Journal of Hydrology 527 (2015) 1174–1188

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Corrigendum

Change in event-scale hydrologic response in two urbanizing watersheds of the Great Lakes St Lawrence Basin 1969–2010

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ARTICLE INFO

Article history:
Available online 25 May 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

Keywords:
Urban hydrology
Event-scale flows
High temporal resolution
Flow acceleration
Flow regimes
Hydrologic stationarity

SUMMARY

The cumulative impacts of urban land use change on natural stream flow regimes and lotic ecosystems are poorly understood, and generally under-studied within the hydrologic sciences literature. Moreover, flow assessments using daily or monthly flows cannot adequately characterize long-term trends in event-scale flow dynamics in urbanizing watersheds. Accordingly, we analyzed high temporal resolution (15-min flows) growing season discharge records for two urbanizing watersheds in Canada's Great Lakes Basin, the Don and Humber, over a 42-year period. Results show that total discharge between May 26th and November 15th in the mainstem rivers has increased by about 45%, independent of total rainfall depth, over four decades. Peak rain event flow rates have increased by almost 0.1 $m^3 s^{-1} yr^{-1}$ in both watersheds and event flow variability has increased two-fold in the Don and almost five-fold in the Humber. In the Don, the ratio of rising limb event flows to median flow (for the period May 26 to November 15) increased from 1.5 in the 1970's to 2.3 in the 2000's. A similar comparison of ratios in the Humber showed similar results, with higher variation in flow response Rising limb event flow acceleration increased 2-fold over 4 decades in the Don and slightly more in the Humber. This study provides a new understanding of the changes in event-scale flow regime dynamics associated with over four decades of intensive urbanization, including increased magnitude of rising limb flows and flow acceleration, and systematic increases in the variability of peak discharges. Overall, our analysis demonstrates marked alteration in total and event flow regimes resulting in chronic perturbation of stream flows. The results demonstrate an important application of long-term, high temporal resolution hydrological records. Furthermore, we quantify the degree to which hydrologic stationarity within the Don and Humber watersheds has been compromised over four decades, during a period prior to detectable climate-induced changes in rainfall patterns.

1. Introduction[2]

Land use change, at multiple scales of watershed size, is associated with changes in hydrology (e.g. Muma et al., 2011; Costa et al., 2003; Siriwardena et al., 2006; Schueler et al., 2009). Typical flow regime changes due to urbanization include increases in peak discharge (Hundecha and Bárdossy, 2004), increased high-flow frequency, altered distribution of water between storm flow and base flow, increased daily flow variability (Konrad and Booth, 2005; Tetzlaff et al., 2005b) as well as increased duration of sediment transporting events (Booth and Jackson, 1997). The cumulative effects of land use change on increased risks of flood or other consequences to physical infrastructure are well recognized (e.g. Gilroy and McCuen, 2012; Suriya and Mudgal, 2012; Du et al., 2012). However, flow disturbance and natural flow fluctuations are also important variables in structuring biotic communities in aquatic ecosystems (Bunn and Arthington, 2002; Poff and Ward, 1989; Flecker and Feifarek, 1994). General associations of aquatic biodiversity decline with increased impervious cover have been identified for some time (Klein, 1979; Schueler, 1994; Paul and Meyer, 2001; Löfvenhaft et al., 2004; Stanfield et al., 2006;

DOI of original article: http://dx.doi.org/10.1016/j.jhydrol.2015.01.069 http://dx.doi.org/10.1016/j.jhydrol.2015.05.011

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[2] **Abbreviabtions**: *Organizations*: Meteorological Service of Canada (MSC); Water Survey of Canada (WSC); Toronto and Region Conservation Authority (TRCA). *Analytical:* 80% of rising limb event (80RLE) flows. *Statistical*: Akaike's Information Criterion with correction for finite sample sizes (AICc); Confidence Interval (CI); degrees of freedom (df); likelihood ratio chi-square (LR chi-square); linear mixed effects (LME); *Other*: no date (n.d.).

http://dx.doi.org/10.1016/j.jhydrol.2015.04.031
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Stanfield and Kilgour, 2006; Schueler et al., 2009) but the causal mechanisms for the effect of flow regime change on biota are not well understood (Armanini et al., 2011). Studies of ecological flow regime indices, including magnitude, frequency, timing, duration and rate of change in flow conditions (e.g. Poff et al., 2006; Richter et al., 1996) are typically undertaken using daily and monthly flow records (e.g. Monk et al., 2012; Clausen and Biggs, 1997). At this temporal resolution, flow assessments cannot adequately characterize flow dynamics responding to rain events. The topic of trends in streamflow perturbations at fine timescale resolution (i.e. in response to rain events) has received relatively little attention due to the general lack of suitable long term flow records.

This descriptive, empirical study examines trends in total flow and rain event-scale hydrologic responses in two urbanizing watersheds in the Greater Toronto Region, Ontario, Canada, over a 42 year period, using Environment Canada's (EC) fifteen-minute interval flow records (Arsenault and Thompson, 2010). The rapid increase in flow resulting from rainfall events (called the rising limb of event flows) is examined because it is the interval during which aquatic biota need to shelter (Tetzlaff et al., 2005a), adjust or otherwise sustain themselves as the effects of a storm move through a watershed. The rising limb, until peak event flow, is also the period of highest energy impulse resulting from rain events and thus relevant to understanding both direct and indirect alterations to habitat features of the physical stream channel (substrate stability, for example).

We focus our analysis on the annual time 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. Specifically, for the Don and Humber watersheds, we assess flow regime changes not attributable to changes in rainfall, including (1) total flow volume; (2) rain event rising limb flows; and (3) rain event rising limb flow accelerations (Tetzlaff et al., 2005b) of the mainstem rivers near their confluences with Lake Ontario. The study includes an analysis of rainfall records for the same period. We also discuss the observed flow regime changes in light of their potential for cumulative effects assessment in urbanizing watersheds.

Although hydrologic response varies considerably among watersheds (Jacobson, 2011), previously documented magnitude of responses associated with urbanization include a 2–4 fold increase in peak discharge and runoff volumes (Chin, 2006). This study provides a new understanding of the changes in magnitude of event rising limb flows, changes in the magnitude of acceleration of event flows and changes in variability of peak discharges over four decades of increased watershed urbanization.

2. Methods

2.1. Data sources and study site

We used hydrometric records from EC's Water Survey of Canada (WSC) 15 min stream flow data, called the "instantaneous hydrometric dataset" by EC. Rainfall data were supplied by EC's Meteorological Service of Canada (MSC) in the Daily Record of Hourly Data (HLY) format. ArcGIS shape files for the watersheds were developed using data sets from the Government of Ontario, Integrated Hydrology Data Part 2, including: enhanced flow direction grid; stream grid; and, enforced DEM from the Ontario (Government of Ontario, 2013).

The Don and Humber watersheds in Toronto, Canada were selected for analysis because: (a) both flow and rainfall data were available over a continuous 40-plus year period; (b) they are both known to have experienced substantial increases in urbanization during the period of record; and, (c) both are anticipated to have additional ancillary datasets on historical land cover changes and species presence/absence data that can be used in subsequent research. Population in the Toronto Metropolitan Area has grown from 1,919,000 in 1961 to 3,893,000 in 1991 (Demographia, n.d.) to 5,583,064 in 2011 (Statistics Canada, 2014). The population density per square kilometer in 2011 was 945.4 (Statistics Canada, 2014).

Daily average air temperatures in Toronto range from −3.7 °C in January to 22.3 °C in July (Government of Canada, 2014). Average precipitation is 831 mm/year, with rain occurring in all months and snowfall in winter months (November to April, inclusive) (Government of Canada, 2014). The average frost free period is 203 days, typically occurring from April 13 to November 3 (Government of Canada, 2014).

Selected hydrometric stations were those closest to the confluence with Lake Ontario so that flow changes reflect an integrated response of the watershed from headwaters to confluence over time. The Don River hydrological gauging station (WSC 02HC024) and the Humber River hydrological gauging station (WSC 02HC003) have continuous flow records from 1969 to 2010. The Don watershed at hydrological station WSC 02HC024 is 311 km^2, with an average channel slope of 0.004 m m^{-1} and overall average basin slope of 0.034 m m^{-1}. The Humber watershed at hydrological station WSC 02HC003 is 806 km^2, with an average channel slope of 0.003 m m^{-1} and overall average basin slope of 0.041 m m^{-1}. Only one rain gauge in close proximity to the hydrologic gauging stations had a period of records matching the hydrologic years of record. Rain gauge MSC 6158350/6158355 has rainfall records dating from the 1930's to 2012. The rain gauge equipment changed within the record, at which time a different site number was assigned to the gauge, but the station's location did not change. Fig. 1 indicates the locations of hydrological gauging stations and the rain station used in the empirical statistical flow models.

For the rainfall analyses, data from sixteen rain gauges, including MSC6158350/6158355, were analyzed. Table 1 identifies gauges with available data used in the rainfall analysis, and Fig. 2 identifies rain gauge locations relative to the Don and Humber catchments. The temporal coverage by rain gauges is very uneven, with only three gauges having records post-1995. All available records within either of the catchments terminate by 1988. All gauges within 20 km of the catchments and with more than 25 years of rainfall record are near the shore of Lake Ontario and located outside the catchments. Snowfall records for station MSC6158350/6158355 were examined for accumulated daily "Total Snowfall" and maximum daily "Snow on the Ground" (Daily Climatological Data, Elements 011 and 013, respectively, Government of Canada, 2013). Snowfall records were only available up to March 2009 for Element 011 and December 2006 for Element 013 for this station.

Several potential sources of historical urbanization within the study area were investigated. The method by Thompson (2013), who estimated urban extent for five years (1955, 1970, 1978, 1995, 2005), was found to be the most detailed and comprehensive. Of these five years, four fall within the available high-resolution hydrologic record for the Don watershed.

The study scope is an analysis of hydrologic trends in two urbanizing watersheds in relation to time and urban extent. Stable watershed characteristics, such as soils and slope, are constants and were therefore not included as independent variables in this analysis.

