Journal of Great Lakes Research xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

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

Updated phosphorus loads from Lake Huron and the Detroit River: Implications

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ARTICLE INFO

Article history:
Received 20 October 2022
Accepted 13 January 2023
Available online xxxx
Communicated by Craig Stow

Keywords:
Phosphorus load targets
Lake Huron
St. Clair River
Detroit River
Monitoring
Resuspension
Hypoxia
Lake Erie

ABSTRACT

The binational Great Lakes Water Quality Agreement (GLWQA) revised Lake Erie's phosphorus (P) loading targets, including a 40% western and central basin total P (TP) load reduction from 2008 levels. Because the Detroit and Maumee River loads are roughly equal and contribute almost 90% of the TP load to the western basin and 54% to the whole lake, they have drawn significant policy attention. The Maumee is the primary driver of western basin harmful algal blooms, and the Detroit and Maumee rivers are key drivers of central basin hypoxia and overall western and central basin eutrophication. So, accurate estimates of those loads are particularly important. While daily measurements constrain Maumee load estimates, complex flows near the Detroit River mouth, along with varying Lake Erie water levels and corresponding back flows, make measurements there a questionable representation of loading conditions. Because of this, the Detroit River load is generally estimated by adding loads from Lake Huron to those from the watersheds of the St. Clair and Detroit rivers and Lake St. Clair. However, recent research showed the load from Lake Huron has been significantly underestimated. Herein, I compare different load estimates from Lake Huron and the Detroit River, justify revised higher loads from Lake Huron with a historical reconstruction, and discuss the implications for Lake Erie models and loading targets.

Introduction

In response to Lake Erie's re-eutrophication (Scavia et al., 2014; Watson et al. 2016), the United States and Canada revised the phosphorus (P) loading targets of the Great Lakes Water Quality Agreement (GLWQA, 2016) based on science synthesized in a multi-model effort (Scavia et al., 2016) and public input. The new targets include a 40 % western and central basin total P (TP) load reduction from the 2008 levels to achieve an annual load of 6,000 metric tons to return hypoxic extent to about 4500 km^2, comparable to that in 1990 s to early 2000 s.

Because the Detroit and Maumee River loads are roughly equal and together contribute about 90 % of the TP load to the western basin and 54 % to the whole lake (Scavia et al., 2016; Maccoux et al., 2016), they have drawn significant policy attention. The Maumee is the primary driver of western basin harmful algal blooms (HABs, Michalak et al., 2013; Scavia et al., 2016; Watson et al., 2016). Lake Erie's circulation patterns and the Detroit River's relatively low phosphorus concentrations render it less important for western basin HABs. However, the Detroit and Maumee rivers are key drivers of central basin hypoxia (Leon et al., 2011; Scavia et al., 2014; Bocaniov et al., 2016). The Detroit River load may also stimulate non-HAB biomass in the western and central basins. While TP concentrations in the Detroit River are likely too low to drive HABs, the typical 10–20 μg/l concentrations (Burniston et al. 2018) are sufficient to stimulate non-HAB species. For example, Manning et al. (2019) showed that while the chlorophyll concentrations along the northern shore of the western basin are generally below the 18 μg/l threshold typically associated with HABs (Sayers et al., 2016), values in 2002 – 2016 ranged from 7.3 to 18.6 μg/l, with an overall mean of 12.1 μg/l.

So, accurate estimates of those riverine loads are particularly important. Because the Maumee load has been monitored at least daily for decades (Baker et al., 2014; Stow et al., 2015), its load is well constrained. In contrast, complex flows near the mouth of the Detroit River, along with varying Lake Erie water levels and corresponding back flows, make measurements there a questionable representation of loading conditions. Because of this, the Detroit River load is generally estimated by adding loads from Lake Huron to those from the watersheds of the St. Clair and Detroit rivers and Lake St. Clair (hereafter, Huron-Erie Corridor, HEC, Fig. 1a). However, research since the GLWQA revision showed that Lake Huron's load has been significantly underestimated (Burniston et al., 2018; Scavia et al., 2019a, b, 2020, 2022).

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https://doi.org/10.1016/j.jglr.2023.01.008
0380-1330/© 2023 Published by Elsevier B.V. on behalf of International Association for Great Lakes Research.

