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

Commentary

Detroit River load estimation; the need for a new monitoring approach

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ARTICLE INFO

Article history:
Received 14 February 2023
Accepted 24 May 2023
Available online xxxx
Communicated by Craig Stow

Keywords:
Detroit River
Huron-Erie Corridor
Lake Erie
Nutrients
Monitoring

ABSTRACT

The Great Lakes Water Quality Agreement (GLWQA) established new Lake Erie phosphorus loading targets, including a 40% total phosphorus load reduction to its western and central basins. The Detroit and Maumee rivers' loads are roughly equal and contribute about 90% of the load to the western basin and 54% to the whole lake. They are key drivers of central basin hypoxia and western basin algal production. So, accurate estimates of the Detroit River load are important. Direct measurement of that load near its mouth is difficult due to requiring real-time knowledge of flows around islands and the influence of Lake Erie's seiches. Consequently, most estimates sum the loads to the St. Clair/Detroit River system. But this approach is complicated by uncertainties in the Lake Huron load and load retention in Lake St. Clair. Routine GLWQA reassessments will confirm or adjust over time the goals, loading targets, and approaches based on evolving information. So, there is a need to improve monitoring approaches that ensure accurate Detroit River loads. New approaches should take into account both the characteristics of this dynamic connecting channel and the uses of monitoring results: 1) determining the Detroit River loads to drive models, develop mass balances, set load reduction targets, and track progress; and 2) assessing the sources and processing of the loads to help guide reduction strategies. Herein, we review temporal and spatial variability in the St. Clair/Detroit River system, and suggest adjustments to monitoring that address those variabilities and both uses.

Introduction

The Great Lakes Water Quality Agreement (GLWQA, 2016) established new Lake Erie phosphorus (P) loading targets, including a western and central basin target of 6,000 metric tons per year (MTA) in anticipation of returning the extent of central basin hypoxia to that of the 1990s to early 2000s (ca. 4,500 km^2). The Detroit and Maumee rivers' loads are roughly equal and together contribute about 90% of the TP load to the western basin and 54% to the whole lake (Maccoux et al., 2016). While the Maumee is the primary driver of western basin harmful algal blooms (HABs, Michalak et al., 2013, Scavia et al., 2016, Watson et al., 2017), the basin's circulation patterns and relatively low phosphorus concentrations in the Detroit River render it less important for HABs. However, its TP concentrations (10–20 µg/l, Burniston et al., 2018) are still high enough to potentially stimulate non-HAB biomass (elevated chlorophyll concentrations below 18 µg/l; Sayers et al., 2016), as Manning et al. (2019) showed in their review of the distribution of elevated chlorophyll concentrations in the western basin.

Rucinski et al. (2014, 2016) showed with a mechanistic ecological model, that while hypoxia interannual variability was driven primarily by meteorological variability, long-term averages are controlled by the phosphorus load. More recently, Del Giudice et al. (2018) evaluated statistical relationships between summer hypoxic extent and various potential drivers. They also concluded that interannual variability was driven mostly by meteorology, but that long-term trends were driven by multi-year cumulative TP tributary loads. In their case, the long-term load was estimated from tributaries because of large uncertainties and low temporal resolution of the Detroit River load. However, the load-response curves developed in support of the current targets included the Detroit River load and also show the Detroit River as a key driver of central basin hypoxia (Lam et al., 2008; Bocaniov et al., 2016; Rucinski et al., 2016; Zhang et al., 2016). So, accurate estimates of the Detroit River load are particularly important.

Direct measurement of the Detroit River load near its mouth is difficult due to complicating flow diversions around islands and Lake Erie's seiches and surface oscillations that influence pollutant transport and nutrient loading (Jackson, 2016). During typical

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https://doi.org/10.1016/j.jglr.2023.05.007
0380-1330/

seiche events for example, the NOAA Toledo water level gage #9063085 in the western basin rises above the Gibraltar gage #9044020 that is roughly 3 km upstream of the sampling station (42.06756 N and 83.1677 W). During severe events, the Toledo gage rises to water levels similar to those at the Wyandotte #9044030, 15 km upstream of the sampling station (Fig. 1). While rare, extreme events can even reverse flow of the Detroit River as far upstream as Ft. Wayne MI (Quinn, 1988, Derecki and Quinn, 1990).

Due to the challenge of a direct measurement, most Detroit River loading estimates have been based on summing the loads to the St. Clair/Detroit River system (e.g., Dolan and Chapra, 2012, Maccoux et al., 2016). However, this approach is complicated by uncertainties in the Lake Huron load and load modulation by Lake St. Clair (Scavia, 2023). More recent short-term estimates have explored using measurements upstream of Lake Erie's influence (Burniston et al., 2009, 2018; Totten and Duris, 2019).

The GLWQA called for regular reassessments to confirm or adjust the goals, loading targets, and approaches based on new information. Key new findings since the GLWQA revised targets were established in 2016 are that Lake Huron's load has been significantly underestimated (Burniston et al., 2018; Scavia et al., 2019, 2020, 2022), and that Lake St. Clair retains on average 30% of its TP inputs. In summarizing load estimates for the St. Clair/ Detroit River system, Scavia (2023) estimated that the current load from Lake Huron is 4–5 times higher than previous estimates, making it roughly 50% of the Detroit River load, potentially increasing the Detroit River load by 67%.