2.2. Data preparation

R (R Core Team, 2012) was used both to read raw data files and fit statistical models. ArcGIS was used for: hydrologic station

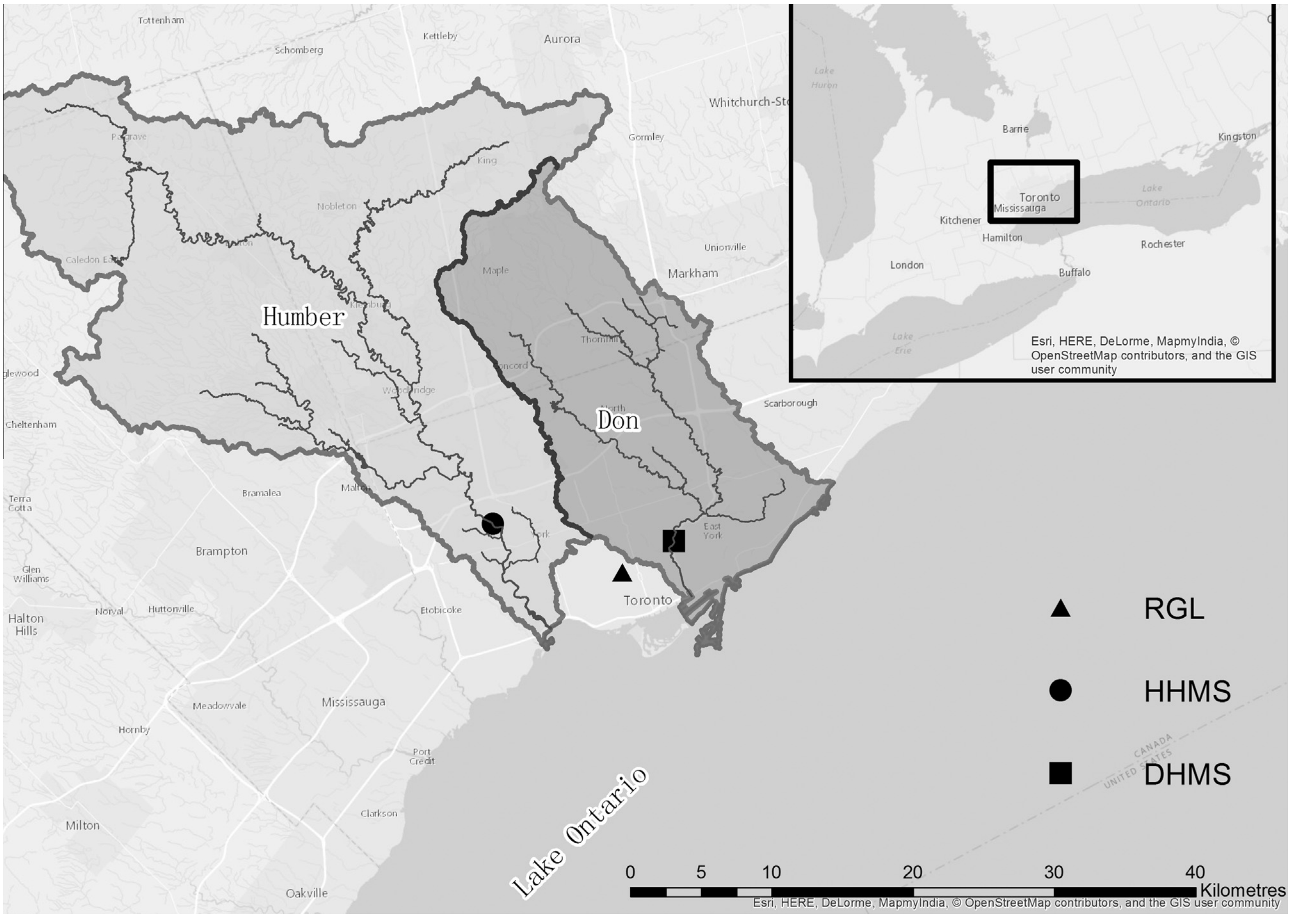

Fig. 1. Study Area. The Don (311 km^2) and Humber (806 km^2) watersheds, with locations of the hydrometric stations and rain gauge (HHMS – Humber hydrologic metering station; DHMS – Don hydrologic metering station; RGL – Rain gauge location). The City of Toronto is among the largest cities in North America by population and is situated in a region experiencing dramatic increases in urban land cover over the past four decades.

Table 1

Rain gauges within and proximal to the two urban catchments studied and number of years of rainfall data available from each gauge within the period of hydrologic record (1969–2010).

Rain gauge MSC station number	Latitude (decimal degrees N)	Longitude (decimal degrees W)	Time span of available records	Number of years with records between 1969 and 2010	Relative position in study area
Group 1: Stations outside the catchments, but within 15 km of the catchments, with more than 20 years of record					
6158350	43.6667	−79.4000	1937–2012	42	Near Lake
6158733	43.67722	−79.6306	1960–2007	37	Mid-region
6158520	43.7667	−79.2667	1966–1995	25	Near Lake
6158665	43.62861	−79.395	1971–1994	24	Near Lake
6158764	43.6500	−79.4667	1966–1990	21	Near Lake
Group 2: All available stations within the Humber catchment					
6158740	43.800	−79.5500	1965–1987	18	Mid-region
6150825	43.88333	−79.7333	1978–1988	8	Upper reaches
6150100	43.93333	−79.8333	1960–1971	2	Upper reaches
6159510	43.9500	−79.4333	1960–1970	2	Upper reaches
Group 3: All available stations within the Don catchment					
6158718	43.76667	−79.4833	1973–1986	13	Mid-region
6158385	43.71667	−79.3167	1973–1984	11	Near Lake
6154950	43.86667	−79.4833	1960–1975	6	Upper reaches
6158732	43.71667	−79.3500	1985–1986	2	Near Lake
Group 4: Other stations within 10 km of catchment that extend Post 1987					
6158406	43.6500	−79.3500	1980–1993	14	Near Lake
6155790	43.91835	−80.0864	1992–2007	10	Upper reaches
6157015	43.9000	−79.4000	1989–1991	3	Upper reaches

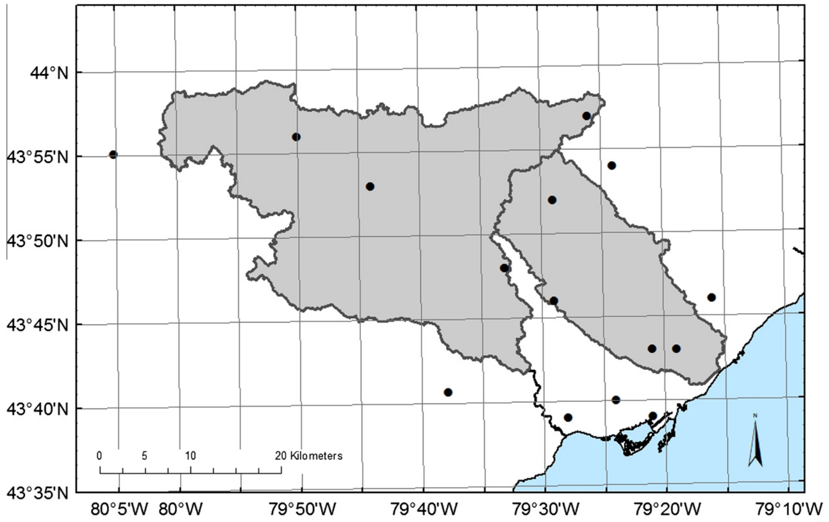

Fig. 2. Locations of 16 rain gauges with available records within proximity of the two catchments studied. Sixteen rain gauges were analyzed. Refer to Table 1 for information on the gauges.

selection in closest proximity to confluence with the lake; estimation of rain gauge site proximity to selected hydrologic stations and rain gauge selection. Data were received from EC in raw text and .csv formats for hydrologic and rainfall stations.

Rainfall records from station MSC6158350/6158355 and hydrologic records for each watershed were matched on a time basis to create a merged rain-flow database for each watershed. Where rainfall or hydrologic records were missing, records for that 15-min time interval were removed.

In our original study design, it was anticipated that rainfall records could assist in identifying storm event flows. However, there are no long-term rainfall records within the catchments upstream of the hydrologic stations. Only one proximal rain gauge, in the vicinity of downtown Toronto, had a suitable continuous record to match the years of hydrologic data.

A subset of the data for each year was extracted for the period May 26th to November 15th inclusive. All flow analyses in this report were undertaken using this subset of data. Total rainfall used for flow analyses is the total rainfall calculated using this data subset. Event flows during the period of interest were isolated from baseflow using a customized R script based on the Hydrograph Separation Program (HYSEP) (USGS, 1996). For each discrete flow event, the rising limb was isolated from the falling limb and subsequently analyzed in further detail; the peak flow for each event was included as part of the rising limb flows. Event flow acceleration was calculated as the change in flow rate from one 15 min interval to the next during rising limb event flows (in units of $\mathrm{m}^3\,\mathrm{s}^{-2}$). Flows can fluctuate during rain events; acceleration analyses included only positive acceleration intervals in the rising limb. An instantaneous flow acceleration-to-peak was also calculated as the change in flow rate between each flow record during the rising limb and the event peak flow rate, divided by the intervening time (for units in $\mathrm{m}^3\,\mathrm{s}^{-2}$); acceleration-to-peak was not used in statistical analyses. All references to event flows and event flow accelerations in this report pertain to the rising limb only.

Only available records with both rainfall and flow measurements were used in the database. Some years within this database are missing records. However, of 84 years (42 years each for the Don and Humber) 74 years have 80–100% of the full 16,708 potential precipitation-hydrology pairs of observations; the highest percentage of missing records is 48% (1973). Years with relatively higher rates of missing records were not used in flow comparisons of earlier with later years.

For coarser time scale analyses of trends, we grouped data into four decadal intervals: the 1970's (1969–1979), 1980s (1980–1989), 1990s (1990–1999) and 2000s (2000–2010). Thus the 1970s and 2000s have one more year each than the 1980s and 1990s.

