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Impacts of Urbanization on Streamflow

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ABSTRACT: This study has concentrated on the temporal and spatial changes in streamflow patterns due to urbanization and/or rainfall trends within the watershed. The analyses were conducted by using the rainfall data from two stations, and streamflow data from three gauging stations. The results of the streamflow analysis showed that there is relative change in the mean and standard deviation of the stream flow with the reference distribution for all three stations. Also, analysis of location, scale and, shape parameters indicated that streamflow data show a non linear trend and statistically significant change for most of the location and scale parameters. A comparison of the earlier and later years of streamflow showed that Erindale, which has been significantly urbanized, has the maximum number of parameters with greater than 2% significance followed by Cataract; which shows a clear indication of effect of urbanization on streamflow. In addition, the pattern of high flow and low flow has changed, and the summer flows in all the gauging stations have become closer to the spring flow. The Frequency Duration Curve analysis showed that except for Orangeville, the order of high flow and low flow curves changed positions with time. The effect of urbanization was tested by taking the relative changes in flow during summer and spring season which showed a reduction of 0.07 m^3 s^{-1} yr^{-1}. The results from rainfall analysis showed that the rainfall intensities have slightly decreased in recent years for Pearson and Fergus stations. It also supports that higher streamflow in recent years is due to urbanization not increase in rainfall amount for the watershed.

INTRODUCTION

During the past century, the average global temperature has increased by about 0.7°C (IPCC, 2001). In accordance with IPCC, there is concern in scientific community and in the public over the importance of climatic changes because of human activities, heat-retention, and green house gases. There is now a broad consensus that these changing compositions of atmosphere have contributed to recent climatic changes. A study by Houghton *et al.* (1996) reported that the warmer temperatures will most likely intensify the hydrological cycle, leading to an increase in the precipitation intensity and number of precipitation events.

Another important issue is urbanization and its impact on water quantity and quality. A number of studies have been conducted to understand this issue having the primary focus on changes in stream flow. The studies on impact of low or high flows due to urbanization are still limited; however, some conservation authorities in Ontario have initiated research in this direction. Although there is a growing concern regarding impact of climate change on the hydrology of an area, studies showing effect of climate change on hydrology in space and time are still scarce. The importance and evaluation of both climate change and urbanization for their effects on hydrological and pollution issues is of great interest in Ontario.

URBANIZATION

Hydrologic impacts due to urbanization are also reported to cause water quality problems such as sedimentation, increased temperatures, habitat changes, and the loss of fish populations. Although there is widespread recognition that these problems are caused by increased runoff volumes and velocities from urbanization and associated increases in watershed imperviousness, much of the reported information has been anecdotal. Agricultural drainage is also increasing in southern Ontario, but its effects on flood characteristics are not well established as those of urbanization (Irwin and Whiteley, 1983; Serrano *et al.*, 1985). Therefore, there is a great need of understanding the potential impacts of urbanization and agricultural drainage on stream flow regime.

An approach of GIS spatial modeling of river flow and precipitation by Ko and Cheng (2004) was applied to the Oak Ridges Moraine area, Ontario, to evaluate how the stream flow records react to the storm runoff patterns. Three statistics indices, the time lag, the optimum auto-correlation range, and the Hurst exponent,

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were applied to the study area. The results of this study showed that land use show the most statistically significant correlations. Also, urban area tends to have negative correlations with all three statistics indexes showing that if the watershed has higher proportion of the urbanized area, the time lag will become shorter. In addition, the stream would need a longer time to respond to the precipitation event in a higher proportion of the vegetated area. Topography including the slope of drainage basin influences the rate of flow and enhances lateral flow instead of vertical percolation.

The hydrological consequences of urbanization over 50 years period in the Laurel Creek Watershed, Waterloo, Ontario, were investigated by Morgan et al. (2004) by using census, climate (temperature and precipitation), land use, and runoff data. The rate of population growth was 1000% over fifty years, and rate of urbanization was almost 1200% over the same time period. The results indicated that the runoff ratio increased significantly over time as compared to other hydrological indices and climate variables. The study also concluded that there are significant challenges to simulate hydrological effects of urban expansion in a changing climate.

Another 5 year study was conducted by Taylor and Roth (1979) to evaluate the effect of urbanization on the runoff response in a small drainage basin in southern Ontario, where 25 percent of its surface has been modified by suburban construction activity. The results indicated that the seasonal contrasts in the effect of partial suburban development on direct runoff response are caused by seasonal variations due to construction surfaces. Seasonal variations effect on the surface runoff response between suburban and rural areas were also observed by Taylor (1977) on a small basin in Peterborough, Ontario. The results showed that runoff response was strong during spring snowmelt as compared to the summer runoff.

