View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

Journal of Great Lakes Research 42 (2016) 1151–1165

Contents lists available at ScienceDirect

Journal of Great Lakes Research

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

Total and soluble reactive phosphorus loadings to Lake Erie

A detailed accounting by year, basin, country, and tributary

Matthew J. Maccoux [a,*], Alice Dove [b], Sean M. Backus [b], David M. Dolan [c,1]

[a] Milwaukee, WI 53222, USA
[b] Water Quality Monitoring and Surveillance Division, Environment and Climate Change Canada, Burlington, Ontario, Canada L7R 4A6
[c] Natural and Applied Sciences, University of Wisconsin-Green Bay, Green Bay, WI 54311, USA

ARTICLE INFO

Article history:
Received 23 December 2015
Accepted 4 August 2016
Available online 3 September 2016

Communicated by Russell Kreis

Index words:
Phosphorus
Soluble reactive phosphorus
Loadings
Lake Erie

ABSTRACT

Information about the loads of total and soluble reactive phosphorus entering Lake Erie is required in order to support commitments made under Annex 4 of the Great Lakes Water Quality Agreement. For these purposes, annual (water year) total phosphorus loads to Lake Erie are updated (2003–2013) and soluble reactive loads are reported on a lakewide basis for the first time (2009–2013). Complete documentation including input data and error estimates are provided. The results confirm previously documented long-term declining TP loads and show how these are driven by early and recent improvements in point source discharges, but are confounded by recent increases in nonpoint source loads that may in turn be due to increasing trends in precipitation and river discharge. The record since 2009 for SRP indicates high interannual variability and no discernible change in loadings over time. Recent TP loads are dominated by nonpoint sources (71%), with lower contributions from point sources (19%) and the balance comprising atmospheric deposition and loads from the upstream Great Lakes. Approximately one-half (49%) of the load of SRP is contributed from nonpoint sources, approximately 39% comprises point sources, and atmospheric deposition and upstream loads comprise 6% each. Loads are highest to the western basin for TP and highest to the Huron–Erie corridor for SRP. U.S. sources account for a majority (>80%) of the phosphorus loads entering the lake. Recommendations for improvements to the study approach are made including the identification of monitoring gaps and the testing of assumptions that require independent verification.

Crown Copyright © 2016 Published by Elsevier B.V. on behalf of International Association for Great Lakes Research. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

The 2012 Protocol to the United States–Canada Great Lakes Water Quality Agreement (GLWQA) calls for the review and revision of nutrient-related targets for the Great Lakes, including the establishment of nearshore and offshore water quality and tributary concentrations or loadings goals in order to meet the General and Specific Objectives as outlined in the Agreement. For Lake Erie, the commitments are time-bounded; phosphorus loadings targets have recently been approved, and the establishment of programs and policies needed to attain these targets is to be completed by 2017.

The existing nutrient targets, set forth in the 1978 Amendment to the GLWQA, were based on mass balance models that related in-lake total phosphorus (TP) concentrations to TP loadings. Given the desired trophic status of Lake Erie's western and central basins as mesotrophic and its eastern basin as oligotrophic, the loadings needed to achieve the corresponding in-lake concentrations were established. The programs and measures that were instituted by both the United States and Canada to meet these targets were largely successful at reducing loadings to the Great Lakes, and in-lake concentrations have declined (DePinto et al., 1986). Indeed, in all of the Great Lakes, with the exception of Lake Erie, the offshore environments have shown evidence of phosphorus declines that have overreached their targets, resulting in offshore oligotrophication (Dove and Chapra, 2015). Lake Erie phosphorus concentrations are now lower than maximum values observed in the early 1970s, but they remain higher than targets, show high interannual variability, and persistent nutrient issues remain. Symptoms of excessive nutrient inputs include a resurgence of algal blooms including harmful cyanobacteria in the western basin of Lake Erie (Michalak et al., 2013; Stumpf et al., 2012) and increased hypoxia in the central basin (Zhou et al., 2013). There is also some evidence that, despite a reduction in overall loading of TP to Lake Erie over time, the proportion comprised by the more bioavailable soluble reactive phosphorus (SRP) component may be increasing (Daloğlu et al., 2012; Richards et al., 2010; Scavia et al., 2014). In Lake Erie, the target TP load of 11,000 metric tonnes per annum (MTA) (GLWQA, 1978) was achieved by 1981 (DePinto

---

* Corresponding author.
E-mail addresses: maccmj02@gmail.com (M.J. Maccoux), alice.dove@canada.ca (A. Dove), sean.backus@canada.ca (S.M. Backus).

[1] Deceased 18 June 2013.

http://dx.doi.org/10.1016/j.jglr.2016.08.005
0380-1330/Crown Copyright © 2016 Published by Elsevier B.V. on behalf of International Association for Great Lakes Research. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

et al., 1986). Despite this success in meeting earlier targets, these symptoms of eutrophication have re-emerged.

Phosphorus continues to limit Great Lakes productivity and is therefore the most appropriate parameter for nutrient management (Bunnell et al., 2005; Dove and Chapra, 2015). The recently approved phosphorus loadings reduction targets for Lake Erie include a 40% reduction in spring loads of TP and SRP for western basin tributaries to reduce harmful algal blooms and a 40% reduction of annual TP loads for western and central basin tributaries to reduce central basin hypoxia (Objectives and Targets Task Team, 2015). The 2008 water year is used as a reference for calculating these reductions because calculated loadings for that year were similar to the existing 11,000 MTA TP loading target for Lake Erie.

In order to be able to track progress and implement the necessary programs and policies to meet these objectives, it is necessary to have detailed knowledge about TP and SRP loadings to Lake Erie. Previous loadings estimates are contained in various reports in the primary literature and these have been used extensively by the Parties to the GLWQA (the United States and Canada) in their work to assess progress and to examine and revise targets. Total phosphorus loadings to Lake Erie have been estimated since 1967. These estimates have been based on monitoring and discharge data which have generally improved in quantity and quality through time although some significant shortfalls remain. Since the 1980s in particular, improvements have been made to estimate loads from unmonitored watershed areas as prescribed by PLUARG (1978). Estimates for periods prior to 2009 have been previously reported elsewhere. Fraser (1987) reported annual TP loadings from 1967 through 1973. Lesht et al. (1991) reported loads from 1974 to 1986 and included basin-specific loads. Dolan (1993) reported loads from 1986 to 1990 by country, and Dolan and McGunagle (2005) reported loads from 1991 to 2002 by basin. Most recently, Dolan and Chapra (2012) reported 1994–2008 TP loads but without watershed-level detail for Lake Erie.

Here, we present the entire record (1967–2013) of TP loadings on a lake-wide basis and we provide basin-specific and country-specific allocations for the period 2003–2013. We have calculated loadings for the 2009–2013 and have modestly updated the 2003–2008 work to reflect new or adjusted information from the data sources. For the first time, we report on the loadings via the Huron–Erie connecting channel corridor instead of including them with the western basin total. We also present information about the two countries' contributions to the total loads and how they have changed over time, and we also provide details on a tributary-specific basis.

We provide a comprehensive overview of the methodology used to be able to understand and continue to profit from this information. Importantly, we present new information about the loadings for SRP for the time period 2009–2013, in order to assess spatial and temporal loadings trends for this increasingly recognized component. Finally, we make recommendations on improving the approach.

2. Methods

Total loadings of phosphorus are calculated as the sum of the loads from point sources, tributaries, atmospheric deposition, and the upstream Great Lakes. Point sources include municipal and industrial discharges and are further divided into direct (i.e., those that discharge directly to Lake Erie, a connecting channel, downstream of a tributary monitoring location, or an unmonitored watershed) or indirect (those that discharge to a monitored watershed upstream of the monitoring location). These two types of point sources need to be considered separately. Indirect point sources are accounted for in the monitored loads of tributaries but must be subtracted before computing the unit area load that may be applied to adjacent or downstream watersheds, as described further below.

Tributary monitoring accounts for all phosphorus delivered to the lake from watersheds upstream of the monitoring locations. Tributaries discharging to Lake Erie as well as the St. Clair–Lake St. Clair–Detroit River connecting channel (hereinafter called the Huron–Erie corridor) are included in this work. Atmospheric deposition of phosphorus to the land is accounted for in the tributary component, but direct deposition to the lake must be determined separately. Direct deposition to each basin of Lake Erie and to Lake St. Clair is accounted for here. Contributions from the upstream Great Lakes are taken as the loadings delivered via the St. Clair River at the outlet of Lake Huron.

2.1. Data sources

All data were obtained directly from the agencies responsible for collecting the information (Table 1). Point source discharges (monthly average TP effluent concentration and associated flows) in the U.S. were retrieved from either the Permit Compliance System (PCS) or its replacement, the Integrated Compliance Information System (ICIS), which began to replace PCS in 2006. Both systems are maintained by the U.S. Environmental Protection Agency (USEPA) and are updated by the individual states. Data for Canadian point sources were retrieved from the Municipal and Industrial Strategy for Abatement (MISA) database, which is maintained by the Ontario Ministry of the Environment and Climate Change (MOECC).

Flow data were obtained as daily mean discharge. Data for U.S. tributaries were retrieved from the National Water Inventory System (NWIS) database, maintained by the Water Resources Division of the U.S. Geological Survey (USGS). Data for Canadian tributaries were retrieved from the Hydrometric Data (HYDAT) database, maintained by the Water Survey of Canada, Environment and Climate Change Canada (ECCC).

Tributary water quality data were retrieved from multiple sources. State water quality monitoring data were obtained directly from Michigan DEQ, Ohio EPA, NWIS, and the USEPA STORET database. The Heidelberg Tributary Loadings Program operated by the National Center for Water Quality Research (NCWQR) at Heidelberg University in Tiffin, OH, provided high frequency monitoring data for rivers sampled in their long-running program. In Canada, the Provincial Water Quality Monitoring Network (PWQMN) operated by the MOECC provided tributary water quality data. For nine of these tributaries, more frequent monitoring data were provided for 2012 and 2013 by ECCC's Water Quality Monitoring and Surveillance Division (WQMSD) as part of their sampling for the Great Lakes Nutrient Initiative (GLNI).

Atmospheric deposition data were retrieved as monthly values of precipitation depth and TP concentrations from ECCC's WQMSD.

All input files that were used to calculate loadings for 2003–2013 will be provided in the Canadian federal data portal for the benefit of others who wish to see the details of the information used.

2.2. Load estimation

Lake loadings are calculated on a water year basis (i.e., October 1 of the previous year through September 30 of the current year). Loading rate (mass per time) is estimated as the product of a concentration (mass per unit volume) and a flow rate (volume per unit time). Total loadings to the lake comprise the sum of point source discharges (e.g., municipal sewage treatment plant effluent or industrial effluent), atmospheric deposition, and contributions via tributaries and the upstream Great Lakes.

2.3. Point sources

Dolan (1993) described the methods for estimation of point source loads to Lake Erie as follows:

$$\text{Loading} = 12\frac{\sum_{i=1}^{n} Q_i c_i}{n}$$

where Loading = average annual P loading (MTA), Q_i = the mean

Table 1
Listing of data sources.