To analyse long-term trends in rainfall, available records between May 26 and November 15 for years 1969 to 2010 from 16 rain gauge stations were compiled. Years with fewer than 35% of potential rainfall hours were not included in seasonal trend analyses although individual rainfall events during those years were retained for rain event trend analyses. No rain records outside the timeframe of the hydrologic record (i.e. 1969–2010) were analyzed. Rain events were defined as events with at least one period of an hour duration during which at least 5 mm of rain was recorded. Individual rain events comprise any consecutive rainfall records before and after the record exceeding 5 mm with no more than one hour break in rainfall. This rain event definition reflects the hourly resolution of the dataset and differs from daily or monthly definitions of rain events using coarser time intervals (e.g. Karl and Knight, 1998; Brunetti et al., 2000; Cannarozzo et al., 2006). The original EC rainfall data file for station MSC6158350/6158355 was used in the database, rather than the rainfall file matched to hydrologic records, so no rain event would be eliminated due to missing hydrologic records. Other database fields included total hours of record for each station by year (including periods with zero rainfall). To test for potential trends in annual snowpack accumulation that could indirectly influence hydrologic conditions in the study season, total daily accumulated snowfall (cm) from October to April was calculated for MSC6158350/6158355 for years 1968/69 to 2008/09 inclusive. Maximum daily snow on the ground was identified for each month from January to May for 1969–2006.

Percent urban area in the Don watershed was estimated for each year of record using the available data on urban extent. A conservative approach was used in which the estimated urban area from Thompson (2013) for each available year of record (4 in total) was applied to that year and all subsequent years until the next estimation (i.e. the last observation was carried forward). For example, the estimated urban extent in 1970 was assigned to 1970 through 1977; 1978 was assigned to 1978 through 1994. An exception was made for urban extent in 1969, which was estimated to be equal to the urban area in 1970 rather than based on the urban area in 1955. Extrapolation of values was avoided because land development does not necessarily progress in a simple linear manner.

2.3. Statistical analyses

Statistical analyses were undertaken to assess trends with year in (1) rainfall; (2) total flow; (3) event flows; and (4) event flow accelerations. The best model fit to predict total flow with independent variables year and total rainfall was tested substituting urban cover for year in the Don watershed. Rainfall was used as an independent variable in statistical models to predict flow characteristics. However, it was important to assess the independence of rainfall with respect to time, thus the first analysis was undertaken to assess temporal rainfall trends.

2.3.1. Rainfall analysis

The purpose of the rainfall analyses was threefold: (1) to assess the suitability of rain station MSC6158350/6158355 (the longest available rainfall record within the region) to represent rainfall in the catchments studied; (2) to assess trends in time of rainfall at all available proximal rain stations in the years with hydrologic records (1969–2010); (3) to assess trends in time of rainfall at rain station MSC6158350/6158355. Mann Kendall tests were run using R Package rkt (Marchetto, 2013). Where appropriate, Regional Mann Kendall (Helsel and Frans, 2006) results were calculated using both median and average methods with multiple records in a year; median results are reported.

To assess the suitability of rain station MSC6158350/6158355 to represent rainfall in the catchments studied, the potential effect of Lake Ontario on rainfall was assessed. Thirteen stations were grouped into two groups: seven stations within 10 km of the lake; and, six stations in the upper reaches of the watersheds (three mid-watershed stations were excluded for analyses for proximity to Lake Ontario). When assumptions for parametric testing were met, a two-sided *t*-test to compare means was performed; otherwise, the Wilcoxon rank sum test was applied. The effect of proximity to Lake Ontario was tested for: total rainfall (*t*-test); rain event frequency (number per year; covariate total hours of record) (*t*-test); rain event maximum intensity in one hour (mm_{max}/hour for each event) (Wilcoxon rank sum test); total rain event depth per event (mm/event) (Wilcoxon rank sum test). Pooled data for the sixteen rain stations were also tested for trend in total rainfall by latitude (Mann Kendall). See Table 1 for relative position of rain gauges in the study area.

To assess temporal trends in rainfall at all available proximal rain stations (1969–2010), Regional Mann Kendall analyses were run for: total rainfall (mm; covariate total hours of record); rain event frequency (number per year; covariate total hours with records); rain event maximum intensity in one hour (mm_{max}/hour/event); total hours with rain; rain event depth per event (mm/event); hours with rainfall in 6 different class intervals (Brunetti et al., 2000) with total hours of record as a covariate (>50 mm; 50–40 mm; 40–30 mm; 30–20 mm; 20–10 mm; 10–0 mm; 0 mm;); 99.999th, 99.99th, 99.9th, 99th, 95th and 90th percentile hourly rainfall (covariate total hours with records); and, proportion of total rainfall contributed by the 90th percentile rain (Karl and Knight, 1998). To assess the proportion of total rainfall contributed by the 90th percentile rain, the 90th percentile value was calculated for each station and year using only records with rainfall greater than 0 mm; all hourly rainfall records greater than or equal to the 90th percentile were summed and divided by the total rain depth for the year. For other percentile calculations, the entire rainfall record (including periods of no rainfall) was used. At least four years of record are needed for the Mann Kendall test; four of the sixteen rain stations did not meet this minimum requirement so rainfall trends were assessed using the remaining 12 stations.

Trends with year at station MSC6158350/6158355 were assessed using the Mann Kendall test for the same rainfall variables listed above, except total rainfall (log transformed) was assessed with a linear model. Mann Kendall was also used to test trend on year for three snow variables: the total daily accumulated snowfall (cm) from October to April; maximum daily snow on the ground by month individually (January to May); mean daily snow on the ground (January to April).

For the period of study, 1969–2010, in addition to the analysis of rainfall records reported herein, a literature review of available rainfall studies was undertaken with respect to statistical trends in rainfall patterns within the Toronto region.

2.3.2. Analysis of total annual flows

For an analysis of total flow by year (May 26th to November 15th), as an initial diagnostic of detectable trends, the Mann Kendall trend test using a Yue-Pilon trend-free pre-whitening (Yue et al., 2003, 2002) approach was applied to several flow variables, including: total; mean; highest; lowest; 1st, 10th, 20th, 50th, 70th, 90th, 99th percentiles; and, the ratio of total flow to total rain (i.e. annual runoff coefficient). Flow duration curves were estimated using R's hydroTSM (Zambrano-Bigiarini, 2012) package.

For statistical modeling of total annual flows using two independent variables (total rainfall depth and year), we use linear mixed effect (LME) models. LME models were fit to the total flow data, with year and total rainfall as fixed effects; watershed was a random intercept effect; and, $\log_{10}$ total rainfall a random slope effect. Heteroscedasticity among watersheds was tested for model fit improvement. Total flow (May 26th to November 15th) was expressed as runoff (mm) by dividing the flow volume for each watershed by watershed area upstream of each hydrologic gauge.

2.3.3. Analysis of event flows

Event flow analyses (rising limb only as described in Section 2.2) included temporal trends in event flows, event flow accelerations, the ratio of event flow to median flow and the range of event flows.

For event flow and event acceleration, we estimated the slope with year for each of the first 4 moments of the distribution using Mann Kendall. The raw data for this analysis included all 15-min records for event rising limbs, up to and including peak flows, of all event flows by year. Density plots (R's ggplot2, Wickham, 2009) were used to visually compare distributions of event flows and event accelerations of earlier years and later years with similar total rainfall depths (depths for each pair of years were within 3% of each other). The area under each density plot is one, and the comparisons by year indicate shifts in relative frequency of plotted flow rates. Density plots of flow attributes were also used to visually compare shifts in relative frequencies by decade.

For event flows, rising limb flow segments were pooled by year and trends over the period of record estimated independently for three different attributes of the distribution: the flow rate below which 80% of rising limb event (80RLE) flows occurred; the ratio of 80RLE to median flow; and, the range of flows. The 80% threshold was selected as the dependent variable based on the earliest years of record when event flows occurred within a narrow value range easily characterized by this threshold. The range of flows was calculated as the highest event flow minus the lowest flow by year.

For both watersheds, 80RLE, the ratio of 80RLE to mean flow and acceleration were assessed by decade using ANOVA (Tukey method of multiple comparisons). Because the ANOVA assumption of normally distributed residuals was violated, a Kruskal–Wallis test was also run to assess consistency with ANOVA results; a Kruskal–Wallis test can only confirm that at least one pair of decades is significantly different. To estimate an annual rate of change in event flows, change in range of flows and event accelerations, Mann Kendall tests were used, with total rain as a covariate.

2.3.4. Substitution of urban extent for year

For the Don watershed, total flow was estimated with the independent variables total rainfall and urban area (instead of year) using a simple linear regression. No comparable model was developed for the Humber because historic urban area estimates were not available for the Humber watershed.

2.3.5. Model selection and data transformation

LME model selection was based on an information theoretic approach using Akaike's Information Criterion with correction for finite sample sizes (AICc) (Mazerolle, 2013). In the case of simple linear models, fit was assessed on the basis of the coefficient of determination (R^2). Interaction terms for independent variables were included among models tested. As a preliminary step in all analyses, histograms of dependent and independent variables were plotted to assess skew in the raw data. Scatter plots of variable pairs were also visually assessed for potential relationships.

The flow and rainfall data are right-skewed. Where variables were log transformed, a correction for the anti-log transformation bias was applied based on the mean of the antilog of the residuals for the model (Rothery, 1988; HERC, 2013).

3. Results

3.1. Rainfall analysis

Rainfall at seven stations in closest proximity to Lake Ontario demonstrated no significant differences from rainfall at six stations in the upper reaches of the Don and Humber watersheds for: total rainfall ($t = -0.76$, df = 49.9, $p = 0.45$); rain event frequency ($t = -0.05$; df = 50.9, $p = 0.96$); maximum event intensity ($W = 244977.5$, $p = 0.91$); rain event depth ($W = 245{,}840$, $p = 0.82$). There was no trend in total rainfall with latitude among the 16 rain stations (Mann Kendall (MK) Score = –8, p = 0.67, median method).

Regional rainfall trends with year for 12 stations were not statistically significant for: total rainfall (MK Partial Score = 30, $p = 0.84$); rain event frequency (MK Partial Score = 211.5, $p = 0.13$); rain event maximum intensity (MK Score = 41, $p = 0.79$); total hours with rain (MK Score = –63, $p = 0.67$); rain event depth (MK Score = –188, $p = 0.20$); proportion of total rainfall contributed by the90th percentile rain (MK Score = 0, $p = 1$); 99.999th, 99.99th, 99.9th, 99th, 95th and 90th percentile hourly records (MK Partial Score range from –245.3 to 165.8, p range from 0.072 (for 95th percentile) to 1 (for 90th percentile)); hours with rainfall in class interval > 50 mm (MK Partial Score = 117.8, $p = 0.40$); class interval 50–40 mm (MK Partial Score = –56.1, $p = 0.69$); class interval 30–20 mm (MK Partial Score = 44.0, $p = 0.76$); class interval 20–10 mm (MK Partial Score = 5.4, $p = 0.98$); class interval 10–0 mm (MK Partial Score = 8.0, $p = 0.96$).

