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Influence of Trend on Short Duration Design Storms

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Abstract Design storms (DS) that are determined from intensity-duration-frequency (IDF) relationships are required in many water resources engineering applications. Short duration DS are of particular importance in municipal applications. In this paper, linear trends were estimated for different combinations of durations and frequencies (return periods) of annual short-duration extreme rainfall. Numerical analysis was performed for 15 meteorological stations from the province of Ontario, Canada. The estimated magnitude (rate mm/h) and direction of trend (increasing, decreasing, or no trend) were estimated and then used to quantify the effect of trend on the frequency of design storms. Significant trends were detected for all durations. It was determined that due to the existence of trends (which might be attributed to climate change), the design storms of a given duration might occur more frequently in the future by approximately as much as 36 years depending on the duration and return period.

Keywords Climate change · Trends · Short-duration annual maximum rainfall · Intensity duration-frequency relationships

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Notation

x_t	annual maximum rainfall time series
α, β	regression parameters
x_r	time series with the trend component removed
x_{obs}	observed rainfall data
S	Mann–Kendall trend statistic
α^2	variance
Z_s	test statistic for normal distribution variable
n	record length
t_i	number of ties to extent i.
p	at-site significance level
F_N	standard normal variate
α, β	method of moment parameters
x	mean
s	standard deviation
I	intensity
T	return period

1 Introduction

The theory of global climate change endorsed by many scientists (Bard 2002), holds that industrial activity is causing a build up of carbon dioxide in the atmosphere, trapping the sun's heat close to the Earth and creating a hotter, more turbulent atmosphere that will lead to more extreme weather events like droughts, storms, heat waves, and floods. There are many studies and research initiatives (International Research Institute 2002, and others) concerned with ameliorating predictions and understanding of the complexity of climate change and its possible consequences on water resources.

The Intergovernmental Panel on Climate Change (IPCC 2007) has reported changes in temperature extremes partly attributable to the increase in concentration of carbon dioxide (greenhouse gases) in the atmosphere. In past studies of climate trends (Nicholls et al. 1996), it was found that the global mean surface temperature has increased by approximately 0.3 to 0.6°C since the late nineteenth century and by 0.2 to 0.3°C over the last 40 years. Zhang et al. (2000) found an annual mean temperature increase between 0.5 and 1.5°C in Canada (south of 60°N) from 1900 to 1998, and found that the greatest warming occurred in the spring and summer periods of Western Canada. From 1950 to 1998, Zhang found warming in southern and western Canada, while northeast Canada generally experienced cooling. Nicholls et al. (1996) indicate that in general, anthropogenic climate change is stronger in high-latitude countries such as Canada.

Some studies (Nicholls 1995; Karl and Knight 1998; Whang and Zhang 2008) suggest that the hydrological cycle could intensify due to the increase in temperature extremes. Zhang et al. (2000) found that annual precipitation totals in Canada have changed by −10% to +35%, with Northern regions generally experiencing the strongest increases. Several other studies (Guttman et al. 1992; Karl and Knight

1998; Douville et al. 2002; Peterson et al. 2008; among others) have found increases in precipitation amounts and intensity across the USA and Canada. Yagouti et al. (2008) found that precipitation indices in Southern Quebec for the period 1960–2005 show an increase in the annual total rainfall, although many stations have decreasing trends in the summer. Bruce (1999) reported increases in the frequency of extreme rainfall events in the United States and Japan.