Moving forward, there is a need to improve monitoring and load estimation to ensure accurate Detroit River loads. Such efforts should take into account both the characteristics of this dynamic connecting channel and two key uses of the monitoring results: 1) determining Detroit River loads that are used to drive models, develop mass balances, set load reduction targets, and track progress; and 2) assessing the sources and processing of the loads to help guide reduction strategies. Herein, we describe the temporal and spatial variability St. Clair/Detroit River system and offer suggestions on how monitoring could be modified to better account for those variabilities and address the intended uses.

The St. Clair/Detroit River system

The St. Clair River, Lake St. Clair, and Detroit River (the Huron-Erie Corridor, HEC) transport water and nutrients to Lake Erie from Lake Huron and the 19,040 km^2 HEC watershed that covers parts of southeastern Michigan and southwestern Ontario (Fig. 2). The watershed is about 49% cropland, 21% urban area, 13% forest, 7% grassland, and 7% water bodies (Dagnew et al., 2019). Overall, 79% of the watershed's agricultural land is in Canada and 83% of the urban land is in the United States. Its annual average discharge (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 Huron – Lake Huron, the second largest Laurentian Great Lake and fifth largest freshwater lake in the world, is oligotrophic based on characteristics of its open waters, although higher nutrient concentrations are found in Saginaw Bay and nearshore areas. Scavia et al. (2019, 2020, 2022) showed that the load from Lake Huron is influenced strongly by the flux of resuspended nearshore sediments containing high concentrations of biologically-available P relative to open water concentrations.

St. Clair River – The St. Clair River, like other Great Lakes connecting channels (St. Marys, Detroit, Niagara, and St. Lawrence rivers), originates from the outflow of a large lake rather than a network of tributaries. The river flows 64 km, dropping almost 1.5 m, from Lake Huron to Lake St. Clair. It is a relatively straight channel with water retention time of about 21 h (UGLCCS, 1988). It is poorly mixed laterally but generally well-mixed vertically, with currents generally slower within 50 m of the shorelines (Derecki, 1985; Sun et al., 2013). In addition to nutrient loads from Lake Huron, the river receives TP inputs from the Black, Belle, and Pine river watersheds, as well as other point and non-point sources (Table 1).

Lake St. Clair – Lake St. Clair is a large (1,115 km^2, 4.25 km^3; Bocaniov and Scavia, 2018), shallow, polymictic lake with a mean depth of 3.8 m, a maximum natural depth of 6.5 m, and an 8.2 m deep navigation channel. Its watershed is one of the most densely populated in the Great Lakes, and an important source of drinking water, commercial and sport fishing, and other forms of recreation. The lake processes water from the St. Clair River, as well as from its proximate ~ 16,000 km^2 watershed that includes additional loads from the Clinton, Thames, and Sydenham rivers and point source

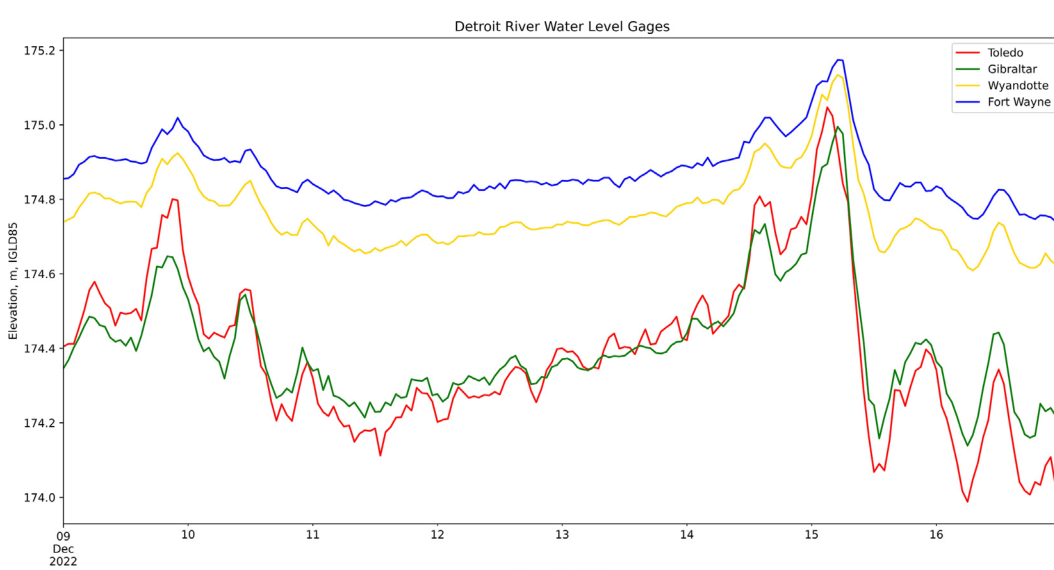

Fig. 1. NOAA water levels from Lake Erie and the Detroit River, December 2022 during typical (left) and extreme (right) seiche events.

