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St. Clair-Detroit River system: Phosphorus mass balance and implications for Lake Erie load reduction, monitoring, and climate change

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ABSTRACT

To support the 2012 Great Lakes Water Quality Agreement on reducing Lake Erie's phosphorus inputs, we integrated US and Canadian data to update and extend total phosphorus (TP) loads into and out of the St. Clair-Detroit River System for 1998–2016. The most significant changes were decreased loads from Lake Huron caused by mussel-induced oligotrophication of the lake, and decreased loads from upgraded Great Lakes Water Authority sewage treatment facilities in Detroit. By comparing Lake St. Clair inputs and outputs, we demonstrated that on average the lake retains 20% of its TP inputs. We also identified for the first time that loads from resuspended Lake Huron sediment were likely not always detected in US and Canadian monitoring programs due to mismatches in sampling and resuspension event frequencies, substantially underestimating the load. This additional load increased over time due to climate-induced decreases in Lake Huron ice cover and increases in winter storm frequencies. Given this more complete load inventory, we estimated that to reach a 40% reduction in the Detroit River TP load to Lake Erie, accounting for the missed load, point and non-point sources other than that coming from Lake Huron and the atmosphere would have to be reduced by at least 50%. We also discuss the implications of discontinuous monitoring efforts.

Introduction

In response to Lake Erie's re-eutrophication (Scavia et al., 2014) that reversed the Lake's recovery from the 1970s (DePinto et al., 1986; Ludsin et al., 2001; Charlton et al., 1993), the US and Canada revised phosphorus (P) loading targets (GLWQA, 2016) based on public input and science synthesized in a multi-model effort (Scavia et al., 2016). The new targets would reduce annual and spring (March–July) P loads by 40% from their 2008 levels. Phosphorus is the key target nutrient because, while there is some evidence of algal co-limitation by nitrogen in late summer (Chaffin et al., 2013, 2018), harmful algal blooms and hypoxia – two key Lake Erie impairments (Zhou et al., 2015; Bridgeman et al., 2013; Michalak et al., 2013) – are driven strongly by P loads (Scavia et al., 2014, 2016; Rucinski et al., 2014, 2016; Obenour et al., 2014; Stumpf et al., 2016; Bertani et al., 2016; Bocaniov et al., 2016).

As the US and Canada develop and implement Domestic Action Plans (IJC, 2017) to reduce those loads, substantial attention will logically be placed on loads from the Detroit and the Maumee rivers because they contribute 41% and 48% of the total P (TP) load to the western basin, respectively (Maccoux et al., 2016; Scavia et al., 2016). There have been several assessments of the relative contributions and potential controls on P loads from the Maumee watershed (e.g., Scavia et al., 2017; Muenich et al., 2016; Kalcic et al., 2016). This study is part of a similar effort (Dagnew et al., in review; http://tinyurl.com/zusf4sx) to assess alternative management strategies for the US and Canadian watersheds that deliver P to the connecting channel between Lakes Huron and Erie – the St. Clair River, Lake St. Clair, and the Detroit River, hereafter referred to as the Huron-Erie Corridor (HEC, Fig. 1).

Based on a 2001–2015 time series from Canadian monitoring programs, Burniston et al. (2018) documented a significant decline in the load from Lake Huron to the St. Clair River and showed that earlier estimates of this flux were low by a factor of three due to historical reliance on sparse water quality sampling. They also measured the load to Lake St. Clair and by comparing it to the Lake Huron load, reported an increasing TP load to the St. Clair River, and suggested the extra TP load is in the particulate form. They also provided comprehensive measurements of P load to Lake Erie for 2014 and 2015, based on extensive observations in Detroit River channels upstream of the influence of the lake. Uncertainty remains, however, regarding the source, potential drivers, and impacts of the unmeasured load, and a more detailed assessment of all nutrient sources in the HEC is needed.

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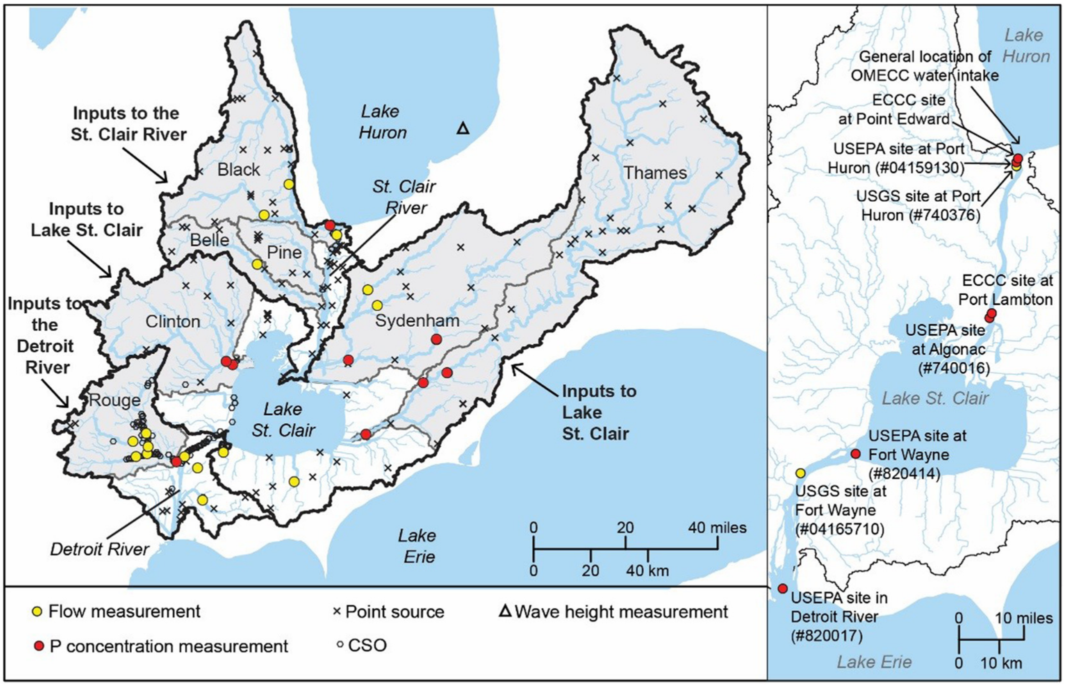

Fig. 1. Left: Map of Huron-Erie Corridor, identifying major tributaries, sampling sites, watershed boundaries (grey lines), and areas contributing to the different water bodies (bold black lines). Shaded areas represent watersheds with monitoring programs; non-point source loads from other areas (non-shaded) were estimated with the area-weighted method. Flow measurements (yellow dots), TP measurements (red dots), point sources (x), CSOs (open dots), location of wave data (open triangle). Right: Flow (yellow dots) and TP (red dots) sampling sites for the main channel.