Rainfall information is required for many theoretical and practical reasons. One of the most common uses of rainfall information in engineering is in developing design storms which are used in calculating design storm runoff (Maidment 1993). Design storm rainfall is defined as a relationship between rainfall intensity (depth in mm), duration (time in minutes), and frequency of occurrence (probability or return period in years). Such relationships are known as IDF curves or equations and are usually derived using observed annual maximum (AM) series at one site (at-site) or several sites (regional analysis). IDF relationships are usually available in graphical form in Canada (Hogg and Carr 1985) and the US (Hershfield 1961) as well as in equation form (Adamowski et al. 1997). In developing these relationships, the estimates of rainfall intensity for a given duration and frequency can be obtained from statistical analysis employing various probability distributions (such as a Gumbel distribution) and parameter estimation methods (such as method of moments). There is much discussion in the literature (Maidment 1993) about the various approaches for statistical analysis of extreme values. This will not be explored in this paper since it should not have a significant impact on the results of this study

IDF relationships are used in the design, construction, and management of many water resources projects involving natural hazards due to extreme rainfall events. For example, many hydraulic structures (culverts, storm sewer systems) are designed to control surface runoff. In the absence of adequate stream flow data, rainfall data is used extensively in the synthesis of peak flows. Many methods such as the rational method, synthetic unit hydrographs, and others, require IDF inputs to determine peak flows. It is therefore very important to have reliable estimates of IDF relationships which can reflect possible future conditions. In developing IDF relationships it is assumed that the rainfall data is independent and without trend. As such, IDF relationships are developed without examining whether rainfall events are subject to climate change (trends). These assumptions unfortunately give rise to many uncertainties

Potential impacts of climate change in Canada could include the following (Bruce et al. 2002): an increase in the frequency and severity of extreme weather events including short-duration/high intensity rainfalls; a change in precipitation distribution, amounts and types; polar ice and permafrost melt in Northern Canada; and sea level rise. Such changes might have multiple national, regional and municipal consequences. Urban areas, having large populations and expensive infrastructure, are particularly vulnerable to climate change impacts. Since significant trends have been reported (Adamowski and Bougadis 2003) in the occurrence of extreme short duration rainfall events in Canada, then the design storms of a given duration might occur more frequently in the future. For example, Zwiers and Kharin (1998) reported that frequency of heavy 1-day rains could occur with return periods halved (for example a 20 year return period rainfall becomes a 10 year event). Adamowski and Bougadis (2003) found that, based on a 5% significance level, approximately 23% of the regions they tested in Canada had a significant trend in annual extreme precipitation, predominantly for short-duration storms. Mailhot et al. (2007) used Canadian Regional Climate Model simulations to analyse present and future climate and found that in the future, the return period of 2 and 6 h storms may be halved due to climate change.

Information on trends in extreme short-duration rainfall is needed to determine climate change impacts on the design, management, and operation of urban infrastructure, and to prepare adaptation measures to deal with extreme events. In this study, it is assumed that the rate of trends estimated from the data would remain the same in the future. Such an assumption could be challenged, but it provides a reasonable basis for approximately quantifying the effects that trends would have on the return periods of design storms.

A review of the literature indicates that quantifying the effect of climate change through an analysis of trends in the intensity of short design storms has not been published. The purpose of this study is (a) to investigate the existence of trends in annual maxima short duration rainfall, and (b) to determine the consequences of trends on the return period of extreme rainfall events.

2 Data

Numerical analysis was performed on annual maximum rainfall series (single storm event depth) for the province of Ontario, Canada for short duration rainfall (5, 10, 15, 30 min, and 1 h), which are typical values used for small urban catchments. IDF estimates were computed for the following assumed return periods: 2, 5, 10, 25, and 50 years, respectively.

A total of 15 stations from 65 available stations were chosen for the analysis and are shown in Table 1 and Fig. 1. Annual maxima data for various durations for the period of record up to 1998 was obtained from the Ontario Ministry of the Environment, and used in this study. They were chosen based on their length of