Data type(s)	Source agency	Division	Hyperlink (email contact)
Tributary discharge	Environment and Climate Change Canada	Water Survey of Canada-HYDAT	http://wateroffice.ec.gc.ca/search/search_e.html?sType=h2oArc
	U.S. Geological Survey	Water Resources Division-NWIS	http://waterdata.usgs.gov/nwis/nwis
Tributary water quality	Environment and Climate Change Canada	Water Quality Monitoring and Surveillance Division	http://open.canada.ca/en/ (wqms-info@canada.ca)
	Heidelberg University	National Center for Water Quality Research	https://www.heidelberg.edu/academics/research-and-centers/national-center-water-quality-research/tributary-data-download
	Michigan Department of Environmental Quality	Water Resources Division	http://www.mcgi.state.mi.us/miswims/ (DEQ-WEBMASTER@michigan.gov) (DNR-MiSWIMS@michigan.gov)
	Ohio Environmental Protection Agency	Division of Surface Water	http://www.epa.state.oh.us/dsw/SurfaceWater.aspx
	Ontario Ministry of Environment and Energy	PWQMN	https://www.ontario.ca/data/provincial-stream-water-quality-monitoring-network
	U.S. Environmental Protection Agency	STORET	http://www3.epa.gov/storet/dbtop.html
	U.S. Geological Survey	Water Resources Division-NWIS	http://waterdata.usgs.gov/nwis/nwis
Point source	Ontario Ministry of Environment and Energy	MISA	https://www.ontario.ca/data/industrial-wastewater-discharges
	U.S. Environmental Protection Agency	Water Division-PCS/ICIS	http://www3.epa.gov/enviro/facts/pcs-icis/search.html
Atmospheric deposition	Environment and Climate Change Canada	Water Quality Monitoring and Surveillance Division	(wqms-info@canada.ca)

effluent flow for the i^{th} month (km^3/yr), $c_i =$ the average P effluent concentration for the i^{th} month (μgP/L), and $n =$ the number of months of monitoring for a particular year. This calculation is performed by outfall for each facility, where multiple outfalls are summed for the entire facility for both municipal and industrial dischargers. Intermittent discharges (i.e., sewage lagoons or retention basins) were adjusted to account for only those months where a discharge occurred.

2.4. Tributaries

Phosphorus loading from tributaries is calculated in either of two ways, depending on data availability. For tributaries sampled by NCWQR, loads are estimated on a daily basis using the results of their near-daily sampling. If a particular day has been sampled, the load is the product of flow and concentration. Loads for missing days are estimated using one of two methods. For a gap of five days or less, the load is estimated by simple linear interpolation. For gaps of more than five days, a multiple regression model of log-load versus log-flow, with additional terms to account for nonlinearity and temporal trends, is used to estimate missing daily loads (Richards et al., 2010).

For tributaries sampled by all other agencies, the Stratified Beale's Ratio Estimator (Beale, 1962; Dolan et al., 1981; Tin, 1965) is used. This method derives an estimate of the mean daily load from the ratio of the mean daily load to the mean daily flow for the dates with water quality information, multiplied by the annual mean daily flow and an adjustment for bias:

$$\tilde{\mu}_y = \mu_x \frac{\mathrm{m}_y}{\mathrm{m}_x}\left(\frac{1+\frac{1}{n}\frac{S_{xy}}{\mathrm{m}_x \mathrm{m}_y}}{1+\frac{1}{n}\frac{S_{x^2}}{\mathrm{m}_{x^2}}}\right)$$

where

$\tilde{\mu}_y =$ estimated load,
$\mu_x =$ mean daily flow for the year being considered,
$\mathrm{m}_y =$ mean daily load when samples were taken,
$\mathrm{m}_x =$ mean daily flow when samples were taken,
$n =$ number of days when samples were taken,

$$S_{xy} = \frac{1}{(n-1)}\sum_{i=1}^{n} x_i y_i - n\mathrm{m}_x \mathrm{m}_y$$

$$S_{x^2} = \frac{1}{(n-1)}\sum_{i=1}^{n} {x_i}^2 - n{\mathrm{m}_x}^2$$

$x_i =$ daily flow for each day a sample was taken,
$y_i =$ daily loading for each day a sample was taken

Where sufficient data were available (generally monthly or better, with event-based sampling), discharge strata were developed to better describe the relationship between water quality concentration and discharge (Dolan and McGunagle, 2005). A positive relationship between discharge and P concentration exists, and we sought to statistically describe these discharge–concentration relationships. Where the development of additional strata reduced the overall error of the estimate, the loading was calculated separately for each stratum and the total annual loading was taken as the product of the daily load of the stratum and the number of days within each stratum, for each year.

Loadings from unmonitored watershed areas were estimated using a unit area load (UAL) approach (Rathke and McCrae, 1989). Briefly, the UAL (or yield, in loading per km^2) is calculated from the upstream or an adjacent monitored watershed and is applied to the unmonitored area, excluding any indirect point sources from the UAL. The unmonitored areas are typically comprised of small tributaries that flow directly to the lake. Areas with several of these adjacent tributaries are classified as a complex, generally situated between larger monitored watersheds. In many cases, the tributaries contained within the complexes are not monitored for discharge. Although it has varied slightly from year to year, in general approximately 28% of the total Lake Erie watershed area of 75,400 km^2 is not monitored. The information contained in PLUARG (1978) was used to guide the selection of adjacent watersheds to match land uses as closely as possible for the application of UALs.

2.5. Atmosphere

Atmospheric deposition of phosphorus to Lake Erie was estimated from monthly precipitation depth and TP concentration data collected from three wet precipitation gauges located on the east shore of Lake St. Clair and the north shore of Lake Erie at Point Pelee and Rock Point by ECCC. Precipitation monitoring stations are further described by Chan et al. (2003). A monthly unit area precipitation depth was multiplied by the concentration of TP in the sample to provide a measured flux of TP to the lake. This flux represents wet deposition only and was doubled to account for dry deposition (Akkoyunlu and Tayanç, 2003; Balestrini et al., 2000).

2.6. Soluble reactive phosphorus

Similar to TP, SRP loadings estimates for tributaries were performed using the Beale's Ratio Estimator and stratified where the sufficiency of data allowed. We did not assume a SRP:TP ratio but only used SRP water quality measurements where they were available. In some cases where no data were available for an important tributary for a particular year, the estimate from an adjacent year was used and adjusted using the ratio of discharge between years. For tributaries monitored by NCWQR, daily loads were summed with missing data estimated using a linear interpolation or regression (as described for TP). Adjustments for unmonitored watershed areas were performed using the UAL approach, using the same watershed or nearest neighbor.

Because SRP is not routinely reported for point sources, a ratio of SRP to TP was applied. A similar approach has been used to estimate chloride loadings in this manner (Maccoux et al., 2013). Based on data from several Midwestern U.S. municipalities, it has been determined that SRP accounts for approximately 70% of TP in municipal point source effluent; this relatively high ratio is due to the high biological activity of effluents. This ratio was also applied to industrial point sources (Dolan and Chapra, 2011).

For atmospheric estimates, it was assumed that SRP accounted for approximately 70% of the wet deposition, with no dry deposition. This resulted in SRP being estimated as 35% of the total TP (wet and dry) load (Dolan and Chapra, 2011).

2.7. Input from Lake Huron and upstream Great Lakes

Earlier estimates of interlake transfer of TP from Lake Huron to Lake Erie via the St. Clair River had been fixed at 1080 MTA, based on estimates using data from 1974 to 1975 (Upper Lakes Reference Group, 1977). These estimates were significantly updated by Dolan and Chapra (2012), employing a mass balance model for the Great Lakes system (Chapra and Dolan, 2012). Flow data for the St. Clair River were combined with observed Lake Huron TP and SRP concentrations from spring ECCC open lake cruises to estimate the interlake transfer. The most recent estimates for 2008 of 321 MTA for TP and 155 MTA for SRP (Dolan and Chapra, 2011) were adopted here to represent this situation.

2.8. Statistical analysis

A statistical assessment of trends was performed using JMP 10.0 (SAS, 2012) by conducting a linear regression of natural log-transformed total and nonpoint source loads versus year. Change-point analysis was conducted using a non-linear modeling package, fitting a two-segment regression line to the log-transformed loads versus year. Significance was assessed at the $\alpha = 0.05$ level.

2.9. Error estimates

There are a number of types of errors that are invoked here; only some of these can be estimated and interpreted. The statistical error, which describes the variance of the input data and the associated error in calculating the total load, is provided here as the standard error. Standard errors of the overall estimates are calculated as the square root of the sum of the variances or mean square errors of each source type, and these are presented in the accompanying tables for each of the calculated loading components. The overall accuracy of the estimates is more difficult to determine as it is related mainly to the adequacy of the underlying sampling programs. Dolan et al. (1981) evaluated various tributary loading estimation methods and concluded that Beale's Ratio Estimator provided the best estimates based on both bias (defined as the difference between the estimate and true mean, i.e., accuracy) and precision. Recommendations are provided below on the minimum requirements for a sampling program designed to accurately estimate tributary phosphorus loadings.

Approximate confidence intervals for the total load are constructed with the standard error and effective degrees of freedom, as described by Rathke and McCrae (1989), and are based on the Student's *t* probability density function. The Student's *t* cumulative distribution function was used to estimate the probability of exceeding the target load in each year, based on the ratio of the difference between the estimated load and the target load compared to the standard error estimated for that year. It is difficult to evaluate the degrees of freedom best used for any particular year because the quantity of the data varies considerably between tributaries, although we note that the choice only impacts the calculated error terms which are one component of the overall error and does not impact the accuracy of the underlying data as described further below. An estimate of 40 degrees of freedom is used here to be consistent with previous efforts (Dolan and Chapra, 2012) and to demonstrate the higher frequency of data available for some Lake Erie tributaries (e.g., NCWQR and WQMSD GLNI sampling) compared to the other Great Lakes (12 degrees of freedom was used for the other Great Lakes in Dolan and Chapra, 2012).

3. Results and discussion

A graphical representation of TP loadings over the entire period of record (1967–2013) is provided in Fig. 1, which also shows temporal changes in the contributions of the different source categories, and a numerical summary is provided in the Electronic Supplementary Material (ESM) Appendix S1. A numerical summary of updated (2003–2008) TP loadings is provided in Table 2, showing the annual (water year) loads by source category and by country. Table 3 provides the details for the Huron–Erie corridor, which accounts for the watersheds draining into the St. Clair River, Lake St. Clair, and the Detroit River. The information for the western, central, and eastern basins of the main body of Lake Erie is provided in Tables 4, 5, and 6, respectively.

3.1. TP loading

Loading of TP to Lake Erie for the 11-year period from 2003 to 2013 ranged from 5839 to 11,946 MTA, with a mean of 9125 MTA (Table 2). The 2010 loading estimate of 5839 MTA was a record low. For the 11 years reported here, the target load of 11,000 MTA was only exceeded twice and only by a small margin. The 2007 load (11,538 MTA) exceeded the target by 5% and the 2011 load (11,946 MTA) by 9%. With the exception of the very low load estimated for 2010, values were within the range reported by Dolan and Chapra (2012) for the period from 1994 to 2008. There is a high probability that the target loading was exceeded for TP in both 2007 and 2011 and a high probability that the target load was not exceeded in any of the other years from 2003 to 2013 (Table 7).

Dolan and McGunagle (2005) presented a segmented regression model of TP loading over time and demonstrated that total loading declined steeply between 1967 and 1990 and that the rate of decline slowed for the period 1991–2001. We extend the trend here (Fig. 2) to provide total loadings from 1967 to 2013. Results of a two-segment piecewise regression on the log-transformed total load over time confirm an initial decline followed by a period of no change. The 95% confidence limits on the model indicate that the change point occurred during the period 1980–1991, with maximum likelihood of 1987. Prior to that time, total loadings declined significantly ($p < 0.001$) at a rate of 5.3% per year. Since 1987, total loadings have declined at a rate of 0.1% per year and this change is not statistically significant ($p = 0.98$). In other words, total loadings show high interannual variability and no significant change over the most recent 26 years (Fig. 2).

