Empirical Trends in Hydrologic Response to Rain Events in Urbanizing Watersheds in the Toronto Region of the Great Lakes Basin, Canada

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Introduction

Urbanization is known to alter natural stream flow regimes (e.g. Schueler et al., 2009) but the nature of these changes has not been fully characterized due to a lack of appropriate long-term, high-resolution records for flow, rainfall and land use. This empirical study draws on 42 years of hydrologic data, between May and November, at a temporal resolution of 15-minutes. This unique dataset allows for detailed estimates of peak flows, rising limb event flows and rising limb event flow accelerations, with the objective of quantifying changes in flow regime attributable to increased urban area.

The study includes temporal and spatial analyses of flows within 27 watersheds of 11 river systems confluent with Lake Ontario and Lake Erie in the Greater Toronto Region of the Canadian Great Lakes Basin. This region experienced heavy urbanization during the study period, 1969 to 2010, making the City of Toronto now the fourth largest city by population in North America (City of Toronto, 2014). The sub-watersheds in the study vary in percent urban land cover from less than 0.1% to over 87% and range in size from 37.5 km^2 to 806 km^2. The rising limb of event flows was studied because flow regime perturbations associated with stress to aquatic communities were of particular interest (e.g. Clausen and Biggs, 1997; Gibbins *et al*., 2001).

The primary objective of this study was to produce a robust empirical estimate of flow regime changes associated with increased urban land use through spatial analysis of catchments of various sizes and varying proportions of urban land use. The study also assesses threshold effects on flow regime of percent urban land use and scale effects of watershed size on flows with increasing urban land use. Urban land use is defined to be lands drained by engineered urban drainage systems.

Methods/Materials

Data were accessed or derived from several sources. The instantaneous (15-minute) hydrometric dataset and one-hour rainfall records were obtained from Environment Canada. Historic aerial photographs were purchased from Natural Resources Canada and urban areas were digitized by our team for watersheds in 5 river systems. Province of Ontario government land and watershed data sets were used to calculate catchment areas and slopes. The Credit Valley Conservation Authority and the Toronto and Region Conservation Authority provided data and support for the land use database, as did P. Thompson (2013).

The study approach was to develop statistical empirical models for total flow, peak rain event flow and rising limb flow acceleration for both temporal and spatial variables. An extensive analysis of available rainfall data was also undertaken to determine whether or not there were concurrent trends in rainfall patterns. Because the study region experiences winter conditions, all flow regime analyses were undertaken for the seasonal period May 26th to November 15th in order to avoid introduced flow variation from spring freshet and winter freeze-up.

Results

A temporal analysis of total seasonal flow (May to November) on two of the sub-watersheds, in the Don (311 km^2) and the Humber (806 km^2) river systems, from 1969 to 2010 inclusive, indicated an increase of about 45% over four decades, with no concurrent trend in rainfall. During the same timeframe, peak rain event flow rates increased by almost $0.1 m^3 s^{-1} yr^{-1}$. In the Don, the ratio of rising limb event flows to median flow increased from 1.5 in the 1970's to 2.3 in the 2000's and rising limb event flow acceleration increased 2-fold over 4 decades. Trends for the Humber were similar. A statistical model for all 27 sub-watersheds, including percent urban cover as an independent variable, explains 88% of the variation in total runoff (mm $season^{-1}$). Spatial analysis indicates that changes in total runoff, event peak flows and event flow accelerations begin at very low rates of urban cover. Rising limb event flows increased with increasing urban cover in all sub-watershed except the very small ones (~50km^2). Very small watersheds reached maximum peak flows by about 20% urban cover, with no additional increase with increasing urban land use. Event flow accelerations began to change at less than 5% urban cover and continued to increase with increasing urban cover for all watershed sizes.

Conclusion

Overall, the study demonstrates marked temporal alterations in total and event flow regimes. The spatial analysis revealed dramatic changes in flow regime, even at very low rates of urban cover, and the particular sensitivity of small watersheds to fundamentally altered water balance. Through quantification of the cumulative changes from urbanization using high temporal resolution hydrological records, these results underscore the importance of managing water resources on a basin scale. The cumulative effects of urban land cover have potential implications for land development decisions, flood risk assessment, urban infrastructure design and ecological habitat protection. Alterations to hydrologic baselines resulting from urban land use are also relevant for assessments of urban infrastructure resilience in the face of changing climate trends (Milly et al., 2008).

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