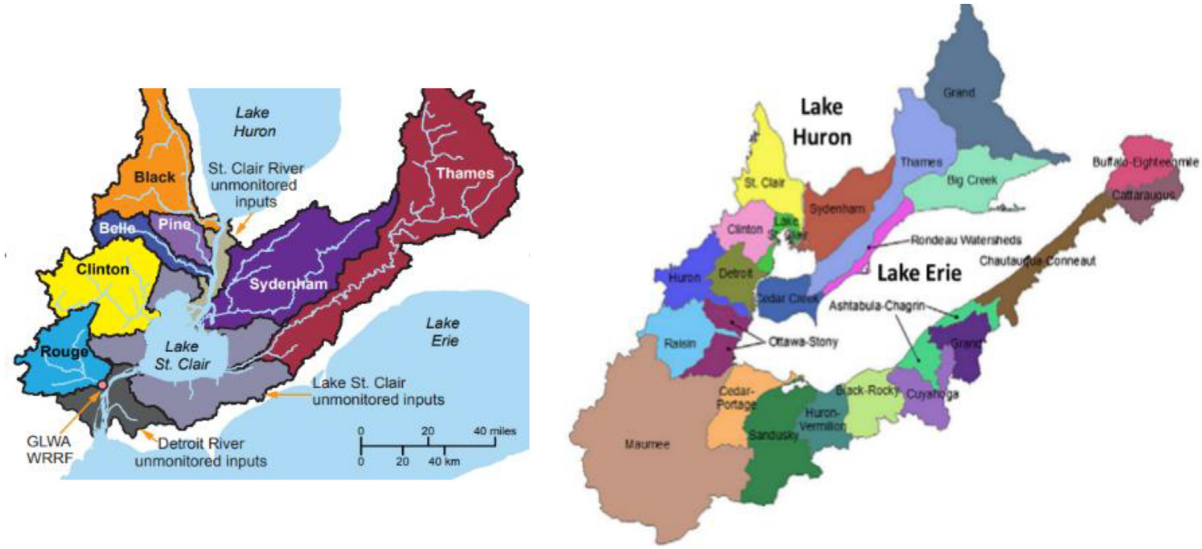

Fig. 1. (a, left) Huron-Erie Corridor watersheds (Scavia et al., 2019c) and (b, right) Lake Erie watersheds (Scavia et al., 2014).

In this paper, I compare different load estimates from Lake Huron and the Detroit River, justify the revised higher loads from Lake Huron based on a historical reconstruction, and discuss implications for Lake Erie models and load reduction targets. This important update should be useful to the GLWQA adaptive management process, a learning process that integrates models and assessments with new knowledge to evaluate if goals and actions are still appropriate (Hollings, 1978; Walters, 1986).

Methods

Study site. Lake Huron, the second largest Laurentian Great Lake and fifth largest freshwater lake in the world, is oligotrophic based on biological, chemical, and physical characteristics of its open waters, although higher nutrient concentrations are found in Saginaw Bay and nearshore areas. The St. Clair River is a connecting channel flowing 64 km from Lake Huron to Lake St. Clair, forming an international boundary between the United States and Canada (Fig. 1). It receives inputs from Lake Huron and the Pine, Black, and Belle rivers, as well as direct discharges from point and non-point sources from both sides of the river (Scavia et al., 2019a, b). Its annual average discharge of 5,200 m^3/s is 35 % of the Mississippi River discharge at Baton Rouge and more than twice that of the Missouri River. Lake St. Clair receives inputs primarily from the St. Clair, Clinton, Sydenham, and Thames rivers; point sources; and the atmosphere. The Detroit River is a connecting channel flowing 44 km from Lake St. Clair to Lake Erie, continuing the international border. It receives inputs from Lake St. Clair, the River Rouge, and US and Canadian point and non-point sources (Scavia et al. 2019a,b), including the region's largest point source discharge from the Great Lake Water Authority (GLWA) in Detroit.

Loading estimates – Burniston et al. (2009a), Burniston et al. (2009b), and Burniston et al. (2018) estimated loads with LOADEST (Runkel et al., 2004) using discharge and phosphorus concentrations measured at the Point Edward station near the head of the St. Clair River (**BH**) and along a detailed cross-section of the Detroit River sufficiently upstream of the influence of Lake Erie (**BD**).