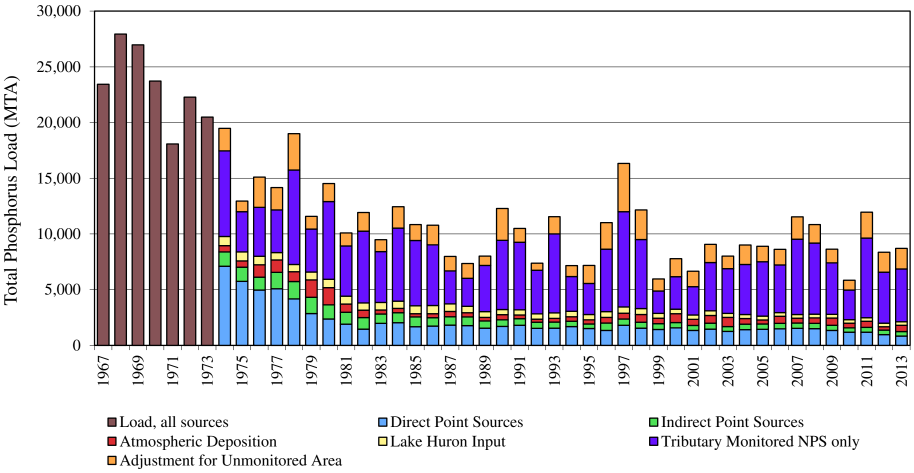

Fig. 1. Total phosphorus loads (MTA) to Lake Erie by source type (1967–2013). No source type attribution data are available prior to 1974.

Lake Erie continues to receive the majority (~60%) of its loading into the western basin, from both the Huron–Erie corridor (25%) and from tributaries and point sources discharging to the western basin itself (35%). Inputs to the central basin account for about 28% of the total lake TP load and those to the eastern basin account for an average of 12%. This distribution of loads between the basins has not changed appreciably over time (Fig. 3).

Nonpoint source loadings dominate the total load, contributing an average of 71% of the TP load to the lake for 2003–2013. Point sources discharging into tributaries contribute an additional 5% of the total load, so that 76% of the TP load entering Lake Erie is discharged via tributaries. An overview of loads from the major tributaries, together with the composition of loads in each basin, is provided for TP graphically in Fig. 4.

Industrial and municipal point source loadings account for approximately 19% of the total loading, with the majority of this (14% of the total lake load) contributed directly to the lake or downstream of tributary monitoring stations and the remainder (5%) discharged upstream of tributary monitoring locations. Atmospheric loading accounts for an average of 6% of the total load, and the input from the upstream Great Lakes accounts for approximately 4% of the total.

Point source loadings of TP have decreased over time (Fig. 1). Municipal sources dominate point source loadings (>95%) and are driving this downward trend. Industrial sources have remained relatively constant with an average of 58 MTA. The decline in point source loadings has occurred at rate of approximately 3.3% per year over the entire 1974–2013 record ($p < 0.001$); however, the trend has not been linear. In the 1970s, direct point sources declined dramatically, with an 80% reduction observed from 1974 to 1982 (annual slope $= -20\%$, $p < 0.0001$). During the 1980s until the late 2000s, there was a much slower rate of decline (1983–2008 slope -1.3%, $p < 0.0001$). Since the late 2000s, there has been another period of more rapid decline in direct point sources (2007–2013 slope -10%, $p = 0.0002$), presumably related to wastewater treatment plant improvements and reductions in combined sewer overflows.

The greatest point source loads of TP to Lake Erie are from U.S. sources discharging to the Huron–Erie corridor (see Table 3), comprising an average of 775 MTA or 9% of the average total load for 2003–2013. The City of Detroit Wastewater Treatment Plant (Detroit WWTP) contributes about three-quarters of this load. Between 2003 and 2008, its load did not change significantly ($p > 0.05$). Since 2008, however, the Detroit WWTP load has shown a statistically significant

Table 2
Total phosphorus loading estimates (MTA) to Lake Erie (2003–2013) by source with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth)

	2003		2004		2005		2006		2007		2008		2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States																						
Monitored Tributary	3870	65	3769	60	4687	145	3884	76	6211	127	5808	53	3577	60	2676	57	5603	138	4427	178	4201	67
Adjustment for Unmonitored Area	1026	32	1384	60	1224	84	1159	39	1730	112	1430	39	845	43	801	86	1705	105	1469	136	1230	66
Direct Industrial Point Source	7	0.6	8	0.7	7	0.5	7	0.8	13	4	7	0.6	6	1	9	2	4	0.4	3	0.4	3	0.6
Direct Municipal Point Source	1169	41	1321	40	1353	53	1389	53	1427	77	1417	45	1271	36	1113	33	1110	40	906	27	772	53
Indirect Industrial Point Source[a]	31	3	27	2	25	2	31	2	33	3	32	2	29	3	24	2	38	5	26	3	23	1
Indirect Municipal Point Source[a]	314	12	372	7	351	6	366	8	366	17	352	9	331	8	286	6	307	7	294	5	303	6
U.S. Total	6072	83	6482	93	7271	176	6438	101	9381	186	8662	80	5699	82	4599	108	8422	177	6806	225	6206	108
Canada																						
Monitored Tributary	572	84	1204	79	662	32	891	90	1041	78	1064	71	1511	121	367	19	1981	440	549	48	939	105
Adjustment for Unmonitored Area	122	20	363	35	158	14	239	43	280	24	232	15	379	32	80	5	611	133	311	35	618	85
Direct Industrial Point Source	27	3	28	2	23	1	25	0.9	24	1	21	1	18	0.8	21	1	17	0.6	17	0.5	19	1
Direct Municipal Point Source	53	3	54	2	61	3	56	2	54	3	51	3	45	5	39	2	44	2	39	2	39	2
Indirect Industrial Point Source[a]			0.0	0.0	0.4	0.1	0.5	0.1	0.6	0.0	0.6	0.0	0.5	0.0	0.5	0.0	0.5	0	0.5	0	0.5	0
Indirect Municipal Point Source[a]	88	2	87	2	90	2	96	2	89	2	93	3	102	3	78	2	85	3	74	2	81	3
Canadian Total	774	87	1648	87	904	35	1211	100	1400	82	1367	73	1953	125	507	20	2653	460	916	60	1615	135
Atmospheric	813	150	511	78	363	62	632	140	432	128	493	148	651	144	412	84	549	86	307	48	559	139
Input from Lake Huron[b]	366		364		354		335		325		321		321		321		321		321		321	
Basin Total	8024	193	9006	150	8892	190	8617	200	11,538	240	10,843	184	8623	207	5839	138	11,946	500	8350	238	8701	222

[a] Included in monitored tributary.
[b] 2003–2008 from Chapra and Dolan (2012); constant load used after 2008.

Table 3
Total phosphorus loading estimates (MTA) to the Huron–Erie corridor (2003–2013) with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2003		2004		2005		2006		2007		2008		2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States																						
Monitored Tributary	145	27	297	27	168	23	394	27	210	16	166	14	214	16	206	36	247	28	229	27	252	36
Adjustment for Unmonitored Area	145	24	344	55	175	38	332	35	159	15	123	23	202	28	317	78	281	51	270	53	283	60
Direct Industrial Point Source	4	0.6	4	0.5	4	0.5	3	0.5	7	4	3	0.5	4	1	8	2	3	0.4	2	0.2	2	0.6
Direct Municipal Point Source	773	37	837	39	903	52	926	53	965	77	969	44	822	35	710	31	685	39	513	26	421	53
Indirect Industrial Point Source[a]	2	0.0	0.9	0.05	0.9	0.6	1	0.2	1	0.2	2	0.1	1	0.1	1	0.4	0.9	0.3	2	0.2	3	0.0
Indirect Municipal Point Source[a]	36	4	51	5	50	3	47	3	60	16	60	7	52	5	38	2	49	3	49	2	43	3
U.S. Total	1067	52	1483	73	1249	68	1655	68	1342	80	1261	52	1242	48	1241	91	1216	70	1014	65	958	88
Canada																						
Monitored Tributary	212	74	615	53	343	19	413	83	508	62	304	35	624	53	147	10	1225	439	192	18	390	92
Adjustment for Unmonitored Area	14	2	154	32	58	13	108	41	120	19	44	4	126	20	20	3	263	91	192	33	392	82
Direct Industrial Point Source	16	2	19	2	16	1	15	0.8	15	0.7	14	0.5	12	0.5	15	1	14	0.5	14	0.5	15	0.7
Direct Municipal Point Source	45	2	44	2	55	3	51	2	48	3	44	2	39	5	32	2	36	2	33	2	33	2
Indirect Industrial Point Source[a]																						
Indirect Municipal Point Source[a]	42	2	43	2	43	2	48	2	44	2	48	3	56	2	34	0.9	40	2	31	1	39	3
Canadian Total	287	74	832	62	472	23	586	93	691	64	406	36	800	57	214	10	1538	448	431	37	831	123
Atmospheric	51	38	32	20	23	16	40	35	27	32	31	37	41	36	26	21	35	22	19	12	35	35
Input from Lake Huron[b]	366		364		354		335		325		321		321		321		321		321		321	
Basin Total	1771	98	2712	98	2098	74	2616	120	2385	108	2019	73	2405	83	1802	94	3110	454	1786	76	2145	155

[a] Included in monitored tributary.
[b] 2003–2008 from Chapra and Dolan (2012); constant load used after 2008.

($p = 0.0001$) decline at a rate of approximately 91 MTA each year, from a maximum of 764 MTA in 2008 to 285 MTA in 2013. The remaining point source loads to Lake Erie (i.e., all point sources minus the Detroit WWTP loads) have also shown a significant decline during the same 2008–2013 period ($p = 0.03$), with an overall reduction of approximately 44 MTA per year from 1144 MTA in 2008 to 816 MTA in 2013. In other words, all point sources have been recently declining, with the most dramatic improvements noted for the Detroit WWTP (Fig. 5).

Total phosphorus loadings from nonpoint sources remain highly variable from year to year (Fig. 6). For the entire record (1974–2013), there is an overall decline of 0.4% per year that is not statistically significant ($p = 0.4$) and no breakpoint is observed. However, when the recent record is analyzed independently, we note a statistically significant increase in nonpoint source loads (1999–2013 slope 4.7% per year; $p = 0.026$). An increase in TP loads was observed for 2000–2013 for the Maumee River, driven mainly by increasing precipitation and river discharge (Stow et al., 2015). We note that Risch et al. (2012) also detected a 20–40 cm net increase in precipitation depth over the period 2002–2008 for the Lake Erie region based on the analysis of data collected from approximately 115 stations. We also found a statistically significant increase in discharge from major Lake Erie tributaries for the 1999–2013 period ($p = 0.013$). Therefore, we postulate that the majority of the recent apparent nonpoint source loading increase is likely due to increasing trends in precipitation and concomitant increases in tributary discharge.

