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Research papers

Empirical assessment of effects of urbanization on event flow hydrology in watersheds of Canada's Great Lakes-St Lawrence basin

M.P. Trudeau [a,b,*], Murray Richardson [b]

[a] Envirings Ltd., 111 Mason Terrace, Ottawa, Ontario K1S 0L2, Canada
[b] A329 Loeb Building, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

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ABSTRACT

We conducted an empirical hydrological analysis of high-temporal resolution streamflow records for 27 watersheds within 11 river systems in the Greater Toronto Region of the Canadian Great Lakes basin. Our objectives were to model the event-scale flow response of watersheds to urbanization and to test for scale and threshold effects. Watershed areas ranged from 37.5 km^2 to 806 km^2 and urban percent land cover ranged from less than 0.1–87.6%. Flow records had a resolution of 15-min increments and were available over a 42-year period, allowing for detailed assessment of changes in event-scale flow response with increasing urban land use during the post-freshet period (May 26 to November 15). Empirical statistical models were developed for flow characteristics including total runoff, runoff coefficient, eightieth and ninety-fifth percentile rising limb event runoff and mean rising limb event acceleration. Changes in some of these runoff metrics began at very low urban land use (<4%). Urban land use had a very strong influence on total runoff and event-scale hydrologic characteristics, with the exception of 80th percentile flows, which had a curvilinear relationship with urban cover. Event flow acceleration increased with increasing urban cover, thus causing 80th percentile runoff depths to be reached sooner. These results indicate the potential for compromised water balance when cumulative changes are considered at the watershed scale. No abrupt or threshold changes in hydrologic characteristics were identified along the urban land use gradient. A positive interaction of urban percent land use and watershed size indicated a scale effect on total runoff. Overall, the results document compromised hydrologic stability attributable to urbanization during a period with no detectable change in rainfall patterns. They also corroborate literature recommendations for spatially distributed low impact urban development techniques; measures would be needed throughout the urbanized area of a watershed to dampen event-scale hydrologic responses to urbanization. Additional research is warranted into event-scale hydrologic trends with urbanization in other regions, in particular rising limb event flow accelerations.

1. Introduction

Urbanization alters natural stream flow regimes (e.g. Hammer, 1972; Booth and Jackson, 1997; Schueler et al., 2009) but the nature of these changes has not been fully characterized due to a lack of appropriate high-resolution records for flow, rainfall and land use. This study used hydrologic records at 15-minute increments, which allowed analyses of event-scale flows and event flow acceleration in urbanizing watersheds.

Stream flows vary by watershed due to numerous variables including catchment size, channel and basin slope, geomorphology, groundwater discharge and land cover. Hydrologic characteristics that change with urbanization include the distribution of water between storm flow and base flow, the frequency of high flows and daily flow variability (Konrad and Booth, 2005; Tetzlaff et al., 2005). These hydrologic changes occur as a result of multiple concurrent alterations to processes and conditions within urbanizing watersheds. For instance, with urbanization, impervious surface area increases while landscape vegetation is reduced. A

Abbreviations: EC, Environment Canada; MSC, Meteorological Service of Canada; WSC, Water Survey of Canada; TRCA, Toronto and Region Conservation Authority; CVCA, Credit Valley Conservation Authority; 80RLER, 80th percentile of rising limb event runoff; 95RLER, 95th percentile of rising limb event runoff; UP, urban percent of watershed area; AICc, Akaike's Information Criterion with correction for finite sample sizes; CI, confidence interval; df, degrees of freedom; GAM, generalized additive model; n.d., no date.

* Corresponding author.
E-mail addresses: m.p.trudeau.water@gmail.com (M.P. Trudeau), Murray_Richardson@carleton.ca (M. Richardson).

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reduction in vegetation reduces the infiltration capacity of soils (Boers and Ben-Asher, 1982) and also reduces water volumes transpired, intercepted and evaporated (Boers et al., 1986). A crust forms on bare soils from the impact of raindrops, further reducing soil infiltration (Morin and Benyamini, 1977). Storage capacity is further reduced where wetlands and surface depressions are filled in. Changes in baseflows attributable to urbanization are difficult to model (Elliott et al., 2010; Hamel and Fletcher, 2014; Fletcher et al., 2014) and groundwater predictions are potentially complicated by the influence of urban water infrastructure, such as leaking potable water mains that increase water supply or cracked sewers that act as drains for groundwater (e.g. Lerner, 2002). Further compounding the complexity, evaporation rates may be higher with heat island effects (Adamowski and Prokoph, 2013), which may offset some of the additional volume leaving as stream flow. The loss of climatic stationarity is expected to further increase the variability of hydrologic processes (Milly et al., 2008).

Stream degradation commences between 2% and 15% impervious cover, depending on the indicator and region (Schueler et al., 2009; Yang et al., 2010). Alterations in channel dimensions and the number of discharges exceeding bankfull change with time, even after land use alterations cease (Dunne and Leopold, 1978). An impervious cover model, proposed as a management tool by Schueler (1994) to anticipate stream conditions based on impervious cover within a watershed, included headwater watersheds sized 5–50 km^2 (Schueler et al., 2009). Larger watersheds (75–150 km^2) had less consistent flow responses to urbanization (Schueler et al., 2009). According to simulated modelling studies, watercourse flows are influenced by the spatial arrangement of impervious areas within catchments (Yang et al., 2011) and the presence of peri-urban areas, which have higher stormwater retention capacity in comparison with conventional urban areas (Jankowfsky et al., 2013).