This study therefore has four objectives based on combining data from US and Canadian monitoring programs: (1) update and extend to 1998–2016 the TP loading trends for the outlet of Lake Huron, the inlet and outlet of Lake St. Clair, input to Lake Erie, and all of the major tributaries and point sources; (2) provide estimates of TP retention by Lake St. Clair; (3) Identify the source and potential drivers of the missing load reported by Burniston et al. (2018); and (4) Discuss the implications of this missing load for Lake Erie's load reduction strategies and for monitoring programs in general.

Study area

The St. Clair River, Lake St. Clair, and the Detroit River transport water and nutrients from Lake Huron and HEC watersheds to Lake Erie. The St. Clair River flows 64 km from Lake Huron to Lake St. Clair, forming part of the international boundary between Canada and the United States. The river drops almost 1.5 m from the elevation of Lake Huron to that of Lake St. Clair in a relatively straight, poorly mixed (Sun et al., 2013; Derecki, 1985) channel. It receives inputs mainly from Lake Huron and the Pine, Black, and Belle rivers from the US (Fig. 1, Electronic Supplementary Material (ESM) Table S1), as well as direct discharges from point and non-point sources from both sides of the river. The Detroit River runs about 52 km from the outlet of Lake St. Clair, dropping 1 m along its path to Lake Erie where measurement of its load to Lake Erie has proven to be particularly difficult due to complexity of the river channel and sporadic backflow effect on river-to-lake hydrodynamics and transport (Burniston et al., 2018). In addition to the outflow from Lake St. Clair, the Detroit River receives P loads from metropolitan Detroit and Windsor and several rivers, most notably the Rouge River (Fig. 1).

Lake St. Clair's watershed is one of the most densely populated in the Laurentian Great Lakes, and this binational lake is an important source of drinking water, commercial and sport fishing, and other forms of recreation. It is a large (1115 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. Located in the connecting channel between Lakes Huron and Erie, the lake processes water from the upper Great Lakes (Superior, Michigan, Huron) via the St. Clair River, as well as from its proximate ~16,000 km^2 watershed that is roughly 65% in Canada and 35% in the United States. In addition to receiving P from the upper Great Lakes and the St. Clair River, it receives P from many tributaries, including significant loads from the Clinton, Thames, and Sydenham rivers, as well as point source discharges.

Data and methods

The water and nutrient budgets for Lake St. Clair were calculated for each water year (October 1 to September 30) from 1998 to 2016. Daily flow into and out of the St. Clair River, Lake St. Clair, and the Detroit River were obtained from gauged stations (Fig. 1). The Lake St. Clair annual water balance was compared against measured annual storage fluctuations to check the accuracy of the calculated values and make adjustments to flow estimates into and out of the lake. Then, annual TP loads into and out of the river-lake system were estimated from daily flow values and observations of TP concentration. The Lake St. Clair annual TP mass balance was used to estimate annual TP retention. Finally, TP load contributions of groundwater, bank erosion, and sediment resuspension were assessed to determine the potential sources of the "missing load" from Lake Huron.

Flow estimates

Daily flow rates for the major tributaries were downloaded from the USGS National Water Information System (https://waterdata.usgs.gov/nwis) for sites in the US and from the National Water Data Archive: HYDAT (http://tinyurl.com/y8be92pz) for sites in Canada. For the St. Clair and Detroit Rivers, flows were available for September 2008 to 2016 from USGS station #04159130 at Port Huron and #04165710 at Fort Wayne (Fig. 1). For 1998 to September 2008, we calculated daily flows based on daily mean water levels and stage-fall-discharge relationships (Fay and Kerslake, 2009).

Because the Black, Rouge, and Sydenham rivers have multiple flow gauges, we used area-weighted calculations to estimate flow at the downstream confluence. Flow values for tributaries without long-term flow gauges were estimated using the area-weighted method based on values from nearby streams with flow gauges. For Canadian watersheds along the St. Clair River and some portion of the southeast side of Lake St. Clair, we used the Sydenham River as reference. For unmonitored US watersheds of the St. Clair River and northern Lake St. Clair, we used the Black River as a representative reference. The Clinton and Rouge rivers were used as reference for the southwest and south sides of the lake, respectively, and the Rouge River and Canard Creek were used for the US and Canadian sides of the Detroit River, respectively. For smaller tributaries, we filled data gaps either with structural time series models (Ryberg and Vecchia, 2017) if the size of the gap is <60 days, or with area-weighted flow from a nearby gauge for the same stream (if any) or a different stream.

Lake St. Clair water balance

To conduct a rigorous Lake St. Clair TP mass balance (see below) for any water year, it is important to ensure a water balance over the same time period. Therefore, we computed Lake St. Clair annual water budgets for 1998–2016. Input was estimated as the sum of outflow from Lake Huron, tributaries and unmonitored areas upstream from Lake St. Clair, and net precipitation based on over-lake precipitation and evaporation data from NOAA (http://tinyurl.com/yacwh5of). After estimating flows from all major tributaries into the lake, there was 1122.5 km^2 of drainage area unaccounted (ca. 7%). To account for this area, we used an area-weighted estimate based on total flow of all tributaries except the St. Clair River and the ratio of total unaccounted drainage to the total drainage area. Outflow from Lake St. Clair was estimated at the USGS gauge station at Fort Wayne. Annual storage changes of the lake were estimated by averaging the observed mean daily levels at the US gauge at St. Clair Shores (station #9034052) and the Canadian gauge near the mouth of the Belle River (station #11965). Annual water balances were then calculated as gains from precipitation and Lake St. Clair tributaries, net changes in lake volume, and losses through evaporation and the lake outflow (Detroit River flow) (Table S2). After taking into account the annual storage changes of the lake, there was consistently more water flowing out of the lake than going in (up to 135 m^3/s), indicating that there might be measurement and/or estimation errors between upstream and downstream flow estimates. Because these errors were <1% of the flows, they were shared equally between flows going into and out of Lake St. Clair to ensure balance over each water year. As expected, the major flows are from the St. Clair and Detroit Rivers; precipitation and evaporation were roughly balanced (ESM Table S2, Fig. S1).

Phosphorus load estimates

TP concentrations in major tributaries were obtained from the Water Quality Portal (https://www.waterqualitydata.us/), the Provincial (Stream) Water Quality Monitoring Network (PWQMN, http://tinyurl.com/ycdvdj7w), the Great Lakes Intake Program (GLIP, https://tinyurl.com/yd35upnk) managed by the Ontario Ministry for the Environment and Climate Change (OMECC), and Environment and Climate Change Canada (ECCC; D. Burniston and A. Dove, personal communication, 2017). The number of samples ranged from 71 to 894 from 1998 to 2016 (Table S3). At the Port Huron and OMECC water intake station, we removed <1% of the data representing extreme outliers defined as concentrations higher than the mean plus four times the standard deviation. For the concentrations at the inlet and outlet of Lake St. Clair, we set the threshold to the mean plus three times the standard deviation, again eliminating <1% of the data.

