Historical Trends In Short Duration Rainfall In The Greater Toronto Area

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1.0 Introduction

Recent short duration intense rain storms have caused significant problems in the Toronto area in the last few years. Research into greenhouse gas induced climate change has predicted an increase in the intensity of such storms (IPCC, 2000) leading to speculation that the recent storms are evidence of the effect of climate change in the Toronto area. This project attempts to examine this possibility by looking for trends in short duration extreme rainfall in the historical records of climate stations in the Toronto and surrounding area. The existence of such evidence would support the conclusion that the short-duration rainfall climate of Toronto has changed in a manner consistent with global climate change and add weight to arguments that planning for infrastructure changes must proceed rapidly to deal with these changes plus provide insight into the magnitude of expected changes.

This study is proceeding in parallel with a study to examine climate records in the Toronto area for evidence of changes in historical records of other climate parameters such as temperature, daily rainfall and snowfall etc. (Mirza, in preparation). In addition, previous studies have examined evidence of historical changes in Canadian precipitation. Mekis and Hogg (1999) found that daily precipitation over much of Canada has increased over the last century but that the increase was generally associated with an increase in the frequency of events rather than an increase in intensity of events. Stone et al (2000) presented evidence that precipitation intensity had increased in selected areas of Canada while Vincent and Mekis (2006) found increases in the number of days with precipitation but a decrease in daily precipitation intensity. This study will focus on possible changes in the greater Toronto area in short duration (< 24-hour) monthly and annual extreme rainfall.

2.0 Methodology

Monthly and annual extremes of rainfall intensities for durations of 5 minutes, 1 hour, 6 hours and 12 hours were examined in Environment Canada intensity-duration-frequency (IDF) data from meteorological stations that record short-duration rainfall. Data for all available stations within 150 km of Toronto were obtained but trends were only examined for records with 30 or more years of data in the period of record for each station ending in 2003 (Figure 1) in order to ensure statistical relevance. It is important to note that trend analysis was only conducted to the year 2003, as Environment Canada IDF data products have not been updated since that time. Since the most intense events occur in the warmer months and many short-duration rainfall stations are only operated in snow-free periods, only trends for the months of April through October were included.

Only stations with tipping-bucket recording gauges provide data for durations less than 1-day. Instrumentation and observing practices in the Canadian tipping-bucket program were quite consistent during the 20th century so the data were not adjusted for changes in the data collection program over the period. Prior to 1998 tipping-bucket data were adjusted so that daily totals matched total rain as measured at co-located standard rain gauges but this practice was abandoned for data collected recently. No adjustment was made to the data to account for this change which may introduce inconsistencies in the data from the final 5 years of the trend analysis.

Data are available for durations of 5-minutes, 10-minutes, 15-minutes, 30-minutes, 1-hour, 2-hours, 6-hours, 12-hours and 24-hours in the short-duration rainfall records. It was assumed that analyzing trends for all of these durations would produce repetitious results but it was desirable to examine results for durations representative of all the scales of meteorological events that are significant for the capacity of urban hydrological structures. Events of 5-minutes were included to sample the most intense rainfall periods within invidual thunderstorms, 1-hour events to sample severe individual thunderstorms, 6-hour events to include organized systems of thunderstorms (mesoscale convective complexes) and 12-hour events to ensure inclusion of heavy convective events embedded within larger synoptic scale systems.

The largest amounts for the durations of interest for each month and for the year at each station were extracted and time series created. Monthly extremes in addition to the annual extremes were examined to determine whether changes in monthly extreme rainfall climate may be occurring even when changes in annual extremes have not occurred. This would be consistent with observed changes in other climate parameters, which have been concentrated in the colder months of winter, spring and fall (IPCC, 2000).

To explore changes in the frequency of large events and to examine possible changes in the magnitude of events less than the largest of each month or year, all events for each duration which exceeded the 75th percentile event were extracted and time series of the number of such events were created for each station by month and year.

The design of structures sensitive to extreme short-duration rainfall is dependent on the calculated probability of occurrence of the event usually expressed as the magnitude of the return period amount. In Canada, this return period amount is determined using the full period of record of data from stations in the vicinity of the proposed structure assuming a Fisher-Tippet type I (Gumbel) distribution. Any change in the estimated return period amount will have a direct impact on the safety of existing structures and the design of new ones. The calculated return period amount is a function of both the mean of annual extremes and their standard deviation. It was considered important to evaluate any trend in calculated return period amounts. This was done by calculating the 10-year return period amount for each station based upon a 10-year moving window in the time series of data. This yielded an estimate of the 10-year return period amount for every year of data starting in the 10th year of data at the station. These estimates were used to create a time series of return period amounts to be used to investigate trends in the computed probabilities of extreme short-duration rainfall at each station with sufficient data.

Another climate parameter affecting the runoff from extreme events is the amount of moisture in the soil when the extreme event occurs. This parameter is not usually measured directly but can be estimated by looking at the amount of rain that has occurred in the days prior to the event. To look for trends in this antecedent moisture, rainfall totals for the 10 days prior to each monthly and annual extreme were computed and time series of antecedent rainfall were created on monthly and annual bases for each station by identifying the date of the first occurrence of the monthly/annual extreme using the tipping bucket data and accumulating the 10-day rainfall from the preceding 10 days of the daily rainfall record at the same location.

