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A commentary on the modelling of the causal linkages among nutrient loading, harmful algal blooms, and hypoxia patterns in Lake Erie

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ABSTRACT

In this study, our primary aim is to evaluate the capacity of past and current modelling efforts to depict the causal relationships between major water quality indicators (e.g., chlorophyll *a*, harmful algal blooms, dissolved oxygen) and nutrient loading in Lake Erie. We first conduct a review of nearly all the modelling projects documented in the pertinent literature, and then evaluate the performance of six of these models applied over the past thirty years. We examine the strengths and weaknesses of the different modelling strategies, their adequacy in representing the processes underlying plankton dynamics, and their ability to reproduce the spatiotemporal variability in hypoxia or harmful algal blooms. Our analysis shows that these models have mainly offered heuristic tools to examine different ecological hypotheses and dictate future data collection efforts. Our study critically discusses the most appropriate next steps to improve the reproduction of the spatiotemporal patterns of major phytoplankton groups, e.g., cyanobacteria, the functional role of dreissenid mussels, and the relative importance of diagenesis processes on the manifestation of hypoxia in Lake Erie. Finally, we advocate the standpoint that a single "correct" strategy does not exist, and therefore we should strive for a synthesis of multiple modelling approaches which can contribute to an integrative view on the functioning of the system.

Introduction

Environmental modelling has been an indispensable tool for addressing lake eutrophication. A variety of *data-oriented* and *process-based* models have been used to examine the impact of nutrient loads to ecosystem integrity and to set water quality goals. The data-oriented (or empirical) models are mainly steady-state, mass-balance approaches that predict lake total phosphorus (TP) concentrations as a function of lake morphometric/hydraulic characteristics, such as the areal phosphorus loading rate, mean depth, fractional phosphorus retention, and areal hydraulic loading, which are then associated with the chlorophyll a and/or hypolimnetic dissolved oxygen (DO) concentrations (Brett and Benjamin, 2008; Cheng et al., 2010). Despite their successful application in predicting average whole-lake TP concentrations and DO levels in smaller inland lakes on the Canadian Shield (Dillon and Molot, 1996; Molot et al., 1992), these models have significant drawbacks when applied to larger systems. Namely, one of their fundamental assumptions that the lake is thoroughly mixed with uniform concentrations throughout is profoundly violated in systems of larger size and complex shape whilst their capacity to predict the impact of episodic events (storm events, upwelling, climate change, and invasive species) is very limited.

An alternative to these empirical strategies has been the development of *process-based* models which can be used to understand ecological processes, to predict aquatic ecosystem responses to external nutrient loading changes, to evaluate management alternatives, and to support the policy making process (Jørgensen, 1997; Reckhow and Chapra, 1999). More than 40 years ago, Chen (1970) introduced a general model structure for addressing a broad class of water quality problems. This modelling framework essentially proposed a general set of ordinary or partial differential equations for describing key physical, chemical, and biological processes with site-specific parameters, initial conditions, and forcing functions, which were then used to reproduce real-world dynamics, to gain insights into the ecosystem functioning and to project future system response under significantly different external conditions (e.g., nutrient enrichment, climate change). The philosophy and the basic set of equations proposed in these early models still remain the core of the current generation of mechanistic aquatic biogeochemical models although advances in scientific understanding and improvements in methods of numerical analysis have

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brought significant progress with regard to the accuracy and sophistication. Reckhow and Chapra (1999) interpreted the fact that all the recent improvements in water quality modelling have built and evolved upon the foundation provided by early studies from the mid-70s as evidence of the strength of the original modelling propositions (Di Toro et al., 1971; Donigian and Crawford, 1976; O'Connor et al., 1975; Thomann et al., 1975). However, Arhonditsis et al. (2006) argued that the absence of novel ideas and creativity may also be a pathological symptom of the field of aquatic ecosystem modelling, inviting one to ask what it would take to prime the pump for significant breakthroughs to come along.

On a similar note, Arhonditsis and Brett (2004) attempted to evaluate the methodological consistency and general performance of 153 aquatic ecosystem modelling studies published in the international peer-reviewed literature between 1990 and 2002. Despite the heterogeneity of the selected papers with respect to model complexity, type of ecosystem modelled, spatial and temporal scales and model development objectives, this study reported a number of findings indicating that aquatic ecosystem modellers do not seem to consistently apply conventional methodological steps during the development of their models. The first striking feature of this analysis was the absence of systematic goodness-of-fit assessment of the original models (Fig. 1a). In the cases in which measures-of-fit or comparison plots were presented, Arhonditsis and Brett (2004) independently assessed state-variable performance as expressed by the relative error (RE) and the coefficient of determination (r^2) (Fig. 1b). Also the performance of existing mechanistic aquatic biogeochemical models was declined from physical–chemical to biological components of planktonic systems. The large majority of the published studies in the field over the last decade did not properly assess model sensitivity to the input vectors (Fig. 1c) whilst aquatic ecosystem modellers are still reluctant to embrace optimization techniques during model calibration, and assess the ability of their models to support predictions in the extrapolation domain (Fig. 1d). Thus, the establishment of a systematic methodological protocol for model assessment which is widely accepted by the aquatic biogeochemical modelling community should be a top priority. The modellers should understand that the methodological consistency is an analogue to the way a chemical analyst strives to attain clean laboratory conditions, excellent standardization curves, and faithful application of the analytical protocol. These methodological considerations will be some of the criteria for evaluating the rigour of eutrophication modelling in Lake Erie although the present study will place more emphasis on the implications of the parameterization of the existing models about the ecosystem characterization.