Statistically significant trends in the regional analyses were identified for three variables: total number of hourly records per year (MK Score = –406, $p = 0.005$, slope = –2.79 records/year); hours in the class interval with zero rainfall (MK Partial Score = –131.1, $p = 0.037$, slope = –6.4 h/year); hours in class interval 40–30 mm (MK Partial Score = 377.9, $p = 0.008$, slope = 0.08 h/year).

No statistically significant rainfall trends with year were identified at station MSC6158350/6158355, including: total rainfall ($t = -0.028$, df = 39, $p = 0.98$); rain event frequency (MK Partial Score = 101.1, $p = 0.29$); rain event maximum intensity (MK Score = –44, $p = 0.64$) (Fig. 3); total hours with rain (MK Score = –90, $p = 0.33$); rain event depth (MK Score = –149, $p = 0.11$); proportion of total rainfall contributed by the 90th percentile rain (MK Score = –37, $p = 0.69$); 99.999th, 99.99th, 99.9th, 99th, 95th and 90th percentile hourly records (MK Partial Score range from –155.5 to 33.4, p range from 0.07 (for 95th percentile) to 1 (for 90th percentile)); hours with rainfall in class interval > 50 mm (MK Partial Score = 73.9, $p = 0.40$); class interval 50–40 mm (MK Partial Score = –41.7, $p = 0.65$); class interval 40–30 mm (MK Partial Score = 72.8, $p = 0.43$); class interval 30–20 mm (MK Partial Score = –93.4, $p = 0.31$); class interval 20–10 mm (MK Partial Score = 6.2, $p = 0.95$); class interval 10–0 mm (MK Partial Score = –76.4, $p = 0.41$); class interval with 0 rainfall (MK Partial Score = 27.0, $p = 0.53$); total number of hours with records per year (MK Score = –9, $p = 0.93$).

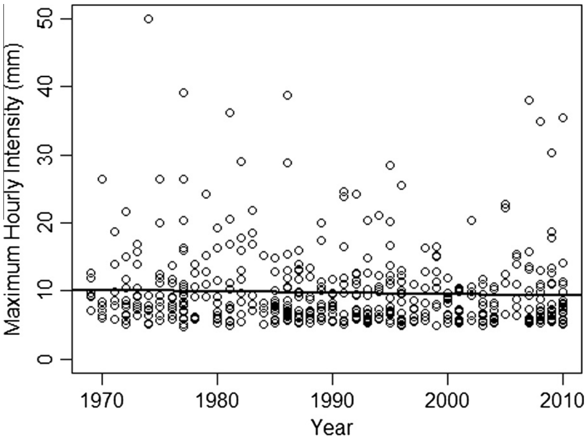

Fig. 3. Maximum hourly intensity rainfall events. Time series of maximum hourly intensity of rainfall events over 5 mm.

No statistically significant trend with year in accumulated daily total snow (October to April) was identified between winters 1968/69 and 2008/09 inclusive (MK Score = –143, $p = 0.11$). No statistically significant trend with year in maximum depth of snow on the ground was identified between 1969 and 2006 inclusive for January (MK Score = –91, $p = 0.26$), February (MK Score = –8, $p = 0.93$), March (MK Score = 34, $p = 0.68$), or April (MK Score = –56, $p = 0.45$). No statistically significant trend with year in mean depth of snow on the ground was identified for January to April inclusive between 1969 and 2006 inclusive (MK Score = –63, $p = 0.44$).

Our results indicating no relevant significant trends in rainfall are consistent with literature results for Southern Ontario. Palynchuk (2012), Hogg and Hogg (n.d.), Zhang and Burns (2009), Adamowski and Bougadis (2003) and Hodgkins et al. (2007) also report similar results for Southern Ontario rainfall characteristics during contemporaneous timeframes.

3.2. Total flow trend

For both the Don and Humber mean flow, 1st percentile (i.e. the highest 1% of flows) (Fig. 4), 10th percentile, 20th percentile flows and the ratio of total flow to total rain each increased over the period of record ($p < -.05$). The Don Watershed also indicates a statistically significant increase in 50th percentile flows. The Humber indicates a statistically significant increase in highest flows and total flow. Trends in other characteristics assessed were not statistically significant at $p = 0.05$.

Linear mixed modeling of $\log_{10}$ total flow (mm/year) shows a large positive effect of $\log_{10}$ total rainfall depth at gauge (mm) ($\beta_1 = 0.82 \pm 0.07$, $t = 12.0$, df = 80, $p < 0.0001$) as well as year ($\beta_2 = 0.0039 \pm 0.00067$, $t = 5.8$, df = 80, $p < 0.0001$) with substantial heterogeneity between watersheds ($\sigma^2_{0DON} = 0.058$; $\sigma^2_{0HUMBER} = 2.16$

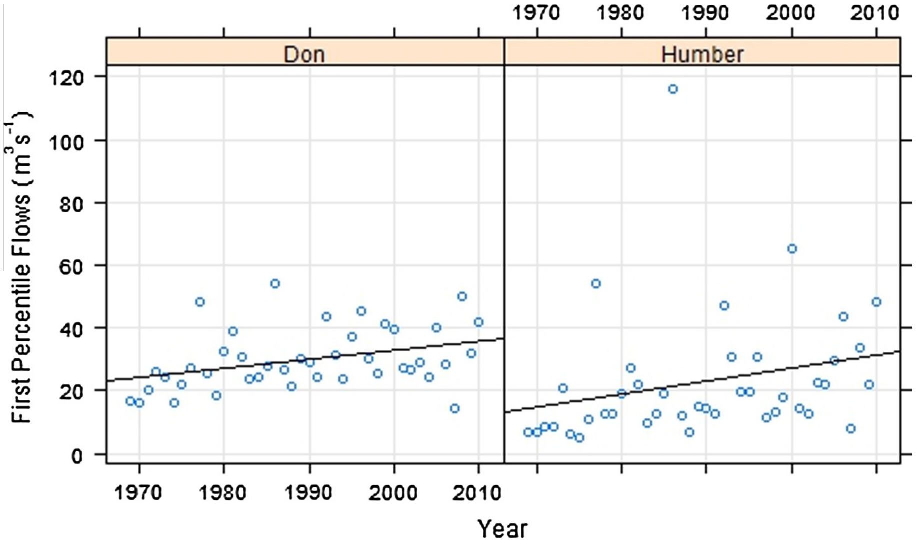

Fig. 4. Top one percentile of flows. Time series of first percentile flows with simple linear trend line indicated.

Table 2
Comparison of actual flow and modeled flow for pairs of years with similar rainfall spanning 27–36 years of the historical record.

Watershed	Year 1	Year 1 rain (mm)	Actual year 1 flow (mm/season)	Modeled year 1 flow (mm/season)	Year 2	Year 2 rain (mm)	Actual year 2 flow (mm/season)	Modeled year 2 flow (mm/season)	Actual% increase in flow	Modeled% increase in flow
Don	1969	279	111	102	2005	272	156	138	40	35
Don	1971	268	111	101	2006	270	117	138	5	38
Don	1981	476	170	176	2008	474	243	223	43	27
Don	1982	442	159	167	2009	445	189	214	19	28
Humber	1969	279	38	38	2005	272	62	52	64	35
Humber	1971	268	36	38	2006	270	52	52	43	38
Humber	1981	484	64	67	2008	474	87	84	36	25
Humber	1982	438	73	62	2009	445	98	81	33	29

σ^2_{0DON}, L.Ratio = 21.2, $p < 0.0001$). Table 2 summarizes actual and modeled flow for pairs of years with similar total rainfall.

Based on the estimated effect of year, flow (standardized by watershed area) has increased annually by approximately 1 mm per season (May 26th and November 15th) from 1969 to 2010, independent of total rainfall (increase estimated as the antilog$_{10}$ of 0.0039).

3.3. Event (rising limb) flows

Density plots of rising limb event flows in the Don and Humber (Figs. 5 and 6) indicate that earlier years (1969 and 1971) showed much more peaked distributions (greater maxima, smaller variance) compared to later years. Trends with year in moments of the distribution of event flows indicate increasing means and standard deviations in both watersheds (Table 3).

Over time, peak event flows increased in both watersheds. In the Don in the 1970's (1969–1979), 80% of event flows were equal to or less than 2.7 $m^3 s^{-1}$ (std. deviation 0.7 $m^3 s^{-1}$) on average; by the 2000's (2000–2010), the decadal average had increased to 4.8 $m^3 s^{-1}$ (std. deviation 1.6 $m^3 s^{-1}$), (ANOVA multiple $R^2 = 0.23$, $p = 0.0047$; Kruskal–Wallis test results consistent at $p = 0.004$) (Fig. 7).

Similarly, in the Humber in the 1970's, the 80RLE was equal to or less than 3.5 $m^3 s^{-1}$ (std. deviation 0.8 $m^3 s^{-1}$) on average; by the 2000's, it had increased to 6.5 $m^3 s^{-1}$ (std. deviation 3.7 $m^3 s^{-1}$). A Mann Kendall test on 80RLE by year, with total rain as a covariate, indicates an annual increase in the Don of 0.06 $m^3 s^{-1}$ (MK Partial Score316.7, $p = 0.0001$) and in the Humber, an annual increase of 0.07 $m^3 s^{-1}$ (MK Partial Score 252.9, $p = 0.002$), consistent with the magnitude of decadal changes identified in the ANOVA and increases in mean event flows. However, as indicated by the ANOVA and Fig. 7, the cumulative change in 80RLE was not uniform by year.

In the Don, there is a statistically significant ($p = 0.05$) increase in the ratio of 80RLE to median flow between the 1970's and each of the other decades. In the 1970's, the rate below which 80% of event flows occurred was 1.5 times higher (std. deviation 0.3) than the median flow; in the 2000's, for example, this ratio was 2.3 times higher (std. deviation 0.6); (ANOVA $R^2 = 0.28$, $p = 0.0013$; Kruskal–Wallis test results consistent, $p = 0.002$). Similarly, in the Humber, the ratio of 80RLE to median flow was significantly different between the 1970's and each of the other decades. In the 1970's the ratio was 1.6 (std. deviation 0.4) and in the 2000's, it was 2.4 (std. deviation 0.9); (ANOVA $R^2 = 0.25$, $p = 0.0032$; Kruskal–Wallis test results consistent, $p = 0.0021$).