Table 1 Stations used in the analysis

Region (1)	Station (2)	Station ID (3)	Latitude (4)	Longitude (5)	Record length (6)	Gauge period (7)
North	Big Trout Lake	6010738	53°50′	89°52′	23	1968–1990
	Moosonee	6075425	51°16′	80°39′	23	1968–1990
	Sudbury	6068150	46°37′	80°48′	20	1971–1990
	Chalk River	6106400	45°59′	77°26′	34	1961–1994
	Timmins	6076572	48°28′	81°16′	39	1952–1990
Central	Kingston	6104175	44°14′	76°29′	38	1961–1998
	Orillia	6115820	44°37′	79°25′	27	1965–1991
	Oshawa	6155878	43°52′	78°50′	29	1970–1998
	Bowmanville	6150830	43°55′	78°40′	31	1968–1998
	Burketon	6151042	44°02′	78°48′	30	1969–1998
South	Port Colborne	6136606	42°85′	79°15′	34	1964–1997
	Preston	6146714	43°23′	80°21′	25	1971–1995
	Sarnia	6127514	43°00′	82°19′	28	1970–1997
	Delhi	6131982	42°52′	80°33′	34	1962–1995
	Waterloo	6149387	43°27′	80°23′	28	1971–1998

Fig. 1 Station locations across the Province of Ontario

record, up-to-date data and location to represent various regions across Ontario. Five stations (Big Trout Lake, Moosonee, Sudbury, Chalk River, and Timmins) located in the geographically defined North region (greater than 45°50′) have gauge records ranging from 1952 to 1994. The Central region has five stations (Kingston, Orillia, Oshawa, Bowmanville, and Burketon) with record lengths ranging from 1961 to 1998, while the South region (less than 43°50′) has five stations (Delhi, Waterloo, Sarnia, Preston, and Port Colborne) with record lengths ranging from 1962 to 1998.

3 Methodology

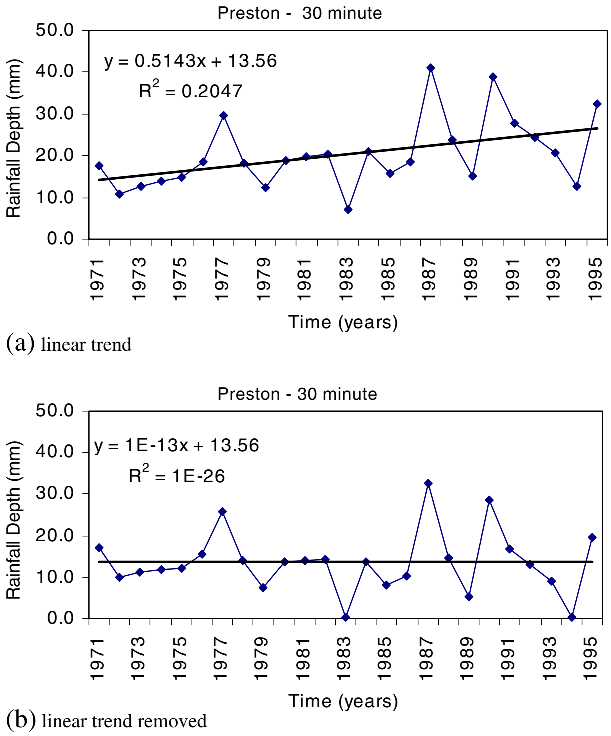
A number of parametric and non-parametric tests for trends are available. One of the parametric tests to detect and estimate linear trends is the method of linear regression. However, linear regression requires certain assumptions (such as normality of residuals, constant variance, and true linearity of the relationship) which are frequently not met in practical applications. Alternatively, a non-parametric test can be used where no assumptions are required. The non-parametric Mann–Kendall test for trend (Mann 1945; Kendall 1962) as well as linear regression were used in this study (Maidment 1993).