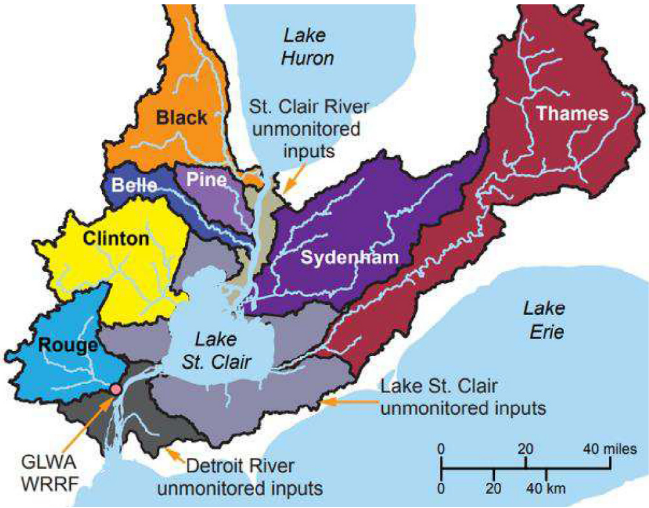

Fig. 2. Huron-Erie Corridor watersheds.

discharges (Table 1). While the lake's theoretical flushing time is roughly 9 days, that flushing time varies seasonally and spatially (Bocaniov and Scavia, 2018) such that during summer, water in the southeastern part of the lake flushes more slowly than water in the northwestern part. This, in combination with different timing and magnitude of tributary loads, leads to the lake being oligotrophic in the northwest part and mesotrophic in the southeast (Bocaniov and Scavia, 2018).

Detroit River – The Detroit River runs about 52 km from the outlet of Lake St. Clair, dropping 1 m along its path to Lake Erie. Nearly the entire Detroit River outflow is from Lake Huron via Lake St Clair, with only 2% contributed by tributaries (UGLCCS, 1988). Its flow, with a flushing time of 19 h (Derecki, 1985), is generally well-mixed vertically (Burniston et al., 2009; Duris, 2019) but complicated by branching around islands and through navigation channels, particularly in its lower reaches. In addition to the outflow from Lake St. Clair, it receives P loads from several rivers, most notably River Rouge, and from US and Canadian point sources, including the region's largest point source discharge from the Great Lake Water Authority (GLWA) in Detroit (Table 1).

Temporal and spatial variability

Capturing variability is a key aspect of environmental monitoring, especially when estimating loads. For tributary loads, focus has primarily been on capturing precipitation-based episodes due to changes in discharge and concentration (e.g., Hirsch et al., 2010; McCullough et al., 2012; Jennings et al., 2012, Carpenter et al., 2015), and most load estimation methods (e.g., Weighted Regressions on Time, Discharge, and Season, WRTDS; Load Estimator, LOADEST) assume spatial uniformity in the tributary cross section. These assumptions are generally acceptable for tributary loads within the HEC; however, Scavia et al. (2020, 2022) showed that daily-scale episodic wind-driven resuspension events impact the load from Lake Huron. Lateral and temporal variability has also been reported for the upper St. Clair River (Yaksich et al., 1982, 1985; Scavia et al., 2022) and the lower Detroit River (Burniston et al., 2018; Totten and Duris, 2019). Below, we review the temporal and spatial variabilities that would need to be considered in an updated monitoring program.

Annual variability – Annual estimates of the Detroit River load, based on summing HEC loads for 1998–2016 (Scavia et al., 2019), shows a linear decline (R^2 = 0.78) with little year-to-year variability. In contrast, during that same period, the Lake Huron load change was not significant (Fig. 3), and it comprises an increasing portion of the Detroit River load. The larger interannual variability in the Lake Huron load is to be expected because the resuspension component of that load is wind-driven (Scavia et al., 2020). Variability in the Detroit River load is likely dampened by the roughly 50% of the total load coming from other sources.

Daily variability – Scavia et al. (2020, 2022) showed substantial daily variability at the head of the St. Clair River, and further downstream at Marysville. This variability, reflected in turbidity, is also seen further downstream at Marine City and Algonac, as well as at the head of the Detroit River near Belle Isle (Fig. 4). Burniston et al. (2018) measured daily and weekly TP concentrations in the lower Detroit River and found it can vary by a factor of 3–5 over a few days, roughly corresponding to similar variation in turbidity in the Detroit and St. Clair rivers. Based on turbidity-phosphorus regressions (Scavia et al., 2022), the difference between a nominal baseline turbidity (20 NTU) and event turbidity (60 NTU) represents a change from 0.029 to 0.067 mg/l TP, similar to that measured by Burniston et al. (2018). This daily TP variability can be missed by weekly samples (Fig. 4), indicating that, like the load from Lake Huron, higher-frequency sampling is likely needed.

Spatial variability – Most observations and models have shown that the St. Clair and Detroit rivers are well mixed vertically (Derecki, 1985; Anderson and Schwab, 2012; Sun et al., 2013; Totten and Duris 2019), Vertical mixing in Lake St. Clair is more complicated, and is discussed below.