Major tributary load calculations

Daily loads for the direct tributaries to the St. Clair River, Detroit River, and Lake St. Clair were estimated with two commonly used load estimation approaches for analysis of long-term surface water quality data: Weighted Regressions on Time, Discharge, and Season (WRTDS, Hirsch et al., 2010) and LOAD ESTimator (LOADEST, Runkel et al., 2004). Daily loads were summed to annual loads based on water year (October 1 to September 30). We used default settings for WRTDS.

While LOADEST has often been used in the Great Lakes region (Wellen et al., 2012; Merriman, 2015; Burniston et al., 2018), we relied primarily on WRTDS because it is more appropriate for our time series and addresses some of LOADEST's shortfalls (Runkel, 2013). While both methods are based on relationships between flow, nutrient concentration, and time, only WRTDS allows these relationships to change over time. Moyer et al. (2012) compared both methods and found that WRTDS performed better based on root mean square error and bias in estimated load. A similar study by Lee et al. (2016) concluded that WRTDS's flexibility in defining the relationships between nutrient concentration and flow conditions results in more accurate TP loads estimates. Lee et al. (2016) also noted that using LOADEST to estimate loads for flows outside of the range used for establishing the regression equation reduces its accuracy. WRTDS avoids some of the more serious consequences of extrapolation through its ability to change the regression equations over time and by using data near the area of extrapolation.

We compared LOADEST and WRTDS annual load estimates for 1998–2016. In most cases LOADEST estimates were slightly higher than WRTDS. With one exception where LOADEST was used for comparison, we used WRTDS throughout the study. When LOADEST was used, we used its default settings and automated selection to choose the regression models that best fit observations.

Main channel load calculations

The St. Clair and Detroit rivers are called rivers, but they are actually connecting channels with relatively stable year-round flows determined by the differences in water levels between Lakes Huron and St. Clair, and between Lakes St Clair and Erie. In Lake Huron and its water mass inflowing into the St. Clair River, the nutrient concentrations are not driven by precipitation and/or snowmelt events but rather determined by the lake internal physical and bio-chemical processes and their temporal and seasonal dynamics. Therefore, neither WRTDS nor LOADEST are appropriate for estimating loads in the St. Clair River and the Detroit River because TP concentrations are not correlated with flow in the main channel (Hirsch et al., 2010; Runkel et al., 2004). For these locations, we therefore used the Generalized Additive Model by using the R package "mgcv" (Wood, 2011; Wood, 2017) to approximate daily TP concentrations as a function of time. The smoothing parameters were selected by the Restricted Maximum Likelihood (REML) method. The estimated daily TP concentration and associated standard error were multiplied by daily discharge to estimate daily loading. The daily estimates were then aggregated to estimate annual loadings.

TP loads to the St. Clair River from Lake Huron were based on concentrations measured by USEPA at Port Huron (station #740376) and by ECCC at the Point Edward station (Fig. 1). Data from Great Lakes Intake Program station operated by OMECC in offshore Lake Huron were also accessed and used to help identify water from Lake Huron proper for comparison purposes. Loads to Lake St. Clair were based on concentrations measured at USEPA station #740016 at Algonac and ECCC station at Port Lambton (Fig. 1). Because the river is not well mixed laterally (Sun et al., 2013; Derecki, 1985), it generally operates as parallel streams. Therefore, at both the Lake Huron and Lake St. Clair input sites, we averaged loads calculated separately for US and Canadian stations.

Loads leaving Lake St. Clair were based on concentration measurements at USEPA station #820414 at Fort Wayne, and load estimates to

Lake Erie were based on concentrations measured at USEPA station #820017 near the mouth of the Detroit River.

Other tributary loads

Loads from other tributaries were based on concentration measurements near the outlet of the rivers, with the additional loads contributed downstream of the measurement station estimated as described below. Because there are more data in the upstream reaches of the Sydenham and Thames rivers, we used linear regressions to estimate downstream concentrations based on upstream concentrations. In the Sydenham River, data from PWQMN station #04002701602 and ECCC station #ON02GG1000 at Florence were combined, and the regression was based on the 109 dates when both upstream and the downstream stations had measurements. We applied the same approach for the Thames River based on 82 sets of concentration samples from upstream locations (PWQMN station #04001305802 and ECCC station #ON02GE1000) to estimate downstream concentrations. While there was as much as a 46 h time lag between stations, the regression results were the same with and without lags.

The sampling location on the Clinton River was moved from downstream to just upstream of the weir in 2011. This move was possibly due to the influence of a close by weir and/or periodic intrusions of Lake St. Clair water because its concentrations tended to be lower than those at the newer upstream station. Because there was less than a 3 h time lag between stations, we used the ratio of the average concentrations from the two stations during the 2011–2013 period of overlap to correct the downstream concentrations for 1998–2010.

The 1999 Black River annual average flow was extremely low (3.61 m^3/s) compared to the 1998–2016 average (12.5 m^3/s; SD = 4.72 m^3/s), resulting in load estimates lower than point sources from that predominantly agricultural watershed. Because this is unlikely, we assumed the load in 1999 was similar to the year with the second lowest flow (2003; an average flow 5.54 m^3/s).

Other non-point source loads

We used area-weighted estimates based on nearby streams for unmonitored areas prior to adding upstream point sources. Atmospheric loads to Lake St. Clair were from Maccoux et al. (2016). Following the approach of Lang et al. (1988), loading from shoreline erosion in Lake St. Clair was estimated by multiplying the shoreline length (210 km) by the annual P loading rate for the Lake St. Clair basin (196 kg/km/year; Monteith and Sonzogni, 1976).

Point source loads

For all US point sources other than the Great Lakes Water Authority Water Resource Recovery Facility (GLWAF), data were downloaded from the EPA Enforcement and Compliance History Online (http://tinyurl.com/ybgda4u3) for October 2008 through December 2015. For discharge from combined sewer overflows (CSO), we downloaded volume and treatment level for each CSO event from the Michigan Department of Environmental Quality Database (http://www.deq.state.mi.us/csosso) and obtained the outfall locations from the MiWaters database (https://miwaters.deq.state.mi.us). For the GLWAF, we received daily discharge and nutrient concentration data for the main discharge outfalls from the Great Lakes Water Authority for October 2004 through September 2016 (M. Khan, C. Willey, Great Lakes Water Authority, personal communication, 2018). We used Maccoux et al. (2016) for point source data from 2003 to 2008 and Panek et al. (2003) and Hartig et al. (2007) for data from 1998 to 2002. If data were not tabulated in the latter two references, we used the WebPlotDigitizer (Rohatgi, 2017) to extract values from graphs.

For all Canadian point sources, discharge and concentration data were obtained from OMECC's Effluent Monitoring and Effluent Limits (EMEL) Regulations (http://tinyurl.com/y7j9fqhq). These loads were discharged to the St. Clair River, Lake St. Clair, and the Detroit River based on sub-basin delineations of a parallel watershed modeling study (Dagnew et al., in review; http://tinyurl.com/zusf4sx).

