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Factors influencing the phosphorus distribution near the mouth of the Grand River, Ontario, Lake Erie

Krista M. Chomicki [a,*], E. Todd Howell [b], Emma Defield [a], Amanda Dumas [a], William D. Taylor [a]

[a] Department of Biology, University of Waterloo, 200 University Ave W, Waterloo, ON, N2L 3G3, Canada
[b] Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment and Climate Change, 125 Resources Rd., Toronto, ON, M9P 3V6, Canada

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ABSTRACT

Phosphorus distribution in the nearshore of Lake Erie near the mouth of the Grand River, Ontario, reflects the extent of the mixing area between the river and the lake, with elevated concentrations observed directly within the river plume decreasing as the plume is mixed with the nearshore waters. Easterly alongshore currents were dominant within the area and affected the spatial distribution of phosphorus (P). Suspended solids concentration declined by an order of magnitude between the river and lake, and particulate P (PP) transitioned from being largely organic phosphorus and non-apatite inorganic phosphorus (NAIP) to predominantly NAIP only. Dominant processes transitioned from PP transport in suspension or resuspension in the river below Dunnville Dam to consumption and sedimentation in the lower reaches of the river and the nearshore. Higher dreissenid mussel density and mussel phosphorus content were at times associated with the mixing area of the Grand River, suggesting that river P influences the local ecology (e.g., *Cladophora* and mussel growth). Mussels and *Cladophora* in the study area are estimated to contain 8.6 and up to 4.9 tons of phosphorus in the standing biomass, respectively, which can be supplied by the Grand River in approximately 16–25 days.

Introduction

Despite the phosphorus control programs initiated in the 1970s that led to reductions in total phosphorus (TP) loadings and water column concentrations in Lake Erie (Lesht and Rockwell, 1985, 1987; Rosa, 1987; Rockwell et al., 1989; Dolan and Chapra, 2012), nuisance benthic algae are once again an issue in nearshore regions of eastern Lake Erie (e.g., Higgins et al., 2005; Depew et al., 2011; EC and USEPA, 2014). Since 1996, Lake Erie has experienced an increase in seasonal average phytoplankton biomass throughout the lake (Conroy et al., 2005) with cyanobacterial blooms in the western basin and the nearshore of the central and eastern basins (Budd et al., 2001; Vanderploeg et al., 2001; Vincent et al., 2004; Conroy and Culver, 2005). However, despite increases in biomass and blooms in the western basin, eastern basin nearshore regions have been experiencing a decrease in chlorophyll *a* and primary production in comparison to the offshore (Depew et al., 2006).

Offshore waters of the eastern basin of Lake Erie are oligotrophic to oligo-mesotrophic with low TP (e.g <13 μg/L: Makarewicz and Bertram, 1991; North et al., 2012; Dove and Chapra, 2015) and moderate to high water clarity (e.g., average summer Secchi depth of 5–11 m since 2000; Dove and Chapra, 2015). Phosphorus (P) is the limiting nutrient for phytoplankton and *Cladophora*, the dominant nuisance benthic alga, even though TP can be elevated in the nearshore (e.g., Schwab et al., 2009). Phosphorus dynamics within these nearshore regions can be affected by a number of mechanisms including tributary discharge (Makarewicz et al., 2012), shoreline erosion, sediment resuspension (Mayer and Manning, 1989), and biological activity (Hecky et al., 2004). However, it is difficult to apportion the contributions of these mechanisms to the observed nutrient gradients in the coastal regions of Lake Erie.

Tributaries can strongly affect water quality in the nearshore (Baker, 1985; Chen and Driscoll, 2009). Nutrient dynamics and mixing zones are shaped by temperature gradients between the tributary plume and the lake (e.g., Murthy et al., 1986) and features of alongshore circulation (e.g., Rao and Schwab, 2007; Howell et al., 2012; Howell et al., 2014). Modeling studies on river plumes entering the Great Lakes indicate that they can periodically extend far into the offshore (e.g., Ji et al., 2002; Chen et al., 2004), with seasonal changes in river flow influencing the nearshore.