To further investigate water quality trends, we calculated flow-weighted mean concentrations (FWMCs) for each tributary in each year. These are provided in the ESM Appendix S1 and a graphical representation of the mean FWMCs for 2003–2013 is provided in Fig. 7. The symbol sizes in Fig. 7 represent concentrations below the median value of the mean tributary FWMCs (small and green), between the median and 80th percentile (medium and orange), and above the 80th percentile (large and red). As demonstrated, the top five tributaries with respect to FWMCs are located in the southwestern region of Lake Erie. These

Table 4
Total phosphorus loading estimates (MTA) to the western basin of Lake Erie (2003–2013) with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2003		2004		2005		2006		2007		2008		2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States																						
Monitored Tributary	2393	39	1998	48	2898	93	2256	48	3959	102	3982	41	2440	46	1755	32	3222	36	2615	26	2346	35
Adjustment for Unmonitored Area	177	12	190	18	205	18	246	11	551	107	475	28	309	30	207	30	515	12	445	14	294	8
Direct Industrial Point Source	0.5	0.1	0.7	0.1	0.5	0.1	0.4	0.1	0.4	0.0	0.3	0.0	0.3	0.0	0.4	0.1	0.3	0.0	0.8	0.4	0.4	0.0
Direct Municipal Point Source	105	4	123	4	121	6	124	4	123	4	119	4	120	5	116	5	114	3	108	4	103	4
Indirect Industrial Point Source[a]	23	3	20	2	21	2	27	2	29	3	27	2	25	3	21	2	32	5	23	3	19	1
Indirect Municipal Point Source[a]	161	6	186	5	173	4	179	6	167	4	164	4	145	5	134	4	140	5	131	3	137	4
U.S. Total	2676	41	2311	51	3224	95	2626	50	4634	148	4577	50	2869	55	2079	44	3850	38	3169	30	2743	36
Canada																						
Monitored Tributary																						
Adjustment for Unmonitored Area																						
Direct Industrial Point Source																						
Direct Municipal Point Source	2	0.4	2	0.3	3	0.3	2	0.3	3	0.6	3	0.4	3	0.4	4	0.4	4	1	3	0.8	3	0.4
Indirect Industrial Point Source[a]																						
Indirect Municipal Point Source[a]																						
Canadian Total	2	0.4	2	0.3	3	0.3	2	0.3	3	0.6	3	0.4	3	0.4	4	0.4	4	1	3	0.8	3	0.4
Atmospheric	111	56	70	29	50	23	86	52	59	47	67	55	89	53	56	31	75	32	42	18	76	51
Basin Total	2788	69	2383	59	3276	98	2714	72	4695	155	4648	74	2961	76	2139	54	3930	50	3214	35	2822	63

[a] Included in monitored tributary.

Table 5
Total phosphorus loading estimates (MTA) to the central basin of Lake Erie (2003–2013) with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2003		2004		2005		2006		2007		2008		2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States																						
Monitored Tributary	1332	45	1474	25	1622	109	1203	52	2025	73	1660	29	923	35	715	31	1761	50	1144	23	1403	39
Adjustment for Unmonitored Area	414	14	483	9	556	73	336	15	679	29	538	14	221	9	183	17	481	30	305	7	427	22
Direct Industrial Point Source	1	0.2	2	0.4	1	0.2	2	0.6	5	0.7	3	0.4	1	0.1	0.9	0.0	0.4	0.1	0.4	0.0	0.4	0.0
Direct Municipal Point Source	222	16	287	8	262	7	270	6	273	8	263	7	265	5	231	11	255	8	230	6	194	5
Indirect Industrial Point Source[a]	6	0.5	6	0.3	3	0.2	3	0.2	3	0.1	3	0.3	3	0.3	2	0.2	5	0.4	1	0.1	2	0.1
Indirect Municipal Point Source[a]	118	9	135	3	128	3	138	4	136	3	128	4	134	4	114	4	116	5	112	2	120	3
U.S. Total	1969	49	2246	27	2441	131	1812	54	2980	79	2464	33	1410	37	1130	37	2497	58	1680	25	2025	45
Canada																						
Monitored Tributary	107	33	169	45	46	7	196	20	142	23	261	28	404	40	24	7	123	13	156	16	121	16
Adjustment for Unmonitored Area	36	11	70	9	33	3	44	8	53	9	63	9	84	14	20	2	116	56	33	6	61	14
Direct Industrial Point Source	0.8	0.1	0.6	0.1																		
Direct Municipal Point Source	4	0.4	5	0.3	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	0.6	0.0	1	0.1	1	0.1	0.4	0.0	0.4	0.0
Indirect Industrial Point Source[a]					0.4	0.1	0.5	0.1	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
Indirect Municipal Point Source[a]	0.8	0.2	1	0.1	5	0.3	6	0.4	5	0.4	5	0.3	6	0.4	4	0.2	6	0.4	5	0.4	6	0.3
Canadian Total	148	35	245	46	80	7	241	22	196	25	324	29	489	43	45	8	241	57	190	17	182	21
Atmospheric	464	114	292	59	207	47	361	106	247	97	282	112	372	109	236	63	314	65	176	36	320	105
Basin Total	2581	129	2783	80	2729	140	2414	121	3423	127	3070	121	2271	122	1411	73	3052	104	2046	47	2527	116

[a] Included in monitored tributary.

tributaries therefore contribute concentrated phosphorus to the lake relative to the Detroit River which contributes a similar load but is delivered as a much higher flow with a lower phosphorus concentration (see also Fig. 1 of Scavia et al., in this issue).

Regression of the log-transformed FWMCs over the 2003–2013 period indicated no change for any of the 28 monitored tributaries with the exception of significant declines observed for the Cuyahoga River (slope −6% per year, $p = 0.002$), the Ashtabula–Conneaut complex (slope −16% per year, $p = 0.0011$), and the Grand River (Ohio; slope = −12%/year, $p = 0.0018$) and a significant increase observed for the Portage River (slope +16%/year, $p = 0.002$). We did not investigate for shorter term trends or change points, nor did we examine seasonality or changes in seasonal trends over time. However, for the period 1999–2013, when nonpoint loads and total discharge appeared to be increasing, the FWMCs showed a declining trend that was not statistically significant (slope −0.9%, $p = 0.084$). Therefore, the detection of loading changes that can be uncoupled from changes in precipitation and discharge may require these FWMC assessments to be conducted and periodically updated to report on trends.

The highest contribution of TP to Lake Erie is delivered via the Maumee River, with a 2003–2013 average TP load of 2617 MTA. The next highest contributing tributaries, on average, are the Sandusky River (776 MTA), Cuyahoga River (450 MTA), Grand River (Ontario; 340 MTA), and Thames River (323 MTA). Collectively, these top five tributaries deliver approximately half (4506 MTA) of the average TP loading to Lake Erie (9125 MTA). Most of these tributaries show no significant change in TP loads over time. Regression of the log-normalized tributary loads over the period 2003–2013 indicated no change for the Maumee River (slope −0.4%, $p > 0.1$), the Sandusky River (slope +1.7%, $p > 0.1$), the Grand River (slope +3.1%, $p > 0.1$), and the Thames River (slope +2.2%, $p > 0.1$). The Cuyahoga River has shown a significant, consistent decline for the period 2003–2013 (slope −6%, $p = 0.012$). As noted by Baker et al. (2014), the Cuyahoga is unique among the rivers monitored by NCWQR in that it receives a high loading from point sources. The Cuyahoga River TP load decline appears to be related to both wastewater treatment plant improvements and reductions in nonpoint source loads, as both are observed to have declined significantly over the past 11 years. Nonpoint source reductions of

Table 6
Total phosphorus loading estimates (MTA) to the eastern basin of Lake Erie (2003–2013) and standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2003		2004		2005		2006		2007		2008		2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States																						
Monitored Tributary							30	8	17	2							373	120	439	172	200	21
Adjustment for Unmonitored Area	290	12	366	7	288	4	246	5	341	7	293	6	113	6	93	10	429	86	448	124	225	15
Direct Industrial Point Source	0.9	0.1	1	0.2	1	0.1	0.9	0.1	1	0.1	1	0.1	0.3	0.1	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0
Direct Municipal Point Source	70	3	74	3	68	3	68	3	66	2	66	2	64	2	56	2	56	2	56	2	55	2
Indirect Industrial Point Source[a]																						
Indirect Municipal Point Source[a]							2	0.1	2	0.1							2	0.2	2	0.1	2	0.1
U.S. Total	361	12	442	8	357	5	345	10	425	8	360	6	177	6	149	11	859	147	943	212	480	26
Canada																						
Monitored Tributary	253	24	420	39	273	25	282	28	391	42	499	56	483	101	196	15	633	28	201	42	428	47
Adjustment for Unmonitored Area	72	16	139	12	67	4	88	11	107	12	125	12	169	20	40	4	232	79	85	11	166	20
Direct Industrial Point Source	10	2	8	0.1	7	0.1	10	0.2	10	0.8	8	1	6	0.6	6	0.1	3	0.3	3	0.3	4	0.7
Direct Municipal Point Source	2	0.1	3	0.1	3	0.1	3	0.2	2	0.1	3	0.1	3	0.1	3	0.1	3	0.1	2	0.2	2	0.1
Indirect Industrial Point Source[a]			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indirect Municipal Point Source[a]	45	2	42	0.3	43	0.4	42	0.5	40	0.4	41	0.9	40	2	39	1	40	2	38	2	36	0.9
Canadian Total	338	29	569	41	350	25	383	30	510	44	634	57	661	103	244	15	870	84	292	44	600	51
Atmospheric	186	72	117	37	83	30	144	67	99	61	113	71	149	69	94	40	125	41	70	23	128	66
Basin Total	884	79	1128	56	790	39	872	74	1034	76	1107	91	987	124	487	44	1854	174	1305	218	1207	88

[a] Included in monitored tributary.

Table 7
Total phosphorus loading estimates (MTA) to Lake Erie (2003–2013), 95% confidence limits, standard error, and probabilities of exceeding the current GLWQA target load of 11,000 MTA.

Year	Load	Lower 95% confidence limit[a]	Upper 95% confidence limit[a]	Standard error	Probability of exceeding target load[a]
2003	8024	7635	8413	193	<0.0001
2004	9006	8703	9308	150	<0.0001
2005	8892	8509	9276	190	<0.0001
2006	8617	8213	9020	200	<0.0001
2007	11,538	11,052	12,023	240	0.9845
2008	10,843	10,472	11,214	184	0.1989
2009	8623	8204	9042	207	<0.0001
2010	5839	5560	6119	138	<0.0001
2011	11,946	10,935	12,957	500	0.9671
2012	8350	7869	8831	238	<0.0001
2013	8701	8253	9149	222	<0.0001

[a] Based on 40 effective degrees of freedom.

approximately 17 MTA per year ($p = 0.03$) and point source reductions of about 5 MTA per year ($p = 0.009$) are evident in the data.

Of the total nonpoint source loads delivered to Lake Erie, 75% is accounted for by monitored tributaries, with the remaining 25% comprising the adjustment to account for unmonitored areas. Collectively, unmonitored areas are estimated to contribute approximately 17% of the total load to the lake and 39% of the load that is delivered via tributaries. Approximately 72% of all watershed areas are monitored; however, this does not speak to the sufficiency of the monitoring data. In the Huron–Erie corridor, an average of 66% of the area is monitored; for the west, central, and eastern basins the monitored areas comprise 85%, 71%, and 58%, respectively, of the total area draining to the lake. The number of samples taken in each year and the number of resulting strata used for the calculation of the Stratified Beale's Ratio Estimator is provided in the ESM Appendix S1 for each monitored tributary. Improvements to the tributary loading estimates could be achieved by the establishment of new monitoring stations and/or the application of watershed modeling approaches to better describe water quality in currently unmonitored areas.

The measured atmospheric deposition of TP to Lake Erie contributes less than 10% of the total load, even with the assumption that dry deposition equals the contribution from wet precipitation. There is a moderately significant ($p = 0.008$) increase (+1.5%) in atmospheric deposition observed for the period 1982 to 2013; although not specifically examined here, we suspect that this increase is due to an increase in precipitation depth as noted for the region surrounding much of Lake Erie for 2002–2008 by Risch et al. (2012). The implications of this increase in deposition are small given the low contribution of atmospheric deposition to the lake's total load. Further resolution of the atmospheric deposition component does not appear to be warranted at this stage.

Loadings from the upstream Great Lakes are estimated to be the smallest component of the total load of TP to Lake Erie, currently accounting for only 4% of the total TP load to Lake Erie. However, the modeling of interlake transfer was based on offshore Lake Huron water quality measurements and has not been updated since 2008 (Chapra and Dolan, 2012). The modeled load from the upstream Great Lakes needs to be validated with the monitoring data that are being updated from St. Clair River monitoring conducted by ECCC.

