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Total and soluble reactive phosphorus loadings to Lake Erie A detailed accounting by year, basin, country, and tributary

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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.

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

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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