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Spatial distributions of external and internal phosphorus loads in Lake Erie and their impacts on phytoplankton and water quality

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ABSTRACT

Re-eutrophication in Lake Erie has led to new programs to reduce external phosphorus loads, and it is important to understand the interrelated dynamics of external and internal phosphorus loads. In addition to developing phosphorus load response curves for algal biomass in the western basin and hypoxia in the central basin, we used a two-dimensional (vertical-longitudinal) hydrodynamic and ecological model to show that both external and internal phosphorus loads were distributed homogeneously in the water column in Lake Erie's western basin. In the stratified central and eastern basins phosphorus released by organic matter decay and crustacean zooplankton excretion was concentrated in the upper water column, contributing 100–119% of the phytoplankton phosphorus demand, while phosphorus released by dreissenids and from anoxic sediments was distributed primarily in the hypolimnion during the growing season. Simulated reductions in external phosphorus loads decreased individual phytoplankton groups most at times when they were normally most abundant, e.g., *Microcystis* decreased the most during September. Phosphorus was limiting over the simulation periods, but water temperature and light conditions also played critical roles in phytoplankton succession. While water column phosphorus responded quickly to external phosphorus reduction, pulses of phosphorus (riverine input or sediment resuspension) occurring immediately before the *Microcystis* bloom period could allow it to bloom despite long-term external phosphorus load reduction. Studies are warranted to assess the contribution of seasonal dynamics in phosphorus loading (including sediment resuspension) to *Microcystis* bloom development.

Introduction

A strong correlation between the concentration of total phosphorus and phytoplankton (hereafter simplified to algae) biomass in freshwater lakes has been well documented (e.g., Lean, 1973; Scavia and Chapra, 1977; Schindler, 1977; Smith, 1982; Knoll et al., 2003), and phosphorus (P) is the most common limiting macronutrient in freshwater lakes (Schindler, 1977; Arnott and Vanni, 1996; Wetzel, 2001; Wilhelm et al., 2003). Excessive P inputs have dramatically increased water productivity and caused the eutrophication of many lakes (Chapra and Robertson, 1977; Beeton, 2002; Jin, 2003; Schindler, 2012).

Lake Erie was severely eutrophic in the 1960s, resulting from excessive external P loading (Burns and Ross, 1972). Water quality management in Lake Erie demonstrated that control of external P loading provides an effective means of decreasing eutrophication. An external P load reduction program for point sources was carried out in the early 1970s, and soon led to encouraging water quality responses. Not only did total phosphorus concentrations decrease in the water column (Rockwell et al., 1989), but total algal biomass decreased 40% in the western basin by the late 1970s, 65% by the mid-1980s, and both Cyanobacteria and filamentous greens decreased by 80% by the mid-1980s (Makarewicz and Bertram, 1991; Gopalan et al., 1998). Oxygen concentrations increased at the bottom of both the western basin (Krieger et al., 1996) and the central basin (Bertram, 1993; Ludsin et al., 2001).

Recent studies show that dissolved reactive phosphorus loads in some tributaries have increased since 1995 (Baker et al., 2014; IJC, 2014; Scavia et al., 2014) and algal biomass has increased as well (Conroy et al., 2005a). In recent years increases in the frequency and magnitude of *Microcystis* blooms (Michalak et al., 2013; Stumpf et al., 2012) suggest that climate may be an additional factor triggering the resurgent blooms, which are correlated with an increased soluble phosphorus fraction from agriculturally dominated tributaries (Kane et al., 2014) and the total phosphorus load from spring freshets (Stumpf et al., 2012). The changes in loads are driven by climate-induced variability in precipitation (Scavia et al., 2014) and are accompanied by trends toward warm, calm meteorology during summer,

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which combine to cause bloom-favorable conditions (Michalak et al., 2013). Consequently, further reduction in the external P load targets has been recommended (Rucinski et al., 2014; Scavia et al., 2014, in this issue), and the governments of Canada and the United States announced a target of 40% reduction in total phosphorus loads to Lake Erie on February 22, 2016 (USEPA, 2016).

While external loading reduction can reduce symptoms of eutrophication, this result is often delayed by release of internal nutrient loads from years of accumulations and decay of P-rich organic matter in the sediments (Phillips et al., 2005; Turner et al., 2008). Hypoxia in the central basin (and to a lesser extent in the western basin) can cause sediment ferric phosphate deposits to change to the much more soluble ferrous phosphate form, promoting diffusion of soluble reactive phosphate out of the sediments. Another important internal P source to Lake Erie is excretion by zebra mussels (*Dreissena polymorpha* Pallas) and quagga mussels (*Dreissena rostriformis bugensis* Andrusov). These taxa excrete considerable phosphate (Arnott and Vanni, 1996; James et al., 1997) at rates up to 2.8 $mg/m^2/d$ (Conroy et al., 2005b), sufficient to replace the pool of soluble reactive phosphorus (SRP) in the water column in <10 days (Conroy et al., 2005b). However, other studies indicate that dreissenid mussels intercept incoming nutrients in the nearshore area and lead to offshore 'desertification' (e.g., Hecky et al., 2004). The mussel populations retain a large amount of phosphorus in their body tissue (Mellina et al., 1995), which can be released into the water with unclear temporal and spatial patterns. An ecosystem with a high cumulative internal P loading rate from these sources can sustain a eutrophic state well after external P loading has decreased. Thus, the amount and spatial distribution of internal P loading strongly affect the efficiency of any external P reduction program.

