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Improving the representation of internal nutrient recycling with phosphorus mass balance models: A case study in the Bay of Quinte, Ontario, Canada

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ABSTRACT

We evaluate the relative importance of the causal connection between exogenous total phosphorus (*TP*) loading and internal nutrient recycling with the water quality conditions in the Bay of Quinte, Ontario, Canada. First, we examine the temporal trends of all the major point and non-point loading sources over the last four decades. We then enhance the mechanistic foundation of an existing simple mass-balance total phosphorus (*TP*) model, originally developed to guide the eutrophication management in the system. The structural improvements include the incorporation of macrophyte dynamics, the explicit representation of the role of dreissenids in the system, and the improved portrayal of the interplay between water column and sediments. The upgraded model was in good agreement with the observed *TP* variability in the system during the study period (2002–2009) and successfully reproduced the *TP* accumulation patterns toward the end of the summer-early fall. We provide evidence that phosphorus dynamics in the upper Bay are predominantly driven by the inflows from Trent River, while the middle and lower segments likely receive substantial internal subsidies from the sediment diagenesis mechanisms and/or the activity of macrophytes and dreissenids (e.g., pseudofeces production, nutrient pump effect). We also forced the model with scenarios of reduced nutrient loading and examine the likelihood of the system to meet its water quality delisting targets, although we caution that our complex overparameterized modeling construct is primarily intended for heuristic purposes. The present study together with the companion paper by Zhang et al. (2013) illustrate how phosphorus mass balance models can offer useful tools for improving our understanding of freshwater ecosystems.

1. Introduction

In many parts of the Laurentian Great Lakes, the arrival of dreissenid mussels has induced a major reengineering of the biophysical littoral environment with profound alterations on the retention and recycling of nutrients (Coleman and Williams, 2002). This nearshore shunt (sensu Hecky et al., 2004) is hypothesized to have modified the processing of particulate material in the littoral zones, with critical ramifications for their relative productivity and their interplay with the offshore areas. Depending on the concentration of food particles, dreissenid mussels can filter twice as much material as they actually ingest (Walz, 1978), and thus a large proportion is excreted in soluble form or released in particulate form as either feces or pseudofeces. Given also that a significant portion of the latter particulate material is thought to be subsequently remineralized by the community of detritivores and decomposers, the contemporary literature hypothesized that dreissenids mediate the nutrient cycling and may significantly modulate the nearshore nutrient concentrations (Holland et al., 1995; James et al., 1997). Following the establishment of the causal link between dreissenids and nutrient variability in the littoral zone, Hecky et al. (2004) questioned the structural adequacy of the nutrient mass-balance models developed during the pre-dreissenid period in the Great Lakes. Because of their founding assumption that the lakes resemble well-mixed reactors, it was argued that the lack of discrimination between nearshore and offshore regions and the adoption of a lake-wide sedimentation rate to reproduce particle and nutrient removal from the water column will introduce systematic biases (Hecky et al., 2004). An additional problematic feature that undermines the suitability of simple mass balance phosphorus models as

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management tools is their failure to explicitly consider the capacity of the nearshore shunt to shape the relationship between external loading and ecosystem response in both space and time.

In the Bay of Quinte, recent efforts have focused on the delineation of the ecological implications of the establishment of invasive zebra and quagga mussels in the mid-1990s relative to a substantial (≈50%) reduction in the point-source phosphorus loading into the upper segments during the winter of 1977–1978 (Nicholls and Carney, 2011; Nicholls et al., 2002). Existing evidence suggests that the presence of dreissenid mussels in the system may have induced a series of cause–effect relationships that could be translated into an ecosystem regime shift (deYoung et al., 2008; Scheffer et al., 2001). Namely, contrary to the limited macrophyte response to the point-source phosphorus control, the significant increase of the light penetration, stemming from the filtration of lakewater by dreisseinds, is likely to have triggered the growth of submerged macrophytes and the rapid expansion of existing shallow-water beds into deeper water (Leisti et al., 2006; Seifried, 2002). Dreissenids can consume particles in a wide size range including microzooplankton (e.g., protozoa, ciliates, rotifers, veligers and nauplii), and thus may have shaped the zooplankton community structure in the Bay, such as the low rotifer biomass that represents less than 5% of the total zooplankton biomass (Bowen and Johannsson, 2011). Dreissenid-induced declines in larger zooplankton could indirectly occur through their impact on food abundance as well as through the changes in predation, as the increased water clarity leads to an easier detection by higher predators (Bowen and Johannsson, 2011).