3.1 Regression Analysis

To describe a trend, a simple linear regression model can be used and is given by

$$x_t = \alpha + \beta \quad (t = 0, 1, 2, .. n) \tag{1}$$

where x_t is the annual maximum rainfall time series, α is the intercept, β is the slope (trend), and n is the length of the data. The annual maximum precipitation data was tested (Adamowski and Bougadis 2003) and found independent (serially



(a) linear trend

(b) linear trend removed

Fig. 2 Station 6146714 (Preston) fitted with linear trend and with linear trend removed

uncorrelated). For illustration purposes, Fig. 2a presents the raw observed data for station 6146714 (Preston) for a storm duration of 30 min. It clearly indicates the presence of a trend in the data.

The trend component can be removed by

$$x_{\mathrm{r}} = (x_{\mathrm{obs}} - x_{\mathrm{t}}) + \alpha \tag{2}$$

where x_{r} is the time series with the trend component removed, x_{obs} is the observed rainfall data, and x_{t} is the linear trend estimated from Eq. 1. Figure 2b shows the time series (x_{r}) with the trend component removed for the 30 min storm duration at Preston. The observed time series and the time series with trend removed are used to determine the difference in IDF estimates produced at a given station.

3.2 Mann–Kendall Test for Trend

The Mann–Kendall test for trend is applied to an annual extreme value time series x_{i}, ranked from $i = 1$,..., $n-1$, with x_j ranked from $j = i + 1$,..., n. Each data point x_{i} is used as a reference point and is compared to all other data points (x_{j}) such that (Kendall 1962)

$$\operatorname{sign}(x) = \begin{cases} 1 & x_j > x_i \\ 0 & x_j = x_i \\ -1 & x_j < x_i \end{cases} \tag{3}$$

The Kendall S statistic is calculated as (Kendall 1962)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}\left(x_j - x_i\right) \tag{4}$$

If the data is identically, independently distributed (iid), then the mean is zero and the variance for the S statistic can be defined by (Kendall 1962)

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18} \tag{5}$$

where t_i denotes the number of ties to extent i. The summation term in Eq. 5 is only used if the data values are tied in the series. The test statistic, Z_s, can be calculated as

$$Z_\mathrm{s} = \begin{cases} (S-1)/\sigma & \text{for } S \rangle 0 \\ (S+1)/\sigma & \text{for } S \langle 0 \\ 0 & \text{for } S = 0 \end{cases} \tag{6}$$

where Z_s follows a standard normal distribution (Kendall 1962). Equation 6 can be used for record lengths greater than 10 if the number of tied data is low (Kendall 1962). The at-site significance level (p) can be obtained by using the test statistic in the cumulative distribution function (cdf) for a standard normal variate (F_N), or

$$p = 2\left[1 - F_\mathrm{N}(Z_\mathrm{s})\right] \tag{7}$$

If $|Z_\mathrm{s}|$ is greater than $Z_{\alpha/2}$, where α denotes the significance level, then the trend is significant (Kendall 1962). Where data may be serially correlated, the Mann–Kendall test may indicate a trend where one may not exist (Cox and Stuart 1955). However, because annual short-duration extreme rainfall data was used in this study and found to be uncorrelated, there was no need to modify the Mann–Kendall test.

3.3 IDF Estimates

Design storms are used in Canada to determine peak rainfall intensity for a given duration and assumed return period. The annual maxima (AM) series is commonly used (Hogg and Carr 1985). Generally, AM rainfall data applies to the months of April until October since rain gauges are taken out of service in the winter months.

IDF curves are often fitted with the Extreme Value Type I distribution (EVI) developed by Gumbel (1954), which is the most common distribution used by many national meteorological services around the world to describe rainfall events (World Meteorological Organization 1981). The cumulative density function $F(x)$ of the Gumbel distribution (EVI) is given by Maidment (1993)

$$F(x) = e^{-e^{-y}} \tag{8}$$

in which $F(x)$ is the probability of nonexceedance, and $y = (x - B)/\alpha$ is the reduced variate. The parameter α (positive) is the scale parameter, while B is the location parameter (mode) of the distribution. The skew coefficient of the Gumbel distribution is a constant value of 1.14.