Trends in all of the time series were assessed using the MAKESENS 1.0 freeware from the Finnish Meteorological Service (Salmi et al., 2002). This software uses the non-parametric Mann-Kendall test for testing the presence of monotonically increasing or decreasing trend (see eg. von Storch and Zwiers, 1997) and the non-parametric Sen's test for estimating the slope of the trend and the associated confidence limits of the slope. In the Sen's method, the slope estimate is obtained by determining the slope of all data pairs in the sample and the final slope estimate is taken as the median of these slopes.

Finally, the existence of any spatial patterns in the resultant trends was of interest. Toronto is situated on the shore of Lake Ontario and in the vicinity of the Oak Ridges moraine, a significant terrain feature. Both features are known to affect the local rainfall climate. Any association of trends in extremes with these features was assessed by plotting the trend information on a detailed digital elevation map using GIS software and the results examined for the existence of any patterns.

3.0 Data

The scope of this work required the organization, summary and analysis of two types of climate (rainfall) data: Intensity Duration and Frequency (IDF) and daily data. These data were provided in standard Canadian Daily Climate Data (CDCD) format by the TRCA. Two Microsoft Access databases were created to organize these data, one for IDF data and another for daily data. Each individual station table was then imported into Access using the standard import wizard. When loading the first table of both IDF and daily data Access "specs" were defined using the import wizard and saved in each database, examples can be found in either of the two Access databases in the **Appendix Files** by following the path **DataAppendix\Access**\. Spec column names, widths and types were defined using the record format descriptions for "monthly record of daily data (DLY)" provided by Environment Canada and can be reviewed at the following link http://www.climate.weatheroffice.ec.gc.ca/prods_servs/documentation_index_e.html. These specs were then used on the remainder of the station tables, for both IDF and daily data, to ensure standardized table structure within each of the two databases.

3.1 Standardizing

Next Visual Basic for Applications (VBA) programming was used to format station tables into a structure more suitable for the use of Structured Query Language (SQL) database functions appropriate for this work. Functions used included sum, maximum (max) and count. That said, the default station table format employs unique columns for each day of the month while the aforementioned functions are designed to work on individual columns. Thus, employing said functions would require extensive programmatic work to ensure they include each of the 28-31 days in a month. The addition of a column for day and the transposing of all value data for each day into one column allowed for more efficient use of SQL functions while avoiding additional unnecessary programming. Functions were then easily employed using a single SQL query summarizing the single value column. All VBA code and SQL queries used for this task can be found in **"Sub Normalize Tables()" in the NormalizeStationTables module included in the TRCAMonthlyMax database** in the appendices.

3.2 Organizing, Querying, Summarizing and Formatting IDF Data for Monthly Maximum Analysis

After formatting all station tables, all were joined into one large table using a union query, referred to as the "IDF all station query". All subsequent SQL summaries for monthly maximum and percentile analysis were then performed using the results of this union query. The VBA code and SQL queries used for this task can be found in **"Sub CreateMultiTableSQLString() of the NormalizeStationTables module and the "CreateBigTable" query in the TRCAMonthlyMax database** in the appendices.

This work required maximum value summaries of all stations with greater than 30 years of data existing for the months of April through November and for 5 minute, 1, 6, 12 and 24 hour durations. Additionally, annual summaries were also created for these durations. A combination of VBA scripting and SQL querying were used to perform data manipulation to obtain this information (**see "Sub Create30YearMaxTables()" in the 30YearMonthlyAnalysisTables module of the TRCAMonthlyMax database**). In summary, the results of the IDF all station query were processed sequentially by month to identify those stations with at least 30 years of data. This information was next used in an SQL statement in combination with the MAX function to determine monthly maximum precipitation values for stations with 30 years of data or more. The output of the VBA/SQL script was a number of Access queries by month for a single duration. Therefore, the script was rerun for each duration, manually changing the duration selection criteria for each new duration. Lastly, the data resulting from all output queries were formatted for ease of use in Excel then exported as Excel spreadsheets. An example of the script and the data it produced is provided in "**Sub FormatMaxQueryToExcel()" in the 30YearMonthlyAnalysisTables module of TRCAMonthlyMax.**

3.3 Linear Trend and Mann-Kendall Analysis

Both linear trend and Mann-Kendal analysis were performed for each duration, by month using Excel. Linear trends were graphed using standard Excel graphing functionality with year on the X axis and amount of maximum precipitation on the Y. Trend lines and r^2 values were then added using Excel's graphing trend line function. After honing this process through repetition, an Excel macro was recorded and applied, with minor manual editing, for the remainder of the data. Next, data used for linear trend analysis for each month and duration were manually copied and pasted into the Mann-Kendall spread sheet tool. Mann-Kendall calculations were then completed, again for each duration and month, and summarized by the tool as is shown in the example in the. Lastly, the results of this analysis were further summarized in a table for ease of interpretation This analysis has been provided in Excel file format in the Appendix files and can be accessed by following the path **\DataAppendix\Excel\Max**.

The same processing logic described above for monthly calculations was also applied to create annual calculations, excepting logic used to isolate months. After creating annual maximum queries data were again formatted for excel and both linear trend and Mann-Kendall analysis were performed as described for monthly maximum analysis.