Longitudinal variability – TP loads increase downstream from Lake Huron to Lake Erie (Burniston et al., 2018), with roughly 50% coming from Lake Huron, 7% added from the St. Clair River watershed, 26% added from the Lake St. Clair watershed, and 17% added from the Detroit River watershed (Table 1, Fig. 3). Burniston et al. (2018) showed St. Clair River downstream concentrations along the Canadian side at Port Lambton were consistently higher than upstream at Point Edward. While the data are relatively sparse on the US side, they do not show this upstream/-downstream difference (Scavia et al., 2022).

Lateral variability – The St. Clair River flow at the outlet of Lake Huron is often not well-mixed laterally, requiring cross-channel panel sampling (Yaksich et al., 1982, 1985). More recently, Scavia et al. (2022) showed there were often higher concentrations along the US and Canadian shores near the Blue Water Bridge about 1 km downstream from the outlet of Lake Huron. This lack of lateral

Table 1
Loads to the sections of the HEC (MTA). Tributary loads are based on monitoring data and WRTDS. GLWA is the regional water treatment plant in Detroit. "Other sources" include point sources downstream of the tributary monitoring site or discharged directly to the river or lake and estimated non-point sources for unmonitored areas. Lake Huron load is the most recent (2019–2021) update from Scavia (2023). All others are 2013–2016 averages from Scavia et al. (2019).

Loads to the St. Clair River		Loads to Lake St. Clair		Loads to the Detroit River	
Lake Huron	1340	Thames River	320	River Rouge	42
Black River	86	Sydenham River	136	GLWA	326
Belle River	29	Clinton River	128	Other point sources	82
Pine River	19	Other	169	Other	18
Other	46				

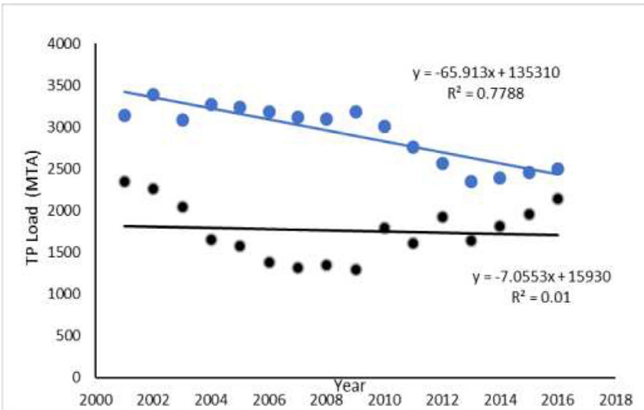

Fig. 3. Lake Huron (black) and Detroit River (blue) annual loads (MTA) from Scavia et al.,(2019a). For consistency across time in this figure, the Lake Huron load is based on measurements at the top of the St. Clair River and WRTDS, including estimates of the previously unmeasured Lake Huron load. The Detroit River load is based on summing the loads to the system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mixing is also reflected in the fact that whereas TP concentrations at the upstream and downstream end of the river on the US side are roughly equal, concentrations at the downstream end, on the Canadian side are routinely higher (Burniston et al., 2018; Scavia et al., 2022).

Spatial differences are also seen further downstream at the outlet of Lake St. Clair (Burniston et al., 2009). Mean TP concentrations for samples taken at 2 depths over seven surveys between mid-July and mid-November 2007 on the US side of Peche Island and the Canadian side of Belle Isle in the Fleming Channel (Fig. 5) were both 10.6 µg/l, but concentrations were higher (16.7 µg/l) on Canadian side of Peche Island and lower (7.4 µg/l) on the US side of Belle Isle. The Fleming Channel (Fig. 5) accounts for 74% of the total flow into the Detroit River (Holtschlag and Koschik, 2002).

Further downstream in the lower Detroit River, roughly 10 km upstream from Lake Erie, Burniston et al. (2009, 2018) and Totten and Duris (2019) sampled transects to define lateral variability across the Trenton, mid-river, and Amherstburg channels. They reported higher nutrient concentrations nearer shore compared to the main river channel (Fig. 6), although Burniston et al. (2009) showed that Trenton Channel TP in 2014–2015 was roughly one-quarter of that in 2007 (Burniston et al., 2018), most likely a result of improvements in sewage treatment discharge on the Michigan side (Khan et al., 2023).

TP concentrations in the Mid-River section are generally lower, with values roughly equivalent to those monitored at the mouth of the St. Clair River at Port Lambton (Burniston et al., 2018) and the outlet of Lake St. Clair (Burniston et al., 2009). While 45% and 37% of the Detroit River discharge flows through the Main and Amherstburg channels, they carry 37% and 42% of the TP load because of the higher concentrations in the Amherstburg Channel.

Lake St. Clair – Even though it is rather shallow and nearly 98% of its water input is from the St. Clair River, Lake St. Clair is not a simple conduit between the St. Clair and Detroit rivers. Concentrations from the Algonac and Port Lambton sites near the entrance to the lake average 12.4 µg/l (Scavia et al., 2019) and the average of 4 sites at its outlet is 12.3 µg/l (Burniston et al., 2009), suggesting that the equivalent of all other TP sources to the lake are retained by the lake. Based on annual mass balances for 2013–2015, Scavia et al. (2019) and Bocaniov et al. (2019) estimated that the lake retained roughly 30% of the TP load. However, which loads are retained is complicated.

