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

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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.

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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

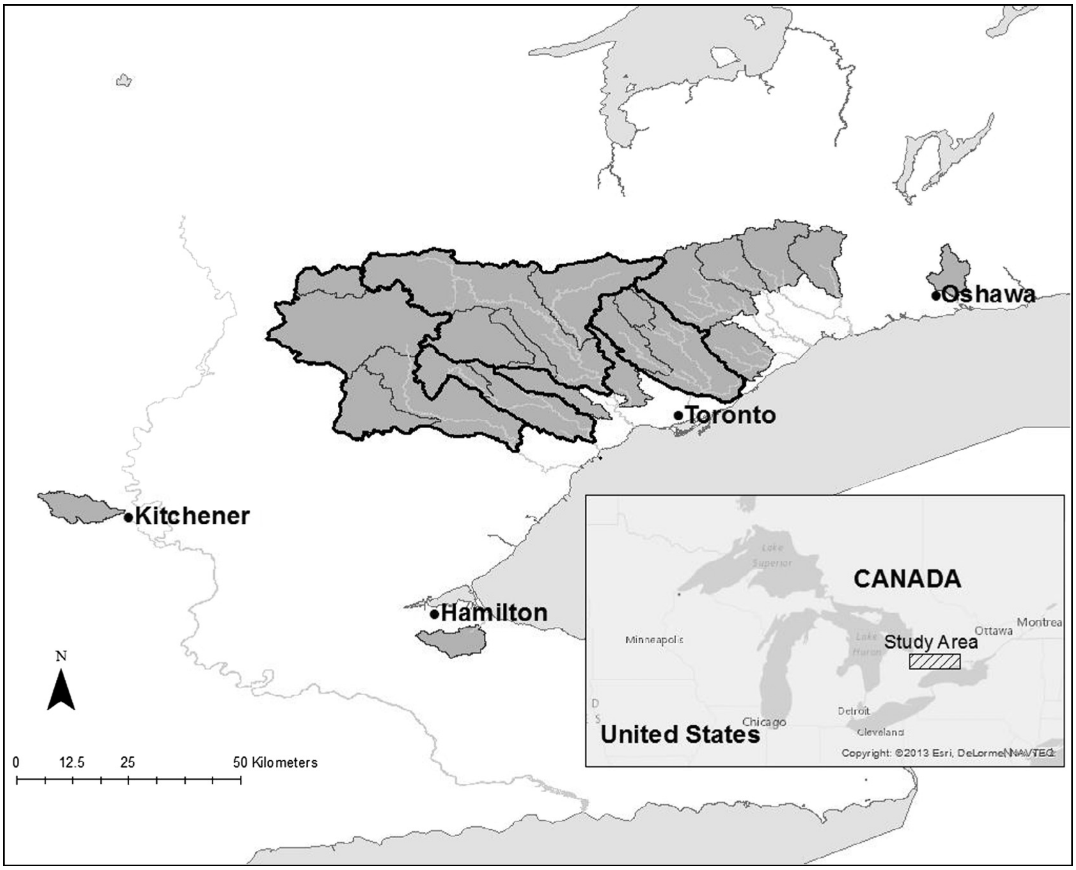

Fig. 1. Watershed locations. Watersheds are located in the vicinity of Toronto, Ontario Canada within the Great Lakes St Lawrence Basin. Some study watersheds are nested within others. Darker outlines indicate the four largest watersheds, from west to east: Credit, Etobicoke, Humber, Don. Light grey lines indicate mainstem and large branch channels.

development (Hess et al., 2007). The study watersheds were predominantly serviced by conventional, separated sewer systems over the timeframe of available hydrologic data (1969–2010), although the historic urban core of the City of Toronto had a combined sewer system and there was some evolution of stormwater management practices to include LID measures in some recent satellite community subdivisions. Runoff quantity control was only introduced in Ontario in the 1980s and LID post year 2000 (CVCA and TRCA, 2010).

2. Methods/materials

2.1. Introduction

In this study, urban land use is defined as lands drained by engineered urban drainage systems. The term *watershed* is used in a generic sense without implications for nested relationships among watersheds. We focus our analysis on the annual period between May 26th to November 15th to exclude freshet variability and complications arising from lack of snowmelt records, and to include seasons with rainfall-dominated precipitation.

This spatial study developed empirical statistical models for total runoff and event-scale hydrologic characteristics using the potential independent variables watershed area, urban percent (UP) of watershed area, total seasonal rainfall, basin and channel slopes, and BFI. The rationale and methods for choice of location, hydrologic data preparation and analyses, and hourly rain data preparation and analyses are given in Trudeau and Richardson (2015). Data sources, data processing and statistical methods are described below. Additional information is available in Trudeau (2016).

2.2. Data sources and study watersheds

Hydrometric records from Environment Canada's (EC) Water Survey of Canada (WSC) 15-min stream flow data were used, called the "instantaneous hydrometric dataset" by EC. The EC instantaneous hydrometric data were available for the years 1969–2010 inclusive. Rainfall data were supplied by EC's Meteorological Service of Canada (MSC) in the Daily Record of Hourly Data (HLY) format.

ESRI's ArcGIS shapefiles for tertiary watersheds were obtained from the Province of Ontario website (Government of Ontario, 2012). ArcGIS shapefiles to delineate study watersheds upstream of hydrologic gauge sites were developed using data sets from the Government of Ontario's Integrated Hydrology Data Part 2 (Southwest), including: enhanced flow direction grid; stream grid; and, enforced *Digital Elevation Model* (DEM) (Government of Ontario, 2013). Watershed delineation information was also provided by P. Thompson for the Don River for the years included in his study (Thompson, 2013). The TRCA provided ArcGIS files for two watersheds and the Credit Valley Conservation Authority (CVCA) provided watershed shapefiles with land use data.

UP estimates were obtained from three sources: (1) Thompson, 2013; (2) CVCA ArcGIS shapefiles for four years; and, (3) digitization of historic aerial photographs, purchased from Natural Resources Canada (NRCan). Inclusion in the database of historic stormwater network information, such as combined, separated or partially separated sewers, presence of stormwater ponds or LID measures was not feasible.

An overview of the 27 watersheds is provided in Table 1. All river systems are confluent with Lake Ontario except Laurel Creek, which is a tributary to the Grand River confluent with Lake Erie. Each hydrologic gauge was matched with a proximal rain gauge with matching years of record. Seven rain gauges were used in the analysis (Appendix A).

BFI data were provided by Dr. J. Buttle (pers. comm., 2015; see Buttle et al., 2015) and a USGS study (G Model, HYSEP1 Method, Neff et al., 2005). Where BFI estimates were not available for a watershed, the BFI of an adjacent watershed or river network was assigned (Appendix B).

2.3. Data preparation

The data processing methods described in Trudeau and Richardson (2015) for two hydrologic stations (02HC024 and 02HC003) and rain gauge number 6158350 were also applied to the additional hydrologic stations and rain gauges in this study. As described in the following sub-sections, additional data processing was required to: delineate watershed areas upstream of each hydrologic gauge; identify catchment slopes; digitize urban extent from aerial photographs; and, assemble data sets for each watershed.

2.3.1. Watershed area upstream of hydrologic gauges

Watershed areas were delineated in ESRI's ArcGIS mapping software. Three Province of Ontario data layers (enhanced flow direction grid, stream grid, and enforced DEM layers (Government of Ontario, 2013)) were extracted and clipped using the Ontario Tertiary Watersheds shapefiles (Government of Ontario, 2012). A point shapefile of pour points was generated for hydrologic stations using R package 'sp' (Pebesma et al., 2014) and snapped to a flow accumulation grid, created using the ArcGIS Flow Accumulation tool. Watersheds upstream of the pour points were delineated using custom script within the ArcGIS Hydrology tool and converted to polygons. These polygons delineated all watersheds, except for those within the Credit River system (where CVCA shapefiles were used) and Red Hill watershed (where the Thompson (2013) effective area was used).

2.3.2. Catchment slopes

Channel slopes (Appendix B) were defined by first creating a polyline file of longest flow path, generated using custom script within the ArcHydro Terrain Preprocessing tool. Input layers included the watershed polygons, Ontario enhanced flow direction grid and Ontario enforced DEM files. Channel slope was calculated using the Compute Line Parameters tool in ArcHydro. Mean basin slopes (Appendix B) were calculated using open source software, SAGA (Conrad et al., 2015), with the Ontario enforced DEM and Ontario stream grid. Slopes were computed in ArcGIS using the ArcHydro Slope tool. A slope grid was created using the ArcGIS Spatial Analyst Raster Calculator tool. SAGA, R code (R Core Team, 2012) and the ArcGIS Grid Statistics for Polygons tool were used to calculate mean basin slopes.

2.3.3. Estimation of urban extent from aerial photographs

Through contract, NRCan scanned selected aerial photos from negatives using the highest potential resolution available (80 dot-

Table 1
Database Overview. River systems, watersheds, watershed areas, hydrologic and rainfall gauge stations, years with urban land use estimates (i.e. urban percent (UP) land use on a watershed basis) and data sources. The database assembled used high-temporal resolution hydrologic data, with rainfall records, for years with available UP estimates (see text and Appendix C).