3.4 Organizing, Querying, Summarizing and Formatting IDF Data for Percentile Analysis

Data manipulation for this component of the study was carried out in two main steps. The first step involved the calculation of the 75^{th} percentile value by month and duration. This was done by extracting raw monthly data, by duration, from each station with more than 30 years of data using the IDF all stations query. Data from each station was then copy and pasted into an excel spreadsheet. These data were then analyzed using the Excel percentile function to determine the 75^{th} percentile precipitation value for each duration and month. Each percentile value was then copied into a separate spreadsheet and organized by duration and month. The resulting spreadsheet was then exported to a comma delimited format and imported into Access as a table for use in the following Access based percentile data summary work. Spreadsheets created for this analysis can be found at **\DataAppendix\Excel\Percentile** while the Access table with percentiles is in the **TRCAMontlyMax** database.

3.5 Percentile Queries

A combination of VBA scripting and SQL querying was used to create percentile count queries (**see "Sub Create30YearPercentileThresholdTables()" in the 30YearMonthlyAnalysisTables module of TRCAMonthlyMax**). Again, scripting was used to sequentially process the results of the IDF all stations query while SQL was used to filter months and durations of interest. Additionally, the SQL count function was used to determine the number of events that were greater than or equal to each unique 75^{th} percentile value for each month and duration, as stored in the percentile table described earlier. Next, using scripting similar to that used for previous analysis, the results of these queries were formatted for excel for follow up linear trend and Mann-Kendall analysis (**see "Sub FormatCountQueryToExcel()" in the 30YearMonthlyAnalysisTables module of TRCAMonthlyMax)**.

3.6 Organizing, Querying, Summarizing and Formatting Daily IDF Data for Antecedent Precipitation Analysis

Daily data was imported into an Access database named "TRCADaily", which can also be found in the Appendix files by following the path **\DataAppendix\Access\,** using the methods described earlier (**see Data Specs and Normalization module in TRCADaily)**. However, based on learning from the monthly maximum and percentile analysis, the sequential processing and querying of the data was carried out in a slightly different way to reduce computer processing time. Scripting was used to process each table sequentially but rather than creating a large query linking each table and querying this (i.e. the IDF all stations query) it was found to be more processing efficient to query each table separately. Additionally, rather than determining which stations had 30 years of data with each script, a table was manually created to hold months and station ID's for all stations with 30 years of data for each month (**see 30YearStations table**). A separate script was written to populate this table with stations with 30 years of data or more for each month (**see "Sub Create30YearStationTable()" in the AntecedentAnalysis module of the TRCADaily database**). This table was then used for sequential processing each time this information was needed.

3.7 Antecedent Precipitation Analysis

Antecedent precipitation analysis was performed for the months April through November for both 1 and 6 hour durations. Again, a combination of scripting and SQL querying was used to extract data necessary for this analysis (**see Sub CreateAntecedantFromIDFData() in the AntecedentAnalysis module of the TRCADaily database**). Two different queries were used in the processing script: one to identify and retrieve monthly maximum dates and another to retrieve the amount of rain occurring on each of the 10 days prior to the maximum precipitation event. Retrieving monthly maximum dates required an advanced query employing an inner join. This query allowed for the reporting of records with unique station, year, month, element number and value information. The VBA function "DateSerial" was especially useful for the second query as this ensured correct information extraction for 10 day durations spanning two months. Lastly, in much the same way as all previous analysis, the results of the second query was then formatted, copied and analyzed in excel using both linear trend analysis and the Mann-Kendall tool. Formatting code used can be reviewed in the **"ExcelFormatting" module** while all Excel analysis spreadsheets can be found in the **\DataAppendix\Excel\Antecedent\ path in the Appendix Files**.

4.0 Results

4.1 Annual and monthly extremes

Time series of annual extremes of 5-minute, 1-hour, 6-hour and 12-hour rainfall were created for each station with at least 30 years of data and are shown in Figure 2 with associated slopes as estimated using the Sen's method. As Figure 2 indicates, the trend plots are very noisy and the slopes of trend lines are inconsistent. No trend is obvious even considering the maximum at all stations for each year.

Next the slopes of trend lines for individual stations were assessed for statistical significance. Examples of the plots for 3 stations are shown in Figure 3. The confidence bands for slope and the indication of significance using the Sen's method are shown on each plot. Table 1 summarizes the trend slope and significance information as computed using the Mann-Kendall method for all stations in the area of interest. The plots for all stations are included in the Appendix Files(Results/Monthly).

As Table 1 shows, trend slopes are almost evenly split between positive and negative and only five of the 42 trends are considered significant at the 90% level or higher according to the Mann-Kendall test. It is interesting to note that 4 of the 42 trend slopes could be expected to be labeled significant at the 90% level purely through chance. There appears to be no consistent trend in annual maximum short-duration rainfall in the Toronto area over the last 30-60 years.

Table 1. Trend statistics for annual maximum rainfall for 5-minutes, 1-hour, 6-hours and 12-hours.