Imputing missing values

Concentration data at the Point Edward (PE) station were only available for water years 2001 to 2015. Therefore, we applied a multiple linear regression on water year (WY) and TP load from OMECC's GLIP water intake station (TP′) to estimate the load for missing years (Adjusted $R^2 = 0.67$):

$$TP = 1.09 * TP' - 129.31 * WY + 260312$$

Data were only available for 1998–2015 at the USEPA Lake Erie station (#820017), and because there was no significant trend in loads, we used the average of all years to fill in values for 2016. Because atmospheric inputs were only available through 2013 (Maccoux et al., 2016), we used the long term average for 2014–2016. For point sources, if data were missing for a month, we used the average from the same calendar month of the same facility in other years. If no data were available from the same calendar month, we used the annual average.

Trend analysis

TP load trend significance was assessed with the Mann-Kendall test (Lettenmeier, 1988) and slopes were estimated following Sen (1968).

Lake St. Clair TP mass balance

The Lake St. Clair TP mass balance was calculated as gains from the St. Clair River, other tributaries and point sources loaded directly to the lake, the atmosphere, and shoreline erosion. Losses were measured at outlet of the lake (EPA station # 820414), and TP retention was calculated as the difference between TP flux into and out of the lake, expressed as a percent of the influx.

Wave heights, satellite imagery, and ice cover

To aid in analysis of long term trends in potential sediment transport from Lake Huron, we analyzed trends in wave heights, ice cover, and sediment resuspension along the south-eastern (S-E) shore of Lake Huron. Satellite imagery was used to estimate frequency of occurrences of sediment resuspension events in the S-E part of Lake Huron. MODIS image collections with two images per day for 2010, 2012, and 2016 for the same area were filtered using Google Earth Engine to remove images with >60% cloud cover, and then manually filtered to remove additional cloudy and unusable images. After filtering, there were on average 141 usable images per year. These images were classified visually as to whether or not there was visible sediment resuspension in the region influencing the Lake Huron outlet to the St. Clair River (ESM Fig. S2). The results were used to estimate the frequency and duration of these events.

Daily maximum wave heights for southeastern Lake Huron (Station 93259, Latitude: 43.32° N, Longitude: −81.88° W; depth: 55 m; Fig. 1) were calculated from data downloaded from US Army Corps of Engineers (USACE) wave information study (http://wis.usace.army.mil/). Lake Huron lake-wide ice coverage was downloaded from NOAA (https://www.glerl.noaa.gov/data/ice/) and annual average daily percent cover was determined for the standard ice-cover period of December 1 through April 30.

Results

TP load estimates

Estimates of annual loads for Lake Huron, the Detroit River, tributaries, and point sources were determined for the 1998–2016 water years, and loads into Lake St. Clair were determined for 2001–2015

(ESM Table S4). The uncertainties associated with the load estimates are sufficiently low for our analysis (ESM Table S5, Fig. S4). For example, mean loads across all years for stations at Lake Huron, into and out of Lake St. Clair and into Lake Erie are 1401, 1946, 2330, and 2479 MTA (metric tonnes per annum), while the mean standard errors of the regression across all years at each location are 237, 152, 242, and 201 MTA, and the standard errors divided by the means are 19, 8, 10, and 8%, respectively.

Non-point sources declined significantly at a rate of 100 MTA/year (90% CI: 64–133), driven primarily by the decline in Lake Huron load (64 MTA/year; 90% CI: 48–90). Point sources also declined at an average rate of 18 MTA/year (90% CI: 8–27), driven mostly by a significant decline in the Great Lake Water Authority Water Resource Recovery Facility (GLWAF) from 630 MTA in 2007 to 331 MTA in 2016. Other than the GLWAF, which is on average 18% of the TP load to Lake Erie, no other single point source is a large contributor (Fig. 2). The GLWAF reduction reduced its fraction of the total load from a high of 22% in 2008 to 13% in 2016.

The Lake Erie load (Fig. 3), calculated as the sum of loads from Lake St. Clair and the Detroit River watershed, declined from over 3956 MTA in 1998 to roughly 2425 MTA on average for 2013–2016. This decline was driven by the declines in the Lake Huron and GLWAF loads; there were no significant trends in other point or non-point sources.

The load to Lake St. Clair from the St. Clair River, calculated by summing all loads into the St. Clair River, is dominated by flux from Lake Huron (Fig. 4) and it decreased from 2493 MTA in 1998 to a 2013–2016 average of 1159 MTA. The Lake St. Clair load measured at Algonac and Port Lambton (Fig. 1) followed a similar pattern, but with higher values overall and less decline over time (Fig. 5). As such, the difference between these two estimates grew to 991 MT in 2015, averaging 456 MTA. This discrepancy ("missing load") was also noted by Burniston et al. (2018), and is discussed in detail below.

Lake St. Clair TP retention

Measured Lake St. Clair TP inputs were generally higher than outputs, but both declined over time (Fig. 6). Contributions from shoreline erosion and the atmosphere were small (76 MTA) relative to other sources. Based on all inputs and outputs, the calculated TP retention averaged 20% of inputs, with a relatively high standard deviation (10%) due to inter-annual variability (range: 4% to 34%).

Wave heights, storm frequency, ice cover, and sediment resuspension

Wave heights

Wave heights over 1.5 m and 2.0 m during 1998–2014 averaged 31 and 15 per year, respectively (Fig. 7). Over a longer period (1967–2014), the events over 2.0 m increased at a rate of 0.29 per year. An analysis of return frequencies for storms at stations along the southeastern shore of Lake Huron indicate that storms with wave height > 2 m occur 10 times per year (USACE, 2018).

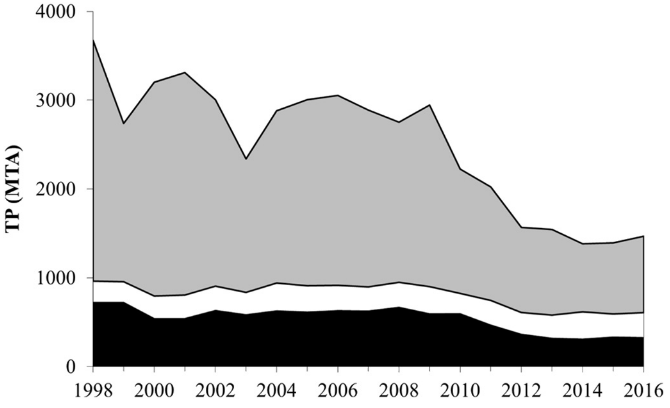

Fig. 2. Point and non-point source TP loads to the Huron-Erie corridor. Grey shade: Non-point sources; Black shade: Great Lakes Water Authority treatment facility (GLWAF); White shade: Other point sources.