Maccoux et al. (2016) estimated loads from Lake Huron based on discharge and open Lake Huron concentrations (**EH**), and from the Detroit River by adding the Lake Huron load to inputs from the watersheds of the St. Clair and Detroit rivers and Lake St. Clair. These loads include atmospheric and point sources, and load estimates from tributary monitoring data from government agencies when sufficient data were available and via the Stratified Beal's Ratio Estimator (Beale, 1962; Dolan et al., 1981) otherwise. Estimates from unmonitored areas were based on the unit area load approach (Rathke and McCrae, 1989). Environment and Climate Change Canada and the US Environmental Protection Agency (ECCC/EPA 2022, pers. comm., T. Greenberg, ECCC) used similar methods to update the Canadian loads between 2008 and 2013, and both US and Canadian loads between 2014 and 2021. Herein I use the Maccoux et al. (2016) US estimates and the ECCC/EPA Canadian estimates for 2008–2013 and the ECCC/EPA data for both countries for 2014–2021 to estimate the Detroit River load (**ED**).

Scavia et al. (2019a) estimated loads from monitored tributaries throughout the HEC with the Weighted Regressions on Time, Discharge, and Season method (WRTDS, Hirsch et al., 2010). Estimates for unmonitored watersheds were area-weighted estimates based on nearby streams prior to adding upstream point sources. Loads from Lake Huron and within the St. Clair and Detroit rivers were estimated with daily discharge times concentration data interpolated using a Generalized Additive Model. The load from Lake Huron was based on US and Canadian concentration measurements at the top of the St. Clair River (**SH_1**) and by combining SH_1 with an additional load determined from a St. Clair River TP mass balance (**SH_2**). Scavia et al. (2022) estimated the load from Lake Huron from daily water treatment plant turbidity and phosphorus-turbidity relationships derived from Lake Huron and St. Clair River data (**SH_3**).

Scavia et al. (2019a) determined the Detroit River loads in three ways. The first (**SD_1**) added the load leaving Lake St. Clair, based on flow and phosphorus concentration near the outlet of the lake, to point and non-point sources to the Detroit River. The second (**SD_2**) added the augmented Lake Huron load (SH_2) to loads from the St. Clair and Detroit rivers and Lake St. Clair watersheds. The third estimate (**SD_3**) used phosphorus concentrations near the mouth of the Detroit River. A final estimate (**EDS**) was derived by replacing the Lake Huron load used in ED with the average of the SH_2 and SH_3 loads from Scavia et al. (2019a) and Scavia et al. (2022) (ESM Figure S2). All load estimates are given in Electronic Supplementary Material (ESM) Table S1 and Figure S1.

Results and discussion

Historical development of Lake Huron load estimates - In his review of Lake Erie studies between 1928 and 1977, Mortimer

(1987) noted that "the lake also receives sediment, via the Detroit river from Lake St. Clair, which in turn is fed from the Thames River and from the actively eroding shores at the SE corner of Lake Huron". Using data collected in the 1970 s at the head of the St. Clair River by the U.S. Army Corps of Engineers (Yaksich et al., 1982, 1985), Janus and Vollenweider (1981) estimated that the load from Lake Huron contributed 6 % of the total load to Lake Erie. Mortimer (1987) estimated that it represented 17 % of the load to the western basin. Those 1970–1980 loads ranged between 1,187 and 3,122 MTA (Mean ± SD = 2133 ± 644, Fig. 2), and Rumer (1977) and DiToro and Connolly (1980) used those values in early Lake Erie eutrophication models.

More recent estimates using data from the Canadian monitoring site near the outlet of Lake Huron (BH, Burniston et al., 2018) and from both the US and Canadian sides of the river (SH_1, Scavia et al., 2019a) were similar to those earlier estimates (Fig. 2). Based on a St. Clair River TP mass balance, Scavia et al. (2019a) suggested that on average the TP loads were even higher due to infrequent sampling that misses Lake Huron resuspension events. Scavia et al. (2020) used a suite of physical measures and models, along with turbidity measurements at the Canadian monitoring site, to provide additional evidence that this load is from wave-induced resuspended Lake Huron sediment. Newer estimates (SH_3), based on turbidity from Canadian and US water treatment plants and a turbidity-phosphorus regression (Scavia et al., 2022) are consistent with those higher loads and the significance of resuspension (Fig. 2).