TREND STATISTICS Annual Maxima

			5 minute		1 hour		6 hours		12 hours	
Station #	Station Name	n	Slope mm/yr	Mann-Ke Signific.	Slope mm/yr	Mann-Ke Signific.	Slope mm/yr	Mann-Ke Signific.	Slope mm/yr	Mann-Ke Signific.
6137287	St. Catherines A	31	-0.667		-4.267	99%	-5.167	95%	-2.000	
6140954	Brantford MOE	37	-0.089		-0.391		0.398		-0.613	
6142400	Fergus Shand Dam	40	0.418		1.019		0.624		0.349	
6149387	Waterloo A	33	0.000		0.817		-1.432		-2.129	
6150830	Bowmanville Mostert	36	0.571		1.972		2.217		2.075	
6151042	Burketon McLaughlin	33	0.000		0.944		1.866		2.816	
6153020	Greenwood MTRCA	30	2.235	99.9%	1.760		0.261		-0.231	
6153194	Hamilton A	34	0.130		-0.714		0.231		-0.250	
6153300	Hamilton RBG	35	-0.059		-0.471		1.727		0.800	
6155878	Oshawa WPCP	34	0.667		2.667	90%	2.652	90%	1.522	
6158350	Toronto	62	-0.024		-0.518		-1.045		-1.337	
6158520	Tornto Ellesmere	30	-0.071		-0.500		-3.286		-3.667	
6158733	Perason International A	44	-0.692		-1.728		-1.710		-1.638	
6166418	Peterborough A	32	0.374		-0.279		-1.260		-2.000	
Blank in the significance column indicates that the trend slope is not statistcally significant										

Figure 4 shows a mapped presentation of the 1-hour annual maximum trend values to aid in determining whether the positive and negative trends are spatially grouped. The negative trends are generally grouped near the shoreline of the western end of Lake Ontario with the positive trends located north of the Oak Ridges Moraine or east of Toronto near the lake. The “not significant” negative trend at Peterborough is the exception. It is not known whether there is any physical reason for this grouping. Maps for the other durations are contained in the Appendix files (Results/Annual) and show similar results.

Short duration rainfall annual maxima usually occur in the summer months. Time series of monthly maxima of short duration rainfall were analyzed to determine if trends in extremes existed in other seasons. Table 2 shows trend statistics for all stations for months April through November and Figure 5 shows examples of time series of 1-hour maxima for May. As expected, trend slopes for the warmest months (July-August) are almost equally divided between positive and negative similar to findings for annual maxima but trends for May for all durations examined are almost all significantly positive.

Table 2. Trend statistics for April through October for monthly maximum rainfall for 5-minutes, 1-hour, 6-hours and 12-hours.

TREND STATISTICS 5-Minute Maxima

Station	n yrs	April		May		June		July		August		September		October		November	
		Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.
6137287	*31*			0.632	90%	0.148		-0.767		-0.348							
6140954	*36*	*-0.286*	*95%*	0.138		0.049		-0.688		-0.246		0.628		0.026			
6142400	*38*					0.000		0.200		1.056	95%	0.029		-0.171			
6149387	*31*					0.050		-0.200						-0.167			
6150830	*33*			0.200		0.000		0.231		-0.215		0.810	90%	0.051			
6151042	*32*			0.067		-0.667	90%	0.263		-0.292		0.545					
6153194	*32*	0.304		0.000		-0.194		0.000		0.166		0.063		0.045			
6153300	*33*	0.000		0.795	95%	-0.306		-0.222		-0.455		0.286		-0.131			
6155878	*33*	-0.133		0.157		0.292		0.843	90%	0.000							
6158350	*60*	0.025		0.182		0.000		-0.579	99%	0.455	95%	0.371	95%	0.044		0.000	
6158733	*43*	0.000		0.179		-0.267		-0.299		-0.366		0.000		0.000		0.060	
6166418	*32*					0.226		-0.583		0.474		-0.067					

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

TREND STATISTICS 1-Hour Maxima

Station	n	April		May		June		July		August		September		October		November	
		Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.
6137287	*31*			0.200		-0.167		-1.625									
6140954	*36*	-0.586		0.500		1.152		-0.319		-1.560	90%	1.679	90%	1.679	90%		
6142400	*43*	0.000		1.609	99%	0.067		1.244		-1.122		0.663		0.663			
6149387	*31*					-0.308		0.588									
6150830	*33*			0.593		-0.764		1.333		0.983	95%	2.444	95%	2.444	95%		
6151042	*31*			1.000		-0.722		-0.037		0.000	90%	2.105	90%	2.105	90%		
6153194	*32*	0.226		0.117		-0.196		0.500		-0.573		0.151		0.151			
6153300	*33*	-1.500	90%	2.065	95%	-0.273		0.269		-2.069		2.200		2.200			
6155878	*32*	-0.955	90%	0.667		1.045		1.190									
6158350	*61*	-0.080		0.467		-0.033		-1.592	95%	0.722	95%	0.933	95%	0.941	95%	0.242	
6158733	*43*	0.000		0.929	90%	-0.806		-1.721	90%	-0.500		-0.102		-0.102		0.000	
6166418	*32*					1.902		-2.938	90%	0.479		0.000					