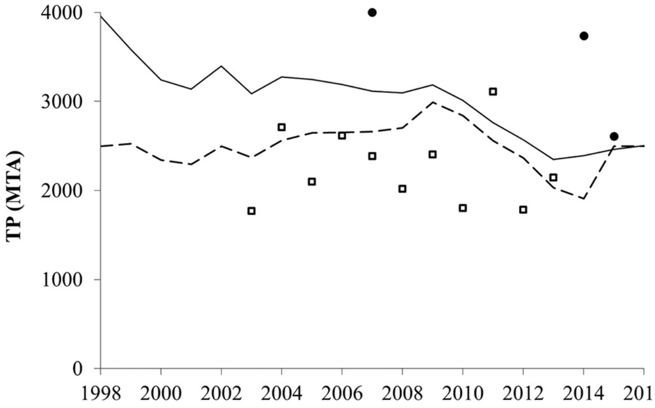

Fig. 3. TP loads to Lake Erie calculated as the sum of the load at the Lake St. Clair outlet and loads to the Detroit River (solid line), estimated at the mouth of the Detroit River (dashed line), estimated with LOADEST by Burniston et al. (2018) (solid circles), and estimated with the Stratified Beale's Ratio Estimator by Maccoux et al. (2016) (open boxes).

Ice cover

During the same time period when the frequency of significant wave height events increased, average lake-wide ice coverage declined at a rate of 0.45% per year. While the increase in the number of significant wave events is likely driven by increases in storm frequencies (Angel and Lsard, 1998), it is interesting to note that declining ice cover explains over 32% of the increase in the number of wave events over 2.0 m (Fig. 7). However, this is not surprising because wave height is a function of both wind speed and fetch over the open water, and reducing ice cover increases fetch.

Resuspension frequencies

Analysis of MODIS imagery for 2010, 2012, and 2016 identified 6, 10, and 7 strong sediment resuspension events per year, with mean durations of 7.3, 4.7, and 7.3 days, respectively. These are likely underestimates because only 36%, 43%, and 37% of the images were sufficiently cloud-free for analysis in those years.

Discussion

Trends in TP loads from Lake Huron and to Lake Erie

Our estimate of the current (2013–2016) mean load from Lake Huron (981 MTA) is similar to that of Burniston et al. (2018), three

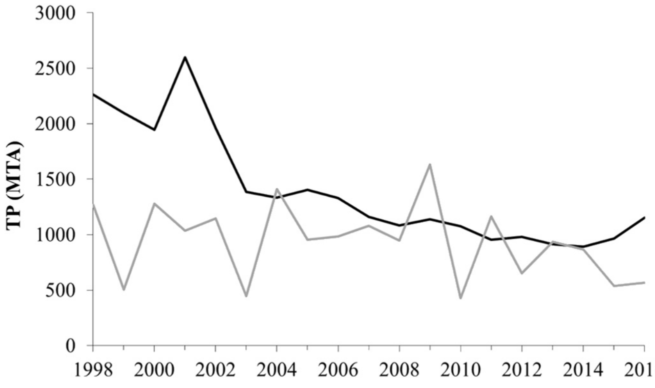

Fig. 4. TP loads to the St. Clair River from Lake Huron (bold black line) and from other tributaries and point sources (grey line).

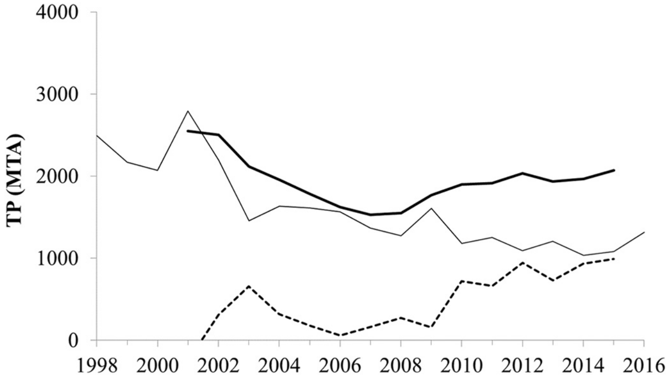

Fig. 5. TP inputs to Lake St. Clair calculated from Lake Huron and St. Clair River point and non-point source contributions (grey line); Lake St. Clair load measured at Algonac and Port Lambton (black line); and the difference (dashed line).

times that of earlier estimates (Maccoux et al., 2016), and it decreased from about 2261 MTA in 1998 to a 2008–2016 average of 1017 MTA (Fig. 4). This decline is likely driven by the oligotrophication of Lake Huron in response to the expansion of invasive dreissenid mussels (Evans et al., 2011; Yousef et al., 2017) because the load decrease coincides with the major reduction in nutrients and primary production in Lake Huron that occurred between 2000 and 2005 (Evans et al., 2011).

Because of significant Lake Erie water level fluctuations caused by seiches, wind set-up, and corresponding back flow, the downstream Detroit River station is not a good representation of the river nutrient load. So, to better estimate that load, we summed all loads into the Detroit River. Adding the load leaving Lake St. Clair and all point and non-point source contributions to the Detroit River, our load estimates to Lake Erie ranged from 2348 to 3956 MTA, averaging 3029 MTA (Fig. 3). The load decreased at a rate of 64 MTA/year (90% CI: 52–82), driven primarily by changes in loads from Lake Huron and the GLWAF. In contrast, the measured load at the EPA station near the mouth of the Detroit River ranged between 1823 and 2989 MTA, with an average of 2479 MTA.

Our calculated loads (mean = 3029 MTA) to Lake Erie are higher than those estimated by Maccoux et al. (2016) (mean = 2259 MTA for 2003–2013), but lower than the 2007, 2014, 2015 mean (3450 MTA) estimated by Burniston et al. (2018) (Fig. 3). Maccoux's estimates are based on summing loads from Lake Huron through the Detroit River. So, it is not surprising that without accounting for the higher load or the missing load their values would be underestimates. While the Burniston et al. (2009, 2018) estimates are based on the sum of measurements made sufficiently upstream of the influence of Lake Erie's surges and seiches (Mortimer, 1987), and should be the most accurate directly measured loads, their use of LOADEST for calculating main channel loads is probably not appropriate because it is predicated on correlations between concentration and flow (Runkel et al., 2004, Runkel, 2013). We did not find such correlations, and when tested, we found LOADEST to produce higher loads than WRTDS or GAM. Burniston et al. (2018) reported that the loads to Lake Erie are 2.0–2.5 times the load from Lake Huron for 2014 and 2015. Our estimates for 1998–2016 ranged from 1.2 to 2.9, with an average of 2.3.