Excluding atmospheric and Lake Huron inputs, the U.S., on average, accounts for approximately 84% of the total lake loading (yearly values for 2003–2013 range from 74% to 90%). The mean contributions for 2003–2013 are shown in Fig. 8, by country and source category. Further basin-specific analyses indicate that the U.S. accounts for an average of 68% of the load to the Huron–Erie corridor, more than 99% of the load to the western basin, and approximately 90% of the load to the central basin. In the eastern basin, contributions are more similar between the countries, with Canada accounting for 54% of the total load on average and the U.S. accounting for 46%.

The standard error (a measure of precision) of lakewide TP estimates (Table 2) ranged from 1.7 to 4.2% of the total load. These errors are within the ranges reported in Dolan and Chapra (2012). Examination of the errors associated with each source category reveals that the highest standard errors relative to the loads are observed for the atmospheric component (average of SE:load for each year = 21%), U.S. direct industrial point sources (14%), and Canadian unmonitored (12%) and monitored (10%) tributaries. Some of the lowest standard errors (~2%) are associated with U.S. monitored tributaries.

The high standard errors for atmospheric deposition relate to the variability in the measurements of TP concentrations and precipitation depth. For the monitored tributary loads, relatively high errors are observed for Canadian tributaries because water quality data are primarily

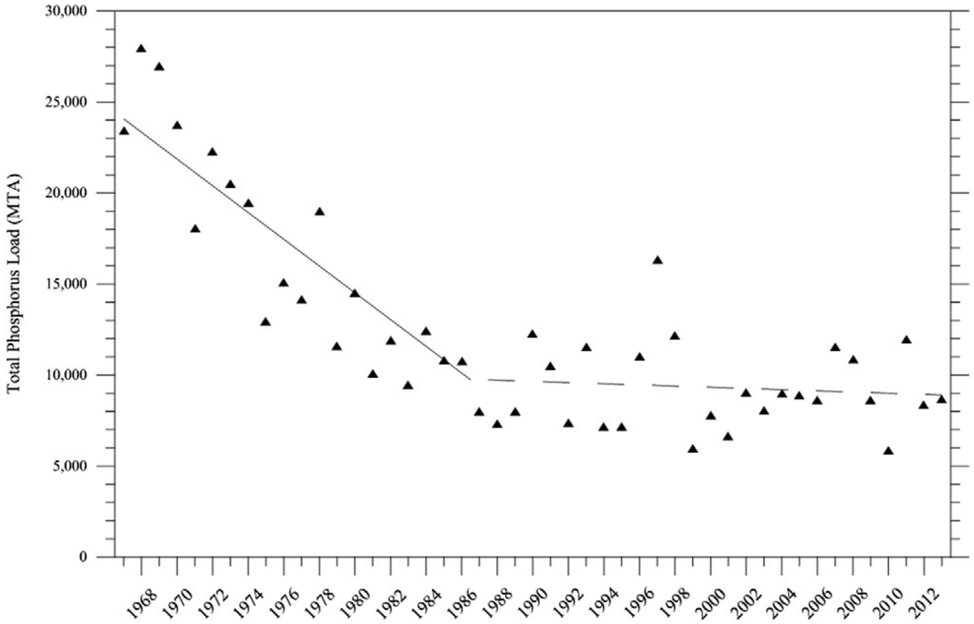

Fig. 2. Trend analysis of total phosphorus loading (MTA) to Lake Erie (1967–2013). A two-segment piecewise regression shows the breakpoint at year 1987. A significant decline is noted for 1967–1987 (solid line; $p < 0.001$); since that time, no significant trend is observed (dashed line; $p > 0.05$)

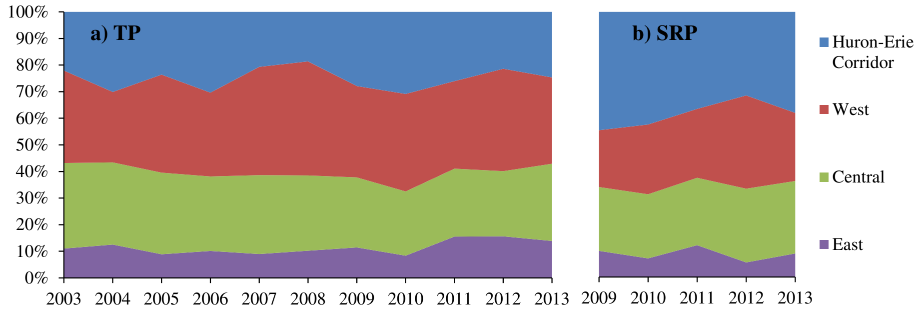

Fig. 3. Percent contribution of Lake Erie's basins to the total lake load of a) total phosphorus (2003–2013) and b) soluble reactive phosphorus (2009–2013).

derived from the Provincial Water Quality Monitoring Network, which was designed to examine long-term water quality trends and not to estimate loads. The occasional capture of high flow events (with insufficient frequency to permit the establishment of higher flow strata) has increased the standard error. The near-daily sampling of many major tributaries in the U.S. resulted in improved accuracy and lower errors. In some cases, however (e.g., the Huron River in Michigan), exceptionally low variability of TP concentrations were observed, and this should be validated with more frequent monitoring data. As mentioned previously, our error assessment relates only to statistical errors associated with estimating loads based on the input data and do not reflect uncertainty due to the adequacy of the underlying monitoring programs.

Because tributaries undergo wide fluctuations of both water quality and discharge, high standard errors (i.e., lower precision) may result from increased monitoring intensities that more adequately capture the range of water quality and discharge, and these may be more accurate than estimates generated with low-frequency (yet lower error) data. Higher errors in themselves are therefore not an indication of poor accuracy. Rather, the greatest emphasis should be placed in attaining a sufficient frequency of monitoring and in capturing important runoff events for the accurate establishment and tracking of loads. An assessment of the adequacy of the underlying data can be achieved by reference to the sample counts provided for each tributary and year in the ESM Appendix S1. For many tributaries, fewer than 12 samples are available annually; often, runoff events are not captured. Enhanced tributary monitoring implemented during 2012 and 2013 by ECCC for the Great Lakes Nutrients Initiative will help improve the accuracy of priority Canadian tributary estimates.

3.2. SRP loading

Soluble reactive phosphorus loading estimates for Lake Erie for the period 2009–2013 (Table 8) ranged from 2190 MTA for 2010 to 3482 MTA for 2011, with an average loading of 2792 MTA. SRP comprised between 29 and 37% of the TP load with an average of 33% and no significant change over time as determined by linear regression ($p > 0.1$). Detailed information and error estimates for SRP loads to the Huron–Erie corridor, west, central, and east basins are provided in Tables 9, 10, 11, and 12, respectively. An overview of SRP loads from the major tributaries and the composition of the loads in each basin is provided in Fig. 9. On average, the distribution of SRP loads by basin (Fig. 3b) is slightly different than for TP, with a higher proportion of the load

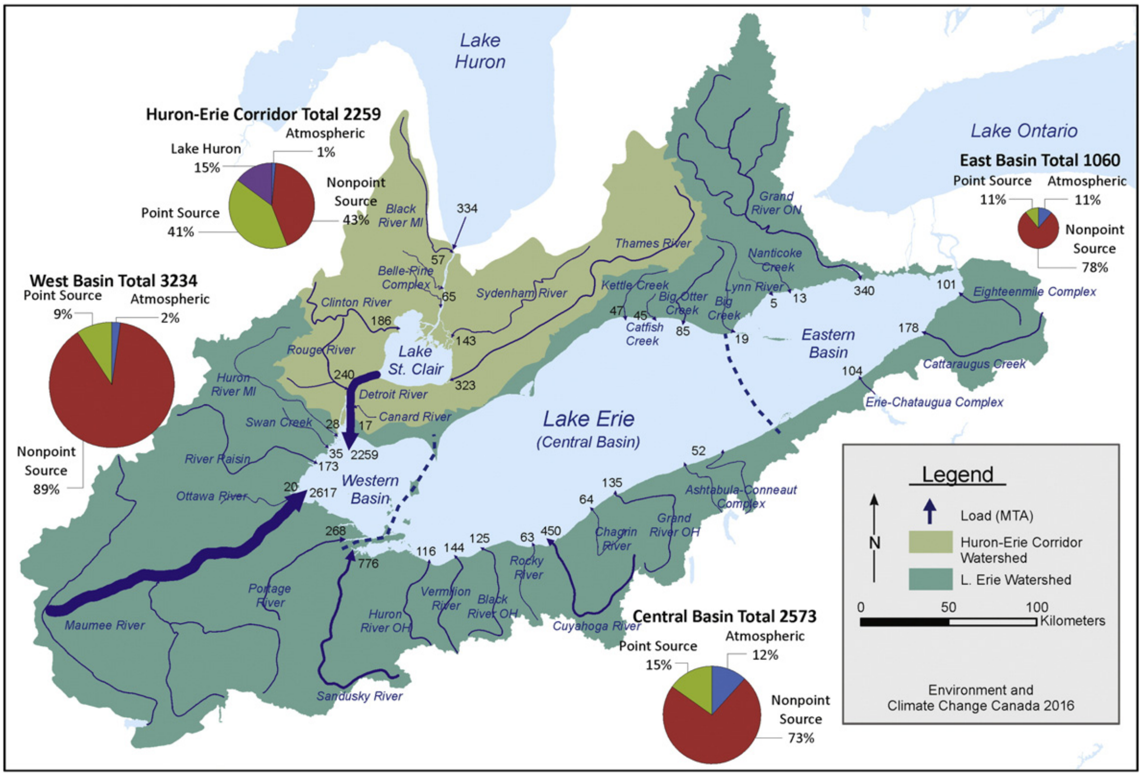

Fig. 4. Mean total phosphorus loadings (MTA) to Lake Erie (2003–2013).

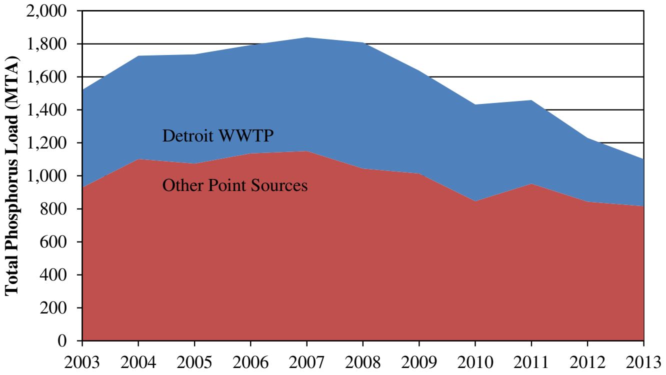

Fig. 5. U.S. direct point source total phosphorus loading (MTA) to Lake Erie (2003–2013). Temporal trend shows an overall reduction that is driven by loading changes from the Detroit Waste Water Treatment Plant (WWTP).

being delivered via the Huron–Erie corridor (39%). Inputs of SRP to the western and central basins are nearly equivalent (27% and 26%, respectively), with the remainder of the total SRP load being delivered to the eastern basin (9%).

Approximately one-half (49%) of the average total SRP load is from nonpoint source loads via tributaries, with the majority of the remainder comprising point source discharges (39%) delivered either directly or indirectly; relatively small amounts of SRP are delivered by atmospheric deposition and the upstream Great Lakes (6% each; Fig. 8). This distribution of loading contributions from the source categories has remained consistent from 2009 to 2013. The high proportion of point source loading, coupled with the use of a coefficient (70% of TP) to estimate these loads, results in relatively high uncertainty in the overall estimate of point source SRP when compared to point source TP loads.

The highest tributary contributors to the total SRP load (Fig. 9), on average, are the Maumee River (20%), the Sandusky River (6%), the Thames River (5%), the Rouge River (4%), and the Grand River (Ontario; 4%). There are no temporal trends of SRP loads for any of these tributaries with the exception of the Cuyahoga River, which shows a significant ($p = 0.008$) decline in SRP load with a slope of approximately 5 MTA per year. Tributary loadings of SRP also account for most of the interannual variability in the total loads.