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

TREND STATISTICS 6-Hour Maxima

Station	n	April		May		June		July		August		September		October		November	
		Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.
6137287	*31*	-1.783	95%	0.063		-1.250		-3.214		-4.917	99%						
6140954	*36*	0.031		0.750		0.327		-1.779		-1.761		1.255		1.611			
6142400	*43*			2.045	95%	0.138		0.189		1.364		0.542		0.238			
6149387	*31*					0.368		-0.091						-0.375			
6150830	*33*			1.600		-0.941		1.765		-0.792		2.091		1.020			
6151042	*31*			2.588	90%	-0.199		-1.444		-0.881		3.083					
6153194	*32*	0.750		20%		-0.725		2.702		-588%	95%	-1.615		1.389			
6153300	*33*	-1.400		3.033	95%	0.000		1.522		0.087		211%		-0.442			
6155878	*32*	-2.667	95%	0.885		1.159		3.370	90%	-2.026							
6158350	*61*	-0.058		0.678		0.300		-2.271	99%	0.442		1.500	95%	-0.100		0.000	
6158733	*43*	-0.154		1.755	95%	-1.273		-2.960	95%	-1.539		1.088		1.486	90%	0.207	
6166418	*32*					5.246	90%	-5.125	90%	-4.444		-0.125					

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

TREND STATISTICS 12-Hour Maxima

Station	n	April		May		June		July		August		September		October		November	
		Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.
6137287	*31*			1.162		-1.250		-3.313		-6.909	99%						
6140954	*36*			0.714		0.327		-3.624		-2.365		1.083		1.394			
6142400	*43*			1.973	90%	0.138		0.328		0.868		0.500		0.345			
6149387	*31*					0.368		-0.125									
6150830	*33*			1.571		-0.941		1.632		-1.070		2.368		-1.357			
6151042	*31*			2.250		-0.199		-3.205		0.286		3.067		1.130			
6153194	*32*			0.187		-0.725		2.063		-7.040	95%	-0.742					
6153300	*33*			2.771	90%	0.000		1.400		-0.667		2.462		1.545			
6155878	*32*			1.000		1.159		2.789		-1.882				-0.188			
6158350	*61*	-1.059		0.887		0.300		-3.000	99.9%	0.510		1.617	95%			0.686	
6158733	*43*	-0.500		2.000	95%	-1.273		-3.924	99%	-1.807		1.523		-0.068		1.078	
6166418	*32*					5.246	90%	-5.375	90%	-5.067	95%	-0.778		1.778	90%		

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

4.2 Trends in Frequencies of events.

To investigate the possibility that the frequency of heavy rainfall events was changing independent of changes in the annual maximum event, time series of the number of events exceeding the 75th percentile event each year were created for each station and are shown in Figure 6 for each of the durations examined. The 75th percentile threshold was selected to restrict the time series to heavy events while ensuring that at least one event occurred each year. As was the case for time series of annual maxima, the trends of frequencies are quite noisy and inconsistent for all durations.

Table 3 shows the trend statistics for all stations with more than 30 years of data. Of the 11 cases with Mann=Kendall trend significant at the 90% level or higher, 7 were negative trends.

Table 3. Trend statistics for the annual number of events exceeding the 75th percentile event for all 12 stations with more than 30 years of data.

TREND STATISTICS Annual frequency > 75th Percentile										
			5 minute		**1 hour**		**6 hours**		**12 hours**	
Station #	**Station** *Name*	**n**	**Slope mm/yr**	**Mann-Ke Signific.**	**Slope mm/yr**	**Mann-Ke Signific.**	**Slope mm/yr**	**Mann-Ke Signific.**	**Slope mm/yr**	**Mann-Ke Signific.**
6137287	*St. Catherines A*	*31*	-0.100		0.042		0.000		0.000	
6140954	*Brantford MOE*	*36*	-0.154	90.0%	-0.203	95.0%	-0.229	95.0%	-0.286	99.9%
6142400	*Fergus Shand Dam*	*40*	0.051		0.103		0.059		0.000	
6149387	*Waterloo A*	*33*	-0.102		-0.114		-0.143		-0.059	
6150830	*Bowmanville Mostert*	*36*	-0.091		0.125	90.0%	0.068		0.000	
6151042	*Burketon McLaughlin*	*32*	0.000		0.095		0.167	90.0%	0.082	
6153020	*Greenwood MTRCA*	*30*			0.043		0.036		0.091	
6153194	*Hamilton A*	*34*	-0.130		0.000		-0.150		-0.200	
6153300	*Hamilton RBG*	*35*	0.133		0.111	90.0%	0.000		0.032	
6155878	*Oshawa WPCP*	*34*	-0.133		0.000		-0.067		-0.094	
6158350	*Toronto*	*61*	0.000	95.0%	0.026		-0.035		-0.034	
6158520	*Tornto Ellesmere*	*30*	-0.250		-0.167	90.0%	-0.182	90.0%	-0.176	95.0%
6158733	*Perason International A*	*44*	-0.070		0.028		0.000		0.000	
6166418	*Peterborough A*	*32*	-0.053		0.000		0.000		0.000	
Blank in the significance column indicates that the trend slope is not statistcally significant										

Monthly time series of the number of events exceeding the 75th percentile were also created. An example of these time series is shown in Figure 7. As Table 4 shows, the number of heavy events are increasing over the last 30-60 years at all stations in May but trends in other months are mixed.