A report by Grand River Conservation Authority, Ontario, (GRCA, 2003) reveals major land use changes during post-European settlement era in which wetlands were drained for crop production in the Grand River Basin, Ontario. This land use change has reduced the cover and increased potential of runoff and nonpoint source pollution. Also, the changes such as artificial drainage and urbanization have affected the streamflow regime in the basin.

RAINFALL TRENDS

Any global change in climate could have major impacts on the magnitude, location and duration of hydrological extremes. The changes in hydrological extremes will have significant impact in the design of hydraulic structures, flood-plain development, and water resource management. Ontario is also experiencing an increase in the frequency and intensity of flood damages across. The potential impacts of climate change could include: an increase in the frequency and severity of extreme weather events including short duration/high intensity rainfall and change in precipitation distribution amounts (Bruce *et al*., 2002).

Past studies have examined the trends in precipitation. A study by Kunkel *et al*. (1999) for stations in the US and Canada showed that 1 to 7 day large precipitation events with a longer than 1 year recurrence intervals have a statistically significant increasing trend in the United States and a small upward, but non-significant, trend in Canada. In Canada, it is also important to evaluate the summer torrential rains and impacts of extreme climatic events on the environment. However, very few studies of Canadian data have been reported in literature dealing with estimation of trends in extreme short duration rainfall events (Adamowski *et al*., 2003).

Cunderlik and Simonovic (2005) evaluated the effect of the potential impact of changed climate on the timing and magnitude of hydrological extremes in a densely populated and urbanized river basin in southwestern Ontario, Canada, using a weather generating algorithm linked with GCM outputs. The results showed that the future river flows would be less extreme and more variable in terms of magnitude and seasonal occurrence in future. Overall, they concluded that the simulated future scenarios may have positive effects on the distribution of hydrological extremes in the area.

Effect of climate change on water quality and quantity was evaluated by Booty *et al*. (2005) for a watershed in southern Ontario. Two internationally recognized climatic models, the Canadian Centre for Climate Modelling and Analysis (CCCMA) and the Hadley Center HadCM2, were used for various climate change scenarios with the AGNPS model to simulate changes in stream water quality and quantity. The results from land use scenarios showed much smaller changes in peak flows than those of simulated for the climate change scenarios. They also emphasized the importance of understanding of climate change responses for the development of strategies for source water protection.

Whitfield and Cannon (2000) examined the climatic and hydrologic variations between the decades 1976–1985 and 1986–95 for 210 climate stations for temperature, 271 climate stations for precipitation, and

642 hydrology stations across Canada. They concluded that variations in climate are distributed across the country. However, there were significant decreases in precipitation in the north and increases in the south, except for Ontario and Quebec where little or no change was observed.

To effectively protect populations and infrastructure, it is vital to accurately estimate the risks associated with extreme rainfall events. Firch *et al.* (2002) indicated that a significant portion of the global land area has been affected by significant change in climatic extremes during the second half of the 20th century (1946–1999). Vincent and Mekis (2004) examined the possible variations in selected climate change indices for Canada over 1950–2001 and 1900–2001 periods and found a reduction in the intensity of precipitation events at most stations in the south and an increase at a few stations in north. They concluded that there are no consistent changes in the extreme precipitation pattern.

The literature review shows that there is considerable uncertainty regarding impact of climate change and urbanization on hydrologic regime of a river basin. In some cases, the rainfall events of short durations (1 hour or less) are more important. Also the frequency distributions of heavy rainfall of short durations are of importance to engineers and others involved in design and operation of structures, such as agriculture drainage systems, urban stormwater sewers and retention ponds. Due to unavailability of adequate stream flow data, many methods (such as: rational method, synthetic unit hydrographs, etc) rely on rainfall IDF curves as input to determine peak flows. The IDF curves can be developed by the frequency analyses of extreme rainfall data of short durations.