An ANOVA comparison of other decades for both watersheds indicates no significant difference among decades for the ratio of 80RLE to median flows (Fig. 8), including the 1980's, 1990's and 2000's ($p > 0.6$ for all comparisons in both watersheds). With the high variability of event flow responses, no definitive conclusions can be drawn about monotonic increases in decadal trends in ratio of peak event flows to median flows since the 1980s.

A Mann Kendall analysis of flow range (maximum event flow minus minimum flow) with year, with total rain as a covariate, for the Don indicates an increase of 1.1 $m^3 s^{-1}$ per year (MK

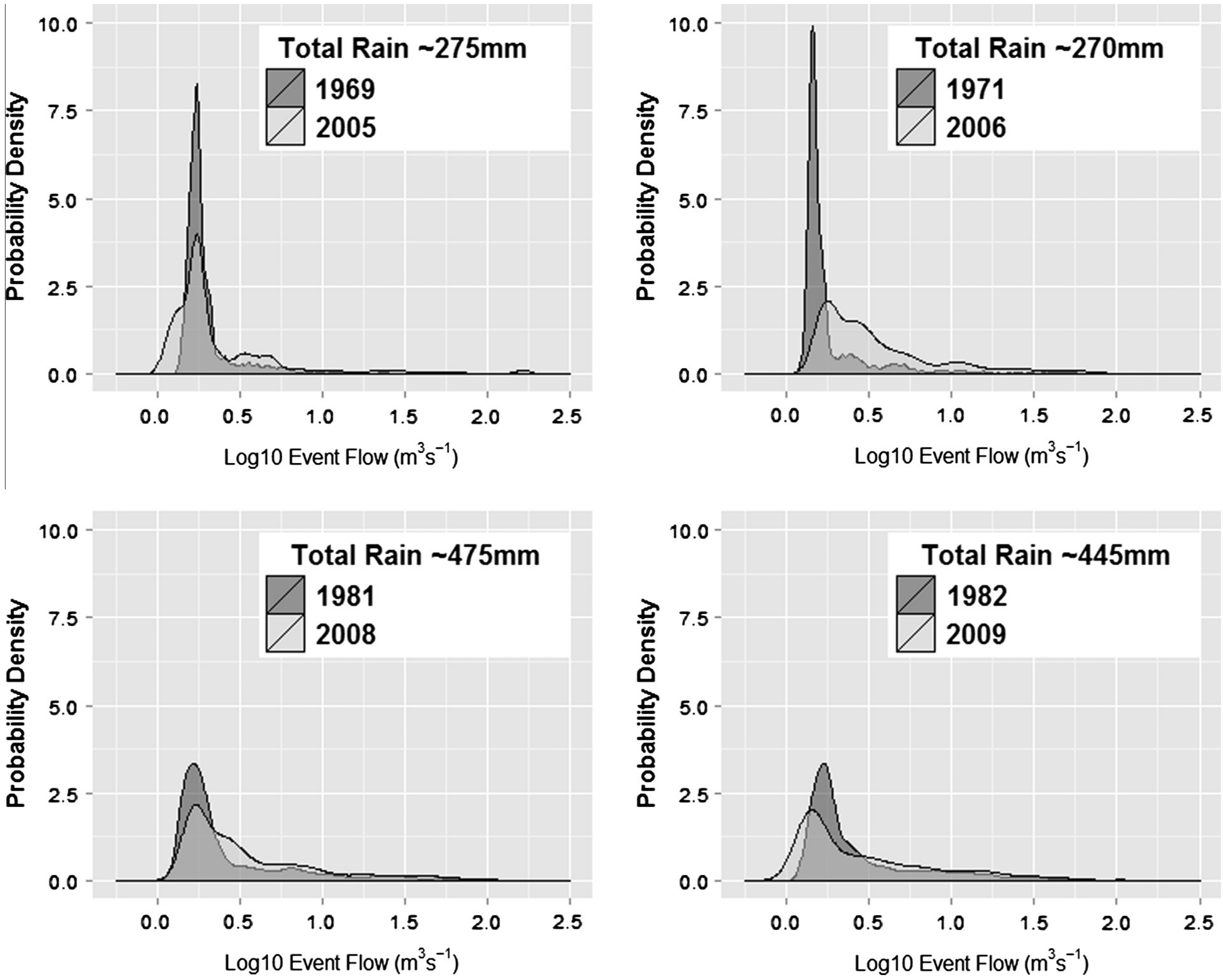

Fig. 5. Don River event flow probability density distributions for 4 pairs of early and late period years with similar total rainfall. In 1969 and 1971, rising limb event flows were most likely to be between about 1.3 $m^3\,s^{-1}$ and 2.4 $m^3\,s^{-1}$ (converted from the $\log_{10}$ scale) with maximum flows of 51.6 $m^3\,s^{-1}$ and 84.8 $m^3\,s^{-1}$ respectively; by 1981, event flows occur within a less predictable and broader range, with event flows occasionally exceeding 140 $m^3\,s^{-1}$ (converted from the $\log_{10}$ scale) within a 15 min interval. The figure plots pairs of years with similar total rainfall and low rates of missing records.

Partial Score 197.3, $p = 0.019$) and for the Humber, an increase of 0.8 $m^3\,s^{-1}$ per year in the flow range (MK Partial Score 202.9, $p = 0.022$).

3.4. Event flow acceleration

Density plots of rising limb event flow acceleration in the Don and Humber (Figs. 9 and 10) indicate that earlier years (1969 and 1971) showed more peaked distributions compared to later years. Trends in the moments of distribution (Table 4) indicate increasing mean accelerations and increasing standard deviations of acceleration in both watersheds. An ANOVA of $\log_{10}$ mean acceleration by decade indicates significant differences between the 1970's and each of the two more recent decades (1990's and 2000's), with mean accelerations in the Don 2.0 times higher in 2000's ($p = 0.0012$) compared to the 1970's (4.4e−04 $m^3\,s^{-2}$ in the 1970's to 8.8e−04 $m^3\,s^{-2}$ in the 2000's, ANOVA $p = 0.0012$) and in the Humber 2.3 times higher (1.4e−04 $m^3\,s^{-2}$ in the 1970's to 3.2e−04 $m^3\,s^{-2}$ in the 2000's, ANOVA $p = 0.0030$). Kruskal–Wallis non-parametric tests confirm significant differences between at least two decades (Don $p = 0.0036$; Humber $p = 0.0048$).

A Mann Kendall analysis of event flow acceleration with year, with total rain as a covariate, for the Don indicates an increase of 0.15e−04 $m^3\,s^{-2}$ per year (MK Partial Score 385.1, $p = 5.2\text{e}{-06}$) and for the Humber, an increase of 0.06e−04 $m^3\,s^{-2}$ per year in the flow range (MK Partial Score 324.5, $p = 9.8\text{e}{-05}$). A decadal time series plot conveys the differences in event flow response over time within the two watersheds (Fig. 11). A decadal time series plot of rising limb event acceleration-to-peak flow conveys the change in acceleration in context of changing event flows with higher peak flows and higher accelerations (Fig. 12).

3.5. Substitution of urban extent for year (Don watershed)

A simple linear regression to estimate $\log_{10}$ total flow (mm/year) in the Don with $\log_{10}$ total rainfall (mm) ($\beta_1 = 0.81 \pm 0.08$, $t = 9.75$, df = 39, $p = 5\text{e}{-12}$) and minimum urban area (km^2) ($\beta_2 = 0.0013 \pm 0.0003$, $t = 4.65$, df = 39, $p = 4\text{e}{-05}$) has $R^2 = 0.720$, $p = 6.2\text{e}{-12}$, and residual SE = 0.059. For comparison purposes, the same model structure with $\log_{10}$ total rainfall (mm) ($\beta_1 = 0.78 \pm 0.08$, $t = 9.63$, df = 39, $p = 7.4\text{e}{-12}$) and year ($\beta_1 = 0.0036 \pm 0.0007$, $t = 4.90$, df = 39, $p = 1.75\text{e}{-05}$) has $R^2 = 0.731$, $p = 2.97\text{e}{-12}$, residual SE = 0.058. Thus year explains about 1% more variation than minimum urban area using the same model structure. A model using only $\log_{10}$ total rainfall (mm) as an independent variable ($\beta_1 = 0.76 \pm 0.10$, $t = 7.53$, df = 39, $p = 3.5\text{e}{-09}$) has $R^2 = 0.576$,