Table 4. Trend statistics for monthly number of events exceeding the 75th percentile event for all stations with more than 30 years of data.

TREND STATISTICS Frequency > 75th Percentile - 5-Minute

Station	n yrs	May Slope mm/yr	May M-K Sig.	June Slope mm/yr	June M-K Sig.	July Slope mm/yr	July M-K Sig.	August Slope mm/yr	August M-K Sig.	September Slope mm/yr	September M-K Sig.
6137287	*31*	0.000		0.000		0.000		0.000			
6140954	*36*	0.000		0.000		0.000		0.000		0.038	
6142400	*38*	0.000		0.000		0.000		0.000		0.000	
6149387	*31*			0.000		0.000					
6150830	*33*	0.000		0.000		0.000		0.000		0.038	90%
6151042	*32*	0.000		0.000		0.000		0.000		0.000	
6153194	*32*	0.000		0.000		0.000		-0.040		0.000	
6153300	*33*	0.000		0.000		0.000		0.000		0.000	
6155878	*33*	0.000		0.000		0.000		0.000			
6158350	*60*	0.000	90%	0.000		0.000	99.9%	0.023		0.032	99%
6158733	*43*	0.000		0.000		0.000		0.000		0.000	
6166418	*32*			0.000		0.000		0.000		0.000	

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

TREND STATISTICS Frequency > 75th Percentile -1-Hour

Station	n	April Slope mm/yr	April M-K Sig.	May Slope mm/yr	May M-K Sig.	June Slope mm/yr	June M-K Sig.	July Slope mm/yr	July M-K Sig.	August Slope mm/yr	August M-K Sig.	September Slope mm/yr	September M-K Sig.	October Slope mm/yr	October M-K Sig.	November Slope mm/yr	November M-K Sig.
6137287	*31*			0.200		-0.167		-1.625		-1.560							
6140954	*36*	-0.586		0.500		1.152		-0.319		-1.122		1.679	90%	1.679	90%		
6142400	*43*	0.000		1.609	99%	0.067		1.244				0.663		0.663			
6149387	*31*					-0.308		0.588						2.444	95%		
6150830	*33*			0.593		-0.764		1.333		0.983		2.444	95%	2.105	90%		
6151042	*31*			1.000		-0.722		-0.037		0.000		2.105	90%				
6153194	*32*	0.226		0.117		-0.196		0.500		-0.573		0.151		0.151			
6153300	*33*	-1.500	90%	2.065	95%	-0.273		0.269		-2.069		2.200		2.200			
6155878	*32*	-0.955	90%	0.667		1.045		1.190									
6158350	*61*	-0.080		0.467		-0.033		-1.592	95%	0.722		0.933	95%	0.941	95%	0.242	
6158733	*43*	0.000		0.929	90%	-0.806		-1.721	90%	-0.500		-0.102		-0.102		0.000	
6166418	*32*					1.902		-2.938	90%	0.479		0.000					

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

TREND STATISTICS Frequency > 75th Percentile -12-Hour

Station	n	April Slope mm/yr	April M-K Sig.	May Slope mm/yr	May M-K Sig.	June Slope mm/yr	June M-K Sig.	July Slope mm/yr	July M-K Sig.	August Slope mm/yr	August M-K Sig.	September Slope mm/yr	September M-K Sig.	October Slope mm/yr	October M-K Sig.	November Slope mm/yr	November M-K Sig.
6137287	*31*	-1.100		1.162		-1.278		-3.313		-6.909	99%						
6140954	*36*	0.446		0.714		1.476		-3.624		-2.365		1.083		1.394			
6142400	*43*			1.973	90%	0.176		0.328		0.868		0.500		0.345			
6149387	*31*					-0.091		-0.125						-1.357			
6150830	*33*			1.571		-2.105		1.632		-1.070		2.368		1.130			
6151042	*31*			2.250		-0.333		-3.205		0.286		3.067					
6153194	*32*	0.429		0.187		-1.065		2.063		-7.040	95%	-0.742		1.545			
6153300	*33*	-0.810		2.771	90%	-0.129		1.400		-0.667		2.462		-0.188			
6155878	*32*	-2.778	95%	1.000		0.604		2.789		-1.882							
6158350	*61*	0.229		0.887		0.483		-3.000	99.9%	0.510		1.617	95%	-0.068		0.686	
6158733	*43*	0.100		2.000	95%	-1.850	90%	-3.924	99%	-1.807		1.523		1.778	90%	1.078	
6166418	*32*					3.629		-5.375	90%	-5.067	95%	-0.778					