The Upper Great Lakes Reference Group et al. (UGLRG, 1977) of the International Joint Commission (IJC) also reported similar loads at the top of the St. Clair River in 1973 (2,450 MTA, Fig. 2). However, based on the analysis of material from eroded bluffs (Thomas and Haras 1978), they recommended using open Lake Huron concentrations to estimate the load (1,080 MTA) because samples from the head of the river "include a contribution from material eroded from the shoreline", and "this material does not become available" to algae. As a result, models (Chapra and Sonzogni, 1979) and loading estimates (Dolan, 1993; Dolan and McGunagle, 2005) used 1,080 MTA. Subsequent models (Chapra and Dolan, 2012) and load estimates (Dolan and Chapra, 2012; Maccoux et al., 2016) continued to use annual open lake concentrations to estimate loads that decreased over time from 1080 MTA to 321 MTA (Fig. 2).

However, Scavia et al. (2022) determined that 37 % (±15 %) of the particulate P in resuspended material along the southeastern shore of Lake Huron is potentially bioavailable, with 54 % (±13 %) biologically available at the head of the St. Clair River (Fig. 3). These estimates are comparable to those from the Maumee River, a highly agricultural watershed that drains into Lake Erie's western basin (30 ± 7 %, summarized in Bertani et al., 2016). These higher percentages, in comparison to those reported by Thomas and Haras (1978), are because the resuspended lakebed material is more likely from autochthonous algal production and/or tributary loads of organic material, as opposed to eroded bluff material. Thus, the earlier recommendation to use open lake concentrations appears to have been unwarranted.

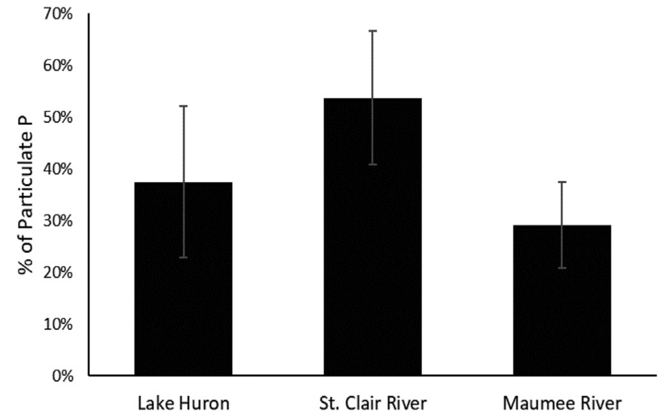

Fig. 3. Bioavailable phosphorus as a percent of particulate phosphorus for samples from southeastern Lake Huron, the top of St. Clair River, and the Maumee River (Scavia et al., 2022).

The interannual variability in total load (Fig. 2) is to be expected because the resuspension loads are wind-driven (Scavia et al., 2020). The general downward trend in these estimates (symbols in Fig. 2) is consistent with the oligotrophication of the upper Great Lakes (Evans et al., 2011), reflected in the declining base loads estimated from open lake concentrations (line in Fig. 2). The resuspension load from both time periods, approximated by subtracting the base load from the total loads (Fig. 4) are comparable, suggesting the resuspension load has been fairly persistent over the decades (Fig. 6).

Lake Huron and Detroit River loading updates – The 2008–2015 average (Fig. 5) Lake Huron load estimates (Fig. 5, S1; Table S1) using data from the Canadian monitoring site (BH, 963 MTA, Burniston et al. 2018) and both US and Canadian data sites (SH_1, 1,000 MTA, Scavia et al. 2019a) are three times higher than estimates based on open lake concentrations (EH, 321 MTA, Maccoux et al., 2016). The mass-balance based estimates accounting for load missed by infrequent sampling (SH_2, 1,676 MTA, Scavia

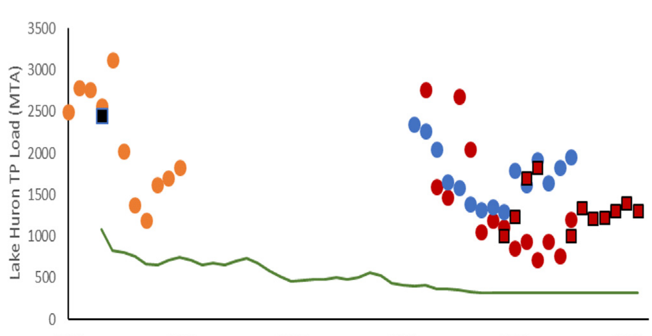

Fig. 2. Estimates of the TP load from Lake Huron. Yaksich et al., 1982 (orange dots); UGLRG, 1977 (black box), based on open-lake concentrations (green line); Burniston et al., 2018 (red dots); Scavia et al., 2019a (blue dots); Scavia et al., 2022 (red boxes).