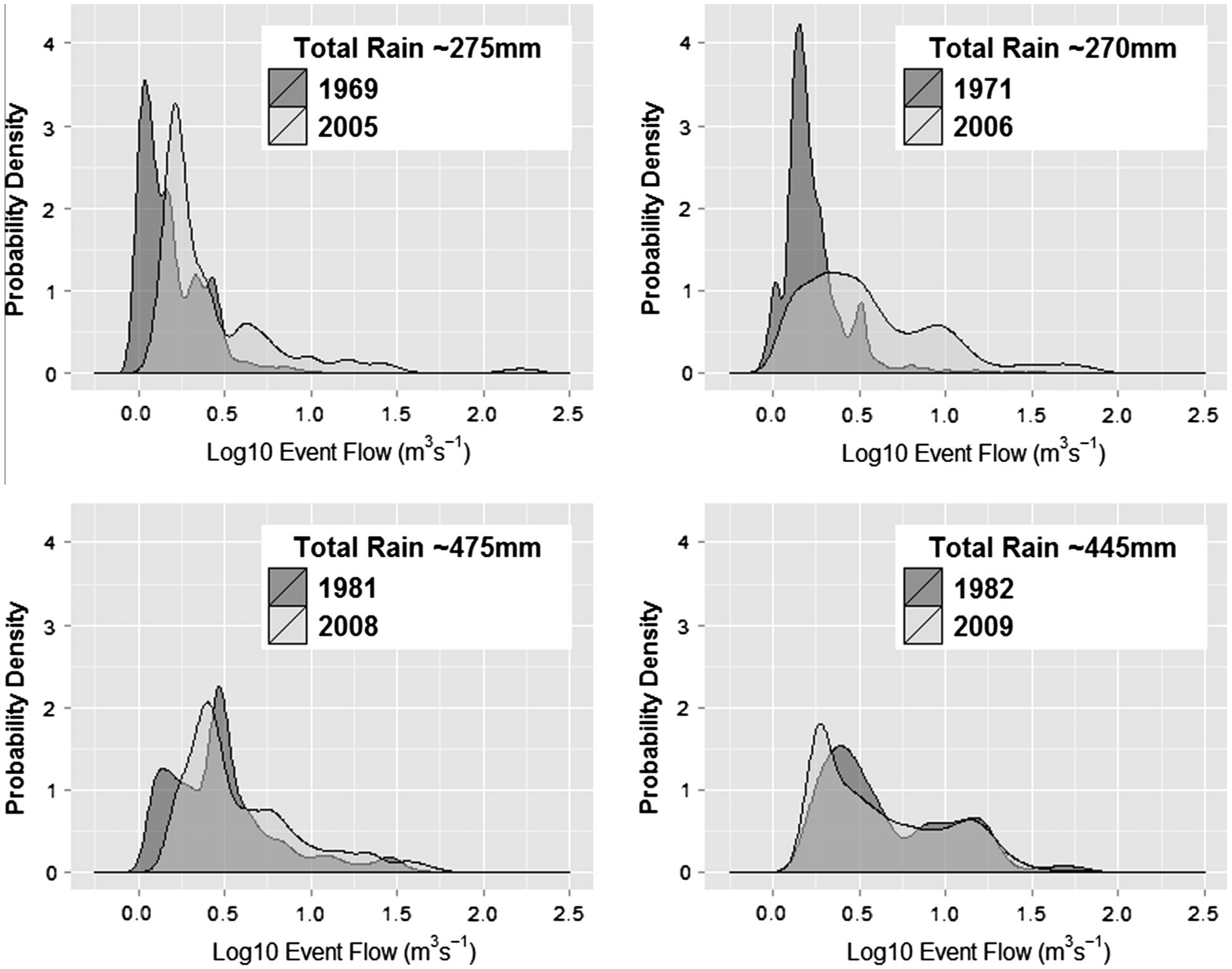

Fig. 6. Humber River event flow probability density distributions for 4 pairs of early and late period years with similar total rainfall. In 1969 and 1971, most rising limb event flows were less than 2.5 $m^3 s^{-1}$ (converted from the log_{10} scale); in 1981 and later years, event flows occur over a higher and less predictable range. The maximum event flow in 1969 is 17.4 $m^3 s^{-1}$; in later years plotted (1981–2006), maximum flows are between 47.6 $m^3 s^{-1}$ and 204.9 $m^3 s^{-1}$. The figure plots pairs of years with similar total rainfall and low rates of missing records.

Table 3
Results for non-parametric Thiel–Sen estimate of slope, with confidence intervals, for moments of the distribution of rising limb event flows (in $m^3 s^{-1}$) at 15 min intervals, on year.

Watershed	Moment	Slope (Upper Confidence Interval (CI), Lower CI)	Summary
Don	Mean	0.06 (0.02, 0.09)	Increasing
	St. Dev.	0.14 (0.06, 0.23)	Increasing
	Skew	−0.03 (−0.07, 0.01)	No Trend
	Kurtosis	−0.37 (−1.01, 0.19)	No Trend
	Coefficient of variation	0.55 (−0.26, 1.36)	No Trend
Humber	Mean	0.06 (0.02, 0.11)	Increasing
	St. Dev.	0.12 (0.06, 0.21)	Increasing
	Skew	−0.04 (−0.08, −0.01)	Decreasing
	Kurtosis	−0.48 (−1.07, −0.14)	Decreasing
	Coefficient of variation	1.31 (0.38, 2.33)	Increasing

$p = 3.51e{-}09$, residual SE = 0.072. The addition of year or minimum urban area as an independent variable in the respective models explains about 13% and 12% additional variation, respectively.

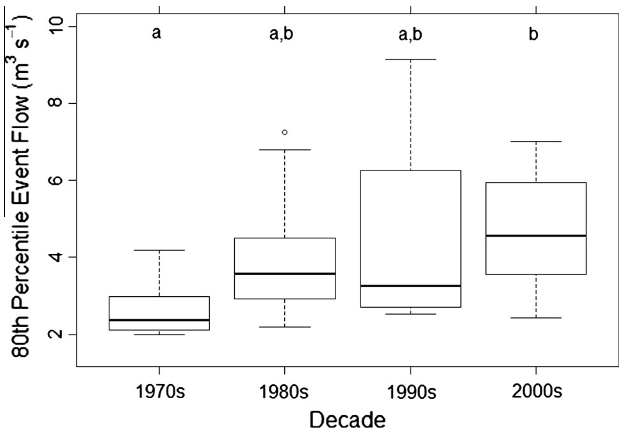

Fig. 7. Boxplots of Don River 80RLE by decade. ‘a’ and ‘b’ indicate Tukey multiple comparison results. Heavy horizontal lines are means; boxes indicate 25th and 75th percentiles and whiskers extend to 1.5 times the interquartile range for the mean.

4. Discussion

In this discussion, we first address the results in context of potential confounding issues of rainfall trends, data quality and

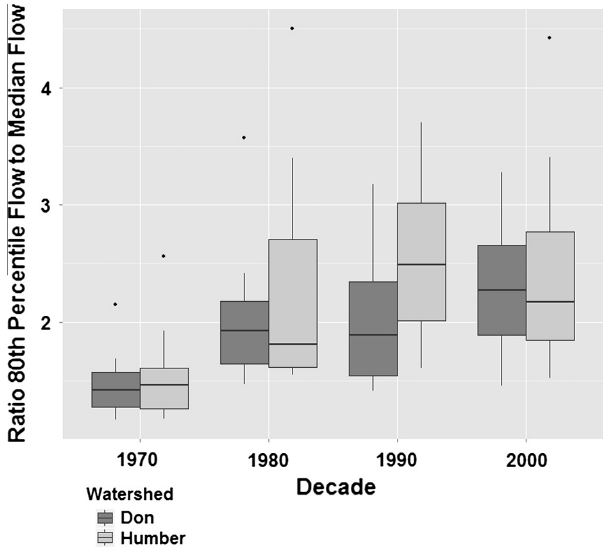

Fig. 8. Ratio of 80th percentile flows to median flow for the two watersheds. Heavy horizontal lines are medians; boxes indicate 25th and 75th percentiles and whiskers extend to 1.5 times the interquartile range for the median.

issues outside the scope of study. Following this, we discuss the implications of the results.

4.1. Results in context of potential confounding issues

In this study, the collective evidence from available rain gauges indicates there have been no statistically significant changes in precipitation patterns (rainfall depth, intensity and frequency) between 1969 and 2010 that could account for the observed changes in stream flow. The number of records decreases significantly with year, as does the number of hours with zero rainfall but there is no trend in total hours with rain. A decline in the number of records with year is unsurprising, given the decline in stations with time. The 90th percentile record was consistently zero for all stations, so a decrease in the number of records (and stations) will most readily impact the number of zero rain hours. Thus, these statistically significant trends appear to reflect the number of rain records rather than a trend in rainfall itself. This conclusion is supported by the lack of trend in any other variable assessed, with the exception of an increase in the regional trend for hours with rain in class interval 40–30 mm. There is no statistically significant decrease in another class interval so, as an isolated statistically significant result, it may be the chance generation of a statistically significant outcome when multiple tests are run (Livezey and Chen, 1983). Rain station MSC6158350/6158355 can be used to represent rainfall within the two catchments of interest as no effect of proximity to Lake Ontario on rainfall was detected.

Changes in snowpack do not contribute to the identified hydrologic trends during the May to November period. An increasing trend in snowpack would have confounded an analysis of temporal trends during the season of interest.

The rain storm literature for this region is consistent with our finding of no trend over time. There is little peer reviewed literature for the applicable time period, possibly because there is no trend in rainfall to report. Trends in more recent rainfall records, or over longer time periods (e.g. Karl and Knight, 1998), may be emerging but have no statistical relevance for the present study of temporal trends in flow from 1969 to 2010.

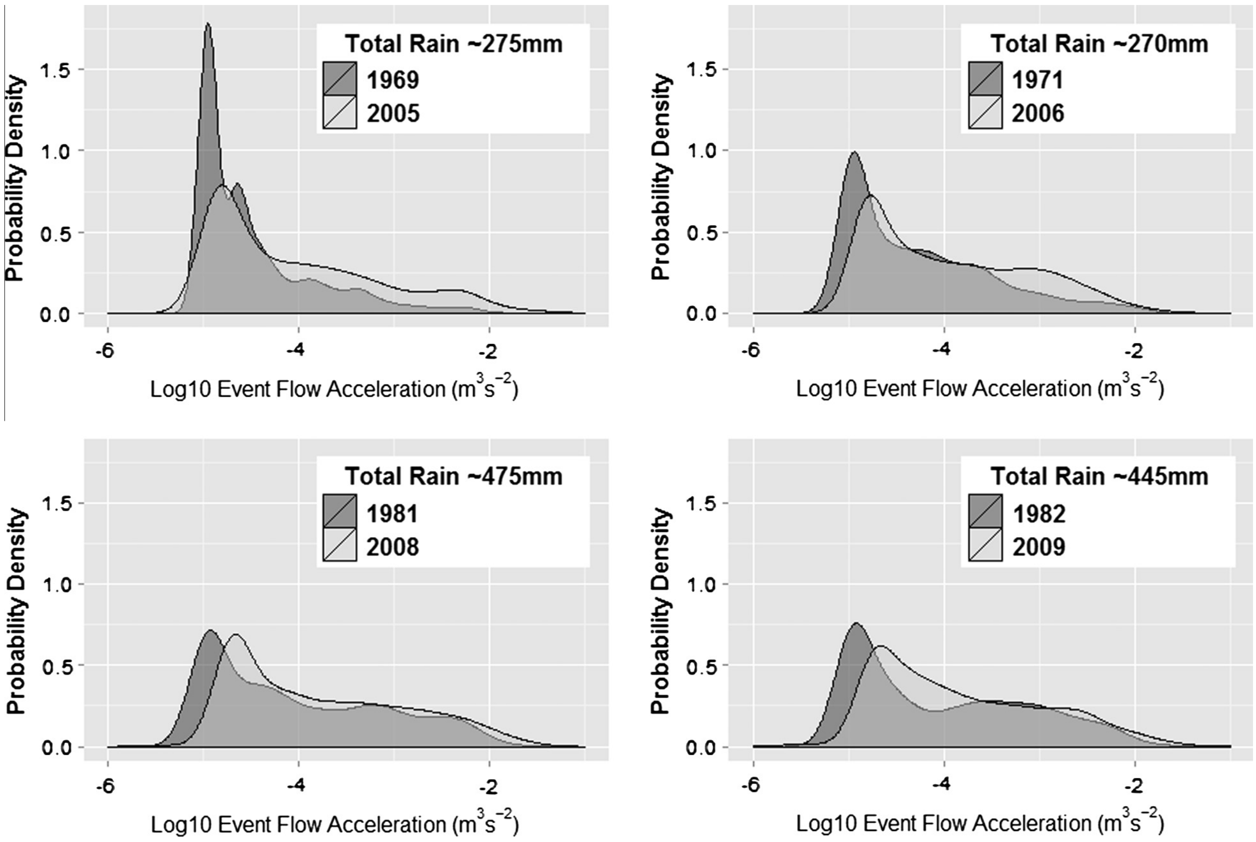

Fig. 9. Don River rising limb event flow acceleration probability density distributions for 4 pairs of early and late period years with similar total rainfall, for accelerations greater than zero. The figure plots pairs of years with similar total rainfall and low rates of missing records.