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

TREND STATISTICS Frequency > 75th Percentile -6-Hour

Station	n	April Slope mm/yr	April M-K Sig.	May Slope mm/yr	May M-K Sig.	June Slope mm/yr	June M-K Sig.	July Slope mm/yr	July M-K Sig.	August Slope mm/yr	August M-K Sig.	September Slope mm/yr	September M-K Sig.	October Slope mm/yr	October M-K Sig.	November Slope mm/yr	November M-K Sig.
6137287	*31*			0.063		-1.250		-3.214		-4.917	99%						
6140954	*36*	-1.783	95%	0.750		0.327		-1.779		-1.761		1.255		1.611			
6142400	*43*	0.031		2.045	95%	0.138		0.189		1.364		0.542		0.238			
6149387	*31*					0.368		-0.091						-0.375			
6150830	*33*			1.600		-0.941		1.765		-0.792		2.091		1.020			
6151042	*31*			2.588	90%	-0.199		-1.444		-0.881		3.083					
6153194	*32*	0.750		0.195		-0.725		2.702		-5.880	95%	-1.615		1.389			
6153300	*33*	-1.400		3.033	95%	0.000		1.522		0.087		2.105		-0.442			
6155878	*32*	-2.667	95%	0.885		1.159		3.370	90%	-2.026							
6158350	*61*	-0.058		0.678		0.300		-2.271	99%	0.442		1.500	95%	-0.100		0.000	
6158733	*43*	-0.154		1.755	95%	-1.273		-2.960	95%	-1.539		1.088		1.486	90%	0.207	
6166418	*32*					5.246	90%	-5.125	90%	-4.444		-0.125					

Blank in slope column undicates < 30 years data for that month

Blank in the significance column indicates that the trend slope is not statistcally significant

4.3 Trends in Return Period Calculations.

The design of hydrological structures is usually based upon frequency or return period statistical calculations of annual maxima time series. These calculations are dependent on both the mean extreme and the variance or standard deviation of those extremes so it is possible that a trend in return period calculations is present even when no trend in the value of the extreme events is present. This would occur if a trend in standard deviation of events is present in the absence of a trend in the annual maximum event. This possibility was explored by examining the time series of the 10-year return period amount calculated for a moving window of events, 10 years wide, for a sample of stations in the Toronto area. Examples of these plots for three stations are shown in Figure 8. As demonstrated by the stations shown in Figure 8, no consistent trend in the time series of 10-year return period amount is visible in the data for the long-record stations in the Toronto area although the Bowmanville station does show an upward trend for the 1-hour and 24-hour durations. Other stations (e.g. Fergus Shand Dam) showed a downward trend in 10-year return period amounts.

4.4 Trends in Antecedent Rainfall.

Another factor possibly affecting the design of hydrologic structures in the absence of trend in the amount of rain in extreme events is the presence of a trend in the amount of rain falling immediately prior to the extreme event. An increase in the antecedent rainfall could lead to an increase in the amount of runoff from an event even when the extreme event is not increasing. To explore this possibility, time series of the amount of rain falling in the 10 days preceding the annual extreme event were created for each station and for 1-hour and 6-hour events and the trend in this parameter examined. The trend statistics are summarized in Table 5. The trend statistics are inconclusive with positive and negative trends almost evenly split varying dependent upon station and month with few statistically significant trends present. There are more positive trends in May, as was the case for the extreme event time series but none are statistically significant and some negative trends in antecedent rainfall exist even in May.

Table 5. Monthly trend statistics for 10-day antecedent rainfall for all stations in the Toronto area with more than 30 years of short-duration rainfall data and for events of 1-hour and 6-hours.

TREND STATISTICS 10-day Antecedent Precipitation -1-Hour events

		April		May		June		July		August		September		October		November	
Station	n	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.
6137287	*28*					-3.857		2.460		4.000							
6140954	*36*	1.575		2.455		2.387		3.842		3.116		0.396		-0.786			
6142400	*40*	0.571		0.941		0.053		1.665		0.881		0.118		0.429			
6149387	*29*					0.857		1.611						2.142			
6150830	*33*			0.492		1.549		1.186		-3.773	90%	2.500		3.962	90%		
6151042	*31*			1.750		-0.381		-4.483	90%	6.211	95%	-2.333					
6153194	*33*	2.059		-2.608		-3.932		-0.205		-3.826		-0.113		-3.667			
6153300	*35*	3.680		0.485		0.191		1.200		0.250		1.875		2.519			
6155878	*32*	1.654		1.080		-0.181		-0.136		-2.333		-0.625					
6158350	*60*	-0.873		0.659		-0.333		-2.104	90%	1.067		1.985		0.316		-1.923	
6158733	*44*	1.905		1.153		3.462	90%	-0.177		1.261		2.409		-1.444		-2.385	90%
6166418	*30*					-0.577		-0.185		2.037							
Blank in slope column undicates < 30 years data for that month																	
Blank in the significance column indicates that the trend slope is not statistcally significant																	

TREND STATISTICS 10-day Antecedent Precipitation -6-Hour events

		April		May		June		July		August		September		October		November	
Station	n	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.	Slope mm/yr	M-K Sig.
6137287	*31*					-2.778		2.650		3.462							
6140954	*36*	2.604		2.000		0.958		1.000		3.905	90%	1.069		0.083			
6142400	*43*	-0.125		-0.556		-0.517		4.336	90%	0.424		-0.304		0.462			
6149387	*31*					-0.833		0.388						1.974			
6150830	*33*			-2.321		-2.196		1.020		-1.899		2.231		1.429			
6151042	*31*			0.889		-0.097		-4.000	90%	4.640	95%	0.737					
6153194	*32*	-0.333		-1.582		0.118		-1.215		-2.928		-0.485		-3.000			
6153300	*33*	3.600		1.638		-0.208		-7.043	95%	1.571		2.083		0.604			
6155878	*32*	1.407		3.714		-2.984		0.195		-0.890							
6158350	*61*	-0.659		0.410		-2.091	95%	-0.941		0.638		-1.500		-0.153		-1.940	
6158733	*43*	0.519		1.601		4.000	95%	1.138		1.507		0.560		-0.088		-0.500	
6166418	*32*					0.175		0.000		1.231		2.500					
Blank in slope column undicates < 30 years data for that month																	
Blank in the significance column indicates that the trend slope is not statistcally significant																	