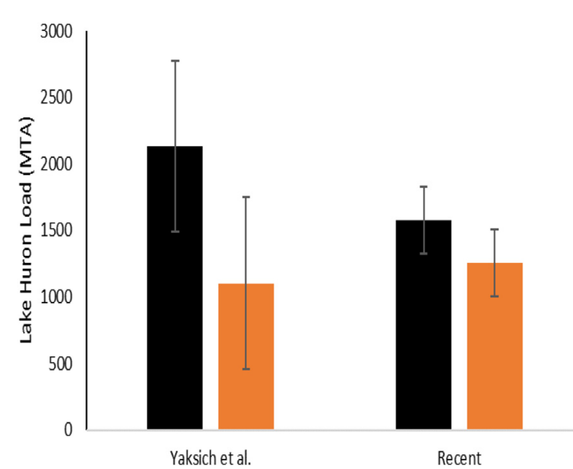

Fig. 4. Mean ± SD of Lake Huron loads (black) from the 1970 s (left) and 2019–2022 (right), and those loads minus loads based on open lake concentrations (orange).

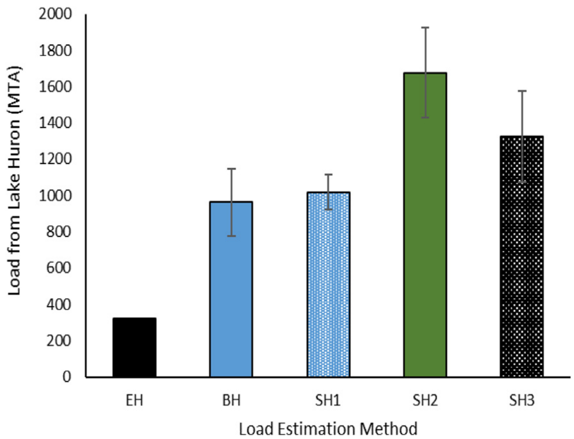

Fig. 5. Estimates of total phosphorus load from Lake Huron based on open lake concentrations (EH, black, Maccoux et al., 2016), measurements at the Canadian station (BH, blue solid, Burniston et al., 2018), measurements at US and Canadian stations (SH_1, stippled blue, Scavia et al., 2019a), St. Clair River mass balance (green, SH_2, Scavia et al., 2019a), and turbidity-based (SH_3, stippled black, Scavia et al., 2022).

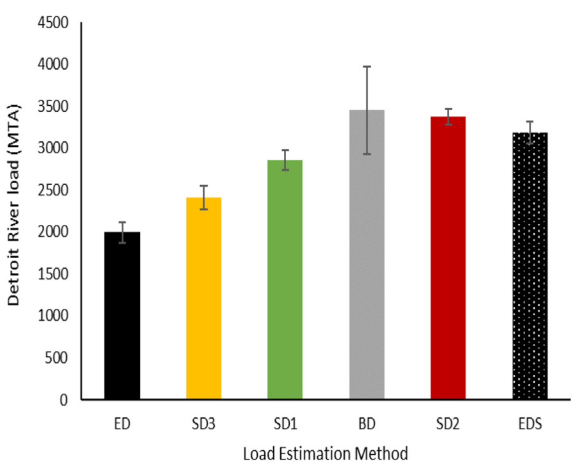

Fig. 6. Detroit River load estimates (MTA) for 2008–2016 based on summing loads from Lake Huron using open lake concentrations (ED, black), lower Detroit River concentrations (SD_3, yellow), loads leaving Lake St. Clair (SD_1, green), upstream Detroit River concentrations (BD, grey), summing loads from the Lake Huron including the additional load from resuspension (SD_2, red), and the ED load corrected with SH4 Lake Huron load (EDS, black stipple).

et al. 2019a) and that based on turbidity (SH_3, 1,356 MTA, Scavia et al., 2022) are even higher. These significantly higher Lake Huron loads, based on a more realistic consideration of the phosphorus content of the source waters, have substantive impacts on Detroit River load estimates.