Bocaniov and Scavia (2018) and Bocaniov et al. (2019) showed that Lake St. Clair's circulation patterns, combined with the spatial and temporal differences among tributary loads, influence their respective exports to the Detroit River (Fig. 7). For example, the nutrient load from the Thames River, which enters the southeastern part of the lake and is higher in spring and fall when residence times in that portion of the lake are shorter, is likely to have relatively higher export from the lake. Conversely, the load from the Clinton River, which enters in the northwest and is higher in summer when local lake residence times are longer and sedimentation losses are higher, would have relatively lower export from the lake. The timing of the load from the Sydenham River, which enters in the northeast, is similar to the Thames, but it is located much

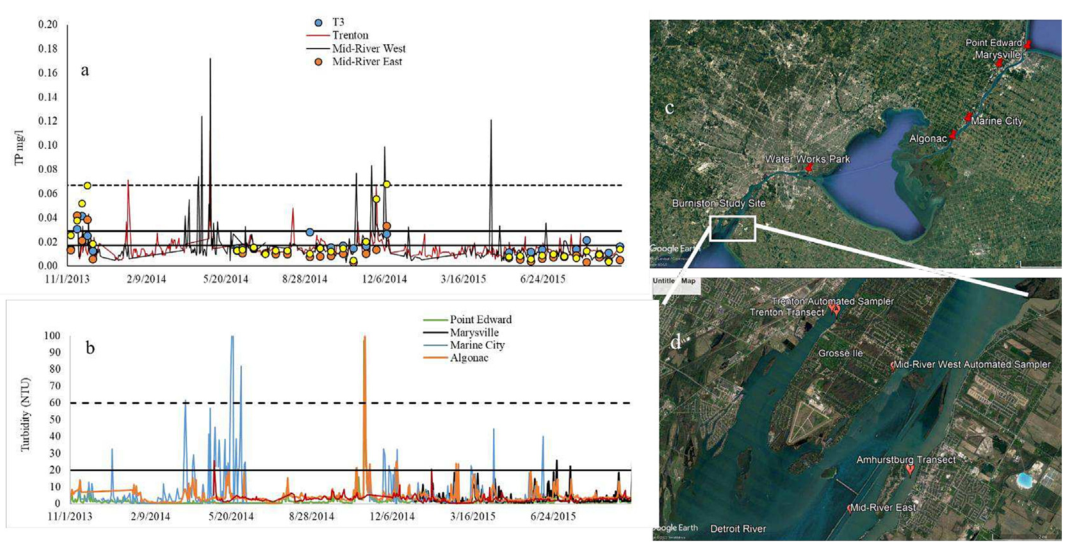

Fig. 4. a) daily TP concentrations (mg/l) measured on the western sides of the mid-river channel (black line) and the Trenton channel (red line) and less frequently in the middle of the Trenton channel (t3, blue), the east side of the mid-river channel (orange dots), and the middle of the Amherstburg channel (yellow dots) (see Fig. 5). The horizontal lines represent TP concentrations calculated from 10 NTU (solid) and 60 NTU (dashed) turbidity. b) Daily turbidity (NTU) from WTPs along the St. Clair and Detroit rivers, with horizontal lines representing 10 NTU (solid) and 60 NTU (dashed). c) Sampling locations in Burniston et al., (2010, 2018) and Totten and Duris (2018). d) Locations of water treatment plant intakes. Phosphorus data provided by M. Graham, Environment and Climate Change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Sampling locations at the outlet of Lake St. Clair (Burniston et al., 2010).

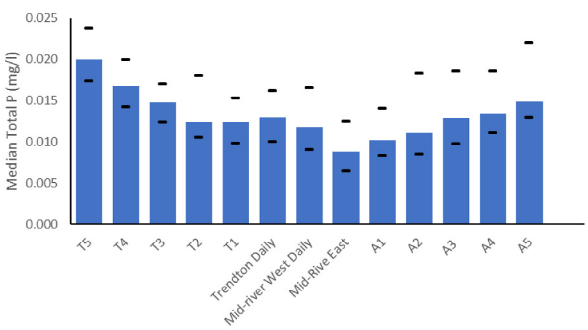

Fig. 6. TP concentrations from west to east in the lower Detroit River in 2014 and 2015. Bars are medians and horizontal lines are the 25th and 75th percentiles. Sample locations in Fig. 3c. From Burniston et al. (2018) and M. Graham, Environment and Climate Change Canada.

further from the lake outflow and separated from it by a basin deep enough to be net depositional, enhancing phosphorus retention.

Monitoring approaches to address variabilities

Given the temporal and spatial variabilities outlined above, and the need to have accurate load estimates to assess progress under the GLWQA, we suggest improvements for addressing two key aspects of monitoring. The first is to determine the Detroit River TP load to Lake Erie. These loads are used to drive models, develop mass balances, set load reduction targets, and track progress over time. It does not generally require detailed information on their sources and for most other systems it only requires sampling near the river's mouth (e.g., Runkle et al., 2004; Hirsch et al., 2010; Baker et al., 2014). However, as described above, interference with Lake Erie limits how far downstream those measurements are reliable. The second use of monitoring is to assess sources and processing of the loads to help guide reduction strategies. This requires, not only estimates of loads from all significant sources, but also the extent to which the load from each source is modulated as it travels through the system. While flows in the St. Clair and Detroit rivers are likely sufficient to ignore internal processing there, Lake St. Clair is clearly a key modulator.