In frequency analysis, the probability of interest is the probability of exceedance (i.e. the complementary probability to $F(x)$) given by

$$G(x) = 1 - F(x) \tag{9}$$

The return period T is the reciprocal of the probability of exceedance. Therefore

$$1/T = 1 - e^{-e^{-y}} \tag{10}$$

The EVI distribution was used in this study along with the method of moments. No attempt was made to study the distribution selection and fitting techniques since this would not have had a significant effect on the trend detection results. The EVI distribution requires the first two moments and the mean and standard deviation to be computed from the data. The method of moments estimates for the parameters are (Maidment 1993)

$$\hat{\alpha} = \frac{1.28}{s} \tag{11}$$

$$\hat{\beta} = \bar{x} - 0.45s \tag{12}$$

where $\overline{x}$ and s denote the mean and standard deviation of the observed data set. The intensity of rainfall is fitted to the Gumbel distribution by using the following equation

$$y = \hat{\beta} - \frac{\ln\left(-\ln\left(1 - \frac{1}{T}\right)\right)}{\hat{\alpha}} \tag{13}$$

Rearranging Eq. 13 yields an equation to determine the return period (T) defined by

$$T = 1/1 - e^{-e^{-y}} \tag{14}$$

Equation 14 was used to determine the change of return period between the time series with and without trend for a given station, intensity, and duration.

4 Results and Discussion

4.1 Trend Rates

The majority of the regression slopes (trend rates) for all durations and stations were found to be positive, indicating an increase in annual extreme precipitation across the various regions in Ontario (Table 2). The average rates for the 5, 10, 15, 30 min and 1 h storms were found to be: 0.07, 0.09, 0.14, 0.20, and 0.21.

It can also be seen from Table 2 that the Preston station had the highest average slope increase (0.34), while Waterloo, Oshawa, and Moosonee had lower rates of increase (0.26, 0.23, and 0.22, respectively).

4.2 Significance of Trends

The Mann–Kendall test was used to test the significance of linear trend. Results are shown in Table 2. A total of 12 (16%) tests were found to be significant at the 5%

Table 2 Rates and trends for different storm durations

Stations	Storm duration											
	5 min		10 min		15 min		30 min		1 h		Average	
	Rate (mm/h)	S^1	Rate (mm/h)	S	Rate (mm/h)	S	Rate (mm/h)	S	Rate (mm/h)	S	Rate (mm/h)	S
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Big Trout Lake	0.12	**2.09**	0.14	1.59	0.19	**2.46**	0.17	1.41	0.06	0.57	0.14	1.62
Moosonee	0.11	1.35	0.11	1.27	0.20	*1.69*	0.35	*1.88*	0.33	1.51	0.22	1.54
Sudbury	0.01	0.00	−0.06	−0.36	0.08	0.52	0.18	0.59	0.28	1.20	0.10	0.39
Chalk River	0.05	0.96	0.12	1.31	0.14	1.33	0.12	0.95	0.14	0.18	0.11	0.95
Timmins	0.05	1.63	0.11	**2.08**	0.14	**2.29**	0.11	*1.94*	0.08	1.54	0.10	1.90
Bowmanville	0.06	0.71	0.11	1.24	0.12	1.12	0.16	1.19	0.22	1.53	0.13	1.16
Burketon	−0.01	0.27	−0.01	0.00	0.08	0.34	0.20	1.39	0.34	*1.75*	0.12	0.75
Kingston	0.02	0.54	0.04	1.02	0.03	0.77	0.04	0.54	0.07	0.40	0.04	0.65
Orillia	0.19	**2.82**	0.17	**2.13**	0.21	**2.19**	0.11	1.17	0.08	0.65	0.15	1.79
Oshawa	0.12	*1.93*	0.17	*1.84*	0.22	*1.91*	0.30	**2.40**	0.35	**2.05**	0.23	2.03
Port Colborne	0.02	0.15	−0.01	−0.43	0.03	0.06	0.02	0.00	0.08	0.15	0.03	−0.01
Preston	0.11	*1.92*	0.27	**2.20**	0.36	**2.17**	0.51	**2.62**	0.46	1.36	0.34	2.05
Sarnia	0.07	0.83	0.00	0.26	0.05	0.45	0.17	0.75	0.22	0.63	0.10	0.59
Waterloo	0.10	1.34	0.19	*1.94*	0.28	*1.94*	0.36	1.50	0.35	1.21	0.26	1.59
Delhi	−0.03	−0.68	0.04	0.64	0.05	0.43	0.11	0.00	0.10	0.31	0.06	0.14