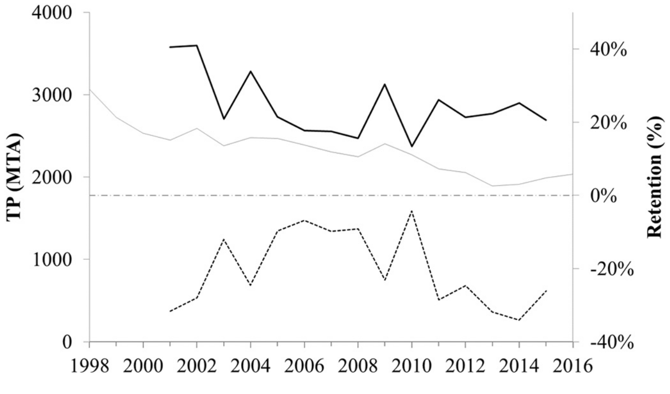

Fig. 6. Lake St. Clair TP retention (dashed line) calculated from total inputs (thick line) and outputs (thin line). Horizontal dashed line represents 0% retention; negative retention values indicate net loss from the lake.

Lake St. Clair phosphorus retention

The Lake St. Clair TP mass balance produced a long-term average retention of 20%, with significant year to year variation. In an earlier analysis for 1975–1980, Lang et al. (1988) reported that Lake St. Clair TP inputs and outputs were balanced over the six year period, but they also observed significant year-to-year variations in annual retentions. They calculated inputs from the St. Clair River by summing inputs from Lake Huron and the St. Clair River watersheds; whereas, ours were based on inputs measured at the inflow to Lake St. Clair. As discussed below, loads determined by summing upstream inputs underestimate the measured inputs to Lake St. Clair, especially when using earlier underestimates of the Lake Huron load. There were some other significant differences (e.g., our estimates of current inputs from the Canadian watersheds are considerably lower than theirs), or, it is possible the difference could also have been caused by the invasion of dreissenid mussels into Lake St. Clair in the 1980s (Nalepa et al., 1996, 2001; Baustian et al., 2014).

The "missing load" to the St. Clair River

Burniston et al. (2018) reported a difference between the TP flux out of Lake Huron and into Lake St. Clair for 2014 and 2015. Our results also showed that a difference remained even after accounting for all known loads to the St. Clair River. The remaining discrepancy averaged 456 MTA over the 2001–2015 time period, growing to 991 MTA in 2015 (Fig. 5). Because our estimation errors were low (ESM Table S5), the discrepancy is likely due to the presence of unmeasured loads. We explored this in detail in the following sections where we consider four potential loads to the St. Clair River that are not accounted for in current monitoring programs: additional point sources, groundwater sources, river bank erosion, and Lake Huron shoreline resuspension.

Point sources

The 2013–2015 average total point source loads to the St. Clair River is 51 MTA. This estimate would have to be low by more than a factor of 17 to account for the missing load. This would make the load more than twice the point source loads to Lake St. Clair and the Detroit River. This is highly unlikely because the population in the St. Clair River watershed is substantially lower than that around Lake St. Clair and the Detroit River.

Groundwater and river bank erosion

It is also unlikely that groundwater flux to the St. Clair River could account for much of the load discrepancy. Groundwater flux from the Michigan side of the river has been estimated as 9.81×10^6 m^3/year (Gillespie et al., 1988). Assuming similar flux from the Canadian side, the groundwater TP concentration would have to be over 30 mg/L to account for the discrepancy. Concentrations this high are unlikely because, for example, a Michigan statewide groundwater survey (Cummings, 1989) reported TP concentrations between 0 and 0.6 mg/L, with a mean of 0.01 mg/L. River bank erosion is also not likely to be a significant source because Knap and Mildner (1978) estimated that stream bank erosion for entire Laurentian Great Lakes system was only 426 MTA P.

Resuspended sediment from Lake Huron

Delivery of resuspended sediment from along the southeastern shore of Lake Huron could provide a significant load, as pointed out by

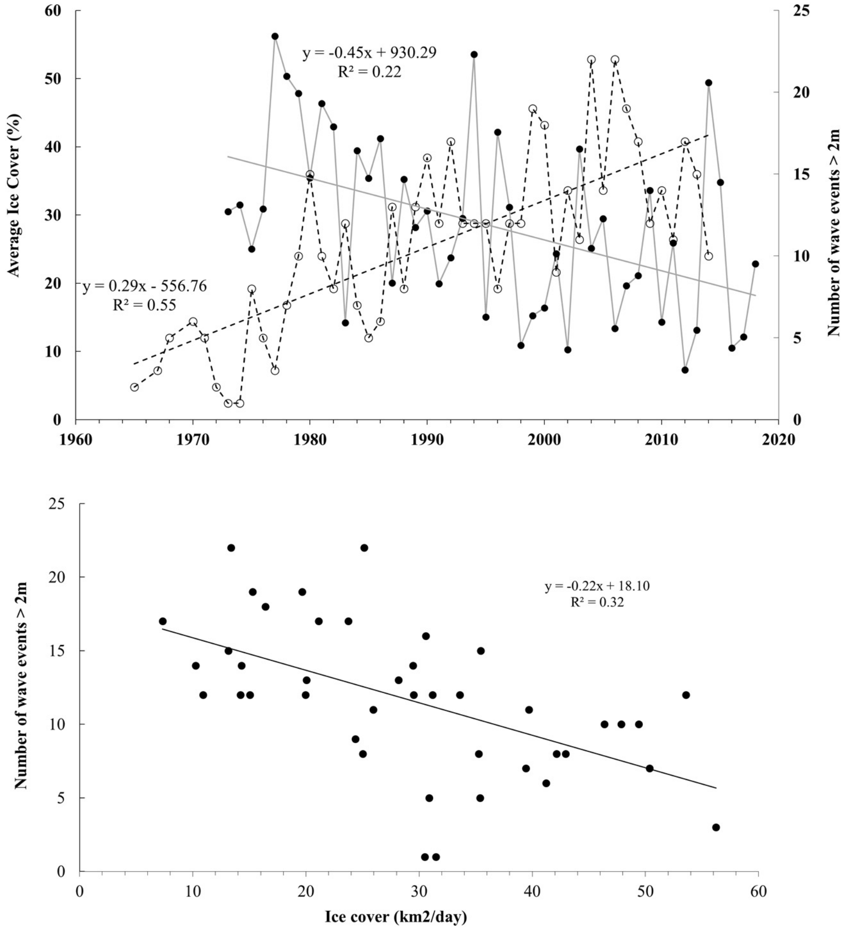

Fig. 7. Upper: Lake Huron percent ice cover (dashed line) and number of wave events over 2 m (solid line). Lower: Relationship between wave events > 2 m and percent ice cover.

Mortimer (1987), because currents generally flow southerly along that shore toward the outlet at the St. Clair River (Rao and Schwab, 2007). Burniston et al. (2018) suggested the missing load would be in particulate form, and there is likely enough material to account for it because Chapra and Sonzogni (1979) and IJC (1980) estimated that the TP contribution from Lake Huron's shoreline erosion was 675 MTA and 794 MTA, respectively. These estimates do not include resuspension of previously eroded but then settled material, which could be substantial as has been shown for Lake Michigan (Schwab et al., 2006). Because the most active resuspension zones are in the southeastern part of the lake, this could produce a significant load. However, for this to contribute to the missing load, it has to be missed by the monitoring programs. Below, we explore the likelihood of this happening.