Improving estimates of the Detroit River load – Because Lake St. Clair retains, on average, 30% of its TP inputs, the common approach of summing HEC loads will overestimate the load to Lake Erie. Ignoring the impact of Lake Huron's resuspended nearshore load will lead to an underestimate of that load. The most direct

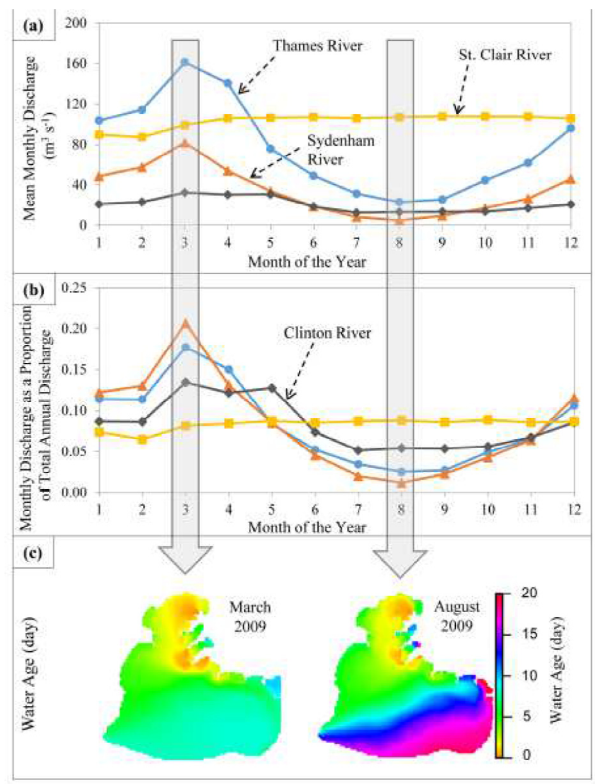

Fig. 7. Mean monthly discharges averaged from 2000 to 2017 for the St. Clair River (yellow squares) and three major tributaries: Thames (blue circles), Sydenham (brown triangles), and Clinton (black diamonds) rivers (the St. Clair River discharge has been reduced by a factor of 50 to show it on the same scale); (b) mean monthly discharge as a proportion of total annual discharge over the period 2000 through 2017 for the same rivers as in (a); (c) Lake St. Clair water age in May and August 2009 estimated by Bocaniov and Scavia (2018). . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) Reproduced from Bocaniov et al. (2019)

method for determining the Detroit River load would be to replicate the approach taken by Burniston et al. (2018) and Totten and Duris (2019), sampling a cross section of the lower river, upstream of the influence of Lake Erie. They showed higher concentrations along both banks of the two narrow channels and lower values across the main central channel in this physically complex portion of the river (Fig. 6).

Option 1: A simpler, and perhaps less logistically and financially challenging approach, would be to sample a single cross section further upstream where the channel is narrower and without the complexities of flow around islands. For example, near Fort Wayne where the state of Michigan routinely samples (Fig. 8) and the USGS measures and reports discharge. Temporal variability there (Fig. 5) would require frequent cross-channel sampling. For example, Burniston et al. (2018) sampled shore-based stations every 2–3 days and bi-weekly at river stations. Cross-channel sampling might be simplified if relationships could be developed between shore-based and river station sampling. Burniston et al. (2009) showed this was possible for TP concentrations in the Trenton Channel, but similar relationships for the Amherstburg Channel were not significant, perhaps because of the location of the shoreline sampler (Burniston et al., 2018). This would have to be tested across the narrower and simpler upstream transect near Ft. Wayne.

Option 2: Another option would be to sample the channels north and south of Belle Isle, and use proportional flows (Holtschlag and Koschik, 2002) to estimate the load. There might be less cross-channel variability than in the more complex channels in the lower river, but that would have to be confirmed. If not, the potential relationships between shore-based and river stations would have to be tested.

For either option, moving upstream would not substantially impact the estimate of the load to Lake Erie because the additional loads to the river represent only 17% of the total load (Table 1), and the two largest sources (River Rouge and point sources) are well estimated through River Rouge monitoring and point source permit reporting. The remaining sources represent only 1% of the load, and can also be estimated in traditional ways. Both options also integrate for the difficult to measure Lake Huron load and phosphorus retention in Lake St. Clair.

However, lateral (Fig. 6) and temporal (Fig. 4) variability likely make taking occasional mid-river grab samples inappropriate. The USGS (2006) describes two sampling techniques appropriate for measuring constituent loads in rivers, Equal-Discharge-Increments (EDI) and Equal-Width-Increment (EWI). Where channel depths and velocities are variable (e.g., in the lower Detroit River with shallow, off-channel areas, and deep navigation channels), EDI sampling is recommended along with discharge measurements to select sample locations that represent equal proportions of the total discharge. Where channel depths and velocities are more uniform (perhaps further upstream), EWI can be used.