Annual flow-weighted mean SRP concentrations (ESM Appendix S2) showed no significant change over time with the exception of the Black River (Michigan; slope + 1.2%/year, $p = 0.05$) and the Vermillion River (slope + 1.6%/year, $p = 0.0275$) which showed statistically significant increases for 2009 to 2013.

Point source contributions are highest in the Huron–Erie corridor from U.S. sources, contributing an average of 15% of the total SRP load to the lake. There has been a significant decline in this load during the 2009–2013 period at a rate of approximately 64 MTA per year ($p = 0.0018$). This is an estimated rate of decline based on an assumed SRP:TP ratio of 0.7 and the documented decline of point sources discussed above.

The proportion of all watershed areas that are monitored for SRP (70%) is similar to that for TP (72%), and the proportions by basin are also similar for these two variables. We note that Ohio does not include SRP in some of its tributary monitoring which results in a lower fraction of monitored areas for the central basin for SRP (53%) compared to TP (71%). As for TP, this statistic does not account for the adequacy of monitoring but only indicates if the parameter is included in the suite of monitored analytes.

Atmospheric deposition and inputs from the upstream Great Lakes are each estimated to contribute 6% of the total SRP loading to Lake Erie. Recall that SRP is not measured directly in precipitation and is assumed to comprise a constant fraction. While this may not be entirely accurate, the significance of this loading component is relatively small. Because the load of TP via atmospheric deposition is based on monitoring data, adjustments are not likely to result in significant changes to the overall SRP budget for the lake. Similar to TP, estimates of SRP inputs from the upstream Great Lakes are based on interlake transfers using offshore Lake Huron water quality data. Improvements to the estimates of SRP inputs via the St. Clair River might therefore be realized by validating the incoming load with monitoring. Other improvements might be achieved by measurement of SRP concentrations in point source discharges; however, as noted by Baker et al. (2014), the SRP:TP in point source effluents may have declined as loadings have decreased.

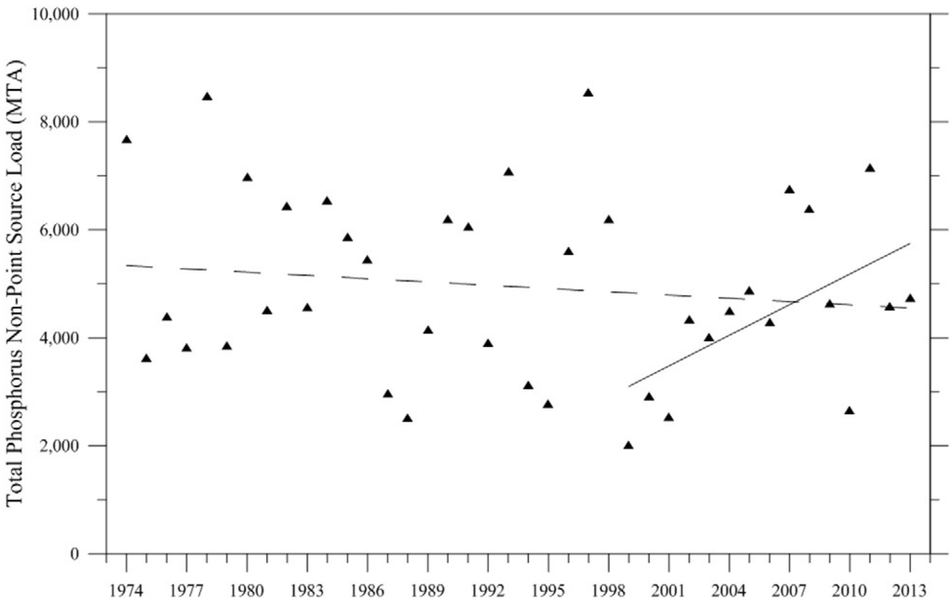

Fig. 6. Temporal trend in total phosphorus nonpoint source loading (MTA) from monitored and unmonitored tributaries to Lake Erie (1974–2013). Regression of loads over time indicated a statistically insignificant decline (dashed line; $p > 0.1$). However, an assessment of the 1999–2013 data indicates a significant increase (solid line; $p < 0.03$) that is likely due to increasing tributary discharge over this period ($p < 0.02$; not shown).

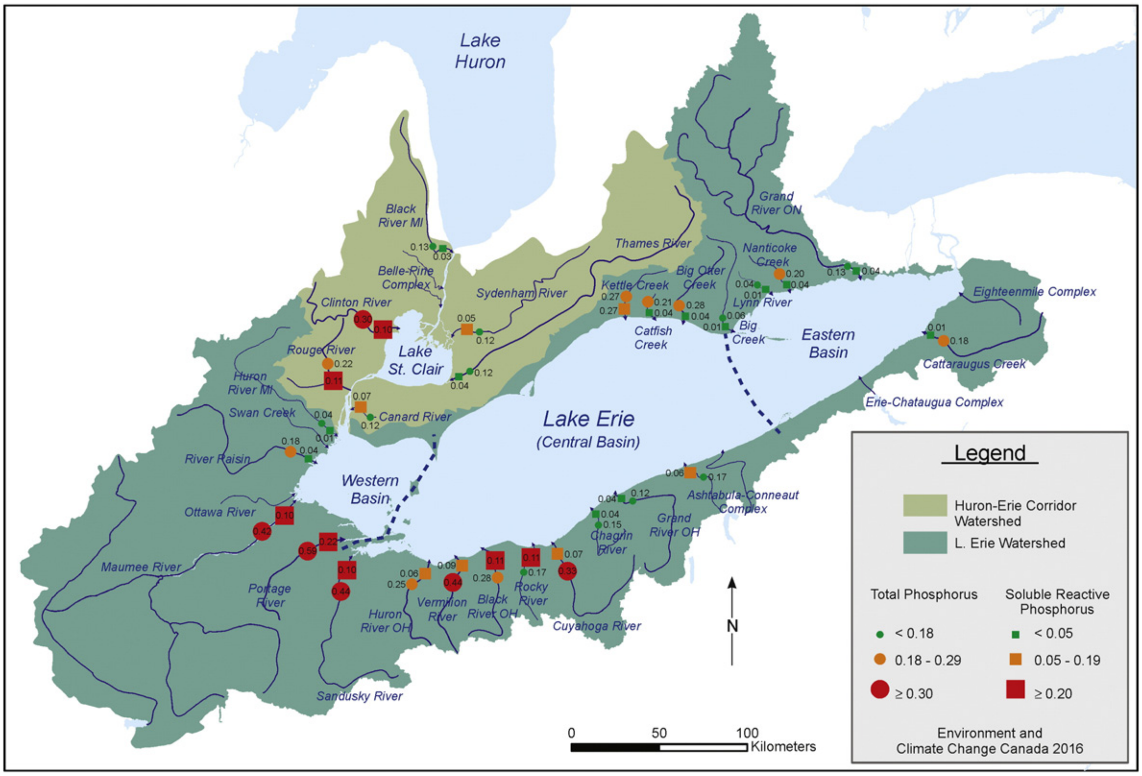

Fig. 7. Mean flow-weighted mean concentrations (mg/L) for total phosphorus (2003–2013) and soluble reactive phosphorus (2009–2013) in Lake Erie tributaries.

The re-eutrophication of Lake Erie cannot be attributed to point source inputs as these have declined over the same time period that Lake Erie has re-eutrophied.

Approximately 82% of the total SRP loading is from the U.S. The allocation of loads by country is very similar to that observed for TP, with a slightly higher proportion of SRP in the Huron–Erie corridor allocated to U.S. sources (71%; likely due to the greater importance of direct point source loads) and a slightly higher proportion of SRP accounted for by Canadian sources in the eastern basin (67%).

Standard errors as a percent of the total load ranged from 1.3 to 4.1% during 2009–2013, and are in a similar range as those for TP. As also observed for TP, the highest ratios of standard errors to loads were observed for the atmospheric deposition component and for Canadian tributaries.

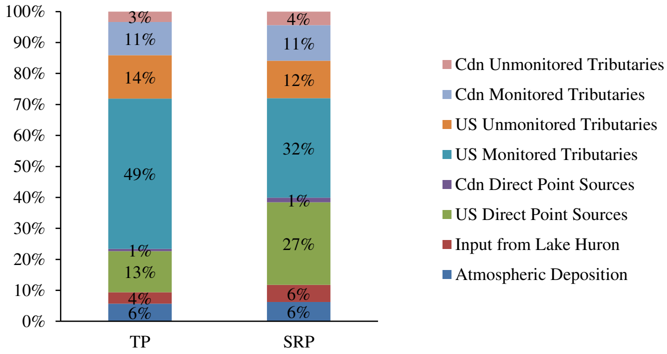

Fig. 8. Mean percent contribution by source type and country for total phosphorus (TP) loadings (2003–2013) and soluble reactive phosphorus (SRP) loadings (2009–2013).

4. Recommendations and conclusions

Building upon a body of previous work, we have updated loading estimates to Lake Erie for TP through 2013, and for the first time, we report SRP loads (2009–2013). The information has been interpreted with respect to the distribution of loads by basin and by source category, and provides country-specific allocations of these observations. The tributary-specific loading estimates are provided in the ESM Appendices S1 and S2, and the input data are being made available online via the Canadian federal data portal.

In these ways, this update provides background information for more detailed analysis and program and policy development; for example, for the development of U.S. and Canadian Domestic Action Plans to make progress toward the targets recently adopted under the Nutrients Annex by the Parties to the Great Lakes Water Quality Agreement. These targets include a 40% reduction of annual TP loadings to the central and western basins of Lake Erie and a 40% reduction of spring loadings of SRP from western basin tributaries (Objectives and Targets Task Team, 2015). These reductions are proposed relative to the 2008 water year, when the total load (10,627 MTA) was most similar to the target load (11,000 MTA) compared to other recent years. The ESM Appendices will be useful in assessing tributary-specific targets as well as the sufficiency of the underlying information that was used in developing the 2008 estimates.

There is much additional analysis that should be conducted that lies beyond the scope of this paper, some of which will require additional monitoring and modeling. For example, we assume that the monitored loads from tributaries are entirely delivered to the lake. We do not account for usage of phosphorus by in-stream processes that may occur downstream of monitoring locations. It is known that instream usage or sedimentation can be significant, particularly for the bioavailable forms (for which SRP is used here as a proxy). The work conducted by Baker et al. (2014) indicates that TP from point sources can be highly (>70%) bioavailable while TP from nonpoint sources is less (<45%) so,

Table 8
Soluble reactive phosphorus loading estimates (MTA) to Lake Erie (2003–2013), with standard errors (S.E.) of the estimates to Lake Erie (2009–2013). Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States										
Monitored Tributary	696	19	679	15	1146	38	1078	8	888	21
Adjustment for Unmonitored Area	287	24	255	36	468	43	354	19	330	44
Direct Industrial Point Source	5	0.8	7	1	5	0.3	3	0.3	2.5	0.4
Direct Municipal Point Source	906	25	794	23	792	28	650	19	555	37
Indirect Industrial Point Source[a]	20	2	16	2	25	4	18	2	16	0.7
Indirect Municipal Point Source[a]	215	6	185	4	200	5	190	3	198	4
U.S. Total	1894	40	1735	45	2411	64	2084	28	1774	61
Canada										
Monitored Tributary	497	85	99	10	530	88	163	11	310	69
Adjustment for Unmonitored Area	147	26	14	3	152	48	77	8	223	41
Direct Industrial Point Source	12	0.6	14	0.9	12	0.4	12	0.4	13	0.7
Direct Municipal Point Source	31	4	28	2	31	2	27	1	27	1
Indirect Industrial Point Source[a]	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0
Indirect Municipal Point Source[a]	71	2	54	1	60	2	52	1	57	2
Canadian Total	687	89	155	11	724	100	280	13	574	80
Atmospheric	228	50	144	29	192	30	108	17	196	49
Input from Lake Huron[b]	155		155		155		155		155	
Basin Total	2964	110	2190	55	3482	123	2627	35	2699	112

[a] Included in monitored tributary.
[b] Constant load from 2008 (Dolan and Chapra, 2011).

and particulate forms can become “positionally unavailable” through deposition of suspended solids and burial in bottom sediments. Additional monitoring and modeling are needed to understand the fate of nutrients that are monitored in tributaries as well as in point source discharges. Furthermore, we do not account for possible sedimentation or other in-stream processes in the case of indirect point sources discharges when apportioning the total loads into source categories and calculating unit area loads.