[1] Computed using Eq. 4

level (these are shown in bold in Table 2). An additional 10 tests were significant at the 10% level, resulting in 29% of the tests having a significance of 10% or lower (these are shown in italic in Table 2). In terms of storm duration, average trend coefficients of 1.06, 1.11, 1.31, 1.22, and 1.00 were found for the 5, 10, 15, 30, and 60 min storms, respectively.

Preston station had the highest average trend coefficient (2.05), with three and four tests being statistically significant at the 5% and 10% level, respectively. Oshawa station had the second highest average trend coefficient (2.03), with two and five tests being statistically significant at the 5% and 10% level, respectively. Timmins station had the third highest average trend coefficient (1.90), with two and three tests being statistically significant at the 5% and 10% level, respectively.

4.3 The Effect of Trends on Design Storms

Results showing the effect of trends on design storms are shown in Fig. 3. For a 2 year return period, IDF estimates for station time series with trend were on average 12% to 15.73% higher than the time series at a station with no trend. The highest percent increases were recorded for short storm durations, with the 15 and 30 min storms having 15.55% and 15.73% increases, respectively. Only four stations (Sarnia, Sudbury, Delhi, and Kingston) did not have increases greater than 10%. Oshawa and Moosonee had differences of 23% and 22%, respectively.

As the return period increased to the 50 year event, the range of percent increases in IDF estimates with and without trend decreased. This is also shown in Fig. 3. The range of percent increase for all durations for the 5, 10, 25, and 50 year return periods were: 4.79% to 12.70%; 4.2% to 11.5%; 3.7% to 10.4%; and 3.4% to 9.8%, respectively. The average percent increase in stations also decreased with return period. For the 2 year event, ten stations had percent increases higher than 10%; however, the 5, 10, 25, and 50 year return periods had percent increases of 6%, 4%, 3%, and 3%, respectively. Oshawa and Moosonee consistently had the highest differences in the two time series for all return periods.

The pattern of decreasing IDF rate with increasing return period was also related to the trend coefficient, as shown in Fig. 4. The highest average percent difference in IDF estimates for all return periods occurred at the highest trend coefficient registered for the 15 and 30 min storm durations, respectively.

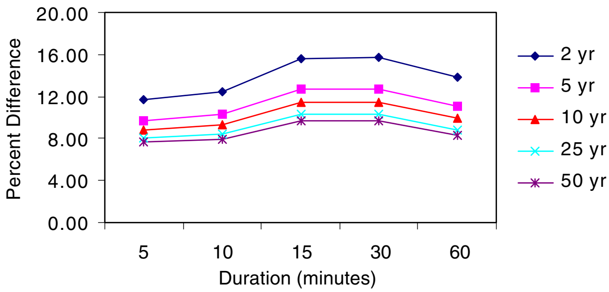
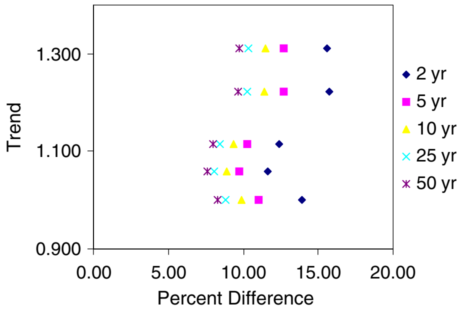