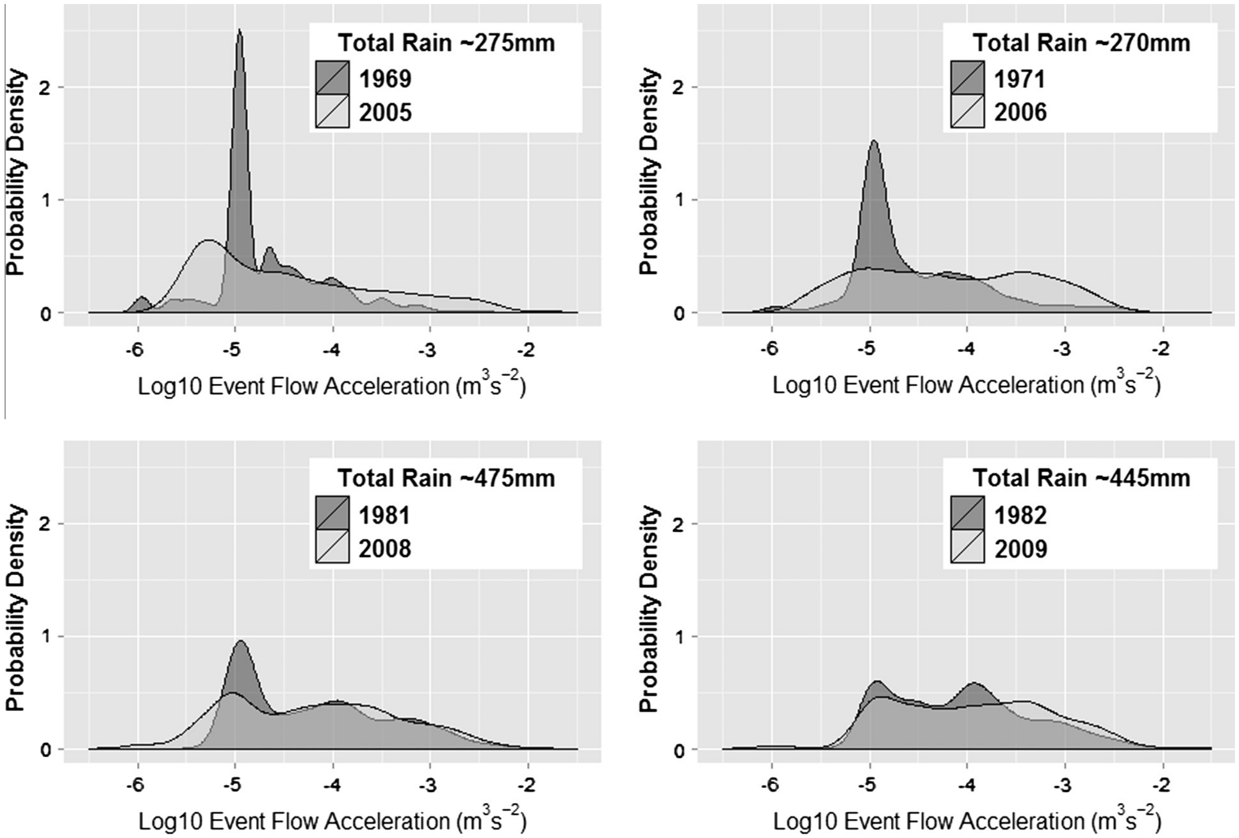

Fig. 10. Humber River rising limb event flow acceleration probability density distributions for 4 pairs of early and late period years with similar total rainfall, for accelerations greater than zero. The figure plots pairs of years with similar total rainfall and low rates of missing records.

Table 4
Results for non-parametric Thiel–Sen estimate of slope, with confidence intervals, for moments of the distribution of positive flow accelerations (in $m^3 s^{-2}$) during the rising limb of rain events, on year.

Watershed	Moment	Slope (Upper CI, Lower CI)	Summary
Don	Mean	0.15e−04 (0.09e−04, 0.22e−04)	Increasing
	St.Dev.	0.37e−04 (0.22e−04, 0.54e−04)	Increasing
	Skew	−0.02 (−0.07, 0.03)	No Trend
	Kurtosis	−0.32 (−1.11, 0.48)	No Trend
	CV	−0.78 (−2.56, 0.69)	No Trend
Humber	Mean	0.06e−04 (0.03e−04, 0.09e−04)	Increasing
	St.Dev.	0.11e−04 (0.01e−04, 0.18e−04)	Increasing
	Skew	−0.08 (−0.16, −0.01)	Decreasing
	Kurtosis	−1.19 (−2.73, 4.5e−03)	No Trend
	CV	−1.92 (−3.95, 0.45)	No trend

The question of data accuracy must also be addressed in a discussion of rainfall-flow trends. Rain gauge measurements are subject to inaccuracies of the equipment and event characteristics, such as strong winds. However, the length of the 42-year record helps to offset inaccuracies introduced by anomalous records. The rainfall gauge equipment at MSC6158350/6158355 was changed in 2002, potentially introducing systematic differences in rainfall readings. Trends in flow relative to rainfall were detected in years and decades prior to and including the 2000s; systematic rain gauge error post-2002 would change the quantification of the trends but not the overall conclusions reached that flow trends relative to rainfall were detected. Convective storms in the upper reaches of the watershed may not have been captured by the single rain gauge location with a long term record. With respect to the flow level readings, for the Ontario ‘instantaneous’ flow dataset, ~99% (Arsenault and Thompson, 2010) of the records fall within the best accuracy category, which means the “daily mean discharge calculated with the instantaneous data from this day is identical to the published value plus or minus one tenth of the trailing significant digit.” (Arsenault and Thompson, 2010, p.121). The length of flow record and the comparable total flow results in two watersheds provide additional assurance that detected trends are not the result of flow gauging equipment error.

A limitation of the database is that precipitation records outside the May 26th to November 15th window are excluded, although antecedent winter snow statistics indicate no significant trends. The timing of spring freshet was not examined and may contribute to unexplained variation in the statistical models by influencing landscape response to rainfall in May and June. The statistical model results are consistent enough among years, and the May to November period long enough each year, to have confidence that the trends detected during the period examined are not a result of phenomena occurring strictly outside the seasonal time interval examined.

4.2. Implications of results

Despite data limitations, it can be concluded that growing season flows have increased with time in the Don and Humber Rivers and that there is no trend in rainfall to explain this increase. An increase of about 1 mm per season over 42 years is substantial. Cumulative changes in event flows are also substantial, with rising limb flows increasing in each river approximately two-fold over four decades, or roughly 0.1 $m^3 s^{-1} yr^{-1}$. In addition to increased event flows, from the earliest decade to the most recent, the variability of event flows increased more than two-fold in the Don and almost five-fold in the Humber. Event flow accelerations increased

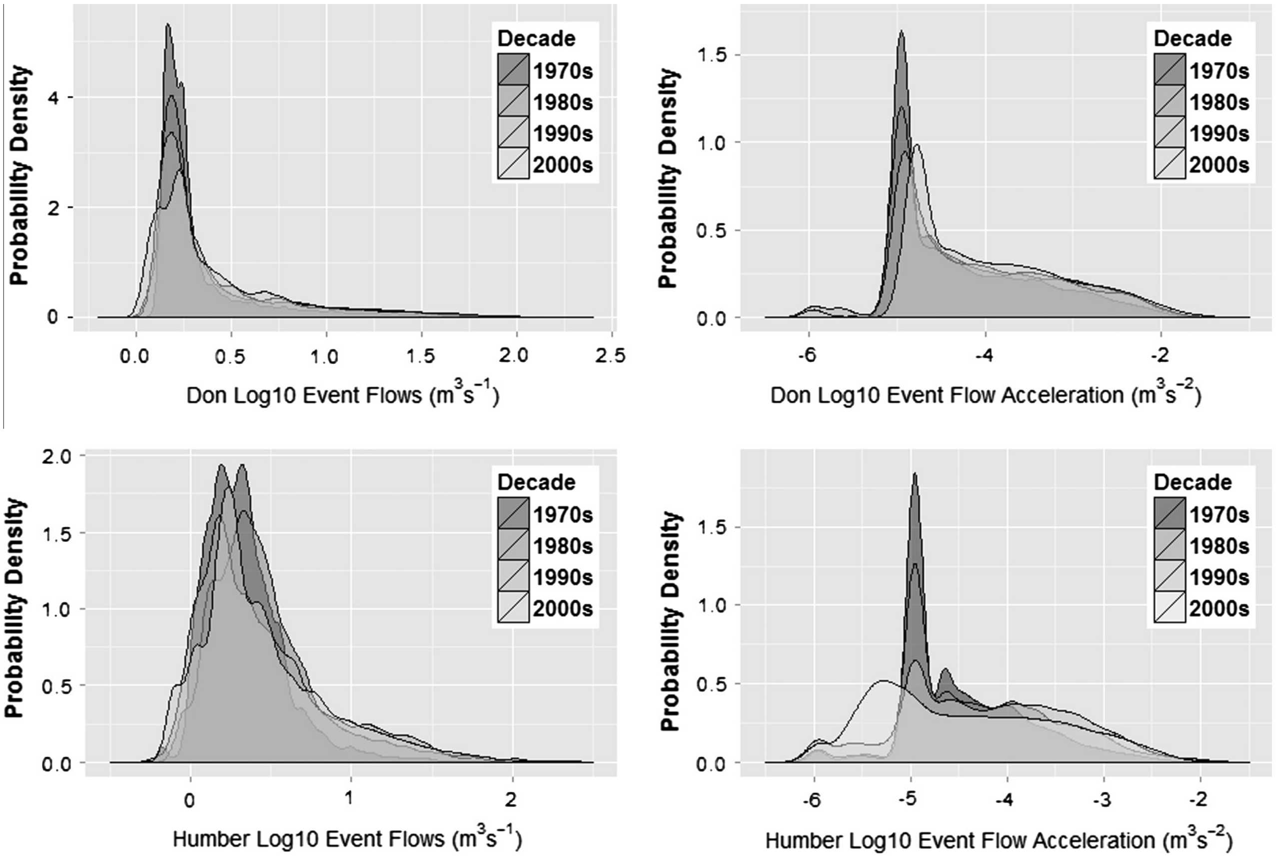

Fig. 11. Decadal time series for rising limb event flows and event flow accelerations for the Don and Humber watersheds. As indicated by the statistical models, the change in event flow response in the Don is more consistent through time than the response in the Humber.