Detroit River loading estimates (Fig. 6, S1; Table S1,) determined by adding HEC loads to the Lake Huron load based on open lake concentrations (ED, 1,997 MTA), is lower than all other estimates. Estimates based on concentration measurements near the mouth of the Detroit River were also low (SD_3, 2,410 MTA, Scavia et al., 2019a), likely due to the influence of Lake Erie's surges, seiches, and backflow. Estimates based on daily measurements made sufficiently upstream of that influence in 2007, 2013, and 2014 (BD, 3,450 MTA, Burniston et al., 2009a; Burniston et al., 2009b; Burniston et al., 2018) are similar to estimates based on adding HEC and augmented Lake Huron loads (SD_2, 3,370 MTA, Scavia et al, 2019a), and by replacing the original ED Lake Huron loads with the average SH_2 and SH_3 loads (EDS, 3,183 MTA). This adjusted EDS load is roughly 60 % higher than ED estimates, the values currently used most often, especially in the GLWQA assessments.

The lower estimate from adding the load from the Lake St. Clair outlet to those downstream (SD_1), compared to estimates that add loads from Lake Huron and downstream (SD_2) are consistent with earlier findings that Lake St. Clair retains 15–20 % of its TP load (Scavia et al., 2019a).

Implications – With the new load estimates, the 2017–2021 average Lake Huron load makes up almost half of the Detroit River load. The revised Lake Huron load estimate is 14 % of the combined western and central basins load and 20 % of the western basin load, similar to the 17 % reported by Mortimer (1987). There is a reasonable argument for Lake Huron being a substantive source of P for central basin hypoxia. The Lake Huron contribution is roughly comparable each year (within +/-30 %, Scavia et al., 2022) and hypoxic extent is similar in most years, with interannual variability controlled primarily by physical factors (Rucinski et al., 2014, Watson et al., 2016). In addition, because there has been hypoxic areas in Lake Erie's central basin since before European settlement (DeLorme, 1982), there is an inherent background level of TP load that drives a base level hypoxic extent.

The significance of the Lake Huron load may also increase in the future due to three climate-related trends: the recent 35 % increase in St. Clair River discharge (Scavia et al., 2022), the loss of Lake Huron ice cover and increased critical wave heights (Scavia et al., 2019a, 2020), and increased variability in Lake Huron water levels (Hanrahan et al., 2010). While the relationships between these trends and climate warming are not definitive (e.g., Hayhoe et al., 2010; VanDeWeghe et al., 2022; Kayastha et al., 2022; Seglenieks and Temgoura, 2022; Channell et al., 2022), combined they would make the contribution from Lake Huron even higher.

Improving estimates of connecting channels loads - The Great Lakes connecting channels (St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence rivers) originate from the outflow of large lakes rather than the accumulation of a network of tributaries. These connecting channels are rivers of great significance, having the largest discharge among rivers in North America, but they are generally under-monitored and under-studied. Our work highlights the importance of developing specific methods of load estimation for these rivers beyond the common methods used in tributaries. In most cases, P load estimates in the connecting channels assume the load can be represented by open lake or average concentrations. However, as shown here and in Scavia et al. (2019a,b, 2020, 2022) for Lake Huron and in Bocaniov et al. (in review) for the outlet of Lake Erie, those assumptions can be biased when nearshore contributions make up a significant portion of the load with sufficient frequency. As such, it is more reliable to use concentrations within the connecting channel.

However, it is not appropriate to estimate these loads with estimators like LOADEST and WRTDS that rely on flow-concentration relationships because those relationships are not strong in the connecting channels. Instead, estimates must rely on the direct product of flow and concentrations in the connecting channel. Large uncertainties can arise when infrequent sampling requires significant interpolation. As outlined in more detail by Scavia et al. (2022), accurate estimates of daily TP loads can be determined efficiently with turbidity measurements and a strong relationship between turbidity and TP concentrations. Turbidity sensors can be deployed independently and/or at water treatment plants. Uncertainties in the generated daily load estimates come primarily from the turbidity-TP regression and assumptions about vertical and cross-sectional mixing.

Impacts on model advice – The GLWQA targets were informed by response curves from an ensemble of previously calibrated and validated models (Scavia et al., 2016), including models of central basin hypoxia (Rucinski et al., 2016; Lam et al., 2008; Zhang et al, 2016; Bocaniov et al., 2016) and chlorophyll (Chapra et al. 2016) that were driven by western and central basin loads. They were calibrated with the underestimated Detroit River loads, potentially influencing the response curves and recommended loading targets. This is especially important for the dynamic three-dimensional models that use the Detroit River loads explicitly. As a result, these and other models need to be recalibrated with updated loads and new response curves developed to determine if the 40 % load reductions are still projected to result in the desired outcome of hypoxic areas similar to those of the 1990 s and early 2000 s, roughly 4,500 km^2. In addition to reassessing the models used for the GLWQA targets, other models that explore the impacts of the loads on algal production in the northern regions of the western and central basin, as well as hypoxia, would also be influenced by the refined load estimates.