River system	Hydrologic station location for study watersheds	Watershed area (to gauge) (km^2)	EC hydro station	EC rain gauge	Years with urban land use data (source)
Credit	West Branch at Norval	131.5	02HB008	6158733	1999, 2003, 2007, 2011 (CVCA shapefiles *in* Trudeau, 2016)
	Mainstem near Orangeville	59.3	02HB013	6155790	
	Mainstem at Boston Mills	414.0	02HB018	6158733	
	Mainstem at Norval	641.4	02HB025	6158733	
	Mainstem at Streetsville	770.7	02HB029	6158350	
Don	Mainstem at York Mills	84.2	02HC005	6158350	1974, 1985, 1988 (Trudeau, 2016) 1970, 1978, 1995, 2005 (Thompson, 2013; adjusted)
	Mainstem at Todmorden	311.0	02HC024	6158350	
	Little Don at Don Mills	127.4	02HC029	6158350	
	East Branch near Thornhill	37.5	02HC056	6158350	
Duffins	Mainstem above Pickering	86.9	02HC019	6153020	1978 (Trudeau, 2016)
	West Branch at Green River	107.4	02HC026	6155878	
	West Branch above Green River	62.0	02HC038	6155878	
Etobicoke	Mainstem at Brampton	72.0	02HC017	6158350	1974, 1985, 1988 (Trudeau, 2016) 1970, 1978, 1995, 2005 (Thompson, 2013)
	Mainstem below QEW	209.3	02HC030	6158350	
Harmony (Ganaraska)	Mainstem at Oshawa	42.9	02HD013	6155878	1995, 2005 (Thompson, 2013)
Highland	Mainstem near West Hill	90.5	02HC013	6158350	1985 (Trudeau, 2016) 1978, 1995, 2010 (Thompson, 2013)
Humber	Mainstem near Weston	805.6	02HC003	6158350	1969, 1988 (Trudeau, 2016) 02HC027: 1970, 1978, 1995, 2005 (Thompson, 2013)
	East Branch near Pine Grove	195.2	02HC009	6158350	
	Mainstem at Elder Mills	296.4	02HC025	6158350	
	Black Creek near Weston	63.7	02HC027	6158350	
	Mainstem at Highway 7	142.4	02HC031	6158350	
	West Branch below Dam	183.3	02HC034	6158350	
Laurel (Upper Grand)	Mainstem at Waterloo	56.9	02GA024	6149387	1971, 1982, 1990, 1995, 2005 (Thompson, 2013)
Mimico	Mainstem at Islington	68.8	02HC033	6158350	1974, 1985, 1988 (Trudeau, 2016) 1995, 2005 (Thompson, 2013)
Red Hill (Niagara)	Mainstem at Hamilton	56.3 (Thompson, 2013)	02HA014	6153300	1978, 1995 (Thompson, 2013)
Rouge	Mainstem near Markham	187.0	02HC022	6158350	1969, 1974, 1978, 1981, 1985, 1988 (Trudeau, 2016) 1995, 2005, 2010 (Thompson, 2013)
	Little Rouge near Locust Hill	83.6	02HC028	6158350	

s per mm). Photo scales included: 1:25,000; 1:30,000; 1:40,000; 1:50,000, resulting in nominal ground pixel sizes of approximately 0.31 m, 0.38 m, 0.50 m, and 0.62 m, respectively. Years for aerial photo analysis were chosen on the basis of: (1) good photo coverage of an entire watershed; and (2) coverage in years with available hydrologic and rainfall data. Partial coverage was accepted for years where earlier and later years' photos covered the missing area. Missing photo coverage tended to be in the upper, less urbanized areas of the watersheds.

Photos were georeferenced using ESRI's ArcMap Georeferencing tool and ground control points from the 2005 Ontario road network (Statistics Canada, 2005). Urban areas were digitized using ArcMap's polygon feature; these areas were used to estimate the urbanized percent of each watershed. The methodology for urban area identification by Thompson (2013) was adopted to the extent possible so Thompson's UP estimates could be included in our analysis. Key features of the Thompson (2013) methodology included identification of engineered storm sewer systems (such as catch basins) to indicate urban areas, exclusion of parks and green spaces, inclusion of major highways but exclusion of regional or county roads without curbs and gutters. For this study, the relevant urban areas were developed post-1968 and therefore were typically designed with readily identifiable suburban road patterns. Urban areas were identified by visual inspection of road patterns. Excluded from urban areas were green spaces larger than 1 ha, golf courses, quarries and farm operations, on the assumption that none of these land uses would generate runoff typical of urban landscapes. Identifiable new subdivisions, even if not yet paved, were included on the assumption that urban storm sewer infrastructure was already in place. Major highways, including cloverleaf interchanges, were included in the urban designation. Thompson (2013) UP estimates in the Don watershed were adjusted for the topographic watershed area rather than effective watershed area. Trends in UP by year for watersheds with multiple UP estimates were reviewed to check for consistent and feasible rates of change with time. Some UP estimates in Thompson (2013) were not used in this study because the trends were discontinuous with our estimates. Appendix C summarizes estimated UP by watershed and year.

2.3.4. Database assembly

A database of observations by watershed was assembled, including flow, rain, watershed area, UP, basin slope, channel slope, number of flow-rain pairs. A complete record of flow-rain observations per year (May 26th to November 15th) comprised 16,708 pairs of 15-min records, created assuming rainfall was constant within each one-hour rainfall record (Trudeau and Richardson, 2015). Years with fewer than 30% of the potential pairs were removed from the dataset. Some years with urban observation did not have flow-rain data available in that year. To maximize the number of records in the database, where no same-year flow-rain records were available, the urban observation was matched to the flow-rain data of the following year. The number of hydrologic records per year used in the analyses ranged from 6,548 to 16,708, with a mean of 14,325 records, mode of 14,996 records and median of 15,085 records. Only six years had fewer than 10,000 records.

Hydrologic responses to rain events with rising limbs lasting longer than 4.5 days to peak were removed from the record since they likely reflect other factors, such as unrecorded rainfall (due to the proximity of the available rain gauge to the hydrologic gauge). The number of events removed per watershed (all years) ranged from 0 to 9, with an average of fewer than three events removed per watershed.

The resulting dataset of 93 watershed-year combinations included instantaneous hydrologic and rainfall records (including isolated rising limb event flows), urban percent land use and watershed characteristics (e.g. BFI, slopes). Individual watersheds had between one and nine observations through time, reflecting the availability of aerial photographs for documentation of change in UP and attempts to collect data on watersheds with initially low UP that transitioned through 10% UP during the period of available high-resolution hydrologic data.

2.4. Statistical analyses

The first statistical analyses assessed the independence of rainfall with time because rainfall was an independent variable in the spatial analyses to predict flow characteristics. Subsequently, we explored the association between various characteristics of the flow regime, including: (1) total runoff; (2) rising limb event runoff (10th percentile, 20th percentile, 80th percentile and 95th percentile); and, (3) rising limb event flow accelerations.

The 27 watersheds flow within 11 river systems and, therefore, some of the smaller watersheds are nested within larger watersheds (see Fig. 1). Preliminary analyses, including spatial and temporal auto-correlation assessments, supported an assumption that the nested watersheds in the database could be assumed to be independent for purposes of flow analyses.

Statistical model fit was compared using Akaike's Information Criterion with correction for finite sample sizes (AICc) (Mazerolle, 2013) and adjusted R-squared. Raw data were plotted and models were fit by sequentially adding independent variables and assessing improvement in fit with F tests. Interactions between and among independent variables were not used unless assumptions for linear models with only main effects were violated and could be corrected with the addition of an interaction term. Selected models had all independent variables added simultaneously. Linear models were tested for conformance to parametric inference assumptions using the following tests (R package 'lmtest'; Hothorn et al., 2015): Breusch-Pagan (heteroscedasticity); Durbin-Watson (serial autocorrelation); RESET (linearity); and, Shapiro-Wilk (normality of residuals). Where assumptions were violated, non-parametric tests, including Mann Kendall, Wilcoxon Rank Sum, Kendall rank sum correlation and Kruskal-Wallis, were employed for hypothesis-testing. Alternatively, in two cases (80th percentile rising limb event runoff (80RLER) and the relationship of event flow acceleration with 80RLER), a generalized additive model (GAM) was fit using R package 'mgcv' (Wood, 2015). Selected models were further assessed with leave-one-out cross-validation (e.g. Burman, 1989) using custom R script to iterate 93 model runs, each omitting one set of observations, which were assessed against predicted values for the regression model fit to the remaining data. Root mean square error (RMSE) was calculated, as well as normalized RMSE (the ratio of RMSE to the difference between maximum and minimum observations). Cross-validation using k-fold technique (e.g. 2–10 folds) was not possible given there were 93 observations with which to assess models with six or more parameters.

2.4.1. Variables

Total runoff means all flow during the seasonal period (i.e. May 26th to November 15th) for a given year, including baseflow and storm event flows, divided by watershed area (mm season^{-1}). *Event runoff* is a rising limb event flow estimation divided by watershed area (mm s^{-1}). Event runoff analyses included the 80RLER and 95th percentile rising limb event runoff (95RLER) for all recorded events during the seasonal period for a given year. The 95RLER was used to represent maximum flows in place of actual maximum flows to avoid variability introduced by very large individual rain storms. The 80th percentile flow rate was used because flow distributions were highly positively skewed; 80th percentile event flows were higher than mean flows for 56

Table 2
Dependent and independent variables used in statistical models. Interactions of independent variables were also included (see text) using the independent variables as described in this table.

Dependent variable	Description	Units	Independent variables tested	Description	Units
Total rainfall	Total rainfall between May 26 to November 15 inclusive	mm·season^{-1}	Year	Seasonal year	Year (also called 'season')
			Total hours with records	Number of hours with rainfall records (includes zero rainfall)	hours ·season^{-1}
Rain event frequency	Number of rain events per season. Rain events are defined to have at least one hourly period with at least 5 mm of rain and with no more than one hour break in rainfall among consecutive records.	number·season^{-1}	Year	Seasonal year	year
			Total hours with records	See above	
Rain event maximum intensity in one hour	Maximum rainfall in one hour for each event in a season	mm·hour^{-1}·event^{-1}	Year	See above	
Total hours with rain	Number of hours with rainfall of any recorded depth.	number·season^{-1}	Year	See above	
			Total hours with records	See above	
Rain event depth per event	Total depth of rainfall during a rain event.	mm·event^{-1}	Year	See above	
Total runoff	Total flow (m^3 s^{-1}) from May 26th to November 15th inclusive, divided by watershed area	mm·season^{-1}	Urban percent (UP)	Urban land area divided by total watershed area times 100	unitless
			Total rainfall	See above	mm·season^{-1}
			Baseflow Index (BFI)	Baseflow relative to stream flow (Buttle et al., 2015)	unitless
			Mean channel slope	Mean estimated slope of water course	m·km^{-1}
			Mean basin slope	Mean estimated slope of watershed basin	m·km^{-1}
			Watershed area	Area of the watershed	km^2
Runoff coefficient (RC)	Total runoff divided by total rainfall	unitless	See total runoff		
80th percentile rising limb event runoff (80RLER)	Flow below which 80% of rising limb event flows occurred, pooled by year, divided by watershed area	mm·s^{-1}	See total runoff		
95th percentile event runoff (95RLER)	Flow rate below which 95% of event flows occurred, pooled by year, divided by watershed area.	mm·s^{-1}	See total runoff		
Mean rising limb event flow acceleration (called mean acceleration)	Mean of rising limb event flow accelerations greater than zero, pooled by year; acceleration was calculated as the difference in flow from one 15 min record to the next divided by the time interval in seconds	m^3·s^{-2}	First model: see total runoff Second model: 80RLER was also an independent variable		

database records and lower for 37 records. Event analyses also included 10th and 20th percentile flows; Mann Kendall slopes were estimated with total rainfall as a covariate.