With respect to the phytoplankton community response, Nicholls and Carney (2011) contended that the arrival of dreissenid mussels may be associated with both desirable (e.g., *Aphanizomenon* and *Oscillatoria* decline) and undesirable (e.g., *Microcystis* increase) changes in the trophic efficiency and ecosystem health integrity. In particular, the post-*Dreissena* increase of the cyanophyte *Microcystis* has significant implications for the esthetics and other beneficial uses in the Bay, through the formation of "scums" on the water surface (Jacoby et al., 2000) as well as due to the fact that some strains of *Microcystis* are toxin producers (Brittain et al., 2000; Vanderploeg et al., 2001), e.g., one of the most common species, *Microcystis aeruginosa*, is a producer of the hepatotoxin microcystin-LR (Repavich et al., 1990). Some of these structural changes in the phytoplankton community composition could stem directly from the feeding selectivity of dreissenids or indirectly from the improvements in the transparency of the water column, but the role of the feedback loop associated with their nutrient recycling activity could conceivably be another important factor (Bierman et al., 2005). Interestingly, total phosphorus concentrations in the post-dreissenid period demonstrate significant intra-annual variability, characterized by relatively low spring and autumn levels, 10–15 $\mu g\ TP\ L^{-1}$, and quite high summer concentrations, >50 $\mu g\ TP\ L^{-1}$, which exceed the targeted delisting criterion of 30 $\mu g\ TP\ L^{-1}$ (Munawar et al., 2011). This pattern may reflect the regeneration of phosphorus from sedimented materials on the lake bottom, the gradual retention of particulate P as algal biomass or biological recycling activity.

In this study, we use mathematical modeling to test the hypothesis that the establishment of dreissenids and the resurgence of macrophytes may be causally linked with the end of summer-early fall TP accumulation in the Bay of Quinte. First, we present the structural augmentation of the eight-segment *TP* mass-balance model, originally developed by Minns and Moore (2004) and recently modified by Zhang et al. (2013). Improvements in the mechanistic foundation of the model include the incorporation of macrophyte dynamics, the explicit representation of the role of dreissenids in the system, and the improved portrayal of the interplay between water column and sediments. We provide the rationale behind the model structure adopted, the simplifications included, and the formulations used during the development phase of the model. We then present the results of a calibration exercise and examine the ability of the model to sufficiently reproduce the observed patterns in the Bay of Quinte during the 2002–2009 study period. We also conduct a local sensitivity analysis to identify the most influential components of the model and to shed light on the spatiotemporal role of the various ecological processes and cause–effect relationships, as postulated by the present parameterization. Our modeling study also undertakes an estimation of the critical nutrient loads that will ultimately lead to compliance of the system with threshold levels of the ambient total phosphorus. Several of the lessons learned during the model calibration and sensitivity analysis are highlighted as pointers for future research and management actions in the Bay of Quinte.

2. Materials and methods

2.1. Dataset description

Daily inflows were based on daily discharge data obtained from Environment Canada (Water Survey Division, Burlington) for gauging stations on five rivers: Trent River, Moira River, Salmon River, Napanee River, and Wilton Creek (Fig. 1). Water quality data for the rivers were provided by the Provincial Water Quality Monitoring Network of Ontario Ministry of the Environment (MOE). The precipitation data used were obtained from Environment Canada (Environmental Services Branch, Burlington) for the weather station at Trenton, consisting of rain and total precipitation in tenths of millimeters. Atmospheric deposition was based on bulk precipitation chemistry data obtained from Environment Canada, comprising samples collected with several different types of samplers at Trenton, Kingston, and Point Petrie. Estimates of point source inputs were based on flows and final effluent *TP* concentrations from the Belleville, Trenton, CFB Trenton, Deseronto, Napanee, and Picton sewage treatment plants (*STPs*), along with the same information for various industrial inputs to the Bay of Quinte. Detailed description about the data compilation and the derivation of the point and non-point nutrient loading estimates can be found in Minns et al. (2004). All *TP* concentrations in the Bay were generated as time-weighted monthly means of data provided by the Project Quinte members (2011). Monthly mean nutrient concentrations for the Lake Ontario outlet basin were also provided by the DFO's Long-term Bio-monitoring (Bioindex) Program (Minns et al., 2004).

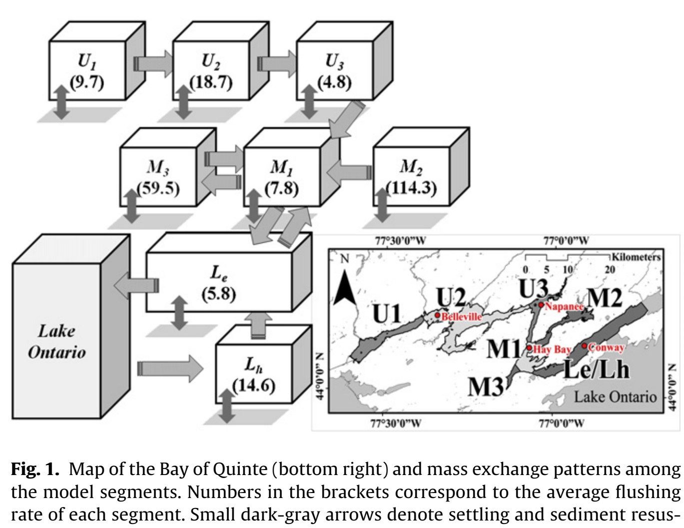

Fig. 1. Map of the Bay of Quinte (bottom right) and mass exchange patterns among the model segments. Numbers in the brackets correspond to the average flushing rate of each segment. Small dark-gray arrows denote settling and sediment resuspension, while large light-gray arrows denote inflows, outflows, and backflows.