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Mass-balance modeling framework for simulating and managing long-term water quality for the lower Great Lakes

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ABSTRACT

A mass balance model is used to simulate total phosphorus (TP) concentrations for the lower Great Lakes based on measured and estimated historical TP loading time series. Although Lake Erie is the primary focus, Lake Ontario is included in order to provide information about its potential response to proposed Lake Erie TP load reductions. The results demonstrate that Lake Erie loading controls would have a measurable effect on both Lake Erie and Lake Ontario's offshore phosphorus concentrations.

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Introduction

Model description

Just over thirty-five years ago, a parsimonious total phosphorus (TP) budget model was developed to assess the impact of population and land-use on Great Lakes eutrophication (Chapra, 1977; Chapra and Robertson, 1977; Chapra and Sonzogni, 1979). The framework was then used, along with several other models, to establish phosphorus loading targets for the 1978 Great Lakes Water Quality Agreement (International Joint Commission, 1978; Bierman, 1980). The TP loading and resultant spring, offshore concentration targets for the lower lakes are listed in Table 1.

A positive initial confirmation of the model's predictive ability was made for Lake Ontario in the early 1980s when reductions in detergent and wastewater phosphorus had induced a significant downward trend in that lake's TP concentration (Chapra, 1980; Stevens and Neilson, 1987). Additional confirmation of model performance was established

for the entire system through 1987 (Lesht et al., 1991). We recently expanded (Chapra and Dolan, 2012) the time frame of the previous modeling considerably by extending the analysis to 2010 based primarily on data collected by Environment and Climate Change Canada (Dove and Chapra, 2015). In so doing, a more complete assessment was provided of whether the model adequately simulated the water-quality improvements observed from the mid-1970s to the present.

In this recent assessment (Chapra and Dolan, 2012), a number of refinements were adopted to improve model performance. First, a more detailed segmentation scheme was employed with finer resolution for the major Great Lakes embayments. A chloride budget model was developed to better parameterize transport with particular emphasis on quantifying the magnitude of mixing across open boundaries. Then, the TP budget model was used to compute concentration trends and compare them with modern TP data for the period from 1965 to the present.

In the present exercise, we use the same framework developed by Chapra and Dolan (2012) to evaluate the impact of total phosphorus loadings on the eutrophication of the lower Great Lakes. Although Lake Erie is our primary focus, we have included Lake Ontario in order to provide a more comprehensive assessment of the impacts of load reductions. In particular, we believe it is important to recognize that Lake Erie controls may have a measurable effect on Lake Ontario. Off-shore total phosphorus concentrations in Lake Ontario are currently in

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Table 1
Great Lakes total phosphorus target loads and resultant spring, offshore concentrations. Note that the target loads include phosphorus inputs from upstream lakes.

Basin	Target TP load (MTA)	Target TP concentration ($\mu\text{gP L}^{-1}$)
Lake Erie	11,000	
Western Erie		15
Central Erie		10
Eastern Erie		10
Lake Ontario	7000	10

the range 5–6 $\mu\text{gP L}^{-1}$ (Dove and Chapra, 2015) which are well below the target concentration of 10 $\mu\text{gP L}^{-1}$ and indicating low nutrient status (oligotrophy). Given the proposed 40% reductions for Lake Erie western and central basin total phosphorus loads, as well as spring soluble reactive phosphorus loads to the western basin (Objectives and Targets Task Team, 2015), it is prudent to understand how these proposed Lake Erie loading reductions will affect Lake Ontario.

Methods

Our model is designed to predict the annual average concentration of total phosphorus (TP) in the offshore waters of each lake as a function of external loadings. Whereas this approach is consistent with the time and space scales required for the establishment of target loads under the GLWQA, it is important to stress that the model does not attempt to resolve finer-scale temporal (e.g., diel or seasonal) or spatial (e.g., nearshore–offshore) variability.

As with the original model (Chapra, 1977), Lake Ontario is represented as a single well-mixed system, whereas Lake Erie is divided into its 3 major subsegments to better resolve horizontal gradients (Fig. 1). TP mass balances for each basin can be written as (Chapra, 1975, 1977, 1997)

Western Lake Erie (*w*):

$$V_w \frac{dp_w}{dt} = W_w + Q_h p_h - Q_w p_w + E_{wc}'(p_c - p_w) - v_{s,w} A_w p_w \quad (1)$$

Central Lake Erie (*c*):

$$V_c \frac{dp_c}{dt} = W_c + Q_w p_w - Q_c p_c + E_{wc}'(p_w - p_c) + E_{ce}'(p_e - p_c) - v_{s,c} A_c p_c \quad (2)$$