Dependent and independent variables are described in Table 2. Year, in all cases, refers to the period from post-freshet to late fall (May 26 to November 15 inclusive). BFI is not independent of stream flow since it is calculated as a ratio of baseflow to streamflow. However, BFI estimates used in the analyses were derived by researchers using multiple years of data (e.g. Neff et al., 2005) in research not connected to this study. BFI explained variation not attributable to UP and so it was used as an independent variable for statistical models.

2.4.2. Rainfall

Total rainfall gives an indication of whether the year was relatively wet, dry or average in terms of precipitation. It does not indicate the number or magnitude of individual rain events in the year. Analyses of three of the seven rain stations in this study (rain stations 6155790, 6158733, 6158350) are described in Trudeau and Richardson (2015). Trends with year at the remaining four stations (6153300, 6149387, 6153020, 6155878) were analyzed with the Mann Kendall test (R Package 'rkt' (Marchetto, 2013)).

2.4.3. Assessment of threshold changes in total flow with urban cover

We used breakpoint analysis (R program 'SiZer' (Sonderegger, 2015); R program 'segmented' (Muggeo, 2015)) for records with UP between 0.1% and 25% to assess whether a threshold change was evident for total runoff and RC. For this analysis, only records with UP less than 25% were used. The initial results indicated that total runoff and RC for watersheds with low baseflows behaved differently from watersheds with higher baseflows for this subset of data. Based on these initial results, the pool of selected observations was sub-divided into watersheds above and below the mean BFI, BFI < 0.6 and BFI ⩾ 0.6.

2.4.4. Data limitations and error

Some judgement was required by GIS technicians in delineating urban areas, especially for: (1) rural areas in transition along the periphery of established urban areas; and, (2) former cottage regions in transition to year-round occupancy. Minor roads outside the urban area were not included in urban cover estimates. Catchment areas were kept the same through time within individual watersheds although, with increasing urbanization, engineered drainage systems redefine drainage boundaries. Error was potentially introduced by the exclusion of green spaces that were actually efficiently drained by urban storm sewers and/or by inclusion of areas that appear, in the aerial photos, to be drained by urban storm sewers but that had attenuated flows (such as stormwater ponds, for example). This potential error is mitigated by the fact that runoff quantity control and LID were not implemented during most of the database records. Urban area delineation is not directly equivalent to impervious area since urban areas include pervious surfaces (e.g. lawns, vegetated boulevards, etc.). No information was collected on historic baseflow data; BFI estimates likely underestimate baseflow at the time of the earliest UP estimates. Error is also potentially introduced with the assignment of BFI on the basis of adjacent watershed or river system. Data on change in channel dimensions and sediment loads were not available for the four decade time period. Limitations of the hydrologic and rainfall data are identified in Trudeau and Richardson (2015).

3. Results

Analyses of the dataset revealed the following two tendencies in the dataset of potential relevance to inferences drawn. There is a statistically significant decrease in BFI for watersheds with higher urbanization (Kendall rank correlation, $z = -3.1$, $\tau = -0.23$, $p = 0.002$), consistent with Buttle et al. (2015) for this region. There is a non-significant tendency (at 95% confidence) for UP to decrease with increasing basin slope ($-0.53\ \text{m km}^{-1} \pm 0.29$, $t = -1.83$, $p = 0.07$; $R^2 = 0.02$, RSE = 25.0, df = 91, $p = 0.07$).

3.1. Rainfall

There were no detectable temporal trends in any of the dependent rainfall variables for rain gauges 6158350, 6155790 and 6158733 (Trudeau and Richardson, 2015). Similarly, there were no temporal trends for the dependent rainfall variables at any of the additional four rain gauges analyzed in this study (Table 3). Fig. 2 plots rain event depth per event by year using data from all seven rain gauges used in this study.

3.2. Urban land use threshold tests

For UP less than 25%, total runoff plotted against UP indicated a different trend with lower versus higher BFI; similarly, the RC trend also differed with BFI. Fig. 3 shows the raw total runoff data for UP less than 25%, differentiated by BFI above and below 0.6. At UP less than ~4%, watersheds with higher groundwater influence (BFI ⩾ 0.6) demonstrated an apparent negative trend in total runoff with increasing UP whereas those with lower groundwater influence (BFI less than 0.6) had a positive trend.

The statistical analyses of the breakpoints and slopes (Table 4) were hampered by the limited number of data points at low UP (i.e. under 25%) and by the variability of the data, especially for BFI greater than 0.6 at UP less than ~4%. When BFI was less than 0.6, total runoff and RC each indicated a non-significant tendency for a breakpoint at about 4% UP; total runoff and RC each increased as UP increased up to 4% (slope 1) but slope 2 (between 4% and ~20% UP) could not be reliably estimated. Where BFI was over 0.6, a RC breakpoint occurred around 2.2% UP; total runoff had a non-significant tendency for a breakpoint around the same UP. In contrast to the results for BFI less than 0.6, slope 1 (i.e. the trend in total runoff with increasing UP at UP less than ~3%) could not be reliably estimated and had a non-significant negative trend.

Table 3
Results for trends in rainfall characteristics. No temporal trends were identified at four rain gauges used in this study. Previous analyses indicated no temporal or spatial trends at other proximal rain gauges (Trudeau and Richardson, 2015). The lower and upper range columns provide the lower and upper Mann Kendall scores for the four rain gauges.

Rainfall variable	Covariate	MK partial score range (p-value)
Total rainfall	Total hours with records	−61.52 (0.34) to 29.02 (0.28)
Rain event frequency	Total hours with records	−33.26 (0.61) to 99.6 (0.15)
Maximum rain event intensity	Not applicable	−15 (0.85) to 10 (0.79)
Total hours with rain	Total hours with records	−57.61 (0.37) to 34.33 (0.49)
Rain event depth per event	Not applicable	13 (0.87) to 79 (0.12)

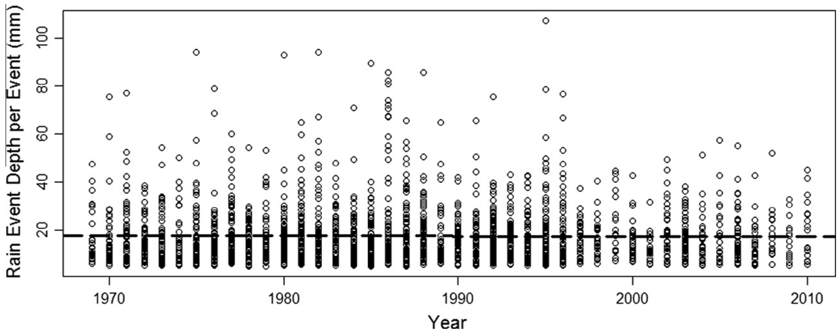

Fig. 2. Rain event depth per event by year. Time series of rain event depth per event for events recorded at each of the seven rain gauges used in this study.

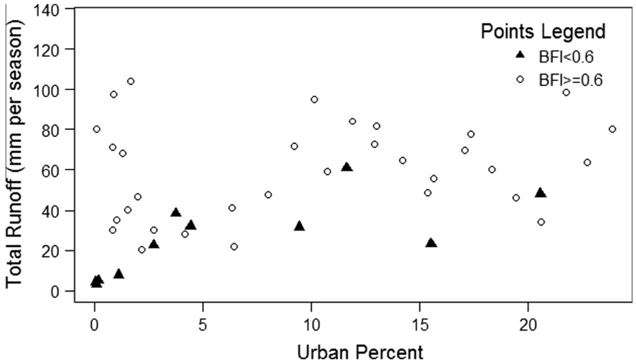

Fig. 3. Total runoff versus UP for UP less than 25%. Raw data plots of total runoff (mm per season) illustrate the differing trends at UP less than ~4% for watersheds with BFI less than 0.6 (solid triangles) versus BFI ⩾ 0.6 (open circles). Total runoff is calculated for the seasonal period between May 26th and November 15th inclusive.

3.3. Total runoff

A model fit to total runoff for the full population of 93 observations had five independent variables (Table 5; Fig. 4). Although total runoff represents streamflow discharge normalized to watershed area, the model identifies a positive interaction of watershed area and UP (Table 5). Ideally, a statistical analysis of total runoff for watersheds grouped by size would have been undertaken to further analyze the interaction term. However, the database had gaps in watershed size-UP combinations that precluded this assessment. For instance, there were no watersheds smaller than 60 km^2 with less than 17% UP and no watersheds over 600 km^2 with more than 20% UP. A leave-one-out cross-validation with 93 iterations had mean RMSE = 18.6 (normalized RMSE = −3.1%); a plot of predicted versus observed total runoff had no outliers. Mean coefficients for the cross-validation matched those of the reported model (Table 5). These cross-validation results indicate stable model performance, to the extent it can be tested with the available data.

3.4. Bivariate relationships of flow characteristics

Bivariate correlations were estimated for total runoff and event flow characteristics in four groups: all observations; large watersheds (sizes greater than 100 km^2); small watersheds (sizes less than 100 km^2); and, non-urban watersheds (with UP less than 4%) (Appendix D). Correlations of RC with event characteristics for urbanizing watersheds were not as strong as those for total runoff. By contrast, in watersheds under 4% UP, total runoff and RC had the same correlations with 80RLER and no relationship with acceleration. RC and total runoff were most highly correlated with each other for watersheds under 4% UP.

Total runoff correlations in large watersheds were higher for 80RLER (0.72, p = 4.6e−06) than small watersheds (0.35, p non-significant), whereas total runoff had the same correlation with

Table 4
Breakpoint analyses for changes in total runoff and RC with increasing UP. Results of breakpoint analyses for total runoff and RC at UP less than 25%, with estimated slopes and confidence intervals (CI). Statistically significant results are indicated in bold.

Dependent variable	BFI	UP breakpoint (95% CI)	Slope 1 (95% CI)	Slope 2 (95% CI)
Total runoff	BFI < 0.6	4.0% (−3.3% to 11.1%)	**8.5 (0.8–16.1)**	0.5 (−1.7 to 2.7)
	BFI ⩾ 0.6	2.3% UP (−0.3% to 4.9%)	−16.4 (−40.9 to 8.2)	1.6 (−0.1 to 3.2)
Runoff coefficient	BFI < 0.6	3.9% UP (−0.4% to 8.1%)	**0.03 (0.01–0.05)**	0.000 (−0.005 to 0.005)
	BFI ⩾ 0.6	**2.2% (0.6%** to **3.8%)**	−0.07 (−0.15 to 0.01)	0.008 (0.003–0.013)

Table 5
Model terms for total runoff. An empirical model for total runoff had five independent variables. Total runoff is the total seasonal (May 26th to November 15th) runoff in mm per season.