We do not take into account that discharges of nonpoint sources are delivered to the lake in pulses following runoff events while point source discharges tend to occur in a more steady fashion. The computational methods used here provide estimates based on water year and do not lend themselves readily to calculations of seasonal loads that are required to establish benchmarks for spring 2008 and tracking of progress with respect to spring TP and SRP loads. Calculation of seasonal loads remains an important area for further work.

There also remains much additional work to understand how best to accomplish loading reductions. The recommendations presented here relate primarily to our ability to monitor and track loadings, but they do not address the important further work that is required to understand the relationships between various land uses and water quality, an assessment of the relative contributions of various land uses to nutrient loadings, or the best means of accomplishing nutrient reductions. Clearly, much additional work remains.

Long-term (1967–2013) declining trends are observed for TP loads, but these are driven by both early and more recent declines in point source loadings. Recent data show no temporal trends in SRP loads. An increase is noted in nonpoint source loads for TP since 1999, but this

Table 9
Soluble reactive phosphorus loading estimates (MTA) to the Huron–Erie corridor (2009–2013) with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States										
Monitored Tributary	96	8	85	11	102	14	79	4	93	20
Adjustment for Unmonitored Area	75	17	118	35	115	32	88	19	100	44
Direct Industrial Point Source	3	0.8	5	1	2	0.3	1	0.2	1	0.4
Direct Municipal Point Source	576	25	497	22	479	28	359	18	295	37
Indirect Industrial Point Source[a]	1	0.0	0.9	0.3	0.6	0.2	1	0.2	2	0.0
Indirect Municipal Point Source[a]	36	4	26	1	35	2	34	2	30	2
U.S. Total	750	31	705	42	698	45	527	26	489	61
Canada										
Monitored Tributary	284	52	32	7	321	80	59	6	186	68
Adjustment for Unmonitored Area	85	20	5	1	65	47	54	7	165	38
Direct Industrial Point Source	8	0.4	10	0.9	10	0.3	10	0.3	11	0.5
Direct Municipal Point Source	27	4	22	2	25	1	23	1	23	1
Indirect Industrial Point Source[a]										
Indirect Municipal Point Source[a]	39	1	24	0.6	28	1	22	0.9	28	2
Canadian Total	404	56	70	7	421	92	146	9	385	78
Atmospheric	14	13	9	7	12	8	7	4	12	12
Input from Lake Huron[b]	155		155		155		155		155	
Basin Total	1323	65	939	43	1287	103	835	28	1041	99

[a] Included in monitored tributary.
[b] Constant load from 2008 (Dolan and Chapra, 2011).

Table 10
Soluble reactive phosphorus loading estimates (MTA) to the western basin of Lake Erie (2009–2013) with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States										
Monitored Tributary	432	14	444	7	693	30	713	4	525	5
Adjustment for Unmonitored Area	85	14	27	6	101	2	116	2	65	1.0
Direct Industrial Point Source	0.2	0.0	0.3	0.0	0.2	0.0	0.6	0.3	0.3	0.0
Direct Municipal Point Source	84	4	81	4	80	2	76	2	72	3
Indirect Industrial Point Source[a]	18	2	14	2	23	4	16	2	13	0.7
Indirect Municipal Point Source[a]	102	4	94	3	98	3	91	2	96	3
U.S. Total	602	20	552	9	874	30	906	5	663	6
Canada										
Monitored Tributary										
Adjustment for Unmonitored Area										
Direct Industrial Point Source										
Direct Municipal Point Source	2	0.3	3	0.3	3	1.0	2	0.5	2	0.3
Indirect Industrial Point Source[a]										
Indirect Municipal Point Source[a]										
Canadian Total	2	0.3	3	0.3	3	1.0	2	0.5	2	0.3
Atmospheric	31	19	20	11	26	11	15	6	27	18
Basin Total	635	27	575	14	903	32	922	8	691	19

[a] Included in monitored tributary.

was driven by increasing tributary discharges, and FWMCs show no significant trend over the same period. The majority of the individual tributaries (24/28) show no recent change in TP FWMCs; a small number (3/28) show statistically significant improvements, and only one shows an increase in FWMC. There is high interannual variability in the loading record due almost entirely to variations in nonpoint source loads delivered to Lake Erie via tributaries. Recent work in selected Lake Erie tributaries with high-frequency monitoring data has shown that these interannual differences are primarily linked to variations in discharge driven by precipitation (Baker et al., 2014). Stow et al. (2015) successfully teased out underlying long-term and seasonal trends, relying on the high frequency of data collection to be able to do so.

Monitoring is warranted for all intermediate and large Lake Erie tributaries to be able to calculate loads; to this end, we have prioritized the tributaries included in this work and provided justification and several specific recommendations (see ESM Appendices). Programs designed to monitor loads, and therefore capture important runoff and winter events, have recently been implemented in priority tributaries by the USGS and by ECCC; these monitoring efforts need to be continued and potentially expanded. It will be important going forward to be able to track temporal trends, most importantly for tributaries delivering high annual and/or spring loads for both TP and SRP. To do this, the adequacy of the existing monitoring programs will need to be assessed and new programs implemented to fill important gaps. Further, it is vital that the discharge monitoring programs continue.

We recommend that tributary water quality data should be collected with sufficient frequency and duration to provide the statistical power to calculate loads and detect trends. We note that the relatively infrequent monitoring of tributary water quality programs for some of the individual States and for the Province of Ontario has been insufficient for the robust computation of loads and has likely led to an underestimate of certain U.S. tributaries and most of the Canadian tributary nutrient contributions to Lake Erie.

Analysis of daily samples is recommended where feasible; at a minimum, the monitoring guidance for the development of a long-term and

Table 11
Soluble reactive phosphorus loading estimates (MTA) to the central basin of Lake Erie (2009–2013) with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States										
Monitored Tributary	163	11	148	7	323	13	282	5	265	4
Adjustment for Unmonitored Area	118	9	105	6	187	14	144	4	158	3
Direct Industrial Point Source	2	0.1	1	0.1	2	0.1	0.6	0.0	0.8	0.0
Direct Municipal Point Source	203	4	178	8	193	5	177	4	150	4
Indirect Industrial Point Source[a]	1	0.2	0.7	0.1	1	0.3	0.7	0.1	0.6	0.1
Indirect Municipal Point Source[a]	75	2	64	3	66	3	63	1	70	2
U.S. Total	486	15	433	12	705	20	603	8	574	6
Canada										
Monitored Tributary	77	4	6	1	34	3	55	6	28	2
Adjustment for Unmonitored Area	21	10	3	1	29	7	7	1	17	9
Direct Industrial Point Source										
Direct Municipal Point Source	0.4	0.0	0.8	0.1	0.8	0.1	0.3	0.0	0.3	0.0
Indirect Industrial Point Source[a]	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0
Indirect Municipal Point Source[a]	4	0.2	3	0.1	4	0.3	4	0.2	4	0.2
Canadian Total	98	10	9	2	63	8	62	6	45	10
Atmospheric	130	38	82	22	110	23	61	13	112	37
Basin Total	714	42	524	25	878	31	727	16	731	38

[a] Included in monitored tributary.

Table 12
Soluble reactive phosphorus loading estimates (MTA) to the eastern basin of Lake Erie (2009–2013) with standard errors (S.E.) of the estimates. Blank cell indicates no reported load; zero indicates reported load is zero or rounds to zero. All values rounded to nearest whole number (numbers below one rounded to nearest tenth).

	2009		2010		2011		2012		2013	
	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.	Load	S.E.
United States										
Monitored Tributary	5	0.5	3	0.3	29	15	4	0.4	4	0.4
Adjustment for Unmonitored Area	8	0.8	5	0.5	66	25	6	0.6	6	0.7
Direct Industrial Point Source	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0
Direct Municipal Point Source	43	1	38	1	39	1	39	2	38	2
Indirect Industrial Point Source[a]										
Indirect Municipal Point Source[a]	2	0.1	1	0.1	2	0.1	1	0.1	2	0.1
U.S. Total	57	2	46	1	134	29	49	2	49	2
Canada										
Monitored Tributary	136	68	61	8	175	37	49	6	97	12
Adjustment for Unmonitored Area	41	14	6	2	58	10	16	2	41	13
Direct Industrial Point Source	4	0.4	4	0.1	2	0.2	2	0.2	3	0.5
Direct Municipal Point Source	2	0.1	2	0.1	2	0.1	2	0.2	2	0.1
Indirect Industrial Point Source[a]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indirect Municipal Point Source[a]	28	1	27	0.9	28	1	26	1	25	0.6
Canadian Total	183	69	73	8	237	38	69	7	143	18
Atmospheric	52	24	33	14	44	14	25	8	45	23
Basin Total	292	73	151	16	415	50	143	11	236	29

[a] Included in monitored tributary.

coordinated monitoring strategy provided by the GLWQA Annex 4 Objectives and Targets Task Team (2015) should be followed by the agencies responsible for monitoring on both sides of the border. Interagency laboratory comparisons are recommended for the monitoring programs to ensure accuracy and comparability of both TP and SRP results.

In particular, we urge more frequent monitoring for the Grand River (Ohio) and Cattaraugus Creek, as these are important watersheds that are relied upon for the extrapolation of loads for adjacent unmonitored tributaries. Opportunities to implement monitoring in these and other currently under- or unmonitored areas should be investigated and pursued. As noted, certain Ohio tributaries lack SRP data; to this end, we also strongly recommend that all tributary monitoring programs include quality-assured SRP measurements in addition to TP.

Important assumptions that are invoked with the scaling of loadings require confirmation. Point sources rarely provide SRP measurements but they are assumed to be 70% of TP. As point source loads have declined over time, this assumption needs to be reassessed with quality-assured monitoring data. Reporting of combined sewer overflows has been implemented and improved for the Detroit region, but they are unreported in many other jurisdictions and may be important local sources, particularly for SRP.