Fig. 3 Percent difference in IDF estimates with and without trend for various return periods

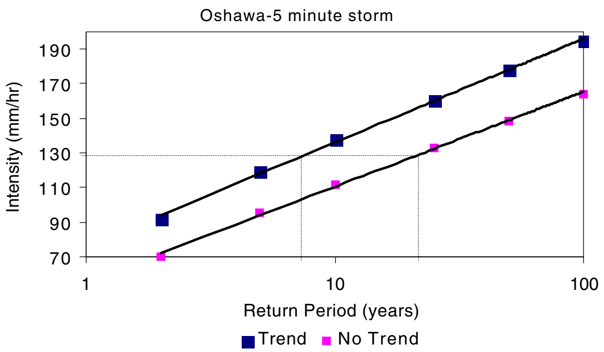
Fig. 4 Percent difference in IDF estimates with trend for various return periods



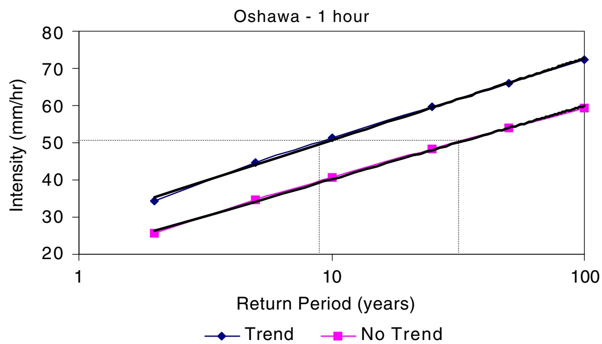
4.4 The Effect of Trend on Return Period

The effect of trend on the return period based on IDF estimates is illustrated for Oshawa for a 5 and 60 min rainfall in Fig. 5. For a given intensity of 130 mm/h, the 5 min storm duration yields a return period of 7.42 (with trend) and 21.83 (without trend). For the 1 h duration, the return period is 8.76 years (with trend) and 30.96 years (without trend) for a constant intensity of 50 mm/h. The difference in return period is quite significant and this indicates that the presence of trends

Fig. 5 IDF curves with and without trend for Oshawa



(a) Station 6155878 (Oshawa) for a 5 minute storm duration



(b) Station 6155878 (Oshawa) for a 1 hour storm duration

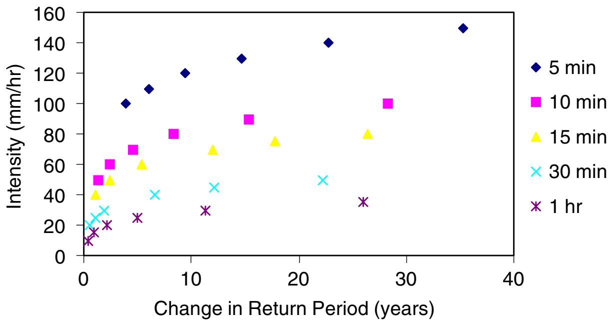


Fig. 6 Intensity versus change in return period for short storm durations

in rainfall observations increases the frequency of occurrences of extreme event analysis.

Repeating this for all durations for Oshawa, Fig. 6 shows changes in the return period as high as 36 years for the 5 min duration. The difference in return period decreases with increasing duration with a peak difference of 22 years found for the 1 h storm.

5 Conclusion

Based on the results of this study, it can be concluded that different parts of Ontario show different trends and tendencies in extremes of precipitation. There seem to be no simple patterns or uniform rates evident for all stations; nevertheless, changes are occurring. These changes could be attributed to either climate change and/or natural climate variability.

Numerical analysis showed significant trends for all durations and stations. It was determined that due to the existence of trends the design storms of a given duration might occur more frequently with return periods increased by as much as approximately 36 years.

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