Dependent variable	Data	Model overview	Independent variable	Coefficient ± s.e. (p-value)
Total runoff	All observations	Model.1	UP to power 2	0.0113 ± 2.52e−03 (2.43e−05)
		R^2 = 0.87; RSE = 17.9, df = 86, p < 2.2e−16	Total rain	0.246 ± 0.023 (<2e−16)
			Basin slope	0.933 ± 0.023 (0.0001)
			BFI	75.50 ± 37.24 (0.046)
			Interaction UP with $\log_{10}$ watershed area	0.364 ± 0.0959 (0.0003)
			Intercept	−110.3 ± 21.9 (2.44e−06)

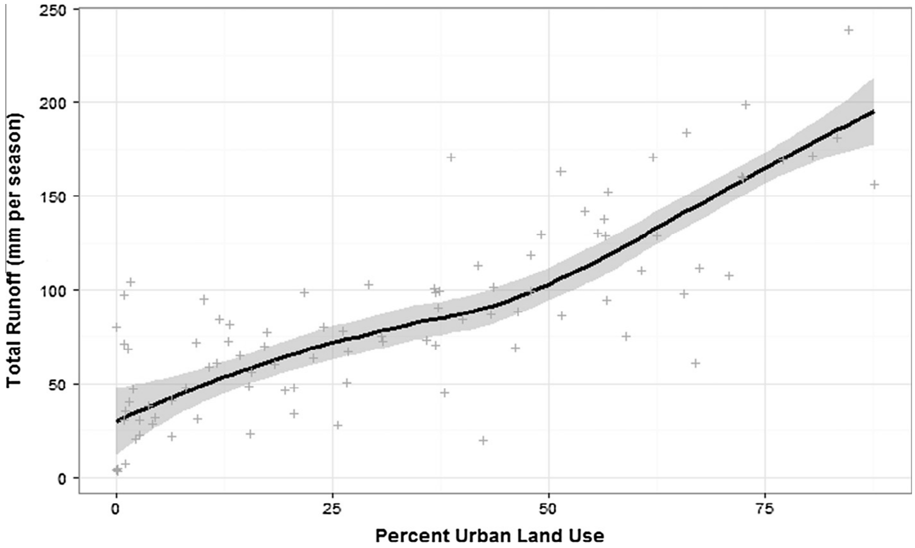

Fig. 4. Fitted total runoff model with urban cover. The fitted model for total runoff is plotted in a solid black line with shaded 95% CI for the mean database values. Actual values are plotted in crosses. Total runoff is the total seasonal (May 26th to November 15th) runoff in mm per season.

acceleration (~0.73, $p < 0.0001$) in both watershed size groups. Total runoff was not correlated with mean event acceleration in non-urban watersheds (<4% UP; 0.13, p non-significant). For small watersheds, 80RLER was not correlated with UP (0.17, p non-significant) whereas other runoff characteristics were correlated with UP for both large and small watershed groups (between 0.58 and 0.86, $p < 0.001$ in all cases). Mean event acceleration was correlated with watershed size in non-urban watersheds (0.75, $p = 0.01$) but there was no correlation of mean acceleration with watershed size in the small or large urbanizing watershed groups.

3.5. Event flow results

Probability density plots of rising limb event runoff and rising limb event accelerations assist in visualization of the trends identified in the statistical models discussed in this section. Fig. 5 plots all rising limb event runoff observations on a log scale for study watersheds, with data grouped within UP ranges. The low flows at low UP and the very high flows at highest UP are evident; further, the lack of clear increase as UP increases over about 25% is also evident (see Section 3.5.2, results for 80RLER). Fig. 6 plots all flow acceleration observations greater than zero on a log scale,

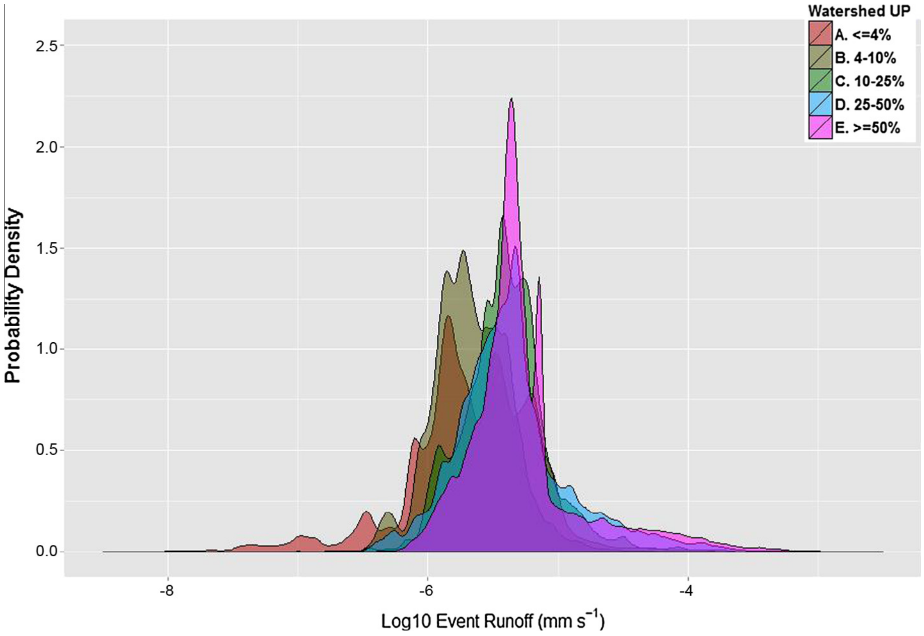

Fig. 5. Density plots of all rising limb event runoff observations for study watersheds. Density plots illustrate the shift in event runoff from low urban cover to about 25% UP and the further shift and clustering of event flows from about 25% to higher UP. The top range of event flows increased with higher UP. Event runoff occurred during the seasonal period between May 26th and November 15th inclusive.

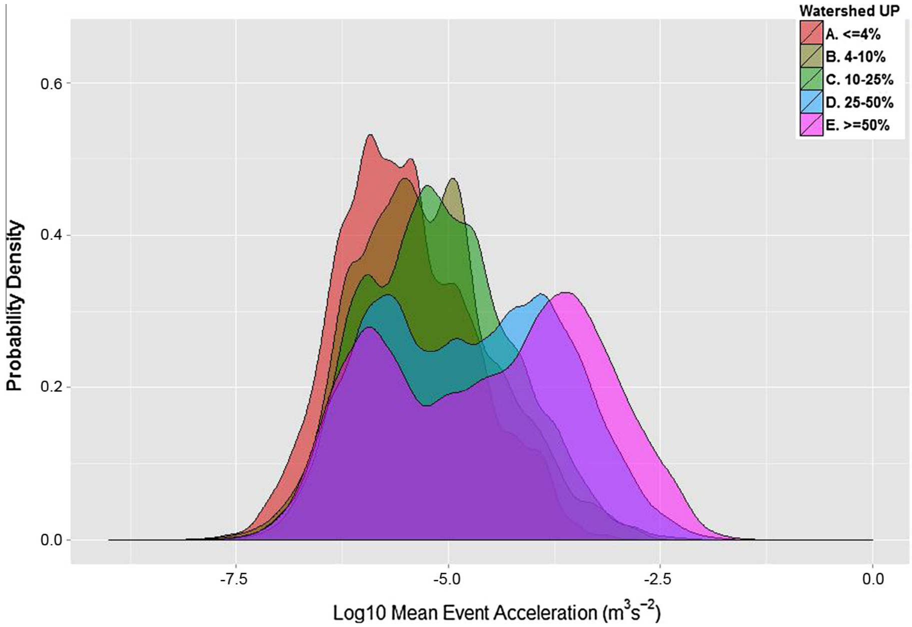

Fig. 6. Density plots of all rising limb event flow accelerations greater than zero for study watersheds. Density plots illustrate the changes in event acceleration with increasing UP. A double peak develops in the later profiles, indicating a shift from the former flow acceleration range to higher accelerations during larger rain events. Event accelerations occurred during the seasonal period between May 26th and November 15th inclusive.

Table 6
GAM Model Results for 80RLER ($\log_{10}$ transformed). For the 80RLER empirical model, total rainfall had a linear relationship. UP and BFI were also significant independent variables in the GAM model.

Dependent variable	Data	Model overview	Independent variable	Modelled form	Coefficient ± s.e. (p-value); F (p-value)
80RLER, log10 transformed	All data (93observations)	Model.2	Intercept	Parametric coefficient	−5.70 ± 0.086 (<2e−16)
		Deviance explained = 70.5%;	Total rain	Parametric coefficient	0.0015 ± 0.0003 (2.14e−07)
		adjusted R^2 = 0.67, N = 93	UP	Gaussian, Smoothed	F = 21.27 (6.64e−12)
			BFI	Gaussian, Smoothed	F = 7.78 (2.83e−07)

grouped within UP ranges. A double peak develops in the acceleration profile as UP increases, likely reflecting a shift from the former flow acceleration range (i.e. the first peak) to higher accelerations during larger rain events (i.e. the second peak).

3.5.1. Tenth and twentieth percentile rising limb event runoff

Both 10th percentile and 20th percentile event runoff increased with increasing UP: 10th percentile event runoff increased 2.20e−08 mm s^{-1} per unit increase in UP (MK Partial Score = 1205.1, p = 6.4e−05); 20th percentile event runoff increased 2.39e−08 mm s^{-1} per unit increase in UP (MK Partial Score = 1256.9, p = 3.1e−05). The range of 10th percentile runoff in the database was 6.4e−06 mm s^{-1} to 436e−06 mm s^{-1}; the range of 20th percentile runoff was 6.7e−06 mm s^{-1} to 763.7e−06 mm s^{-1}.