Environmental conditions in eastern Lake Erie adjacent to the mouth of the Grand River are highly dynamic as a result of the external loading, physical forcing, and internal cycling (transport, uptake and release of phosphorus within the nearshore) that shape nearshore water quality patterns. Spatial gradients in nutrient chemistry and biological activity are observed when river water enters the lake, as nutrients are diluted and assimilated. The size and orientation of the mixing area between

* Corresponding author at: Toronto and Region Conservation Authority, 5 Shoreham Drive, Toronto, ON M3N 1S4, Canada. Tel.: +1 416 661 6600x5857, +1 416 235 6567.
E-mail addresses: kmchomic@uwaterloo.ca, kchomicki@trca.on.ca (K.M. Chomicki).

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the river and the lake are determined by the physical mixing of the two water masses and lake circulation. He et al. (2006) highlight the importance of wind-driven coastal currents to the movement of the Grand River (Ontario) plume in the eastern basin and determined that the frequent current reversals limit the extent that the plume travels. As the physical shoreline laterally constrains water movement and diverts current flow parallel to the shore (Rao and Schwab, 2007), nutrient-rich areas capable of sustaining high productivity are created. Conductivity in the nearshore can be used to map the extent of horizontal mixing and dispersion of the plume (Rao and Schwab, 2007) that is likely the cause of the elevated TP concentrations reported by Nicholls et al. (2001) and the broad scale productivity gradient observed near the river mouth by Nicholls et al. (1983).

The TP load entering Lake Erie is comprised of dissolved and particulate phosphorus. It is generally accepted that dissolved phosphorus (DP) is more bioavailable than particulate phosphorus (PP) and can be accessed by biota. Particulate phosphorus, however, dominates the TP load. Baker et al. (2014) determined up to 30% of the PP entering Lake Erie from Ohio rivers was bioavailable; it is also conceivable that some of the recalcitrant portion of PP can become available as a nutrient source after being assimilated and excreted by mussels (Ozersky et al., 2009) or other particle feeders. The bioavailability of PP is likely important to understanding the nutrient supply to the nearshore. In eastern Lake Erie, shoreline materials are easily eroded clay and silt and contribute turbidity and TP to the nearshore. Suspended solids (SS) in surface waters can contain more bioavailable P than bottom waters (e.g., Mayer and Manning, 1989). Particle size, phosphorus speciation, and particle geochemistry affect the availability of particulate P and rate of soluble reactive phosphorus (SRP) release from tributary particulate matter (DePinto et al., 1981). However, PP also enters the water column by sediment resuspension, especially during late fall and winter storms. Studies in Lake Erie (Williams et al., 1980) have shown that algal uptake of P from lake sediments is positively related to the amount non-apatite inorganic phosphorus. Therefore, particulate phosphorus speciation is likely important to the understanding of nutrient supply to the biota in nearshore regions.

Dreissenid mussels act as both sources and sinks of phosphorus. Conroy et al. (2005) suggest that mussels increase phosphorus nutrient fluxes and might facilitate phytoplankton growth in western Lake Erie, while Zhang et al. (2011) conclude that these nutrient contributions by mussel excretion are concentrated in the bottom waters. Ozersky et al. (2009) found that the SRP excreted from mussels was similar to the amount required by *Cladophora* communities. Dreissenid biomass can retain appreciable amounts of phosphorus over the colonized lakebed (Pennuto et al., 2012, 2014). Bedrock heavily colonized by mussels has been observed at depths of less than 20 m in the vicinity of the Grand River confluence with Lake Erie, east and west of the river mouth. The proximity of the lakebed colonized by dreissenid mussels with gradients of water quality resulting from the river mixing with the lake suggests that interactions between the mixing plume and the biological cover of lakebed may influence P speciation and fate.