Improving estimates supporting reduction strategies – Five categories of loads need to be considered: point sources, monitored tributaries, unmonitored sources, the generally small contributions from the atmosphere and shorelines to Lake St. Clair, and the load from Lake Huron. The Lake Huron load is the most challenging, whereas the other sources have well-established approaches. The influence of Lake St. Clair provides an additional challenge.

Point sources – Point sources are generally assembled from government sources, summed to produce monthly and annual loads, and adjusted for any intermittent discharges (Maccoux et al., 2016). Point sources downstream of tributary monitoring sites or discharging directly to the rivers or lake are added to the totals, whereas those upstream of the monitoring sites are excluded because their load is included in the tributary estimate.

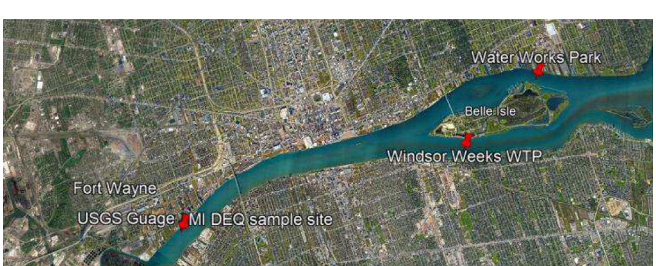

Fig. 8. Upper Detroit River showing location of water treatment plant intakes, the USGS gauge, and Michigan sample site near Fort Wayne.

Tributaries loads – Where flow and concentration are measured frequently (e.g., daily), tributary load is calculated as the sum of daily loads times concentration, accounting for short periods of missing data with various interpolations. Several other methods have been used when sampling is less frequent and flow and concentration are correlated. For example, Maccoux et al. (2016) used the Stratified Beal Ratio (Beale 1962), Burniston et al. (2018) used LOADEST (USGS, 2013), and Scavia et al. (2019) used WRTDS (Hirsch et al., 2010).

Unmonitored sources – Unmonitored areas are typically small tributaries that flow directly to the river or lake. Loads from these watersheds are usually estimated using a unit area load (UAL) approach, where the area-specific load from an adjacent monitored watershed is applied to the unmonitored area, excluding any point sources from the reference watershed (Rathke and McCrae, 1989). Robertson et al. (2022) recently proposed using model-generated unit area loads (MAL) and showed using the characteristics of the reference and target watersheds contained in the calibrated models produced more accurate results than the UAL approach.

Atmospheric and shoreline erosion – Atmospheric deposition is usually estimated from precipitation and TP concentration data collected from wet precipitation gauges in the region, adjusted to account for dry deposition (Maccoux et al., 2016). Shoreline erosion loads are estimated as the product of exposed Lake St. Clair shoreline times erosion estimates (e.g., Monteith and Sonzogni, 1976; Lang et al., 1988).

Lake Huron – The updated 2019–2021 average load estimate (Scavia, 2023) represents almost 50% of the total load to the system. These new turbidity-based daily estimates are slightly higher than those based on concentrations measured at Point Edward taken roughly 60 times per year, but considerably higher than those based on measurements at Port Huron taken only 7 times per year (Scavia et al., 2022). The new estimates account for Lake Huron's episodic resuspension events, and suggest that capturing the true load likely requires substantial increases in sampling frequency, especially at the US site. The fact that the turbidity-based estimates are similar to estimates from TP concentrations taken roughly 60 times per year, suggests sampling at least weekly should capture most events.

As in the Detroit River, the St. Clair River is generally well mixed vertically. However, reduced lateral mixing at the top of the river (Yaksich et al., 1985, Scavia et al., 2022) suggests that transect sampling may be required. Similar to the suggestions for the Detroit River, testing relationships between shore-based and river station samples would have to be evaluated.

Lake St. Clair influence – In considering load attribution and reduction allocations, it is important to recognize that Lake St. Clair has a substantial influence on the ultimate load to Lake Erie. On average, the lake retains 30% of its inputs, thus only 70% of the loads from Lake Huron and the St. Clair River and Lake St. Clair watershed ("upriver") enter the Detroit River. Therefore, in targeting load reduction strategies, it is important to recognize that on average a unit load reduction from an "upriver" source has 70% of the impact as a reduction from a Detroit River source. While loads from the Thames, Clinton, and Sydenham rivers are significant, they are small compared to the load from the St. Clair River, emphasizing the importance of improving monitoring the Lake Huron load.

For the other loads to Lake St. Clair, Bocaniov et al. (2019) suggest that loads from the Clinton and Sydenham rivers are more likely to be retained in the lake compared to the Thames, and thus reductions from the Thames would have a stronger influence on