It is possible that the resulting response curves lead to new reduction targets that are stronger or weaker than what is driving the current load reduction strategies outlined in the Canadian and US action plans. If that is the case, an assessment of the new targets would be required. However, while the models would be recalibrated to updated hypoxia extent estimates, albeit at higher loads, it is worth noting that current and potential target loads generally fall within the linear region of the response curves (Scavia et al., 2016). So, it is also possible that the resulting reduction target remains at roughly 40 %. Under any of these scenarios, new strategies that account for the hard to control sources may be necessary. The next section illustrates the impact of new loads assuming the 40 % target remains.

Potential impacts on loading targets – The original 2008 load estimate was 9,641 MTA, so the reduction target was set to 6,000 MTA (rounding the actual 40 % target of 5,785 MTA). A 40 % reduction of the updated 2008 load of 10,676 MTA is 6,406 MTA. So, rounding would result in roughly the same target. Because the 2017–2021 updated load is 9,354 MTA, reaching the 6000 MTA target requires a 36 % reduction *from current loads* (Fig. 7a).

Lake Huron sources - Because almost half of the Detroit River load comes from Lake Huron, I first consider reductions from that source, which may be in conflict with concerns about the oligotrophication of open lake conditions (Evans et al., 2011; Barbiero et al., 2018) and its implications for fish production (Barbiero et al., 2012; Bunnell et al., 2014). However, based on particle tracking from NOAA's operational forecast model (Anderson et al., 2018), most of the flow into the St. Clair River comes from the southeast and southwest nearshore regions depending on the prevailing winds and currents. Very little comes directly from the open lake (see Fig. 8 in Scavia et al., 2020). So, reducing loads from those areas, if that is possible, may not be as impactful to the open lake.

Using turbidity-based loads, Scavia et al. (2022) showed the additional, episodic loads come from both southeast and southwest nearshore regions. From the southwestern region, El Nicholls (1998) suggested that in normal winters, Saginaw Bay sediments accumulate a high proportion of the water column P under the relative quiescent conditions of ice cover. Then in ice-free periods, resuspended P is dispersed from their nearshore origins. He noted that Dolan et al. (in Bierman et al., 1984) concluded that a wind dependent resuspension mechanism had to be incorporated into a P mass balance model of Saginaw Bay for predictions to match water column P concentrations. During ice-free periods, wind-driven plumes of turbid Saginaw Bay water have been tracked southward in western Lake Huron to the outflow, and wind-induced turbidity from shore erosion also has been documented for parts of Lake Huron (International Joint Commission, 1977), including Saginaw Bay (Beeton and Saylor, 1995). This proposed connection between resuspension and outflow from Saginaw Bay and the load to the St. Clair River remains to be confirmed, and further analysis would be helpful. Either way, strengthening current efforts to reduce the P loading to Saginaw Bay (e.g., Stow et al., 2014) would be beneficial.

The finding that the bioavailability of resuspended particulates from Lake Huron's southeastern nearshore region is comparable to the Maumee River suggests that material is derived from settled algae and other organic material stimulated by tributary nutrient loads. Anecdotal evidence supports that. Elevated phosphorus concentrations occur along the southeast shores, and four of the top ten Canadian sub watersheds with the highest intensities of phosphorus production from livestock manure are located along the southeast shores (ECCC/EPA 2018). Signs of nutrient enrichment in this area occur from the outlet of Saugeen River south to Kettle Point near Sarnia, where the density of pollution-tolerant bottom-dwelling oligochaetes increased 20-fold since the early 2000 s (ECCC/EPA 2018, Nalepa et al., 2007). These watershed nutrients fuel primary production in the nearshore that could eventually contribute to P in resuspended sediments that are transported to the St. Clair River. This requires further analysis because increasing efforts to reduce these loads through strengthened watershed plans for the region (e.g., Brock et al., 2010; King et al., 2014; Laporte et al., 2012; Schnaithmann et al., 2013; Van Zwol et al, 2017) would improve nearshore conditions and potentially be beneficial downstream.