The Grand River is the largest tributary from Canada flowing to Lake Erie and is a major nutrient input to the eastern basin. Despite its potential importance, the influence of the Grand River on nutrient distributions in the adjacent nearshore of Lake Erie is not well understood. While the effects of winter and early spring plumes on primary production (e.g., EEGLE: Episodic Events—Great Lakes Experiment; Green and Eadie, 2004) and the importance of late winter–spring plumes and storms on nearshore–offshore transport (Rao et al., 2002) have been examined in the Great Lakes, summer pulses have not been a focus due to their smaller contribution to load. However, in the western and central basins Michalak et al. (2013) found that extreme precipitation and runoff events extending until June can impact nearshore nutrient regimes; events such as these could provide nutrients for nuisance algae. One might expect that inputs during the growing season might be disproportionately important to the growth of nuisance algae. The influence of the river on the adjacent shores of the lake, and the spatial and temporal scales over which the Grand River discharge affects environmental and ecological conditions in the nearshore environment, remain unclear. Recently, the Annex 4 Objectives and Targets Task Team (US-EPA and Environment Canada, 2015) concluded that while reductions in P loads are expected to result in reductions of *Cladophora*, they were unable to make specific recommendations without additional research. This paper compiles data from a number of programs to examine the distribution of SRP, dissolved P and particulate P at the mouth of the Grand River and the adjacent waters of Lake Erie to better define the Grand River's zone of influence. We use the relationship between TP and suspended sediments, and data on particulate P speciation, currents, and particle-size distribution, to make inferences about the fate and impact of riverine P. We also examine the distribution of dreissenids and *Cladophora* in the nearshore and discuss the possible role of dreissenid mussels in modifying the effect of riverine nutrients on nuisance algae and in the fate of the loaded phosphorus.

Methods

Site description

The Grand River, located in Southern Ontario, Canada, drains a watershed of nearly 7000 km^2. While land use in the basin is primarily agricultural (approximately 70%: Depew et al., 2011), the watershed includes several cities and towns including Kitchener, Waterloo, Cambridge, and Guelph that also affect river quality. They are among the fastest-growing urban areas in Ontario (Jyrkama and Sykes, 2007) and collectively are home to nearly one million residents. Increasing urbanization and nutrient loading have the potential to threaten the water quality of the river (e.g., Winter and Duthie, 2000), the water supply to communities along the Grand, and the nearshore of Lake Erie.

Water quality in the lower river is affected by land use both locally and upstream, and influenced by the local geomorphology (e.g., low gradient and clay-rich soils). The turbid waters of the lower river are eutrophic, being high in TP, nitrates, suspended solids and chlorophyll *a* (e.g., TP up to ~160 μg P/L: MacDougall and Ryan, 2012, and median concentrations of 256 μg P/L reported in Venkiteswaran et al., 2014). Other indicators of degraded water quality include high levels of chloride (MacDougall and Ryan, 2012) and low night-time dissolved oxygen (Rosamond et al., 2011; Venkiteswaran et al., 2014). The river has a high discharge compared to all other tributaries of the eastern basin (average of 60 m^3/s versus 14 m^3/s). Because nutrient concentration gradients in the mixing area of the Grand River and Lake Erie are dependent on the water quality in the river, the fate of nutrients in the Grand River plume is an important aspect of the nutrient regime of the eastern basin. Of particular importance is the large amount of phosphorus the Grand contributes, a significant portion of which comes from sewage treatment plant effluent and agricultural runoff. Annual TP loads from the Grand River to Lake Erie have not been published recently; however, estimates from 1994 (320 metric T/yr; reported in Schwab et al., 2009) and used in the TP loading analysis by Dolan and McGunagle (2005) and Dolan and Chapra (2012) as well as subsequent estimates by Depew et al. (2011; 200–220 T/yr) indicate that the Grand River accounts for a large proportion of the load entering the eastern basin.

Water quality

Multiple years of water quality data were available for this analysis. In 2001, ship surveys were conducted in the lower Grand River (below Dunnville Dam) and in the adjacent nearshore environment in Lake Erie on successive days (Fig. 1). Ship surveys were conducted 5 times per year throughout the ice-free season between April and November 2001. Surveys followed a pre-defined survey track at a speed of <10 km/h and were limited by the water depth needed by the survey vessels (>2.5 m water depth). Geo-referenced measurements were