3.5.2. Eightieth percentile rising limb event runoff (80RLER)

A simple linear regression model could not be fit to the 80RLER (mm s^{-1}) data. A GAM was fit with 3 independent variables: total rainfall, UP and BFI. Total rainfall indicated a linear trend and was fit with a parametric coefficient (Table 6, Fig. 7). The fitted model illustrates a curvilinear relationship of 80RLER to UP. A leave-one-out cross-validation with 93 iterations had mean Deviance explained = 70.3% and R^2 = 0.67 with variance 2.7e−04 and 2.1e−04, respectively. The mean RMSE for observed 80RLER (log transformed) versus predicted was 0.22 (normalized RMSE = 6.2%); a plot of predicted versus observed total runoff had no outliers. The mean coefficient for Total Rainfall matched that of the reported model (Table 6). These cross-validation results indicate stable model performance, to the extent it can be tested with the available data.

3.5.3. Ninety-fifth percentile rising limb event runoff (95RLER)

The 95RLER (mm s^{-1}) (log 10 transformed) model had four independent variables (Table 7, Fig. 8). The square of UP had a negative coefficient, indicating a decreasing effect of UP on 95RLER as UP increased. The change in 95RLER resulting from increased UP in the lower UP range is much greater than the same increase once urban development is more prevalent in a watershed. For example, using the average channel slope in the database and total rain of 350 mm, an increase in UP from 10% to 20% resulted in ~56% increase in 95RLER, whereas an increase from 70% to 80% UP resulted in a ~5% increase in 95RLER. A leave-one-out cross-validation with 93 iterations had mean RMSE = 0.28 (normalized RMSE = 5.8%); a plot of predicted versus observed total runoff had one outlier. Mean coefficients for the cross-validation matched those of the reported model (Table 7). These cross-validation results generally indicate stable model performance, although additional data would be needed to assess performance under conditions similar to those of the outlier.

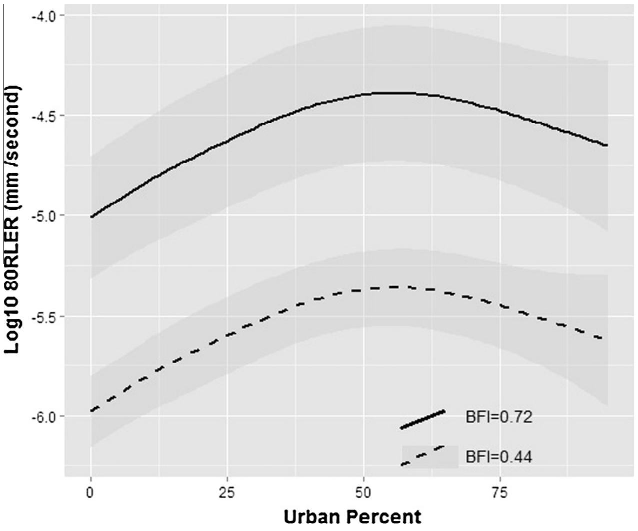

Fig. 7. Fitted 80RLER and UP for GAM model. The relationship of 80RLER with UP indicates the 80th percentile event runoff plateaus around 30% urban cover and declines ~75% UP. Shade indicates 95% CI of the estimates. The plot illustrates the effect of BFI through the range in the database (total rainfall = 350 mm), with maximum BFI (0.72) (solid black line) about one order of magnitude greater than minimum BFI (0.44) (dashed black line). Event runoff for the model occurred during the seasonal period between May 26th and November 15th inclusive.

3.5.4. Event acceleration

The model fit to event flow acceleration observations had five independent variables (Table 8, Fig. 9). Watershed area had a positive coefficient, indicating flow acceleration was higher in larger rivers. The BFI coefficient was negative, indicating watersheds with higher BFI had lower event acceleration given similar other variables. UP had a positive coefficient but UP to the power 2 had a negative coefficient, indicating a decreasing effect on acceleration as UP increased. The change in acceleration resulting from increased UP in the lower UP range was much greater than the same increase once urban development was more prevalent in a watershed. For example, for BFI = 0.57 and total rain = 350 mm, an increase in UP from 10% to 20% results in ~106% increase in mean acceleration, whereas an increase from 70% to 80% UP results in a ~0.5% increase in mean acceleration. Note that, although the fitted empirical model predicts a slight decline in acceleration above UP about 75%, there are insufficient data points in this region of the graph to reliably conclude a decrease occurs; additional data from highly urbanized watersheds would be needed to assess trends in acceleration when UP exceeds 75%. A leave-one-out cross-validation with 93 iterations had mean RMSE = 0.317 (normalized RMSE = 5.4%); a plot of predicted versus observed total runoff had no outliers but increased heteroscedascity for lower acceleration values (i.e. $\log_{10}$ acceleration $<-4.5\ \mathrm{m}^3\,\mathrm{s}^{-2}$). Mean coefficients for the cross-validation matched those of the reported model (Table 8). These cross-validation results indicate stable model performance, although RMSE was higher for the lowest acceleration observations.

3.5.5. Relationship of event acceleration to 80RLER

A model was fit for mean event acceleration with 80RLER as an independent variable, even though it is not certain that 80RLER is independent of acceleration. The model is useful to explore the relationship of the two variables, with each other and with UP. As indicated in Section 3.5.2, 80RLER had a curvilinear relationship with UP but, as indicated in Section 3.5.4, event acceleration dramatically increased in the early stages but leveled off at high UP (over ~60%). Event runoff and event acceleration changed concurrently but with different responses to UP; the relationship between these two event-scale hydrologic characteristics was not evident from each respective model as UP changed.

A linear model could not be fit to the data. A GAM was fit with 5 independent variables (Table 9). 80RLER and watershed area (both $\log_{10}$ transformed) demonstrated parametric relationships; UP, channel slope and BFI were fit with Gaussian smoothed relationship. This result indicates the change in event acceleration with 80RLER alone as an independent variable was linear, but other watershed conditions (UP, channel slope, BFI) made the overall relationship non-parametric. A leave-one-out cross-validation with 93 iterations had mean Deviance explained = 92% and $R^2 = 0.898$ with variance 4.02e−05 and 3.54e−05, respectively. The mean RMSE for observed acceleration (log transformed) versus predicted was 0.26 (normalized RMSE = 5.4%); a plot of predicted versus observed total runoff had one outlier and increased heteroscedascity for lower acceleration values (i.e. $\log_{10}$ acceleration $<-4.5\ \mathrm{m}^3\,\mathrm{s}^{-2}$). The mean coefficients for 80RLER ($\log_{10}$ transformed) and Watershed Area ($\log_{10}$ transformed) were within the reported error of those for the model (Table 9), with values of 0.516 and 0.89 respectively. These cross-validation results generally indicate stable model performance, although RMSE was higher for the lowest acceleration observations and additional data would be needed to assess performance under conditions similar to those of the outlier.

The linear relationship of event acceleration with 80RLER is plotted in Fig. 10, for the range of 80RLER in the database. In Fig. 10, UP was manipulated from 4% to 90% and the modelled mean acceleration increased two orders of magnitude. In Fig. 10, watershed size, BFI and channel slope were held equal to their mean database values ($174\ \mathrm{km}^2$, 0.60 and $4.15\ \mathrm{m\,km}^{-1}$, respectively).

Note that the range of acceleration in the database for watersheds with low urban cover (i.e. less than 4%, n = 17) did not exceed $7.9\mathrm{e}{-05}\ \mathrm{m}^3\,\mathrm{s}^{-2}$ ($\log_{10}$ −4.10). This maximum value occurred in a large watershed (Humber003, 1969, $805.6\ \mathrm{km}^2$, UP = 3.8%). The modelled watershed in Fig. 10 was only $174\ \mathrm{km}^2$ and it is possible that mean event acceleration at 4% UP would never reach the modelled values. In other words, there are physical processes that likely intervene in the relationship of 80RLER with mean acceleration; the model can be manipulated to predict accelerations that may exceed those that would actually occur in non-urban watersheds. In a similar vein, in the least urbanized watershed (Duffins019, 1978, $86.9\ \mathrm{km}^2$, UP = 0.9%), 80RLER did not exceed $9.6\mathrm{e}{-06}\ \mathrm{mm\,s}^{-1}$ ($\log_{10}$ −5.02).

Table 7
Statistical model for 95RLER ($\log_{10}$ transformed). An empirical model for 95th percentile rising limb event runoff had four independent variables.

Dependent variable	Data	Model overview	Independent variable	Coefficient ± s.e. (p-value)
95RLER, log10 transformed	All data (93 observations)	Model.3	Total rain to the power 2	3.22e−06 ± 0.54e−06 (6.5e−08)
		$R^2 = 0.69$; RSE = 0.274, df = 88, p < 2e−16	UP	0.024 ± 0.004 (2.63e−08)
			UP to the power 2	−1.45e−04 ± 0.50e−04 (0.0047)
			Channel slope	4.61e−02 ± 1.76e−02 (0.011)
			Intercept	−5.75 ± 0.10 (p < 2e−16)

Model note: conforms to parametric assumptions with removal of one outlier (Rouge028 1974, UP = 1.0%, Total Rain = 265 mm)

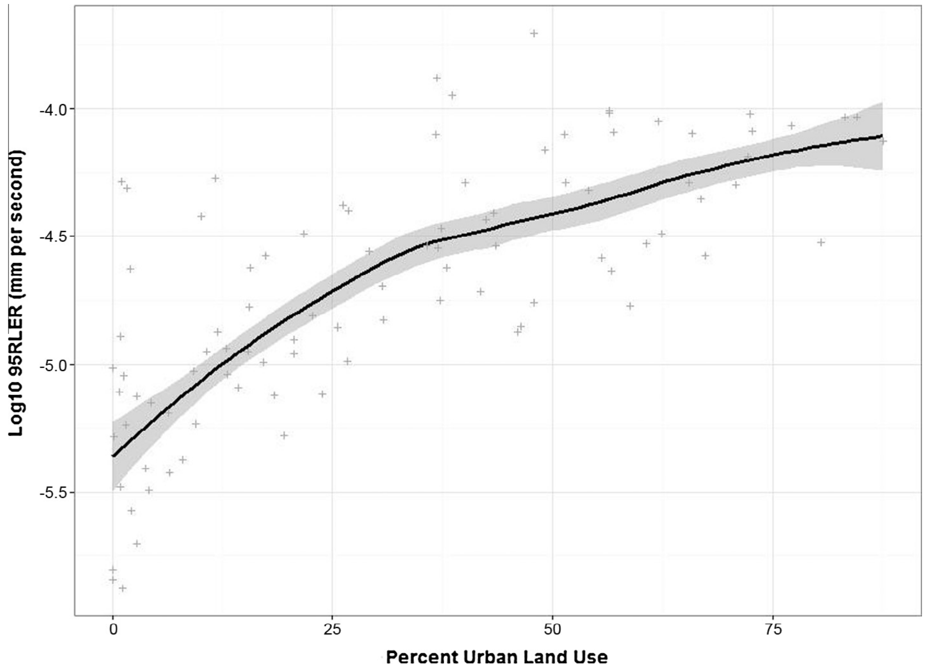

Fig. 8. Fitted model of the effect of increasing UP on 95RLER. The model is plotted in a solid black line with shaded 95% CI for the mean database values. Actual values are plotted in grey points. Event runoff for the model occurred during the seasonal period between May 26th and November 15th inclusive.