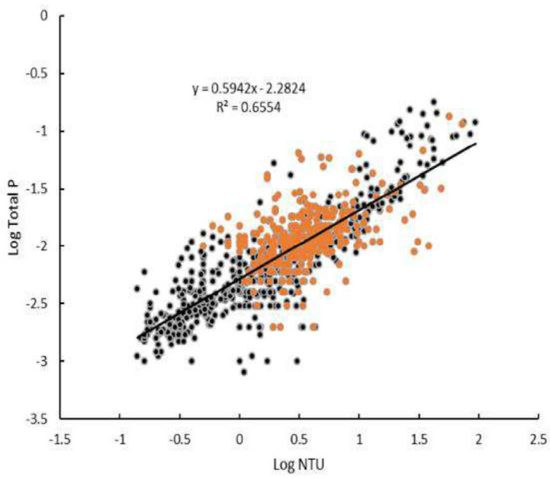

Fig. 9. Log-log regression of TP vs turbidity with data from Lake Huron and the St. Clair River (black dots, Scavia et al. (2022) and the Detroit River (orange dots, J. Varricchione, Michigan Department of Environment, Great Lakes, and Energy, personal communication). All data were used in the regression. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the load leaving the lake. This is consistent with Burniston et al. (2009) who noted that the Thames has a significant effect on the TP concentration on the Canadian side of the head of the Detroit River. Including Option 2 for the Detroit River, as described above, would allow further refinement of the relative influence of the Thames vs. the other tributaries.

Use of surrogates

Temporal and lateral variability within the St. Clair and Detroit rivers suggest the need for higher resolution sampling. While efforts like those described in Burniston et al. (2009, 2018) and Totten and Duris (2019) provide robust load estimates, replicating those approaches annually in both the lower Detroit and upper St. Clair rivers is likely to be challenging programmatically, logistically, and financially. However, strong predictive relationships between phosphorus and turbidity suggest turbidity could be used as an alternative, or supplement, to direct P measurements. For example, Robertson et al. (2018) showed strong relationships between turbidity and TP in Great Lakes tributaries, and found turbidity to be one of the strongest surrogates in their LOADEST estimates. Howell et al. (2014) showed strong TP-turbidity relationships in data from Lake Huron's nearshore, and Scavia et al. (2022) assembled data from Lake Huron and the St. Clair River to produce highly significant regressions. We added available Detroit River data and updated the regression (Fig. 9).

Scavia et al. (2022) used these relationships to estimate daily TP concentrations from turbidity measured at the Point Edward and Marysville water treatment plant (WTP) intakes to estimate the load from Lake Huron. A similar approach could be used with WTP data near Belle Isle or with new turbidity installations at a transect further downstream near Fort Wayne. As suggested above regarding shore-based and river station measurements of TP, it would be important to assess if single-point turbidity measurements could be used to predict cross-channel values.

Summary and conclusion

Given temporal and spatial variability in the St. Clair/Detroit River system, and the need to have accurate load estimates to drive models, develop mass balances, set load reduction targets, and track GLWQA progress over time, we suggest improvements in: 1) estimating the Detroit River TP load and 2) assessing the sources and processing of loads to help guide reduction strategies. These suggestions include:

1. For the Detroit River load, establish a transect at Fort Wayne and/or on either side of Belle Isle, and test the ability to predict cross-sectional variation from shore-based measurements, and test the utility of using strong TP-turbidity relationships to replace or augment TP sampling. The total load to Lake Erie would be those estimates plus the loads to the river below the transects, which are relatively small and easier to estimate with conventional methods.
2. For allocating load source reductions, accurate estimates of the Lake Huron load are needed. We suggest sampling at the top of the St. Clair River at least weekly, and augmenting that with daily turbidity measurements. Lake St. Clair TP retention indicates that a unit load reduction from upstream of the Detroit River has 70% of the impact of a downstream reduction. While the load to Lake St. Clair is dominated by the St. Clair River (and thus Lake Huron), load reductions from the Thames River appear to be more impactful that those from the Sydenham and Clinton rivers. Including transects on either side of Belle and/or Peche Islands would help resolve these relative contributions.

Moving forward – Updating the Detroit River load can lead directly to updates of Lake Erie mass balances, but it is only the first step in a reassessment of GLWQA goals, targets, and approaches. A next step would be to compare response curves from models recalibrated to the new loads with those used to guide the current targets. If the recalibrated models result in substantially different response curves, it could lead to different predictions about Lake Erie's response to load changes, and there may be a need to reassess the targets.

The recalibration could also lead to assessment of the impacts of different sources on hypoxia (e.g., western and central basin tributaries versus the Detroit River). In addition, the increased temporal resolution of the Detroit River loads could also provide new insights into the drivers of harmful algal blooms and hypoxia.

The revised loads and model recalibrations could lead to no change in targets, substantive changes in targets, or something in between. Given the scale and scope of the binational load reduction plan, it is important to know which. These next steps will not be trivial, requiring substantial time and resources. However, the GLWQA calls for routine reassessments and adaptive management as new information becomes available, and this should allow windows of time for adjustments if needed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We appreciate the support of several colleagues. Brad Hill and Matthew Graham provided access to the detailed, daily Environment and Climate Change Canada data collected in the Burniston et al. papers. Jeff Varricchione provided Detroit River TP and turbidity data from the Michigan Department of Environment, Great Lakes, and Energy. Meghan Price of Environmental Consulting & Technology, Inc. provided access to the water treatment plant intake data. Yu-Chen Wang and Serghei Bocaniov provided excellent advice and access to their data sets. This work was funded in part by the US Environmental Protection Agency Great Lakes National Program Office, Great Lakes Restoration Initiative Focus Area 3 through the U.S. Army Corps of Engineers project P2-505224.

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