A variety of indices have been developed to assess hydrologic change, including variation in daily and monthly flows, annual average and maximum flows at critical times of year, variability in annual high peak flows and skewness in daily flow (Olden and Poff, 2003). Although overall flow responses are documented in the literature using daily, monthly or annual flows, responses on finer temporal scales necessary for analyses of responses to rain events are not well studied empirically. In the literature, only one group of studies was identified that used high-resolution hydrologic data to assess urban watercourses. Tetzlaff et al. (2005) examined the relationship of urban land use with flow acceleration, using two sets of flow records (1-h temporal resolution for 16 catchments; and 6-min resolution for 3 catchments). Both simulated and empirical data were used in the analysis. Results were inconclusive with respect to the relationship of urban cover with acceleration (Tetzlaff et al., 2005), possibly because data were analyzed as three separate databases, catchment characteristics (other than size) were not included and rainfall was not taken into consideration.

Geographically diverse studies have associated negative biotic response with impervious land cover, including reports of negative effects around 10% impervious cover or lower (Schueler et al., 2009; Stanfield and Kilgour, 2006; Chin, 2006; Walsh et al., 2005a). Flow regime perturbations that could potentially be associated with stress to aquatic communities were of particular interest for this study; thus, we examined rising limb event flow characteristics (e.g. Clausen and Biggs, 1997; Gibbins et al., 2001). During the rising limb, water column changes occur and increased flows bring increased stream power, with potential for direct and indirect effects on habitat (substrate stability, for example). The paucity of hydrologic data at an event-scale precludes a full understanding of associations of hydrology with aquatic biota.

Watershed protection and restoration efforts in urbanizing watersheds tend to focus on riparian zone protection and existing forested areas. For instance, in the Toronto and Region Conservation Authority's (TRCA) jurisdiction, forest cover is present in rural and upper headwater regions and "along the river and creek valleys" (TRCA, 2013, p.2). In addition, Conservation Authorities within the study region promote low impact development (LID) techniques for new subdivisions (CVCA and TRCA, 2010) because they can reduce the effective imperviousness (Walsh et al., 2005b) of subdivisions, thus reducing runoff volumes (e.g. Wilson et al., 2015). For instance, in two studies comparing subdivisions of approximately 2 ha each, LID measures were found to substantially reduce annual runoff in comparison with conventional storm sewer design (Dietz and Clausen, 2008; Wilson et al., 2015). However, there are many barriers to full implementation of LID techniques (CVCA, 2010; Walsh et al., 2016). In addition, LID measures must be implemented at a parcel scale throughout the urbanized areas of a watershed for measurable improvements in flow response (Burns et al., 2012; Walsh et al., 2016)

This study builds on previous empirical results (Trudeau and Richardson, 2015) that identified strong temporal trends in event-scale hydrologic characteristics in two urbanizing watersheds over a four-decade timeframe. Instead of temporal trends, this study examined trends in flow across an urban land use gradient, with urban percent (UP) land use ranging from 0.1% to 87% of the watershed. The flow records were recorded in 15-min increments, allowing analyses of event-scale flows. Empirical statistical models were developed using a database of 27 urbanizing watersheds of the Great Lakes Basin.

The overarching objective of this study was to empirically determine what changes in flow regime are associated with increased urban land use. Specifically, we asked the following questions: (1) At what UP does an effect of urban cover on total runoff (and runoff coefficient (RC)) become detectable and is there evidence of a threshold effect? (2) Are there scale effects in the response of total runoff to increasing UP when other independent variables are taken into account, including total rainfall, channel slope, basin slope and groundwater contribution (measured as Baseflow Index (BFI))? (3) What is the influence of UP on event-scale hydrograph characteristics including peak event flows and rising limb flow accelerations? and, (4) Are there watershed scale effects evident in event flows with increasing UP? Changes in total seasonal and event-scale flow characteristics in response to urbanization have important implications for aquatic biodiversity, infrastructure design and risk assessments, watershed management and land development protocols, and may exacerbate climate change risks.

1.1. Study region

The 27 watersheds are located in 11 river systems confluent with Lake Ontario and Lake Erie in the vicinity of the Greater Toronto Region within the Canadian Great Lakes Basin (Fig. 1).

This region experienced heavy urbanization during the study period, 1969–2010, and the City of Toronto is now the fourth largest city by population in North America (City of Toronto, 2014).

Toronto Region's climate is moderate humid continental (Koppen climate classification Dfa) (AKCanada, n.d.) with average precipitation of 831 mm $year^{-1}$ (Government of Canada, 2014), including rainfall in all months and snow in winter. The frost free period typically occurs between April 13 and November 3 (Government of Canada, 2014).

Urban lands within the study region included an historic urban core undergoing intensification within the study period, as well as multi-centered satellite communities comprising a variety of residential, commercial, industrial and institutional forms of land