Table 8
Statistical model for mean event acceleration ($\log_{10}$ transformed). An empirical model for rising limb event acceleration had five variables, including UP and UP to the power 2.

Dependent variable	Data	Model overview	Independent variable	Coefficient ± s.e. (p-value)
Mean event flow acceleration, log10 transformed	93 observations	Model.4 $R^2 = 0.78$; RSE = 0.303, df = 87, $p < 2e{-}16$	Total rain	1.65e−03 ± 0.39e−03 (5.41e−05)
			UP	3.93e−02 ± 0.42e−02 (1.25e−14)
			Watershed area, log10 transformed	0.432 ± 0.10 (4.68e−05)
			UP to power 2	−2.60e−04 ± 0.55e−04 (7.79e−06)
			BFI	−1.59 ± 0.59 (0.0081)
			Intercept	−5.42 ± 0.42 (p < 2e−16)

4. Discussion

4.1. Research question one

The first research question was to assess at what UP responses in total runoff and RC were detectable and whether there was evidence of a threshold effect. From the breakpoint analyses, UP began to influence total runoff (and RC) at very low UP on a watershed scale. At around 2–3% UP, the influence of UP on RC was statistically detectable in the higher BFI group of watersheds (BFI $\geqslant$ 0.6). The results for watersheds under ~4% UP indicated that watersheds with lower BFI (BFI less than 0.6) had more predictable responses, specifically increasing total runoff and RC with increasing UP, up to ~4% (see slope1 results in Table 4). Total runoff and RC observations for watersheds in the higher BFI group had high variability under ~4% UP. This high variability indicates that total runoff and RC were more influenced by basin processes and watershed characteristics than by UP at these low levels of urbanization. There was no evidence to suggest a threshold change in total runoff or RC at around 10% UP. Additional data for watersheds in the earlier stages of urbanization (i.e. around 2–4% UP), including a range of baseflow conditions, would be needed to develop statistically significant empirical relationships for urbanization with total runoff and RC. The results suggest hydrologic data needs to be collected as soon as urbanization commences.

Investigation into potential hydrologic changes to explain literature reports regarding 'threshold' effects on biota around 10% UP are still warranted. Our database did not have a sufficient number of observations for UP less than 10% to analyze event-scale flow regime trends (such as changes in acceleration) as urbanization commences. However, Trudeau and Morin (in preparation) identified a negative association of maximum event flow acceleration with fish richness within this study area. Given documented lagged effects of urbanization on stream stability (e.g. Hammer, 1972; Dunne and Leopold, 1978) and of urbanization on aquatic biota (Findlay and Bourdages, 2000; Harding et al., 1998; Löfvenhaft et al., 2004), lagged effects of hydrologic change on biodiversity should be considered. Research is recommended on event-scale hydrologic trends at 2–4% UP and potential causal agents associated with biotic effects that may manifest over time.

4.2. Research question two

The second research question asked whether there were scale effects in the response of total runoff to increasing UP when other independent variables were taken into account. There is a strong

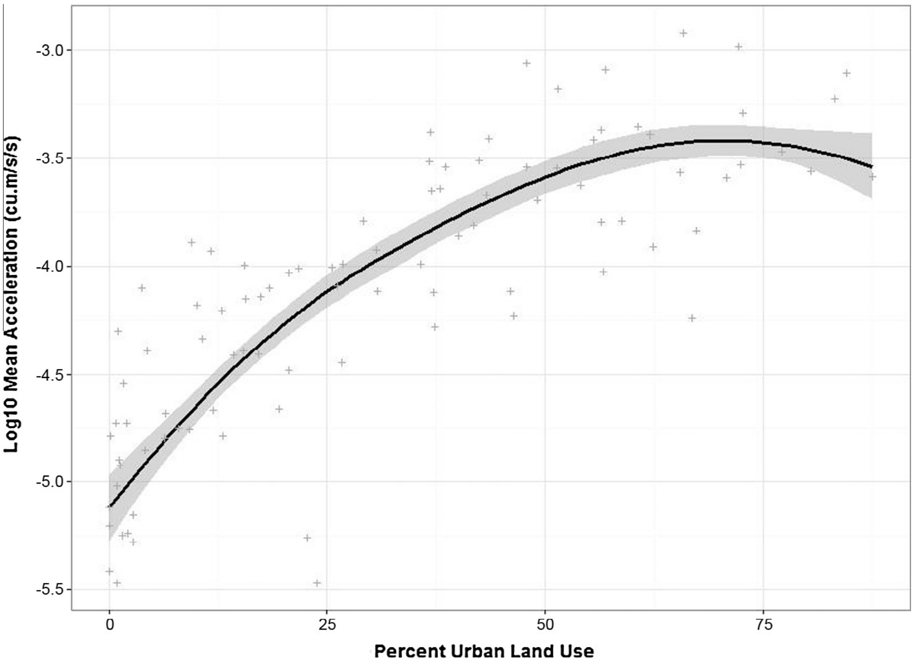

Fig. 9. Fitted model of the effect of UP and watershed area on rising limb event flow acceleration. The fitted model is plotted in a solid black line with shaded 95% CI for the mean database values. Actual values are plotted in grey points. Event accelerations for the model occurred during the seasonal period between May 26th and November 15th inclusive.

Table 9
GAM Model Results for mean event acceleration ($\log_{10}$ transformed) with 80RLER ($\log_{10}$ transformed) as an independent variable. The relationship of two event characteristics, 80RLER and acceleration, was explored through a statistical model using watershed features (size, channel slope, BFI) and UP as independent variables.

Dependent variable	Data	Model overview	Independent variable	Modelled form	Coefficient ± s.e. (p-value); F (p-value)
Mean rising limb acceleration, $\log_{10}$ transformed	All data (93observations)	Model.5 Deviance Explained = 92%; Adjusted R^2 = 0.898, N = 93	Intercept	Parametric coefficient	−3.348 ± 0.644 (1.76e−06)
			80RLER, $\log_{10}$ transformed	Parametric coefficient	0.511 ± 0.106 (8.36e−06)
			Watershed area, $\log_{10}$ transformed	Parametric coefficient	0.905 ± 0.111 (6.5e−12)
			UP	Gaussian, Smoothed	F = 19.93 (<2e−16)
			Channel Slope ($\log_{10}$ transformed)	Gaussian, Smoothed	F = 8.32 (7.08e−06)
			BFI	Gaussian, Smoothed	F = 8.85 (1.44e−09)

effect of UP on total runoff in the empirical model fit for the study watersheds and there was also a scale effect, as indicated by an interaction of UP with watershed size (see Table 5). Although it is a relatively small, positive effect compared to other independent variables, this result cautions against assuming runoff responses are uniform across scales of urbanization and watersheds. From the model, it is not possible to assess which, if either, of the variables (i.e. UP or watershed size) had a greater influence on the interactive effect. Dunne and Leopold (1978) indicated event flow responses become muted as watershed size increases. If so, then the positive interaction would be attributable to UP: as UP increases for a given watershed size, the urban effect on total runoff becomes greater than would be predicted at lower UP. In the study area, this effect could be a reflection of the development patterns; initial urbanization was most intense closest to the Great Lakes and it developed towards the headwaters over time. Thus, watersheds with the higher UP observations in the study database typically would have had more development in their headwaters regions. Headwater regions have higher drainage densities, meaning that proportionately more natural stream length was replaced by engineered drainage as the headwaters areas urbanized. This increasing simplification of the natural drainage system in denser networks could be expected to boost total runoff relative to that predicted for watershed regions with less drainage density. Unfortunately, the study database did not have sufficient data to fully explore the interaction term.

4.3. Research question three

The third research question asked about the influence of UP on event-scale rising limb flows and accelerations. Event-scale flows demonstrated a very strong effect of UP, although not all event characteristics monotonically increased with increasing UP. Eightieth percentile rising limb runoff demonstrated a curvilinear relationship with UP, with the greatest increase in 80RLER occurring as UP increased to ~30%. Although 80RLER levelled off and even decreased at higher UP, rising limb acceleration continued to increase sharply until at least ~60% UP. The analysis of 80RLER versus acceleration indicated acceleration increased ~2 orders of magnitude (for a given 80RLER) when UP increased from 4% to

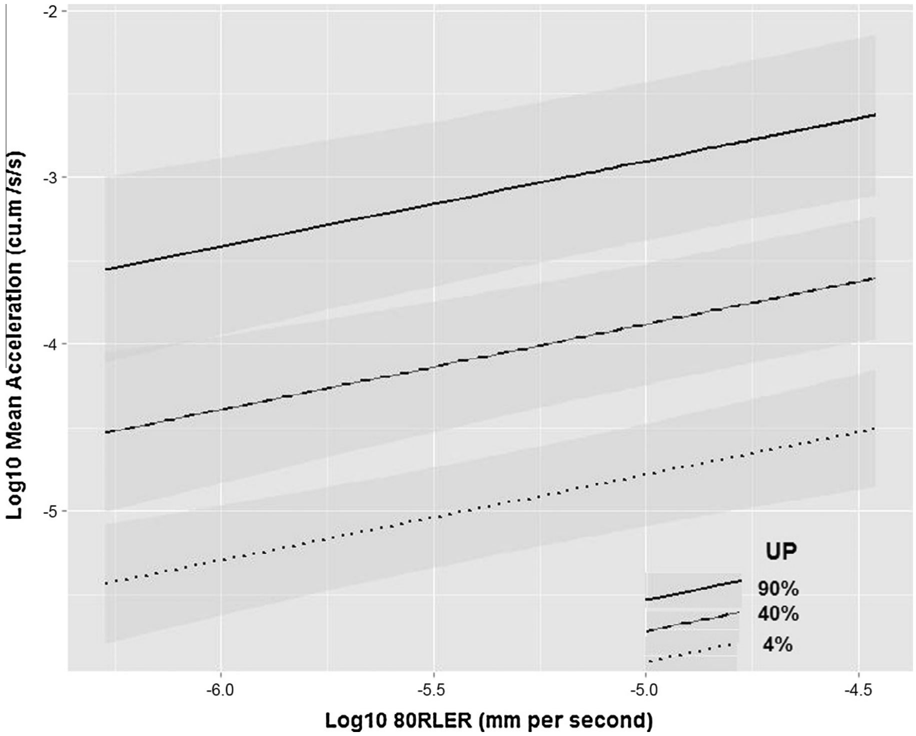

Fig. 10. Illustration of the effect of UP on the relationship of mean acceleration to 80RLER. Three scenarios are plotted to the fitted GAM model: 4% UP (grey dotted curve); 40% UP (black dashed curve); 90% UP (solid black curve). Watershed size, BFI and channel slope were held equal to their mean database values (174 km^2, 0.60 and 4.15 m km^{-1}, respectively). The range of 80RLER was set to the minimum and maximum values in the database. From 4% to 90% UP, modelled mean acceleration increased two orders of magnitude for the same range of 80RLER. Data supporting the model occurred during the seasonal period between May 26th and November 15th inclusive.

