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Evaluation of stormwater and snowmelt inputs, land use and seasonality on nutrient dynamics in the watersheds of Hamilton Harbour, Ontario, Canada

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ABSTRACT

Between July 2010 and May 2012, 87 24-hour level-weighted composite samples were collected from a variety of catchment states (rain, snowmelt, baseflow) from all four major tributaries to Hamilton Harbour, Ontario, Canada. Samples were analyzed for phosphorus- and nitrogen-based nutrients, and concentrations were examined for trends with catchment state, land use, and seasonality. Total phosphorus (TP) and phosphate concentrations were consistently higher during rain/melt events relative to baseflow. Nitrogen parameters, however, exhibited either concentrating behavior or little change in concentration across a range in flows (chemostasis) depending on the parameter and catchment. Despite differences in land use among the four watersheds, TP concentrations during rain/melt events did not vary among stations; however, spatial variability was observed for other parameters, especially nitrate which was elevated in watersheds on the north shore of the Harbour. Seasonal variability was generally not observed for TP concentrations, mirroring the lack of temporal trends for TSS. In contrast, elevated concentrations of nitrate and phosphate were observed during the fall and/or winter period, except in the primarily agricultural watershed where concentrations were elevated during the summer growing season. Highly elevated concentrations of ammonia and nitrate were observed in some watersheds during the unseasonably cold winter of 2010–2011 but not in the comparatively warm winter of 2011–2012. Implications of the study are discussed including the inferred potential impacts of climate change on nutrient dynamics given the strong contrasts in weather patterns observed between years, and exploration of the feasibility of mitigation measures given the data trends.

Introduction

Nutrient concentrations in tributaries are an important driver in determining trophic status, as well as the potential eutrophication of downstream water bodies. While every watershed is unique in terms of the magnitude of nutrient concentrations and the dynamics present, some factors commonly understood to influence the observed variability in nutrient concentrations include catchment state (baseflow or high flow conditions), land use, and seasonality. It has been increasingly apparent for suspended sediment and nutrients like total phosphorus (TP) of which 75–90% of the flux is sediment-bound (Horowitz, 2013) that much of the annual load is associated with a few large storm events (Booty et al., 2014; Horowitz, 2013; Macrae et al., 2007; O'Neill, 1979; Old et al., 2003; Richards and Holloway, 1987; Sharpley et al., 1993). Relatively few datasets have been collected during the peak of storms in general due to the brevity of these events, and even fewer data have been collected on extreme events due to their infrequent nature. This is especially important considering that an increase in the intensity of storm events may occur in many regions due to climate change (Kunkel et al., 2013).

Total phosphorus concentrations correlate strongly with flow, as insoluble constituents are generally transported by overland flow, mobilized from the streambed or bank (Gburek and Sharpley, 1998; Green et al., 2007; OMOE, 2012f), or via soil macropores to tile drains (Blann et al., 2009; Macrae et al., 2007; Vidon and Cuadra, 2011). More dissolved forms of phosphorus such as ortho-phosphate have also been linked to overland flow (Tesoriero et al., 2009), albeit concentration peaks during high flow periods are less pronounced relative to TP (Meybeck and Moatar, 2011). In contrast to TP, a greater proportion of total nitrogen (TN) is found in the dissolved phase (Horowitz, 2013) due to relatively high solubility of nitrogen species such as nitrite and nitrate. As such, TN can be transported by both overland and subsurface flow paths depending on the dominant N species present and other

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conditions (Frank et al., 2000; Green et al., 2007; Hill et al., 1999). Furthermore, subsurface leaching of nitrate, and hence transport to groundwater, is generally greater than phosphate due to immobilization of phosphate by clay and other chemical constituents of soil (Reynolds and Davies, 2001).

While a clear association of the various forms of phosphorus with stormwater has been established across watersheds of diverse character, there is much variability in the flow–concentration relationship potentially due to factors such as antecedent conditions (Hirsch et al., 2010; Macrae et al., 2007; Richards, 1998), a non-linear response to extreme precipitation events in terms of either export (Macrae et al., 2007) or discharge thresholds (Wellen et al., 2014). An overarching flow–concentration paradigm for species of nitrogen is even less clear relative to that for phosphorus. Ammonia fluxes have generally been found to increase less rapidly than river flows (diluting process), whereas total Kjeldahl nitrogen (TKN) fluxes increase more rapidly (concentrating process). Nitrate fluxes have been found to follow either process (Meybeck and Moatar, 2011), a duality in behavior which is critical in understanding the sources and transport of this parameter in each watershed. More data are needed on nutrient concentrations across a variety of catchment states, in particular from urban and agricultural watersheds, to further elucidate nutrient-enrichment processes. These landscapes are generally accepted to export greater nutrient fluxes relative to undisturbed natural systems, and event-based study is needed in order to describe current spatial trends and to evaluate the effect of land use change on nutrient fluxes given the ongoing urbanization of formerly agricultural areas.