The Point Edward station is located upstream of Lake Huron's outlet, 100 m from shore at 15 m below the surface (D. Burniston, ECCC, personal communication). The Port Huron station is located closer to the US shore, in the St. Clair River below the Blue Water Bridge, and the OMECC water intake station is located in Lake Huron proper (Fig. 1, ESM Fig. S3). The TP concentrations at these stations make it clear that the OMECC and Port Huron stations most closely track open Lake Huron water, whereas the Point Edward station could be influenced by the sediment load from the southeast shore. It is also worth noting that Port Edward samples were taken every other week until March 2012 and every four weeks thereafter (Burniston et al., 2018), and the Port Huron samples were taken even less frequently, ranging from 1 to 8 times per year.

Theoretical frequency of missed events

We first compared these sampling frequencies with the theoretical frequency, duration, and TP concentration of resuspension events required to account for the missing load. Using the 2013–2016 average St. Clair River flow (5271 m^3/s, ESM Table S1) and the 2013–2015 missing TP load (991 MTA), and assuming that the highest TP concentrations observed at the Point Edward station (0.12 mg/L) represent typical event concentrations, it is possible to account for the additional load if at least 3 events per year lasting at least 5 days were missed by the sampling programs (ESM Fig. S5). If the concentrations are more like those measured in Lake Huron's nearshore (Howell et al. 2014) and at the Port Lambton station (ca. 0.2 mg/L), the sampling programs would have to miss at least 3 events per year lasting only 3 days. Even fewer events would have to be missed to account for the average missing TP load (456 MTA). For example, it would require missing at least 3 events per year lasting at least 3 day for 0.12 mg/L, or at least 3 events per year lasting at least 2 days, assuming a concentration of 0.2 mg/L. Given these theoretical requirements (ESM Fig. S5), there are several missed events visible in satellite imagery during 2010 and 2012 (Fig. 8) that would have been sufficient to account for the missed load in those years.

Empirical evidence of missed events

There are several sets of observations supporting the case that the monitoring programs could have missed the number of resuspension events required to contribute the missing load.

Wave and storm frequency

Comparing resuspension events and monitoring times revealed that several resuspension events would have been missed each year, with some individual events sufficient to account for the missing load. For example, it is clear from our analysis of satellite imagery that several events would have been missed at Point Edward in 2010 and 2012

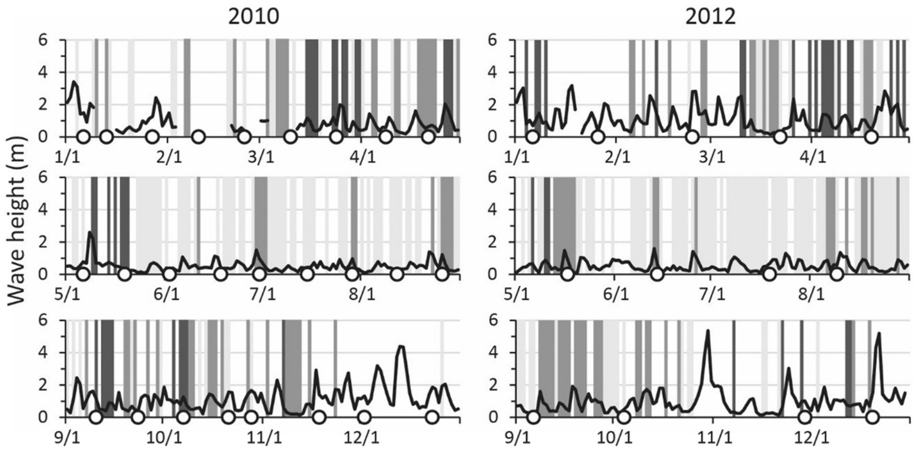

Fig. 8. Large sediment resuspension events (darkest grey bands), moderate events (medium grey bands) and Point Edward sampling times (open circles) plotted along the timeline for 2010 and 2012. Lightest grey bands are for images without resuspension events, and white space represents no data due to cloud cover. Maximum daily wave heights (black lines) at for the Corps of Engineers station 93259 (43.32° N, −81.88° W).

(Fig. 8). The number of missed events is likely an underestimate because cloud cover limited useful imagery to <45% of the days each year. In addition, wave heights along Lake Huron's southeast shore during periods of sediment resuspension were generally above 1.5 m (Fig. 8), and those conditions were often met between sampling times in other years. Storms that generate significant waves and can break up shore-protecting ice occur from 5 to 10 times per month (Angel and Lsard, 1998). Schwab et al. (2006) reported major resuspension events along Lake Michigan's southeastern shore occurred about 14 times per year.

Cyclone frequencies

Angel and Lsard (1998) reported that on average there are about 72 cyclones per year (5–10 per month) crossing the Great Lakes, with strong cyclones between November and April occurring >4 times those in May–October. They also showed that while the frequency of warm season cyclones has held steady, the frequency of winter cyclones increased over the twentieth century. In addition to driving larger waves, the high wind speeds associated with winter cyclones also break up extensive areas of ice cover, exposing the shoreline and adding more sediment to re-suspended loads. Return frequencies for storm events indicate that storms with wave height >2 m occur 10 times per year (USACE, 2018).

Water-level fluctuations

Using water level fluctuations as a surrogate for wave action and physical disturbance, Howell et al. (2014) reported a strong correlation between those fluctuations and fluctuations in turbidity (correlated strongly with TP concentration) along Lake Huron's eastern shore, with 10 and 15 events occurring between May and mid November 2010 at their Inverhuron Bay and Point Clark study areas, respectively (their Fig. 7). These are likely underestimates because cyclones that can drive shoreline erosion and resuspension occur more frequently in winter than in warmer months (Angel and Lsard, 1998).

Climate change drivers of long-term increase in missing load

The factors above describe not only how the sampling program could miss re-suspended loads from Lake Huron to the St. Clair River, but also suggest why the missing load increased over time. The increase in the missing load over the study period (Fig. 5) is consistent with four factors: 1) the change in the Point Edward sampling regime from every 2 weeks to every 4 weeks, 2) the climate-induced loss of ice cover that declined at a rate of 0.45% per year between 1975 and 2014 (Fig. 7; see also Wang et al., 2011), 3) the increase in the number of strong winter cyclones (Angel and Lsard, 1998); and 4) the increase in the number of days per year with wave heights over 2.0 m at a rate of 0.29 events per year between 1967 and 2012 (Fig. 7). Schwab et al. (2006) also reported an increase in resuspension events in Lake Michigan as the number of storms increased and ice cover decreased.

