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Estimation of tributary total phosphorus loads to Hamilton Harbour, Ontario, Canada, using a series of regression equations

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ABSTRACT

Event-based sampling was conducted from July 2010 to May 2012 at four stations in the watersheds of Hamilton Harbour, Ontario, Canada, with the primary objective of estimating total phosphorus (TP) loads. Eighty-seven 24-hour, level-weighted composite samples were collected during a variety of catchment states (rain, snowmelt, baseflow), and TP concentrations were regressed against flow or precipitation in an attempt to mitigate the considerable loading estimation bias arising from event-scale hysteresis. Annual average TP loads were estimated for 2008 to 2012 and were the highest from the Desjardins Canal (17.4 kg/d to 65.6 kg/d), followed by Red Hill Creek (6.4 kg/d to 25.8 kg/d), Grindstone Creek (3.4 kg/d to 33.4 kg/d), and Indian Creek (3.0 kg/d to 7.9 kg/d). Daily TP loads varied by three orders of magnitude between wet and dry conditions, with storm events driving peak daily loads in the urban watersheds, and spring freshet in the agricultural and wetland influenced watersheds. Areal TP loads were higher from the urban relative to the agricultural watersheds. This study demonstrated that the tributaries did not meet the Hamilton Harbour Remedial Action Plan (HH RAP) initial target of 65 kg/d in 2008 to 2011 but did in 2012. Comparison of three loading methods emphasized the vital role of characterizing TP concentrations during high flow events. The higher resolution TP loads generated in this study will assist the HH RAP in forming additional remedial actions in the watersheds for delisting the Hamilton Harbour Area of Concern.

Introduction

Eutrophication of surface waters has long been linked to an overenrichment of phosphorus as it is generally the limiting nutrient for algal growth and biomass in freshwater systems (Schindler, 1977). Such is the case in Hamilton Harbour, a 2150-ha partially enclosed embayment located at the western end of Lake Ontario, Ontario, Canada. Historically, nutrient loads from three wastewater treatment plants (WWTPs), from combined sewer overflows (CSOs), and from industry, urban and agricultural runoff entering Hamilton Harbour via four major tributary inputs resulted in severe eutrophication of the Harbour. In response, Hamilton Harbour was declared an Area of Concern (AOC) under the 1987 Great Lakes Water Quality Agreement.

The Hamilton Harbour Remedial Action Plan (HH RAP) was released in 1992 in part to address nuisance algal growth, reductions in water clarity, and a hypoxic hypolimnion during the summer (HH RAP, 1992). Substantial nutrient loading reductions over the past few decades have led to measurable improvements in the trophic status of the system (Charlton, 1997; Hiriart-Baer et al., 2009); but ambient water quality goals have not yet been achieved (HH RAP, 2012). Recent eutrophication modelling has demonstrated that achievement of the HH RAP TP goal of 20 μg/L is in part contingent on our assumptions of the exogenous loads to the Harbour (Gudimov et al., 2011; Ramin et al., 2012). While it is believed that loads from the point sources have been well characterized, the magnitude of TP loads attributed to the creeks is highly uncertain (HH RAP, 2010).

The TP loads from the creeks were to be revised by the HH RAP utilizing recent monitoring data collected under Ontario's Provincial Water Quality Monitoring Network (PWQMN) (HH RAP, 2010); however, this sampling programme collects monthly samples primarily during baseflow conditions. Accurate characterization of TP dynamics during high flow conditions was deemed critical to increasing the accuracy of TP loading estimates as the majority of annual TP loads occur during brief, high flow events such as storm events and the spring freshet (Booty et al., 2013; Duan et al., 2012; Horowitz, 2013; Macrae et al., 2007; Old et al., 2003; Richards and Holloway, 1987; Sharpley et al., 1993). Thus, not only was an updated event-based monitoring dataset

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needed, but also a simple TP loading estimation method with minimal data requirements will be essential to evaluate compliance with loading objectives and project the future state of the Harbour.

A common technique for estimating tributary loads to the Great Lakes is the stratified Beale Ratio Estimator. When applied to flow stratified data, the basis of this well-described approach (Cochran, 1977; Dolan et al., 1981; Dolan and Chapra, 2012; Dolan and McGunagle, 2005) is the assumption that the ratio of load to flow for all days within a chosen flow stratum will be the same as the ratio of daily load to daily flow on the days when water quality was measured within that flow stratum. Typically, flow strata are selected to cover a range of base flow or low flow conditions, as well as one or more high flow conditions. The Beale Ratio Estimator was originally endorsed by the International Joint Commission (IJC) due to a relatively low bias, high precision, and its robustness (Preston et al., 1989; Rao, 1979; Richards et al., 1996; Richards and Holloway, 1987; Richards, 1998). In reviews of multiple loading methods, however, no group of methods has been found to outperform others for all scenarios examined (Moatar and Meybeck, 2005; Preston et al., 1989; Richards and Holloway, 1987). This suggests that the choice of a loading estimation technique should be driven by the nature of the dataset and end use of the calculated loads.