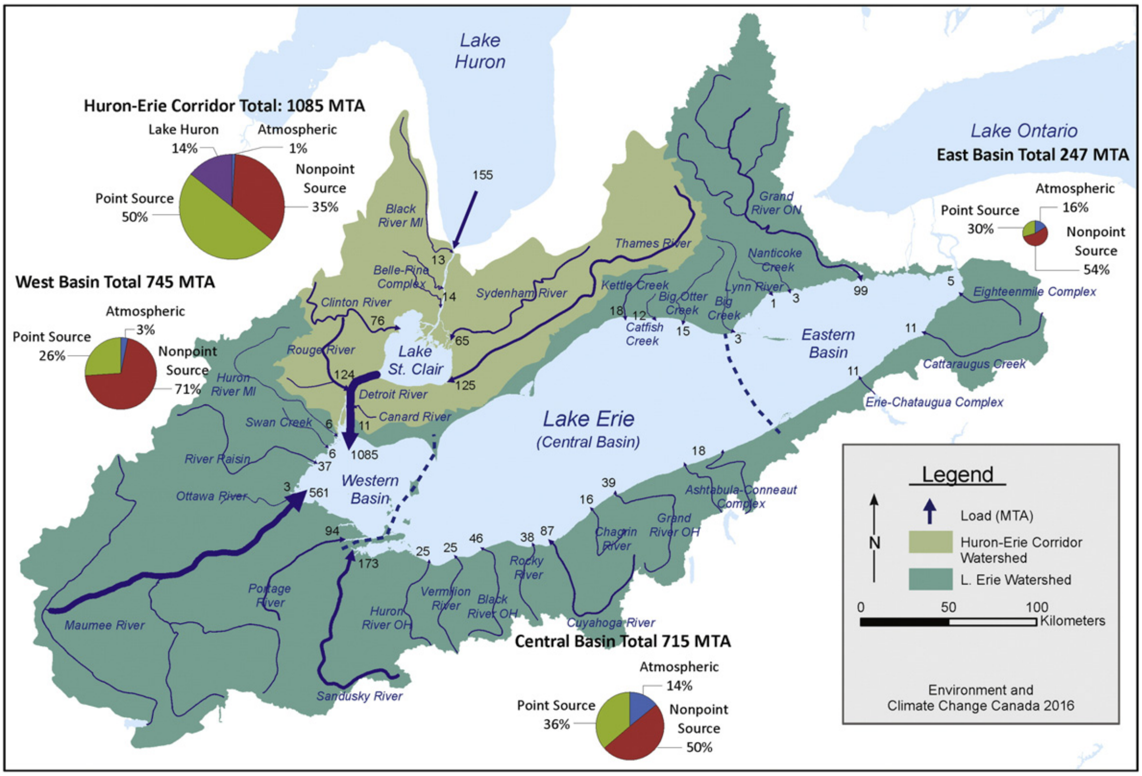

Fig. 9. Mean soluble reactive phosphorus loadings (MTA) to Lake Erie (2009–2013).

We have reported SRP loadings for 2009–2013 but recommend the record be expanded further back in time, as the sufficiency of the data allow. Some SRP loadings were estimated as part of the Ecofore project for specific calendar years (2005 and 2007), but this was not done over consecutive water years. This would complement the work of Kane et al. (2014) and Baker et al. (2014) which has demonstrated a concordance between SRP concentrations, loads, and harmful algal blooms in the western basin of Lake Erie. Although the relationship between SRP and adverse impacts is complicated by the dynamic nature of SRP cycling within the aquatic environment, this extension would potentially enable the tracking of loads during the period of re-eutrophication in Lake Erie (since the early- to mid-1990s).

The assumed constant loading from the upstream Great Lakes (2008–2013) should be updated and the estimates should also be verified with monitoring data from the St. Clair River. Similarly, loadings calculated here for the Huron–Erie corridor should be verified with monitoring information from the Detroit River. In the coming years, such verifications may be possible as monitoring is currently being conducted in these connecting channels by ECCC.

The availability of data continues to inhibit the ability to provide timely basin-wide loading updates. Point source data are not available online but must be requested, and the quality assurance checks are very time consuming. For all data sources, the acquisition of the most recent data in a timely manner can be a challenge. Due to the importance of tracking loadings over time, we recommend that the Parties give priority to implementing the recommendations made here and to develop the capacity and the plan to routinely update these calculations. The work underway as part of the GLWQA Annex 4 tributary monitoring subcommittees will assist the agencies conducting the load monitoring programs to work collaboratively to ensure that a consistent approach and consistent level of information is achieved throughout the basin.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jglr.2016.08.005.

Acknowledgements

This paper is based on a body of work that was developed, implemented, and improved by David M. Dolan, and the remaining authors are honored to be able to continue this work despite his untimely death in 2013. We especially thank Mary Ginnebaugh for her support in completing and publishing Dave's work. The authors would like to thank the following individuals for providing data: James Coleman (USEPA), Daniel Glomski (OHEPA), Jeff Varricchione (MIDEQ), Laura Johnson (Heidelberg University), Aaron Todd and Dong Zhang (OMOEE), and Lisa Bradley and Debbie Burniston (ECCC). We would like to give special thanks to Russ Kreis and Dave Griesmer (USEPA), Matt Dornbush, Mike Draney, and Renee Henning (UW-Green Bay), and Kevin McGunagle for providing access to many of Dave's computer files and legacy data, and Kevin Moore for his knowledge of FORTRAN. ECCC's Great Lakes Nutrients Initiative provided the funding to update and compile the data and conduct this reporting.

References

Akkoyunlu, B.O., Tayanç, M., 2003. Analyses of wet and bulk deposition in four different regions of Istanbul, Turkey. Atmos. Environ. 37, 3571–3579.

Baker, D.B., Confesor, R., Ewing, D.E., Johnson, L.T., Kramer, J.W., Merryfield, B.J., 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: the importance of bioavailability. J. Great Lakes Res. 40, 502–517.

Balestrini, R., Galli, L., Tartari, G., 2000. Wet and dry atmospheric deposition at prealpine and alpine sites in northern Italy. Atmos. Environ. 34, 1455–1470.

Beale, E., 1962. Some uses of computers in operational research. Ind. Organ. 31, 27–28.

Bunnell, D.B., Johnson, T.B., Knight, C.T., 2005. The impact of introduced round gobies (*Neogobius melanostomus*) on phosphorus cycling in central Lake Erie. Can. J. Fish. Aquat. Sci. 62, 15–29.

Chan, C.-H., Williams, D.J., Neilson, M.A., Harrison, B., Archer, M.L., 2003. Spatial and temporal trends in the concentrations of selected organochlorine pesticides (OCs) and polynuclear aromatic hydrocarbons (PAHs) in Great Lakes basin precipitation, 1986 to 1999. J. Great Lakes Res. 29, 448–459.

Chapra, S.C., Dolan, D.M., 2012. Great Lakes total phosphorus revisited: 2. Mass balance modeling. J. Great Lakes Res. 38, 741–754.

Daloğlu, I., Cho, K.H., Scavia, D., 2012. Evaluating causes of trends in long-term dissolved reactive phosphorus loads to Lake Erie. Environ. Sci. Technol. 46, 10660–10666.

DePinto, J.V., Young, T.C., McIlroy, L.M., 1986. Great Lakes water quality improvement. Environ. Sci. Technol. 20, 752–759.

Dolan, D.M., 1993. Point source loadings of phosphorus to Lake Erie: 1986–1990. J. Great Lakes Res. 19, 212–223.

Dolan, D.M., Chapra, S.C., 2011. Great Lakes Total Phosphorus Models and Loads: A Fifteen Year Update, Final Report Grant No. GL 00E58501. USEPA Great Lakes National Program Office, Chicago, IL.

Dolan, D.M., Chapra, S.C., 2012. Great Lakes total phosphorus revisited: 1. Loading analysis and update (1994–2008). J. Great Lakes Res. 38, 730–740.

Dolan, D.M., McGunagle, K.P., 2005. Lake Erie total phosphorus loading analysis and update: 1996–2002. J. Great Lakes Res. 31, 11–22.

Dolan, D.M., Yui, A.K., Geist, R.D., 1981. Evaluation of river load estimation methods for total phosphorus. J. Great Lakes Res. 7, 207–214.

Dove, A., Chapra, S.C., 2015. Long-term trends of nutrients and trophic response variables for the Great Lakes. Limnol. Oceanogr. 60, 696–721.

Fraser, A.S., 1987. Tributary and point source total phosphorus loading to Lake Erie. J. Great Lakes Res. 13, 659–666.

GLWQA, 1978. Revised Great Lakes Water Quality Agreement of 1978, as amended by Protocol November 18th, 1987. International Joint Commission, Windsor, Ontario.

Kane, D.D., Conroy, J.D., Peter Richards, R., Baker, D.B., Culver, D.A., 2014. Re-eutrophication of Lake Erie: correlations between tributary nutrient loads and phytoplankton biomass. J. Great Lakes Res. 40, 496–501.

Lesht, B.M., Fontaine, T.D., Dolan, D.M., 1991. Great Lakes total phosphorus model: post audit and regionalized sensitivity analysis. J. Great Lakes Res. 17, 3–17.

Maccoux, M.J., Dolan, D.M., Chapra, S.C., 2013. Chloride and total phosphorus budgets for Green Bay, Lake Michigan. J. Great Lakes Res. 39, 420–428.

Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S., Bridgeman, T.B., Chaffin, J.D., Cho, K., Confesor, R., Daloğlu, I., DePinto, J.V., Evans, M.A., Fahnenstiel, G.L., He, L., Ho, J.C., Jenkins, L., Johengen, T.H., Kuo, K.C., LaPorte, E., Liu, X., McWilliams, M.R., Moore, M.R., Posselt, D.J., Richards, R.P., Scavia, D., Steiner, A.L., Verhamme, E., Wright, D.M., Zagorski, M.A., 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proc. Natl. Acad. Sci. 110, 6448–6452.

Objectives and Targets Task Team, 2015. Recommended phosphorus loading targets for Lake Erie, Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee, May 11, 2015. http://graham.umich.edu/scavia/wp-content/uploads/2015/06/FINAL-Objectives-TT-report-en-150624-3.pdf.

PLUARG (Pollution from Land Use Activities Reference Group), 1978). Environmental management strategy for the Great Lakes system. Final report of the International Reference Group for Great Lakes Pollution from Land Use Activities. International Joint Commission, Windsor, Ontario.

Rathke, D., McCrae, G., 1989. Appendix B, Volume III, Report of the Great Lakes Water Quality Board. International Joint Commission, Windsor, Ontario.

Richards, R., Baker, D., Crumrine, J., Stearns, A., 2010. Unusually large loads in 2007 from the Maumee and Sandusky Rivers, tributaries to Lake Erie. J. Soil Water Conserv. 65, 450–462.

Risch, M.R., Gay, D.A., Fowler, K.K., Keeler, G.J., Backus, S.M., Blanchard, P., Barres, J.A., Dvonch, J.T., 2012. Spatial patterns and temporal trends in mercury concentrations, precipitation depths, and mercury wet deposition in the North American Great Lakes region, 2002–2008. Environ. Pollut. 161, 261–271.

SAS, 2012. JMP 10.0.0. SAS Institute Inc.

Scavia, D., Allan, J.D., Arend, K.K., Bartell, S., Beletsky, D., Bosch, N.S., Brandt, S.B., Briland, R.D., Daloğlu, I., DePinto, J.V., 2014. Assessing and addressing the re-eutrophication of Lake Erie: central basin hypoxia. J. Great Lakes Res. 40, 226–246.

Scavia, D., DePinto, J.V, Bertain, I., 2016. A multi-model approach to evaluating target phosphorus loads for Lake Erie. J. Great Lakes Res. 42 (6), 1139–1150 (in this issue).

Stow, C.A., Cha, Y., Johnson, L.T., Confesor, R., Richards, R.P., 2015. Long-term and seasonal trend decomposition of Maumee River nutrient inputs to Western Lake Erie. Environ. Sci. Technol. 49, 3392–3400.

Stumpf, R.P., Wynne, T.T., Baker, D.B., Fahnenstiel, G.L., 2012. Interannual variability of cyanobacterial blooms in Lake Erie. PLoS One 7, e42444.

Tin, M., 1965. Comparison of some ratio estimators. J. Amer. Statistical Assoc. 60, 294–307.

Upper Lakes Reference Group, 1977. The Waters of Lake Huron and Lake Superior: Report to the International Joint Commission, Vol. II (Part A): Lake Huron, Georgian Bay, and the North Channel. International Joint Commission, Windsor, Ontario.

Zhou, Y., Obenour, D.R., Scavia, D., Johengen, T.H., Michalak, A.M., 2013. Spatial and temporal trends in Lake Erie Hypoxia, 1987–2007. Environ. Sci. Technol. 47, 899–905.