Thus, in comparing the sampling frequencies with likely resuspension events, particularly in the context of the increasing additional load over time, it is likely that significant TP flux events could be missed each year by infrequent sampling, and that these represent the missing load.

Implications for Lake Erie load reduction

Because our Lake Erie load estimates are based on concentration and flow measured at the outlet of Lake St. Clair, accounting for the missing Lake Huron load does not impact our estimates of the Lake Erie load or the reduction needed to meet the GLWQA goal. However, because this additional load may be very difficult to control, it does alter how one views its effect on load reduction strategies. The Great Lakes Water Quality Agreement (GLWQA, 2016) calls for a 40% reduction from the 2008 P loads. We can explore what would have to be done to meet the 40% goal if it was assigned to the Detroit River (Fig. 9). The 2008 Detroit River P load was 3096 MTA. This is a decline from the 1998 load (3956 MTA), driven primarily by the decreased Lake Huron load. A 40% reduction from the 2008 load is 1858 MTA, requiring a reduction of 1238 MTA. The 2013–2016 average declined to 2425 MTA, driven primarily by the decreased GLWAF load, leaving 567 MTA to be reduced further. That is 23% of the 2013–2016 total load. However, to the extent that the re-suspension load from Lake Huron is very difficult to control, the reduction would have to come from other watershed sources (non-point sources, the GLWAF, and other point sources). Their required reduction depends on how the “missing Lake Huron load” is handled. If that additional load is ignored, the average load from watershed sources for 2013–2016 is 1380 MTA, indicating the need to reduce 41% of it, even though there has already been substantial reduction from 2008. However, if one accounts for the missing load, the watershed load is 1138 MTA and 50% of that would have to be reduced to reach the target.

As Lake Huron ice cover continues to decline and storm frequencies continue to increase due to a warming climate (e.g., Angel and Lsard, 1998; Wang et al., 2011), the resuspension-based TP load from Lake Huron will likely increase, and maintaining the Lake Erie GLWQA load reductions in the future will be more difficult. Because this additional load is difficult to control, the additional load reductions will have to come from the St. Clair - Detroit River system watersheds, including from expensive sewage treatment and difficult to control non-point sources. There are no simple solutions to this problem. For example, even if it were possible to further reduce 75% of all point sources,

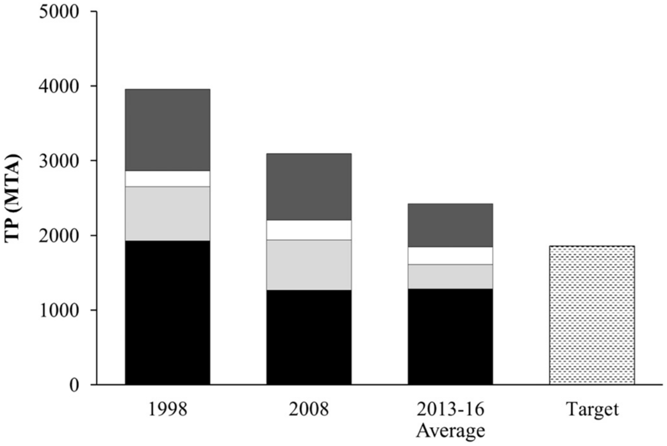

Fig. 9. Relative contributions to the Lake Erie TP load (1998, 2008, 2103–2016 average) from Lake Huron (black), other non-point sources (dark grey), the GLWA treatment facility (light grey), and other point sources (white). The load from Lake Huron includes our estimates of the missing load. Target (stippled bar) represents a 40% reduction from the 2008 load.

reaching the target would still require reducing 25% of the controllable non-point sources.

Implications for monitoring

Load estimation biases from relatively sparse, discrete water quality sampling often miss important characteristics of a dynamic hydrograph, especially for smaller rivers during relatively short storms (Bowes et al., 2015). Recent work that compares load estimates from discrete and continuous water quality sampling has also demonstrated bias for variable systems as large as the Mississippi River (Pellerin et al., 2014). However, the St. Clair River is neither a small river nor does it have a highly variable hydrograph. While its flow is comparable to the Mississippi River at St. Louis (median daily discharge around 5000 m^3/s), it is far less variable (the interquartile range of the St. Clair River [578 m^3/s] is much smaller than the Mississippi River at St. Louis [5154 m^3/s]). Pellerin et al. (2014) showed for the Mississippi River that even though estimates based on discrete samples underestimated continuous measurements by only 3.5% spread over a 2-year period, there were much larger differences at shorter time scales, especially during drought and flood conditions. They attributed this bias to nutrients stored in watershed soils during drought and subsequently flushed during flood. The sediment re-suspension and flush from Lake Huron to the St. Clair River is analogous to this storage and flush from land albeit occurring more frequently.

To provide more accurate estimates of nutrient load to the St. Clair River from Lake Huron, the frequency of water quality sampling would have to be increased to scales at least comparable to the frequency of Lake Huron storms (cyclones), roughly every 7 to 10 days. However, sampling at that frequency can be expensive and potentially weather-prohibitive. Robertson et al. (2018) proposed an alternative for improving standard regression-based approaches for systems with constituents that cannot be measured continuously (e.g., TP). By including surrogates that can be measured continuously (e.g., turbidity) for 30 Great Lakes tributaries, it increased the mean percent concentration variability explained by 26–61%, reduced the residual variance of the flow-only models by ~25–35%, and reduced the mean potential biases by ~4–11%. This was particularly effective for TP estimates because of the strong correlations they found between turbidity and TP. Howell et al. (2014) reported similar strong correlations for nearshore waters in southeastern Lake Huron. So, it should be possible to improve load estimates from Lake Huron by adding continuous turbidity sensors at existing monitoring sites.

Conclusion

By combining US and Canadian long-term data sets, we provide new estimates of the trends in loads from Lake Huron (Fig. 4), to and from Lake St. Clair (Fig. 6), and to Lake Erie (Fig. 3). We attribute the decline in loads to Lake Erie primarily to the oligotrophication of Lake Huron and upgrades to the Great Lake Water Authority treatment facility. From this data set, we estimated that on average Lake St. Clair retains 20% of its TP load.

Similar to Burniston et al. (2018), we found a discrepancy between the load from Lake Huron and the load to Lake St. Clair, and the discrepancy remained even after accounting for additional loads from the St. Clair River watershed (Fig. 5). After exploring several alternative explanations for the missing load, we concluded that it comes from a mismatch of sampling frequency and the transport to the St. Clair River of sediment re-suspended during storm events in southeastern Lake Huron (Figs. 8). The trend of this increased missed load is consistent with several forces driven by climate change and therefore is likely to continue to increase. We offer a potential remedy to account for the missed load by adding continuous measurement of turbidity or other surrogate properties. Finally, we estimated that to reach a 40% reduction in the load to Lake Erie from the Detroit River, accounting for the missed load, point and non-point sources from within the HEC watershed would have to be reduced by 50% (Fig. 9).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2018.11.008.

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