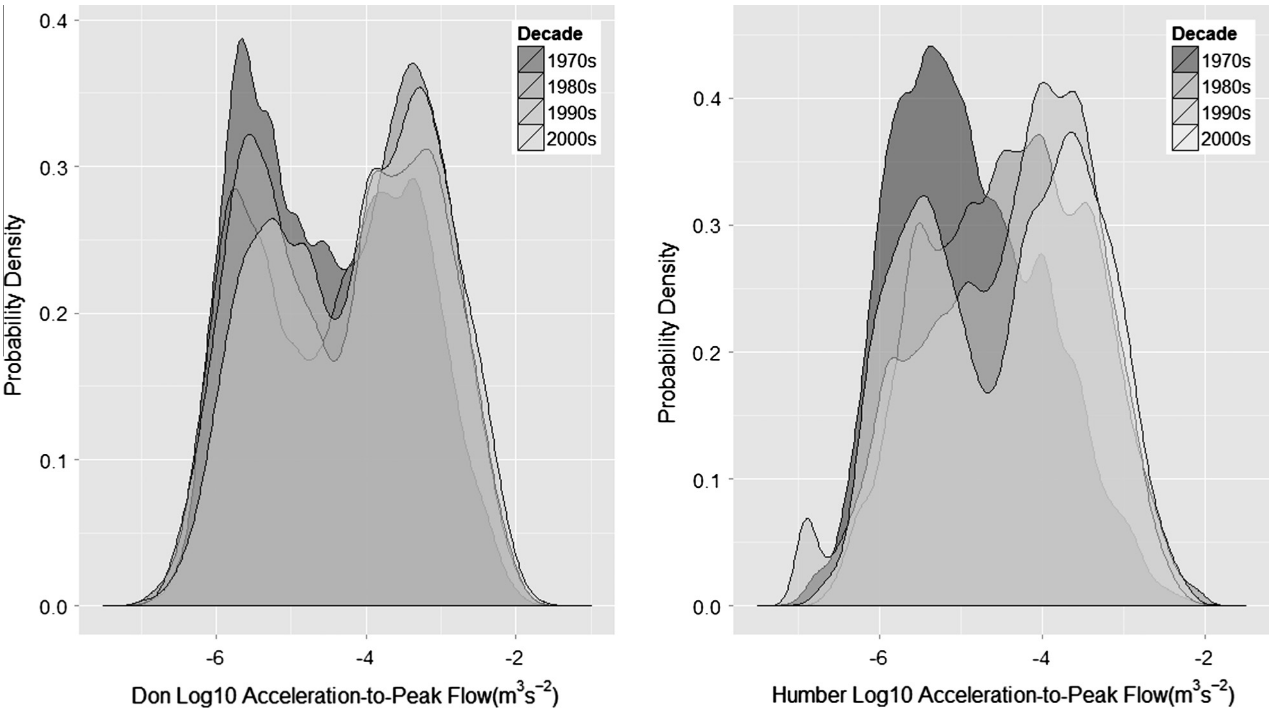

Fig. 12. Decadal time series for event flow acceleration-to-peak for the Don and Humber watersheds. Acceleration-to-peak during the rising limb of events was calculated as the change in flow rate between each 15 min flow record and the event peak flow rate for each event, divided by the intervening time (for units in $m^3\ s^{-2}$). This density plot indicates event accelerations in context of event peak event flow rates. As indicated by the shift along the *x*-axis with decade, accelerations and peak event flows have increased with time.

roughly 2-fold in both rivers. The moments of distribution for flow acceleration in the Humber indicate changes in flow regime that can be most readily characterized as more variable than earlier decades. The magnitude of flow fluctuation (Konrad and Booth, 2005) and increased response of event flows relative to median flows (Gibbins et al., 2001; Clausen and Biggs, 1997) in the Don and the Humber are indicators of flow disturbances that have been associated with effects on aquatic biota.

Results for the Don River indicate that an increase in high event flows was off-set by a corresponding increase in low event flows, thus there was no trend in skew for rising limb event flows. This response is consistent with an increasingly impervious watershed that is more sensitive to small rain events and, concurrently, generates more extreme high flows. In contrast, the trends in moments of distribution for event flows in the Humber are consistent with a watershed that is experiencing higher flows with time, but is not yet experiencing increased low flow responses.

This study examined aspects of magnitude, frequency and rate of change of flow conditions, all of which indicate significant changes with time. The empirical predictive models and statistical moments indicate these mainstem rivers are now experiencing chronically perturbed flow regimes and that the degree of perturbation has increased with time. In addition to aquatic biota, these perturbations also have potential implications for flood risk assessment and management, especially in consideration of expected future increases (e.g. Grillakis et al., 2011; Palynchuk, 2012) in rain event intensities with climate change.

Although significant trends in flow regime are detected with year, other mechanisms are responsible for these changes, not time itself. Potential causal factors for flow regime changes over the 42-year period include: increased impervious land cover (Schueler et al., 2009); loss of wetlands and other natural water storage capacity (Hümann et al., 2011); changes in surface water-groundwater exchange (Barron et al., 2013; Ryan et al., 2010); reduced vegetative cover (Raymond et al., 2008; Costa et al., 2003); drainage infrastructure changes (such as increased drainage efficiency through engineered infrastructure) (Navratil et al., 2013); changes in evaporative demand within the watershed (Tomer and Schilling, 2009), possibly complicated by heat island effect (Adamowski and Prokoph, 2013). Lower impervious land cover in more recent peri-urban subdivisions (Aichele and Andresen, 2013) and efforts to apply low impact development stormwater management techniques (Hood et al., 2007) may alter the relationship of urban land use to flow response in more recent years. Climate-related changes, such as increased evapotranspiration may also be effecting change in flow patterns (Grillakis et al., 2011). The empirical, cumulative effect on runoff generation and mainstem river flow regimes identified in this study may result from one, or a combination of several, of these factors.

Although only four data points were available to estimate minimum urban area over the time period, the fit of the statistical model for total flow explains almost the same variation as the model with year (difference in $R^2 = 0.01$). This result is consistent with a hypothesis that mechanistic factors associated with increasing urban area explain the increase in total flow within the four decade timeframe. Our empirical model results also corroborate spatially-distributed simulated hydrologic modeling results (using MIKE-SHE and MIKE 11) reported by Chu et al. (2013) that show increases in high flow frequencies with increasing urbanization. Further empirical research is warranted to assess whether or not urban extent ultimately explains more variation than year or whether other temporal factors should also be examined to explain the trends.

Climate modeling studies predict rainfall intensity will increase and severe rainfall events will become more frequent (e.g. Grillakis et al., 2011), including within the Toronto region (Palynchuk, 2012). These changes will necessitate revision of urban infrastructure design standards (e.g. Willems, 2013; Langeveld et al., 2013) and influence multiple aspects of water-dependent ecosystems (Barron et al., 2012). Studies have estimated the respective contributions of changes in climate and changes in land use (e.g. Peña-Arancibia et al., 2012; Tu, 2009; Raymond et al., 2008). Our results indicate that hydrologic stationarity within the Don and Humber watersheds has been compromised by urbanization over the past four decades. As the loss of climatic stationarity progresses (Milly et al., 2008), studies of contemporary urban flow regime change will also need to consider the contributions of both urbanization and climate change to fully understand observed trends in event-scale hydrologic response.

5. Conclusions

The present study begins to characterize flow regime changes associated with urbanization using high resolution flow data. The results can be used to: (1) assess the limitations of coarser resolution data in defining flow regime changes; (2) to assist hypothesis development regarding mechanistic causal factors associated with shifts in urban aquatic biodiversity; and, (3) assist in differentiating between loss of hydrologic stationarity associated with climate-induced change and hydrologic shifts attributable to urbanization.

Our findings demonstrate that long-term high temporal resolution mainstem flow patterns can be used to identify significant changes in event flow regimes, including peak event flows, rising limb flows and event flow accelerations, within urbanizing watersheds. These changes are indicative of marked cumulative hydrologic impacts of land cover change during a four decade period prior to detectable alterations in rainfall patterns. The results also point toward research opportunities to identify potential causal mechanisms associated with chronic alteration of event flows and flow accelerations that may contribute to reduced aquatic biodiversity in urbanized watersheds. In light of these results, a precautionary approach is warranted with respect to further hardening of the Don and Humber watershed land surfaces to protect aquatic communities and in consideration of increased flood risks. Overall, the results warrant further research into potential strategies for mitigating physical and biological damage to streams and floodplains within urbanizing watersheds.

Acknowledgements

The authors gratefully acknowledge Tom Arsenault (EC) and James Duncan (TRCA) for responding to data requests and follow-up questions; Pete Thompson for watershed shape files and discussion of his research; Junchi Li for assisting with Fig. 1; C. Scott Findlay, Doug King and Antoine Morin for review of an earlier draft; and, two anonymous reviewers. Funding for M.P. Trudeau's research through Carleton University scholarship and contributions from Environment Canada's research assistant program are gratefully acknowledged. Funders had no role in scoping or undertaking this study.

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