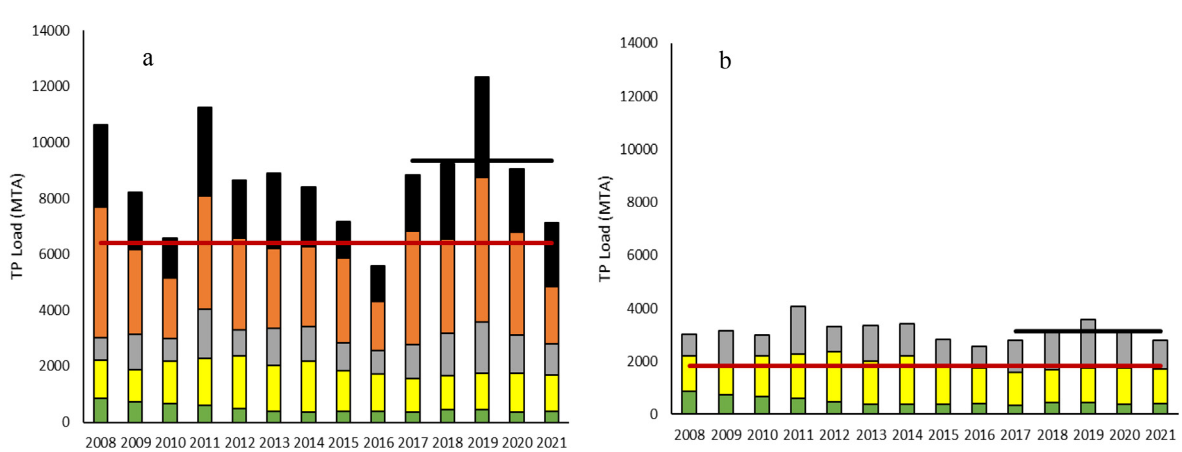

Fig. 7. Total phosphorus loads to the western and central basins (a) and from the Detroit River (b). Sources include the Great Lakes Water Authority treatment plant (green), Lake Huron (yellow), the Huron-Erie Corridor (grey), and direct western basin (orange) and central basin (black) watersheds. Horizontal lines represent the 2017–2021 average (black line) and 40% reduction targets (red line).

Other sources - If efforts to reduce loads to Lake Huron's nearshore regions are not sufficient to reduce the load, then the remaining load to Lake Erie is 7,666 MTA, and a 42 % reduction of that load is required to reach the target. If further reductions from the Great Lakes Water Authority's treatment plant (ca. 396 MTA) are also not included because it has already surpassed their goal, the required reduction increases to 44 %. This 8 % increase in the reduction target may not be significant in the context of implementation at this large scale (Fig. 7a). However, if the focus was on a potential 40 % reduction of the Detroit River load (e.g., see ErieStat, 2022; EPA, 2018), it becomes quite significant (Fig. 7b). A 40 % reduction of the updated 2008 Detroit River load (3,043 MTA) results in a target load of 1,826 MTA. The mean updated 2017–2021 load is 3,126 MTA, requiring 1,301 MTA to be reduced. To reach that goal, 92 % of the remaining controllable load (1,408 MTA) would have to be eliminated.

Under these conditions, it would not be possible to meet a 40 % reduction from the Detroit River. So, putting more sources in play across the Lake Erie system could be required to meet the overall target. After the Detroit and Maumee rivers, the most significant tributary loads are from the Sandusky, Thames, and the Grand (Ohio) rivers that all have loads in excess of 400 MTA, and the Portage, Cuyahoga, Huron, Raisin, and Sydenham rivers that have loads in excess of 200 MTA (Fig. 1b). The Sandusky, Thames, Portage, Huron, and Raisin rivers currently have 40 % spring load reduction targets.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

I appreciate the ongoing support of the Fred A. and Barbara M. Erb Family Foundation and colleagues who shared load estimates and advice: Tracie Greenberg of Environment and Climate Change Canada, Santina Wortman and Cal Buelo of the US Environmental Protection Agency, Matthew Maccoux of the Milwaukee Metropolitan Sewerage District, and Serghei Bocaniov of the University of Waterloo, Michelle Selzer of the Michigan Department of Agriculture & rural Development, and Mari Veliz of the Ausable Bayfield Conservation Authority. The manuscript also benefited from three anonymous reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2023.01.008.

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