Understanding the roles of catchment state and land use on observed nutrient concentrations requires an appropriate sampling program. This can be a challenge to many standard monitoring programs because key sampling periods, such as the winter season as well as storm and melt events, are often overlooked. Tributary studies in temperate regions are typically focused on the ice-free season despite year-round flow data due to logistical challenges in collecting samples in snow or through ice. This scarcity of winter data is problematic as the highest annual loads of TP and nitrates in temperate urban and agricultural watersheds have been attributed to the winter period on account of high flows and high concentration relative to equivalent flows in other seasons (Makarewicz et al., 2012; O'Connor et al., 2011; OMOE, 2012f). In addition, many stream monitoring programs are based on the regular collection of water samples irrespective of stream flow conditions, resulting in a bias towards characterization of baseflow conditions. These generate data that are useful from the perspective of the aquatic habitat and examining long-term and spatial trends but are not ideal for nutrient loading studies. Recent studies have recommended event-based sampling with collection of samples during as many high-flow events as practicable (Horowitz, 2013; Makarewicz et al., 2012) and, further, that flow proportional samples be collected in loading studies (Harmel et al., 2003; Makarewicz et al., 2012; Richards, 1998). Although high frequency point-in-time grab samples during high flow events are useful in revealing details of the chemograph, analysis of composite samples consumes less analytical resources and avoids the confounding effects of first flush and hysteresis (Aulenbach and Hooper, 2006; Butcher, 2003; Hirsch et al., 2010; Macrae et al., 2007; O'Connor et al., 2011; Shih et al., 1994).

The primary goal of our study was to characterize nutrient dynamics in the tributaries of Hamilton Harbour where phosphorus and other nutrients play a pivotal role in the eutrophic status and resulting impaired ecology of Hamilton Harbour, a Great Lakes Area of Concern (AOC) under the Canada–United States Great Lakes Water Quality Agreement of 2012 (Government of Canada, 2013a). Although work was prompted by the needs of the Hamilton Harbour Remedial Action Plan (RAP), the applicability of trends found in these watersheds to similar Great Lakes watersheds may mean that such a protracted sampling effort does not need to be repeated in all watersheds with notable nutrient issues. The specific objectives here are to:

1. Assess the difference between baseflow and event flow nutrient concentrations in the four tributary inputs to Hamilton Harbour;
2. Undertake a comparative basin study to evaluate the role of land use in tributary nutrient concentrations; and
3. Evaluate temporal and seasonal trends of nutrients, with a particular focus on late fall, winter, and early spring conditions where relatively less monitoring data are currently available.

Eighty-seven 24-hour periods were sampled over 22 months, making this study one of the most intensive event-based tributary monitoring programs that has been undertaken in Ontario, Canada (Gaynor, 1978; Macrae et al., 2007; Makarewicz et al., 2012) or elsewhere (Maniquiz et al., 2010; Robinson et al., 1996; Zhang et al., 2010).

Material and methods

Watershed summary

This study was undertaken in the watersheds of Hamilton Harbour, a 2150-hectare partially-enclosed Harbour located at the very western end of Lake Ontario, in Ontario, Canada (Fig. 1). Tributary inputs enter the Harbour via Red Hill Creek, Indian Creek, and Grindstone Creek, as well as through the Desjardins Canal, the hydraulic connection between the Cootes Paradise wetland to the west and Hamilton Harbour to the east. In spring 2010, four tributary monitoring stations were installed at downstream locations in Indian Creek and Grindstone Creek, in Burlington, Ontario, and in Red Hill Creek and the Desjardins Canal, in Hamilton, Ontario, cities with 2011 populations of 176,000 and 520,000, respectively (Statistics Canada, 2012). Land use is primarily urban in the Red Hill Creek and Indian Creek watersheds and agricultural in the Grindstone Creek and Cootes Paradise watersheds (Table 1). The soils of the Hamilton Harbour watershed are predominantly loams, sandy loams, and silty loams, with a relatively even split between the four Natural Resources Conservation Service's soil hydrologic runoff groups, meaning there are soils both likely and unlikely to generate runoff throughout the watershed (Wellen et al., 2013).

Several features of each watershed are important in the interpretation of nutrient data collected in this study. All watersheds are traversed by at least one major expressway, and the density of these major roadways is particularly high in the watersheds of Red Hill Creek and Indian Creek where three major expressways are present. Also in the Indian Creek watershed, there are shale extraction quarries and brick manufacturing facilities which have been noted to contribute high sediment loads (Conservation Halton, 2006). Also, the Indian Creek station integrates inputs from multiple urban sub-watersheds as it was located approximately 50 m downstream of the confluence of the Hagar–Rambo diversion channel, an engineered inter-basin transfer of water from the Hagar and Rambo tributaries. An 800 m stretch of Indian Creek also runs underground in a hardened culvert beneath Francis Road in Burlington; similarly, portions of Rambo Creek (also Burlington) and Chedoke Creek (in the Desjardins Canal watershed, Hamilton) are also redirected underground in sections of their watersheds (Cook, 2013).

The Desjardins Canal station is not on a tributary but does integrate inputs from a number of creeks that discharge to the Cootes Paradise wetland including Spencer Creek (235 km^2), Chedoke Creek (25 km^2), Borers Creek (20 km^2) and other small watersheds (10 km^2) (T. Theysmeyer, 2012, pers. comm.). The interpretation of data from the Desjardins Canal station is complicated by several co-occurring processes, including: large tributary inputs during events, in particular from nearby Chedoke Creek; potential flow reversals from Hamilton Harbour during strong easterly winds and low flow conditions; and ongoing wetland processes.

Water quality data from Red Hill Creek and Cootes Paradise via the Desjardins Canal are intermittently influenced by combined sewer