90%. Thus, for a given rain event in an urbanized watershed, 80RLER runoff would be achieved sooner due to increased flow acceleration than would have been the case when UP was lower. If only flows are measured, stabilized 80th percentile runoff may mask other changes occurring as a result of urbanization. For instance, further research would be needed to assess the role of flow acceleration as an energy dissipation mechanism within the watershed.

When considering the event-scale flow changes with increasing UP, it is important to recall that total runoff also increased. The RC trends indicated increasing partitioning of precipitation to runoff. While 80RLER did not consistently increase with UP, an increase in total runoff can be attributed to trends at the lower and upper runoff ranges: 10th percentile and 20th percentile runoff increased with increasing UP, consistent with the increased efficiency of urban drainage infrastructure to drain smaller rain events; and, peak runoff (95RLER) continued to increase with increasing UP, with some leveling off at very high UP. These relationships raise a larger question pertaining to water balance. BFI had a negative trend with UP and, concurrently, vegetated area decreased (from qualitative observation of historic aerial photographs). Surface storage (such as depressions and gullies) likely also decreased; although data were not available to verify a trend, urban transportation and lot drainage standards in the study region, by design, reduce surface storage (e.g. Government of Ontario, 1997). Reduction in these mechanisms for rain water storage and sub-surface transmission (vegetation, surface storage and interflow) was concurrent with increased drainage efficiency (via engineered sewer infrastructure). Precipitation had no trend. In summary, water discharge became redistributed to runoff during smaller events and during the largest events, at increasing overall total volumes, without compensation from additional rainfall input. These cumulative changes raise the possibility that the water balance in these urban watersheds has been negatively affected by UP during the growing season (i.e. the total volume of water within the highly urbanized watersheds becomes depleted). This study scope included only growing season precipitation and flows, so definitive conclusions on the water balance cannot be drawn. Also groundwater, storage and evaporation trends would need to be assessed to quantify changes in water balance. However, despite the data limitations, the results indicate comprehensive study of water balance in these watersheds is warranted, as are long-term water balance implications of urbanization at larger scales, including the Lake Ontario and Lake Erie basins and the St Lawrence-Great Lakes system.

4.4. Research question four

The fourth research question asked if there were watershed scale effects evident in event flows with increasing UP. Rising limb event acceleration increased with increasing watershed size, as indicated by the positive coefficient for watershed area in the model (see Table 8). Interestingly, mean acceleration in non-urban watersheds (UP less than 4%) was strongly correlated with watershed size (0.75, p = 0.01) whereas, for urbanized watersheds, mean acceleration was not statistically correlated with watershed size (see Appendix D). Coupled with the empirical model for mean acceleration, this result suggests that, prior to urbanization, the highest accelerations occur in the largest watersheds but that UP becomes a stronger determinant of acceleration as urbanization takes place.

Other event-scale runoff characteristics did not have statistically detectable watershed scale effects in the empirical models. The range in our database of UP for various watershed sizes was limited in some instances. Watersheds with additional UP-area combinations would support further analysis of potential event-scale responses. Of particular interest would be potential scale effects in smaller watersheds with denser drainage networks (see Section 4.2 for a discussion of the total runoff interaction term).

The differences in correlation of total runoff with 80RLER for large watersheds (0.72, $p = 4.6e{-}06$) versus no correlation for small watersheds (0.35, p non-significant) suggests the potential for watershed scale effects on event-scale hydrology in urbanized watersheds.

4.5. Other results

In addition to the research questions, two other interesting findings were identified. Firstly, the bivariate correlation results indicated RC was consistently more poorly correlated with event-scale flows than total runoff in urbanizing watersheds. Many jurisdictions will not have historic high-temporal resolution flow records. In the absence of event-scale data, total runoff would provide better surrogate information than RC, even though total runoff was not consistently well-correlated with event-scale flows in urbanizing watersheds.

Secondly, higher baseflow conditions appear to mitigate the effects of urbanization on event acceleration (i.e. the coefficient is negative in the statistical model, Table 8). Baseflow in the channel may provide some inertia to event flow acceleration. In addition, this study was undertaken during the post-spring freshet period when flows are normally lower than their water-year peak, leaving watersheds with channel capacity. Watersheds with high BFI may have had enough capacity in their channel cross-sections to accommodate some event flows without trend detection. Soils and surficial geology were not within the scope of this study and their inclusion (for example, hydraulic conductivity) may explain additional variation in flow responses in future research. Alternatively, there may be other unidentified processes, such as urban development practices, that mitigated the effects of urbanization on flow acceleration in watersheds with higher BFI. For example, LID measures in newer subdivisions may have contributed to unexplained variability.

4.6. Implications and further study

In terms of general applicability, the overall trends with increasing UP in total seasonal flow, event flows and mean event acceleration are expected to reflect trends in other urbanizing watersheds. However, the individual model coefficients are not likely to be broadly applicable. Further, the soils and topography of other regions may require that additional independent variables be introduced or substituted. For instance, the study area was relatively flat; channel slope and basin slope were not simultaneously significant independent variables in any of the models. Thus, regions with more pronounced channel or basin slopes may need to fit altered models that specifically reflect the topography of those regions. The general applicability can only really be assessed once similar studies are undertaken in other regions. Other comprehensive studies of event-scale flows are needed, in particular to better understand changes in event flow acceleration with urbanization. The results of this study indicate changes in water column conditions and momentum, and their subsequent impacts on biota and habitat, cannot be adequately understood using daily or monthly flow records.

On the basis of this study's findings, event-scale hydrologic changes in the early stages of urbanization (i.e. before ~10% UP), including watersheds with a range of drainage densities and baseflows, are worth investigating.

Flow acceleration profiles and other event-scale flows downstream of various stormwater management measures should be investigated. There is variation in biologic responses downstream of stormwater management facilities (Walsh et al., 2012, 2016) and event-scale hydrology, in particular flow acceleration, may account for some of this variation.

The low levels of UP that initiate event-scale hydrologic change support the conclusions from coarser-scale hydrologic analyses (e.g. Burns et al., 2012) that dampening or reversal of hydrologic alterations would require mitigation measures (such as LID stormwater techniques) to be dispersed extensively throughout the urbanized areas of watersheds. Walsh et al. (2016) stated that 'opportunistic' rehabilitation of conventional storm sewer systems will not be sufficient to return flow regimes to pre-development conditions. With event acceleration and other event-scale flow responses detectable at very early stages of urbanization (i.e. well before 20% UP), it can be further concluded that riparian treatments for overland flow or sporadic LID installations are unlikely to offset event-scale hydrologic changes resulting from urban engineered infrastructure discharging to watercourses.

The study results occurred during a period with no detectable changes in rainfall patterns thereby demonstrating that hydrologic stationarity was compromised by urbanization prior to measurable effects of climate change on rainfall. The trends identified in this study may be exacerbated by expected climatic changes, for example by further increased runoff due to higher precipitation (Jyrkama and Sykes, 2007). Climate change may also mask urbanization effects. Where urbanization will continue to expand, the changes in hydrology attributable to urbanization must also be considered as part of future climate change risk assessments; failure to take continued urbanization into account, and the associated loss of hydrologic stationarity, could result in under-estimation of risks associated with future hydrologic conditions.

This study raises many potential research questions. In particular:

- At what level of urban cover do engineering drainage systems begin to dominate stream flow response versus basin processes and characteristics on an event-scale? To what degree can LID techniques off-set the hydrologic effects on an event-scale? Do event-scale responses to urbanization in regions with higher natural drainage density patterns differ from those of mainstem watershed regions?
- What are the long term implications of altered event-scale flow patterns for the water balance in urbanizing watersheds?
- Are there detectable trends associated with urbanization in total runoff or event-scale flows for the larger scale basins in this study region (i.e. Lakes Ontario and Erie or the Great Lakes St. Lawrence Basin)?
- Are modified event-scale flow regimes during initial phases of urbanization associated with effects on aquatic biodiversity?

5. Conclusions

There is a strong effect of urban land use on event-scale hydrologic characteristics and total runoff for the seasonal period from May 26th to November 15th in the study watersheds. Event-scale hydrologic characteristics begin to change at very low levels of urbanization. Low impact development measures would need to be dispersed throughout entire urbanized areas of watersheds to mitigate the effects of urbanization on event-scale flow regimes.

Although no abrupt changes in hydrologic characteristics were identified (i.e. no threshold changes) at any particular urban land use percentage, additional research is warranted with respect to event-scale changes during very early urbanization phases (i.e. around 4% urban) to better understand hydrologic changes and the role of baseflow. Event-scale hydrology, in particular flow acceleration, warrants research to assess the effectiveness of various stormwater management measures in mitigating urban effects on the downstream hydrologic regime. Research into the implications for aquatic biota of changing hydrologic regimes, in particular event flow acceleration during very early urbanization phases, is also warranted. Changes in water column conditions and momentum, and their subsequent impacts on biota and habitat, cannot be adequately understood using daily or monthly flow records.

Hydrologic stationarity was compromised by increasing urbanization with no detectable trends in rainfall. The alteration of event flow distribution has potential implications for long-term water balances. In the face of anticipated climate changes and the clear effect of urbanization on event-scale flows, additional research is warranted into hydrologic trends with urbanization on larger spatial scales within the Great Lakes St Lawrence Basin. In future scenario modelling, climate change risk assessments pertaining to hydrologic risks should take into account the alteration of hydrologic regimes as a result of current and future urbanization.