In this study, we used Zhang et al.'s (2008) model to simulate the spatial distributions of phosphorus throughout Lake Erie's western, central, and eastern basins during 1997 and 1998. In addition to being the calibration and confirmation years for the model, 1997 and 1998 had higher P loads than the annual target load of 11,000 metric tonnes (mt) and displayed varying *Microcystis* bloom tendencies. Phosphorus loads in 1997 were 16,800 mt with no *Microcystis* bloom, whereas 1998 had lower P loads (12,700 mt) with a moderate *Microcystis* bloom. We evaluated the effects of different reduction levels (20%, 40%, 60%, and 80%) of external total phosphorus loading on algae in the western basin by comparing the biomass of three algal groups with and without reductions in external P inputs to explore years that experience annual external P loads higher than the annual target load of 11,000 mt. We also evaluated the effects of different reduction levels of external total phosphorus loading on hypoxia in the central basin by comparing the hypolimnetic oxygen concentration and hypoxic area with and without reduction in external P inputs, which was similar to the analyses in the multi-model team reports of the Great Lakes Water Quality Agreement Nutrient Annex 4 (Scavia et al., in this issue; Scavia and DePinto, 2015). Model simulations under different P reduction scenarios provide an overview of the P fluxes and fates in the Lake Erie ecosystem during the summer growing season, and how they respond to external P loads.

Methods

Model description

A two-dimensional (vertical–longitudinal) hydrodynamic and ecological model, EcoLE, was applied to Lake Erie to simulate the effects of external and internal P loading on the Lake Erie ecosystem. The model is an adaptation of the USACE CE-QUAL-W2 version 2 (Cole and Buchak, 1995), with modifications for large lake hydrodynamics (Boegman et al., 2001), multiple algal groups and dreissenid mussels (Zhang et al., 2008). Hydrodynamics and water quality simulations were calibrated and validated in a previous study (Zhang et al., 2008). EcoLE divides Lake Erie into as many as 65 vertical layers at 1-m intervals and 220 longitudinal segments (2-km wide from west to east). The depths of segments were assigned relative to the Great Lakes Datum (GLD) of 1985. State variables in EcoLE include free water surface elevation, horizontal velocity, vertical velocity, water density, water temperature, suspended solids, dissolved organic matter (DOM), particulate organic matter (POM), diatom-derived particulate organic matter (D-POM), soluble reactive phosphorus (SRP), ammonium, nitrate + nitrite, silicon, dissolved oxygen, algal groups (non-diatom edible algae (NDEA), diatoms, and non-diatom inedible algae (NDIA)), cladocerans and four life stages of copepods (eggs, nauplii, copepodites and adults). Data of water temperature and the water quality state variables mentioned above were taken from the Ohio State University's Lake Erie Plankton Abundance Study database to initialize, calibrate and

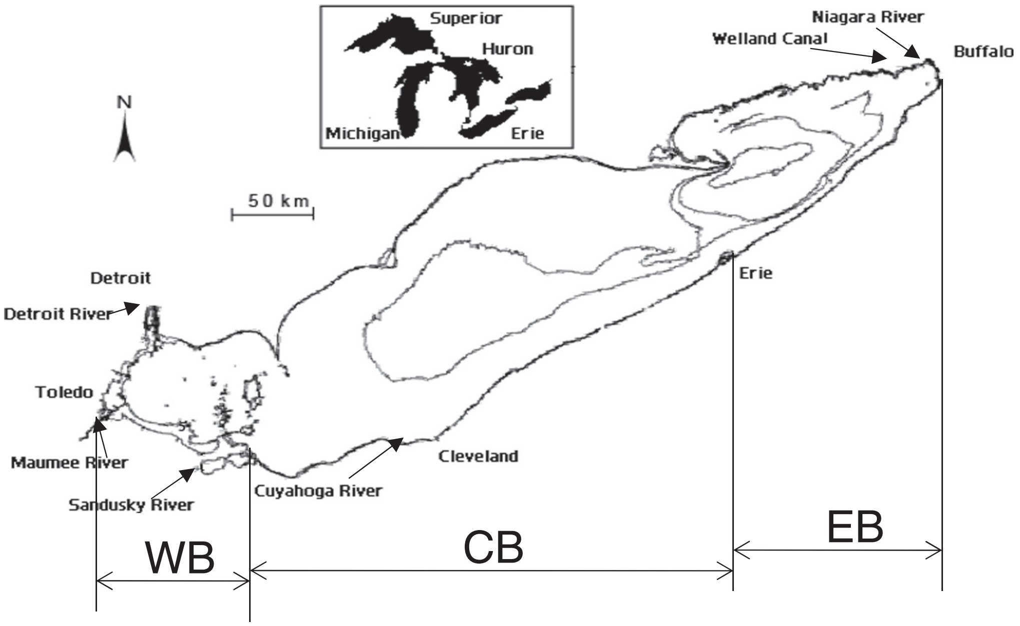

Fig. 1. Locations of tributaries, depth contours of 5, 22, 30 and 50 m, and separations of the Lake Erie western (WB), central (CB) and eastern (EB) basins.

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