Eutrophication modelling in Lake Erie

Lake Erie is the smallest and shallowest system of the Great Lakes; and therefore, it is the most susceptible to nutrient-driven water quality issues. Recent evidence suggests that rapid ecological changes are in fact occurring in the ecosystem, involving a complex and often poorly understood interplay among many factors related to the lake's chemical, physical and biological characteristics (Michalak et al., 2013). A variety of aquatic biogeochemical models have been developed to understand ecological interactions and to predict the response of Lake Erie to external nutrient loading changes. Some of the models were constructed during the mid-1970s (e.g., Di Toro et al., 1987; Lam et al., 1987) whilst a new generation of models has been in place more recently (e.g., Leon et al., 2011; Zhang et al., 2008).

The evolution of eutrophication modelling should ideally follow the advancement of our understanding of the major causal linkages/ecosystem processes underlying the water quality problems in a particular system (Fig. 2). As such, the first type of models must be simple in structure and should revolve around the elucidation of the interplay among the exogenous nutrient loading, ambient nutrient concentrations, and plankton dynamics. Whether statistical (data-driven) or mechanistic, the basic premise of these models is to capture effectively the direct signature of the abiotic forcing

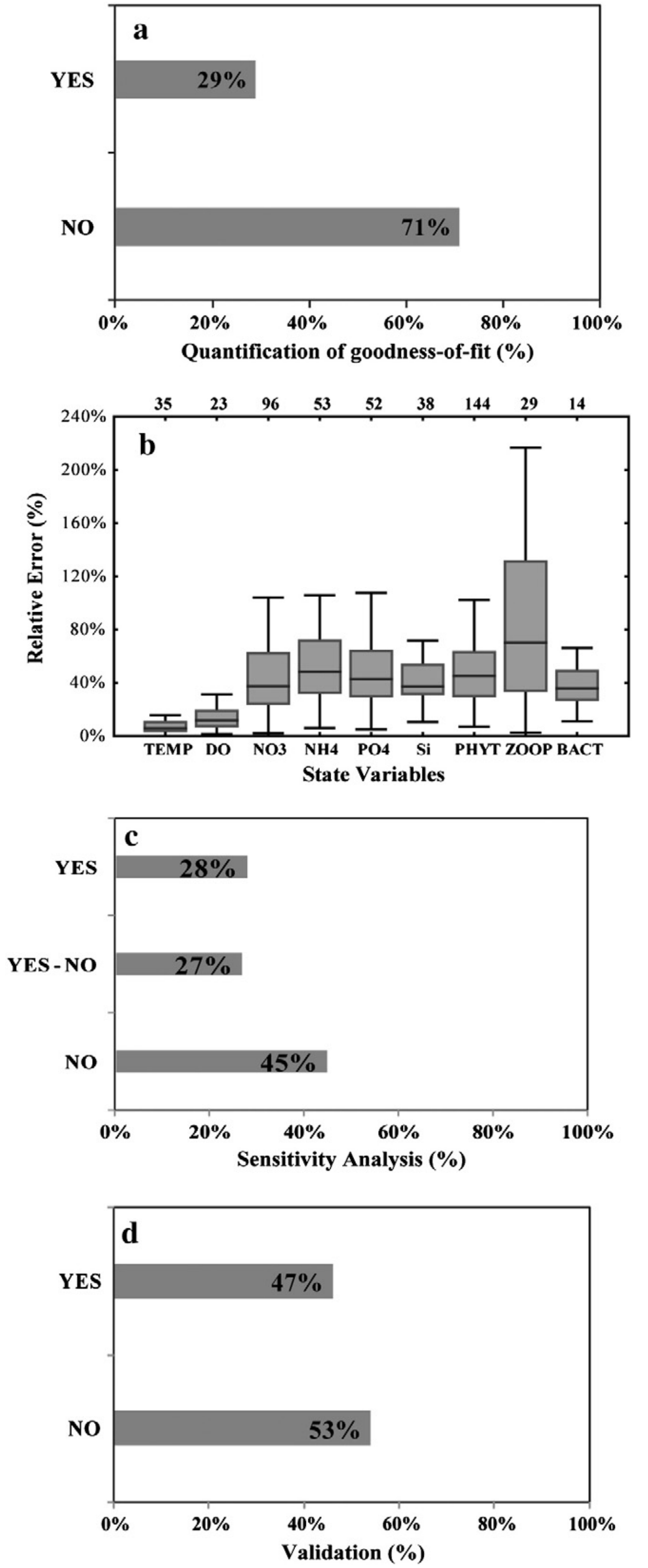

Fig. 1. (a) Percentage of modelling studies that quantified goodness-of-fit; (b) relative error (RE) of aquatic biogeochemical models for the study period 1990 to 2002 [number of studies assessed for each state variable is indicated on the top of the graph]; percentage of modelling studies that reported (c) sensitivity analysis; and (d) model validation. These figures are modified from Arhonditsis and Brett (2004).

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