Eastern Lake Erie (*e*):

$$V_e \frac{dp_e}{dt} = W_e + Q_c p_c - Q_e p_e + E_{ce}'(p_c - p_e) - v_{s,e} A_e p_e \quad (3)$$

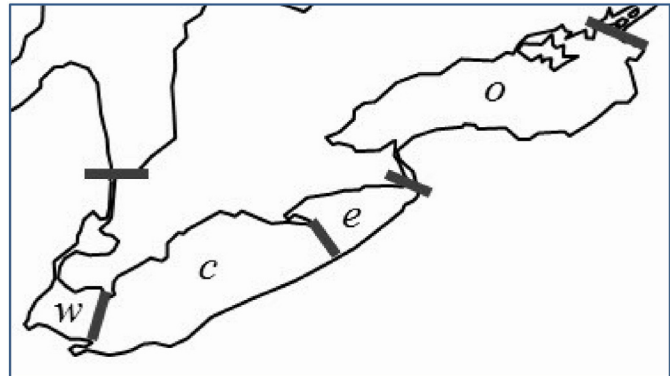


Fig. 1. Segmentation scheme for chloride and total phosphorus models for the lower Great Lakes.

Ontario (*o*):

$$V_o \frac{dp_o}{dt} = W_o + Q_e p_e - Q_o p_o - v_{s,o} A_o p_o \quad (4)$$

where V_i = volume of segment i (km^3), p_i = concentration of segment i ($\mu\text{gP L}^{-1}$), W_i = the mass loading rate to segment i (metric tonnes per annum or MTA), Q_i = advective outflow from segment i ($\text{km}^3 \text{ yr}^{-1}$), E_{ij}' = bulk horizontal eddy diffusion coefficient at interface between segments i and j ($\text{km}^3 \text{ yr}^{-1}$), $v_{s,i}$ = apparent sedimentation velocity for TP for segment i (km yr^{-1}), and A_s = the segment's bottom sediment surface area across which TP is permanently lost from the system (km^2). Note that by setting v_s to zero, Eqs. (1) through (4) apply to conservative substances such as chloride, for which case loadings and concentrations would be expressed in kMTA and mg L^{-1} , respectively. Note that although the apparent sedimentation velocity has velocity units, it should not be confused with an actual particle settling velocity. Rather, as originally defined by Chapra (1975) it is a phenomenological (hence, the modifier “apparent”) and empirically-derived mass transfer coefficient representing all the varied mechanisms that ultimately contribute to the incorporation of water-column total phosphorus into a lake’s bottom sediments.

The bulk mixing coefficient is also a phenomenological parameter that represents large-scale diffusive exchange across open boundaries. As described by Chapra (1979), this parameter accounts for all transport mechanisms over and above advective outflow from a lake or a segment of a lake. These include, but are not limited to, exchange due to large-scale eddy diffusion, and dispersion due to shear flow and spatial non-uniformities. The mixing is related to more fundamental quantities by Chapra (1979)

$$E' = \frac{EA_c}{\ell} \quad (5)$$

where E = horizontal eddy diffusion coefficient ($\text{km}^2 \text{ yr}^{-1}$), A_c = interface cross-sectional area (km^2), and ℓ = mixing length (km). The mixing length parameterizes the length of the zone defining the gradient between adjacent volumes (Chapra, 1997).

The complete system of differential equations provides a quantitative framework to analyze trends of chloride and TP. Given parameters, loading time series, and initial conditions, the equations can be integrated to obtain concentrations as a function of time. To do this, we use a constant-step, fourth-order Runge–Kutta method (Chapra, 2011). By centering the time derivative estimate, the fourth-order scheme tends to minimize the temporal component of numerical diffusion.

In addition to the time-variable solutions, a steady-state solution can also be generated. To do this, the derivatives of Eqs. (1) through (4) are set to zero and the resulting system of algebraic equations written in matrix form as

$$[A]\{p\} = \{W\} \quad (6)$$

where

$$[A] = \begin{bmatrix} Q_w + E_{wc}' + v_{s,w}A_w & -E_{wc}' & 0 & 0 \\ -E_{wc}' & Q_c + E_{wc}' + E_{ce}' + v_{s,c}A_c & -E_{ce}' & 0 \\ 0 & -E_{ce}' & Q_e + E_{ce}' + v_{s,e}A_e & 0 \\ 0 & 0 & 0 & Q_o + v_{s,o}A_o \end{bmatrix} \quad (7)$$

$$\{p\}^T = \{p_w \ p_c \ p_e \ p_o\} \quad (8)$$

$$\{W\}^T = \{(W_w + Q_h p_h) \ W_c \ W_e \ W_o\}. \quad (9)$$

Eq. (6) can be solved for the steady-state concentrations

$$\{p\} = [A^{-1}]\{W\} \quad (10)$$

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