An interaction of urban percent land use and watershed size on total runoff indicates scale effects of urbanization on hydrologic responses. Research into increased effects on event-scale characteristics of urbanization within headwaters regions in comparison with mainstem regions warrants further research.

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Appendix A

Rain gauge metadata (see Table A1).

Appendix B

Watershed baseflow index, channel and slope estimates (see Table B1).

Table A1
Rain gauge metadata. The table summarizes rain gauge locations, first year of data collection, last year of data collection and number of years with record for each gauge. Rain gauge 6158350 was replaced with new equipment in 2002 but maintained the same location and was re-numbered 6158355.

Rain gauge MSC station number	Latitude (decimal degrees N)	Longitude (decimal degrees W)	First year	Last year	Years with record
6149387	43.4500	−80.3833	1970	2007	36
6153020	43.9000	−79.0667	1960	1993	31
6153300	43.2833	−79.8833	1962	1996	35
6155790	43.9184	−80.0864	1992	2007	12
6155878	43.8667	−78.8333	1969	2007	38
6158350/355	43.6667	−79.4000	1937	On-going	>75
6158733	43.6772	−79.6306	1960	2007	47

Table B1
Watershed BFI, Channel and Slope estimates for study watersheds. The table summarizes baseflow index and slope estimates. BFI data sources: J. Buttle (pers. comm.) and Neff et al. (2005). An asterisk indicates assignment of BFI from an adjacent watershed for watersheds without a documented estimated BFI.

River system	Watershed EC hydro station	BFI	Channel Slope (units: m/m)	Mean basin slope (units: m/m)
Credit	02HB008	0.64	0.0056	0.0399
	02HB013	0.64	0.0034	0.0430
	02HB018	0.64	0.0038	0.0438
	02HB025	0.64	0.0031	0.0432
	02HB029	0.64	0.0028	0.0399
Don	02HC005	0.66*	0.0047	0.0271
	02HC024	0.57	0.0040	0.0344
	02HC029	0.57	0.0052	0.0371
	02HC056	0.66	0.0087	0.0449
Duffins	02HC019	0.71	0.0073	0.0578
	02HC026	0.63	0.0059	0.0365
	02HC038	0.69	0.0060	0.0403
Etobicoke	02HC017	0.57	0.0019	0.0186
	02HC030	0.57	0.0026	0.0192
Harmony	02HD013	0.47	0.0103	0.0393
Highland	02HC013	0.57	0.0038	0.0266
Humber	02HC003	0.57	0.0026	0.0406
	02HC009	0.64	0.0020	0.0435
	02HC025	0.72	0.0029	0.0571
	02HC027	0.57	0.0033	0.0313
	02HC031	0.44	0.0035	0.0210
	02HC034	0.44*	0.0030	0.0206
Laurel	02GA024	0.62	0.0030	0.0412
Mimico	02HC033	0.57	0.0036	0.0195
Red Hill	02HA014	0.44	0.0080	0.0302
Rouge	02HC022	0.63*	0.0039	0.0284
	02HC028	0.61	0.0057	0.0248

Appendix C

Urban percent database summary (see Table C1).

Appendix D

Correlations of hydrologic variables (see Table D1).

Table C1
Database Summary: Urban percent coverage for watersheds by year. Urban percent land use by watershed was estimated using historic aerial photographs, documented estimates (Thompson, 2013) and shapefiles from the CVCA. See Trudeau (2016) for additional information.

River system	EC hydro station	Urban Percent (UP) of watershed area **bold** - urban extent estimate by Trudeau (2016); Credit watershed estimates based on shapefiles from CVCA. *italics* - urban extent estimate in Thompson (2013) regular - urban extent estimate based on Thompson (2013) adjusted for Trudeau (2016) watershed delineation																
		1969	1970	1971	1974	1978	1981	1982	1985	1988	1990	1995	1999	2003	2005	2007	2010	2011
Credit	02HB008												**15.4**	**17.1**		**23.9**		
Credit	02HB013													**22.8**		**23.9**		
Credit	02HB018												**9.2**	**11.9**		**13.0**		
Credit	02HB025												**10.8**	**12.9**		**14.2**		
Credit	02HB029															**18.4**		**15.4**
Don	02HC005		25.5		**26.7**	30.8			40.1	**46.1**		51.4			65.5			
Don	02HC024		43.6		**47.9**	51.5			56.9	**60.7**		65.9			72.2			
Don	02HC029		30.7		**37.2**	41.8			49.1	**54.1**		62.0						
Don	02HC056														37.3			
Duffins	02HC019					**0.9**												
Duffins	02HC026					**1.3**												
Duffins	02HC038					**0.1**												
Etobicoke	02HC017		*1.1*		**2.7**	*4.4*			**11.7**	**15.6**								
Etobicoke	02HC030				**20.6**				**36.8**	**43.3**		*47.9*			*56.5*			
Harmony	02HD013											*36.8*			*42.4*			
Highland	02HC013					*66.9*			**72.4**			*83.2*					*84.5*	
Humber	02HC003	**3.8**								**9.4**								
Humber	02HC009	**2.2**								**6.5**								
Humber	02HC025	**0.8**																
Humber	02HC027	**56.6**	*58.8*			*67.3*				**70.8**		*72.7*			*80.5*			
Humber	02HC031	**0.06**								**0.2**								
Humber	02HC034	**0.1**																
Laurel	02GA024			*17.4*				*21.8*			*26.2*	*29.2*			*38.0*			
Mimico	02HC033				**46.4**				**56.4**	**62.4**		*77.1*			*87.6*			
Red Hill	02HA014					*36.9*						*55.6*						
Rouge	02HC022	**4.2**			**6.4**	**8.0**	**10.1**		**15.7**	**20.6**		*26.8*			*35.8*		*38.6*	
Rouge	02HC028	**0.9**			**1.0**	**1.6**	**1.7**		**2.0**	**2.7**								

Table D1
Bivariate correlations of hydrologic variables and three independent variables. Correlations were estimated as pairwise Pearson comparisons using Holm adjustment for multiple comparisons. Correlations in bold indicate statistically significant relationships.

Hydrologic variable	Total runoff	RC	80RLER	95th RLER	Watershed size	Urban percent	Total rainfall
All observations (93 observations)							
Total runoff					−0.12 (p = 1.0)	**0.80** (p < 0.0001)	**0.53** (p = 1.1e−06)
RC	**0.83** (p < 0.0001)				0.09 (p = 1.0)	**0.84** (p < 0.0001)	0.01 (p = 1.0)
80RLER	**0.52** (p = 1.1e−06)	**0.37** (p = 3.1e−03)			−0.05 (p = 1.0)	**0.35** (p = 6.2e−03)	**0.45** (p = 9.3e−05)
95RLER	**0.68** (p = 1.4e−12)	**0.52** (p = 1.3e−06)	**0.80** (p < 0.0001)		−0.18 (0.73)	**0.62** (p = 9.5e−10)	**0.41** (p = 5.2e−04)
Mean event acceleration	**0.68** (p = 9.0e−14)	**0.57** (p2.6e−09)	**0.56** (p = 4.9e−09)	**0.71** (p = 2.2e−15)	0.04 (p = 1.0)	**0.68** (p = 2.0e−12)	0.27 (p = 0.09)
Watersheds over 100 km^2 (46 observations)							
Total Runoff					−0.11 (p = 1.0)	**0.86** (p = 5.4e−13)	**0.49** (p = 0.006)
RC	**0.88** (p = 2.4e−14)				0.00 (p = 1.0)	**0.83** (p = 3.2e−11)	0.06 (p = 1.0)
80RLER	**0.72** (p = 4.6e−07)	**0.51** (p = 3.6e−03)			−0.10 (p = 1.0)	**0.59** (p = 2.7e−04)	**0.57** (p = 5.5e−04)
95RLER	**0.68** (p = 3.1e−06)	**0.53** (p = 1.9e−03)	**0.91** (p < 0.0001)		−0.20 (p = 1.0)	**0.68** (p = 3.1e−06)	**0.44** (p = 0.02)
Mean Event Acceleration	**0.72** (p = 4.6e−07)	**0.67** (p = 6.2e−06)	**0.69** (p = 2.0e−06)	**0.73** (p = 2.1e−07)	−0.02 (p = 1.0)	**0.81** (p = 2.2e−10)	0.24 (p = 1.0)
Watersheds under 100 km^2 (47 observations)							
Total Runoff					0.04 (p = 1.0)	**0.76** (p = 1.0e−08)	**0.56** (p = 9.0e−04)

Table D1 (*continued*)

Hydrologic variable	Total runoff	RC	80RLER	95th RLER	Watershed size	Urban percent	Total rainfall
RC	**0.79** (p = 1.5e−09)				−0.01 (p = 1.0)	**0.85** (p = 1.7e−12)	−0.01 (p = 1.0)
80RLER	0.35 (p = 0.23)	0.23 (p = 1.0)			−0.29 (p = 0.58)	0.17 (p = 1.0)	0.37 (p = 0.17)
95RLER	**0.69** (p = 1.4e−06)	**0.51** (p = 4.5e−03)	**0.62** (p = 6.2e−05)		0.02 (p = 1.0)	**0.58** (p = 3.3e−04)	0.41 (p = 0.06)
Mean Event Acceleration	**0.75** (p = 2.8e−08)	**0.53** (p = 2.0e−03)	0.24 (p = 1.0)	**0.73** (p = 1.5e−07)	−0.02 (p = 1.0)	**0.73** (p = 1.7e−07)	**0.35** (p = 0.02)
Watersheds with < 4% UP (17 observations)							
Total Runoff					−0.06 (p = 1.0)	0.04 (p = 1.0)	0.64 (p = 0.14)
RC	**0.95** (p = 2.5e−07)				0.01 (p = 1.0)	0.02 (p = 1.0)	0.37 (p = 1.0)
80RLER	**0.88** (p = 7.7e−05)	**0.89** (p = 6.1e−05)			−0.15 (p = 1.0)	−0.04 (p = 1.0)	0.44 (p = 1.0)
95RLER	0.48 (p = 1.0)	0.34 (p = 1.0)	0.69 (p = 0.06)		−0.21 (p = 1.0)	0.02 (p = 1.0)	0.55 (p = 0.46)
Mean Event Acceleration	0.13 (p = 1.0)	0.13 (p = 1.0)	0.24 (p = 1.0)	0.42 (p = 1.0)	**0.75 (p = 0.01)**	0.47 (p = 1.0)	0.05 (p = 1.0)

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