP loading contributions in Table 3 are based on combined watershed and on-lake atmospheric inputs. In Table 4, the contributions from atmospheric TP deposition (wet plus dry) alone are separated out. While they are still fairly rough estimates, the atmospheric contributions are not negligible and may account for around 10% of the mean annual TP concentration integrated for the entire LSC-LE system. The results for the direct watershed TP inputs without the atmospheric contributions are given in Table S-9.

Response times

So far, the focus has been on changes in mean annual TP concentrations under steady state conditions. Estimates of how long it takes for the TP concentrations in the various segments of the LSC-LE system to adjust after a step change in TP inputs are determined by the segment-specific R_p values (Equation 8). For example, the time required to converge to within 5% of a new steady state concentration is 3 times R_p. For Lake St. Clair and the western basin of Lake Erie this would be relative fast: 25 and 93 days, respectively. The central and eastern basin would require longer, 540 and 303 days, respectively, extending to 936 days

(2.6 years) for Lake Erie as a whole. Our results are in line with the previous studies of Sonzogni et al. (1976) and Katsev (2017) who proposed that Lake Erie would respond relatively fast to changes in external TP inputs. The characteristic response time of Lake Erie (R_p = 312 days, Table 1) also implies that the observed annual TP concentration in any given year is still influenced by TP loads that occurred in the preceding few years, hence in part explaining the scatter in Fig. 3.

Implications

Load-response curves, such as those shown in Figure 4, can in principle be constructed for any scenario of TP load changes in the LSC-LE system. They can also serve as a basis to develop load-response curves for other bio-physical indicators of water quality linked to TP concentrations (e.g. Figures S-1 and S-2). The response matrices further help identify how changes in TP loads may impact the TP concentrations along the entire LSC-LE continuum by considering the downstream cascading effects. The latter are crucial in large, interconnected multi-basin lake systems such as the Laurentian Great Lakes (LGL). While our analysis here is restricted to the LSC-LE system, the approach can be extended to the other LGL and used, for instance, to assess how TP load reductions in the Lake Erie watershed would translate to water quality improvements in Lake Ontario and, ultimately, TP loads exported to the St. Lawrence River system. From a practical viewpoint, load-response curves and response matrices can help steer P abatement management by optimizing proposed load reductions that most effectively enable reaching the expected water quality improvements.

Conclusions

Lake eutrophication involves a complex set of external and internal drivers and processes, and their interactions. Yet, to this day, controlling external P loads remains a major lever to manage lake eutrophication. A variety of modeling approaches are being used to assess the ecosystem responses to P load reductions in lakes, from simple to highly advanced. Among these, parsimonious mass balance P models make up for their lack of sophistication by their limited number of predictor variables and adjustable parameters while still providing robust and verifiable predictions. Furthermore, as argued here, the mass balance results can be conveyed through metrics (R_p and R_p:R_w), graphics (load-response curves) and tables (response matrices), that is, decision-support tools that are easy to implement for systems ranging from reservoirs, via lakes, to nearshore marine environments.

Data availability

The datasets used in this study comprise those previously disclosed in our publication (Bocaniov et al., 2023: Ecol. Inform., 77, 102131; https://doi.org/10.1016/j.ecoinf.2023.102131), supplemented by additional openly accessible data retrieved from the Federated Research Data Repository (FRDR) accessible at https://doi.org/10.20383/102.0695.

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Supplementary material

Supplementary material for this article can be found online on th publisher's website.

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