Due to their relative simplicity and ease of use, regression models that establish the relationship between TP concentration and flow can be a very useful tool. The United States Geological Survey (USGS) has recently established regression models to estimate real time nutrient loads and concentrations of Great Lakes tributaries in an effort to better understand the water quality impact of land management practices and the impact of other restoration activities (Baldwin et al., 2013). By providing daily load estimates, regression methods elucidate variability in the system, thereby offering important information for forming meaningful remedial actions in the watersheds (O'Connor et al., 2011). Such data resolution is not achieved through the current HH RAP method (HH RAP, 2010), an averaging estimator approach, or a ratio approach. Furthermore, acceptable accuracy of estimated loads can be obtained with less resource requirements through regression techniques if concentration and flow are strongly correlated for a wide range of streamflow values (Preston et al., 1989; Quilbé et al., 2006; Richards, 1998).

A major impediment to stronger regression relationships is hysteresis (Williams, 1989) because distinct TP concentration versus flow relationships have been found for the rising and falling limbs of a hydrograph over the course of an event (Aulenbach and Hooper, 2006a,2006b; Hirsch et al., 2010; Macrae et al., 2007; O'Connor et al., 2011). By addressing the issue of event-scale hysteresis, the performance of the regression approach can be further improved. Use of a flow proportional composite sample collected for the full duration of an event mitigates hysteresis in TP concentration versus flow relationships as the samples are integrative of contributors to the variability (e.g., first flush). Very few studies have used a flow-weighted TP concentration dataset in a regression-based approach to estimate tributary TP loads, but results of these studies have suggested that it is a viable modification of the more traditional approach (Booty et al., 2013).

The primary goal of this study was to reduce uncertainty in the tributary TP loading estimates to Hamilton Harbour due to the pivotal role that phosphorus plays in the trophic status and resulting ecology of this system. Accurate loading estimates are needed to ensure that expectations for improvements to the trophic status of Hamilton Harbour are realistic and that the optimal remedial actions in the watersheds will be implemented. The specific objectives of this paper are to:

1) Develop a relatively simple, empirical TP loading estimation method that can be used by the HH RAP to estimate annual TP loads to the Harbour from the four major tributaries;
2) Calculate TP loads that were delivered to Hamilton Harbour from the major tributaries during the July 2010 to May 2012 monitoring period, as well as annual average loads for 2008 to 2012, and evaluate if these sources have met their HH RAP delisting targets; and
3) Compare updated TP loading estimates to those estimated by methods currently endorsed or considered by the HH RAP and recommend methodological changes if warranted.

While this study was primarily conducted to meet the needs of the HH RAP, reducing the uncertainty in Hamilton Harbour's watershed TP loads has wide-ranging benefits to similar systems. For example, few studies in general have assessed the precision and accuracy of TP loads for the large number and diversity of events measured in this study, especially for small, primarily urban watersheds. Further, our empirical approach is user-friendly and adds to the knowledge base on methods to estimate TP loads, an exercise of the utmost importance in the Great Lakes region (2012 Great Lakes Water Quality Agreement, http://www.ec.gc.ca/grandslacs-greatlakes/default.asp?lang=En&n=A1C62826-1, Accessed: May 13, 2014). Our approach also lends insights into some of the processes driving the loading patterns, thus providing suggestions as to how TP loads can potentially be reduced.

Material and methods

Overview of study area

To sample the four main tributary inputs to Hamilton Harbour, four water quality monitoring stations were installed in the summer of 2010 in Burlington and Hamilton, Ontario, Canada, cities with 2011 populations of 175,779 and 519,949, respectively (Statistics Canada, 2011 Census, http://www12.statcan.gc.ca/census-recensement/index-eng.cfm, last accessed April 21, 2014). The monitoring stations were located at the mouths of Red Hill Creek and Indian Creek – two primarily urban watersheds each traversed by three major expressways – and Grindstone Creek and the Desjardins Canal — two primarily agricultural watersheds (Fig. 1; Table 1). Important to note is that the Desjardins Canal station is not technically on a tributary but rather on the canal that hydraulically joins the Cootes Paradise wetland in the west and Hamilton Harbour in the east. The water sampled at the Desjardins Canal reflects what is delivered to the Harbour from a variety of sources as it is integrative of complex wetland processes in Cootes Paradise, numerous tributary inputs, effluent from the Dundas tertiary WWTP located 3.8 km to the west (18 ML/day; HH RAP, 2010), and six CSOs. Samples collected from Red Hill Creek are also intermittently influenced by CSOs; the two CSO points are located 0.8 km and 4 km upstream. Additional details on the City of Hamilton CSOs pertaining to this study are in the Electronic Supplementary Material (ESM Appendix S1).

Event-based water quality data collected July 2010 to May 2012

Between July 5, 2010 and May 8, 2012, 87 24-hour periods during rain events, spring freshet, or baseflow were sampled at the four monitoring stations. The monitoring station setup as well as sample collection, retrieval, and processing are described in detail in Long et al. (2014) but are described briefly below. The core of each monitoring station was a Teledyne ISCO (Model 6712) automatic water sampler equipped with a water level bubbler module (Model 730) as well as power and telephone connections to permit remote programming and data downloads. Water level data were collected in 15-minute intervals and were used for triggering the sampler during an event, as well as for post-event sample processing. Serial correlation is not an issue for the event-based data collected in our study as the average time between the collection of samples was approximately 1 week, a time interval greater than a characteristic correlation time of 1.12 days calculated for Red Hill Creek and 5.37 days calculated for Grindstone Creek (see ESM Appendix S1).

For each station and event, 1-L water samples were collected hourly for 24 h which, during rain events, was generally enough time to capture the rising limbs well as the peak and falling limbs of the hydrograph.