4.4 Spatial Patterns

As noted previously, there are no obvious relationships between trends in extreme rainfall and the physiography of the Toronto region but it was considered worthwhile to examine actual extremes to identify possible relationships between amount of rainfall and elevation, proximity to Lake Ontario etc. To do this, an isohyetal map of 1-hour 10-year return period amounts in the region using all available station data including those with less than 30 years of record was created and is shown in Figure 9. Interpolation of the 10-year values for this map was carried out using kriging. There are some interesting patterns visible in the resulting map. Maximum values are consistently observed along and west of the Niagara escarpment west of Toronto. A “rain shadow” effect shows up immediately east of the escarpment with lower values observed at stations there. Values in the immediate Toronto area are somewhat higher than those to the immediate west but less than those on the escarpment. There is a suggestion that 10-year values are less at stations close to the cool water of Lake Ontario, especially east and west of the city but this relationship breaks down somewhat in the immediate Toronto region where two lakeside stations had somewhat higher values than those further inland although the maximum value in Toronto was observed away from the lake along the Highway 401 corridor. Uncertainty in the estimated 10-year values due to statistical sampling may be obscuring possible relationships with terrain features in the Toronto region.

5. Conclusions

This study examined the time series of monthly and annual extreme rainfall events at 12 stations in the Toronto area with at least 30 years of record. Trends for a sample of durations from 5 minutes to 12 hours were investigated. Trends for all durations examined were similar. No consistent trend in annual extremes was identified but an increasing trend in extreme events for some months, particularly May, was identified. This is consistent with findings in other trend studies which indicate warming and associated meteorological changes, attributed to greenhouse gas induced climate change, are mostly evident in winter and spring records. Findings were similar for trends in the frequency of occurrence of annual and monthly extremes.

Trends in the 10-year return period amount were investigated by creating time series of this statistic based upon a 10-year wide moving window of annual extremes. Results were inconclusive with both positive and negative trends visible in the data. Trend in another parameter important to impacts on urban hydrology structures, the amount of rain falling immediately prior to extreme events (i.e. the antecedent rainfall) was also examined. Results for this parameter were also inconclusive although there were indications that antecedent rainfall is also increasing in the spring period as was the case for both the amount and frequency of the extreme events themselves.

No relationship between trends in short duration extreme rainfall and the physiography of the Toronto area were found but there were links between topography and patterns in mapped values of extreme short duration rainfall in the Toronto vicinity. Maximum values are consistently observed along and west of the Niagara escarpment, a "rain shadow" effect shows up immediately east of the escarpment and 10-year values are less at stations close to the cool water of Lake Ontario, especially east and west of the city. . However, this is based on limited data and analysis and further investigation would be required to make definitive conclusions regarding physiographic effects.

Heavy short-duration rainfall occurs in brief, small-area events. The heaviest of these events do not occur at the same location every year. This means that samples of extreme short-duration rainfall at a single location often do not record the most intense rainfall in the local area in any given year which means that the rainfall record at a single gauge contains a mix of measurements from the centres and edges of such events, resulting in a statistically noisy record making it difficult to identify trend amid the high variability of the measurements. This study indicates that changes are occurring in the short-duration rainfall climate in the Toronto area, at least as far as the time of occurrence of the event, and other changes may be obscured by the noisy nature of the statistical record. Because of this and the importance of changes in the short-duration rainfall climatology to the urban hydrology infrastructure it is strongly recommended that:

1. the collection of high-quality short-duration rainfall measurements at present locations be continued and that additional stations be established to provide appropriate spatial coverage of the Toronto area

2. the practice of calibrating tipping-bucket measurements with co-located standard gauge measurements be re-instituted to ensure homogenous time series and improve confidence in trend calculations

3. frequent updating of extreme rainfall statistics (which have not been updated since 2003) be carried out to permit early identification of changes and trends in the probability of extreme events

4. use of time series from weather radar records, which sample the most intense portions of all events in the area, be investigated.

Recommendation 4 requires some elaboration. At present, extreme rainfall statistics are based upon measurements at gauge locations fixed in space. As mentioned above, such measurements may not sample the most intense rainfall in specific events. The resulting statistics represent the combined probability of the event occurring and the gauge being located near the most intense rainfall. This is satisfactory when the desired statistics are required for the design of a structure at a fixed location and assuming that the areal extent of the event does not vary. However, to learn about changes in the frequency of events in a larger area (such as over the entire GTA) and to examine changes in the central intensities, areal extent of individual storms and trends in the locations of centres, it is necessary to compile statistics by identifying and following the rainfall at the event centre instead of at a fixed location. This can be done using weather radar data. The resulting analysis would permit statements about changes or trends in the frequency and areal extent of events over the entire GTA, would directly monitor changes in intensity at the storm centre and would identify changes in preferred location of the most intense rainfall in events.

6. References

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