OBJECTIVES OF THE STUDY

To understand the temporal and spatial changes in streamflow and rainfall patterns within the watershed, the main objective of the study was to evaluate the effect of urbanization and/or rainfall pattern on streamflow using historical data. The specific objectives of this study are:

1. To apply Extreme Value Theory of Peak Over Threshold (POT) to annual and seasonal streamflow for different periods;
2. To estimate the Return Level- Return Period of annual and seasonal stream peak flow;
3. To analyze the low-flow and high-flow regions and the shift in high flow (10% excedence) between the spring and summer months for different periods; and
4. To examine the pattern of short duration rainfall extremes events using observed data;

METHODOLOGY

Study Area

Credit River Watershed

The Credit River flows 99 km from the head waters to the shore line of Lake Ontario, The Credit River watershed is 1000 km^2 in area. It has 1,500 km of tributaries with diverse land use. The major division of landuse in the watershed is defined as: 39% agriculture, 18% forest, and wetlands 7%. Although only 21% of the watershed is urbanized, it is one of the most rapidly urbanizing parts of Canada. The population of the watershed is 650,000 and about 87% live in the lower third of the watershed. The watershed also has portions of the World Biosphere Reserve; Niagara Escarpment, and Oak Ridges Moraine making it the home of a significant natural feature.

The mean annual precipitation in the Credit River watershed is 850 mm, of which 15% appears as snowfall (or 125 cm in depth). The greatest precipitation amounts occur in the northern part of the watershed, due to the influence of the Niagara escarpment on 'lake effect' storms originating over Lake Ontario. Lake effect precipitation originating from Lake Huron and Georgian Bay are also possible, but their influence is in the Northern part of the watershed (Credit Valley Conservation Silver Creek Subwatershed Study, 2003). Based on isoheytal maps for southern Ontario (Brown *et al.*, 1974; OMNR, 1984), the mean annual evapotranspiration in the watershed is about 540 mm. The area has an annual frost-free period of 148 days, with a growing period of about 202 days. The mean annual air temperature is 6.0°C, where the mean daily temperature in January is about –6.4°C and 20.3°C in July (Credit Valley Conservation Silver Creek Subwatershed Study, 2006). Total precipitation and air temperature in the Credit River Watershed vary monthly and seasonally. Total precipitation and air temperature also vary between the upper, middle and lower portions of the watershed. Variances in climate conditions can be attributed to the shape and size of the watershed as well as to the existence of the Niagara Escarpment.

The Credit River Watershed has three distinct physiographic zones; namely the upper watershed, the middle watershed and the lower watershed (Figure 1). The upper watershed includes all areas north of Inglewood and also lies on or above the Niagara Escarpment. The middle watershed includes the Niagara Escarpment area between Inglewood and Georgetown and is characterized by steep slopes with the Oak Ridges Moraine. The lower watershed is highly urbanized with the western edge of Brampton and most of

Mississauga. The topography is relatively flat with southward slope towards Lake Ontario (Credit Valley Conservation Silver Creek Subwatershed Study, 2006).

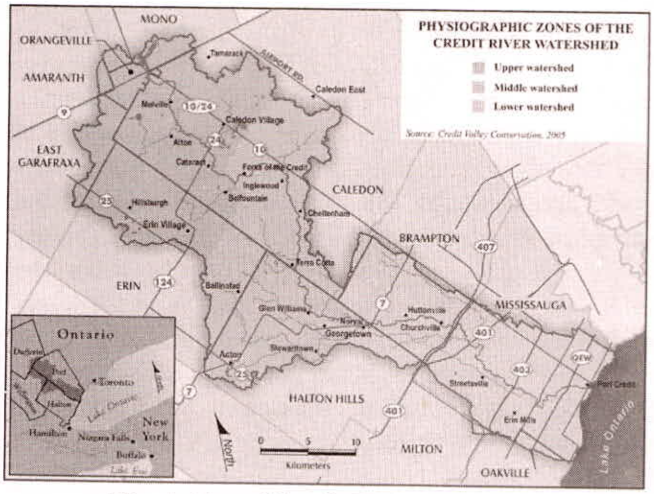


Fig. 1: Map of Credit River Watershed

The watershed had developed over the years due to industrialization and population growth. The land use change has altered the hydrology of the region. The population growth over many years has been given in Table 1. The mean annual precipitation in the upper middle and lower zones has 892 mm, 885 mm and 793 mm respectively.

Table 1: Population Percentage Change from 1996 to 2001 by Municipality

Municipality	*1996 Population*	*2001 Population*	*% Change, 1996–2001*
Mississauga	453,263	517,229	14.11
Brampton	80,801	107,996	33.66
Caledon	21,191	23,827	12.44
Orangeville	21,498	25,248	17.44
Mono	6,552	6,922	5.65
Oakville	14,319	14,062	–1.79
Milton	3,212	3,181	–0.97
Halton Hills	42,390	48,184	13.67
Town of Erin	10,657	11,052	3.71
Entire Watershed	653,883	757,701	15.88

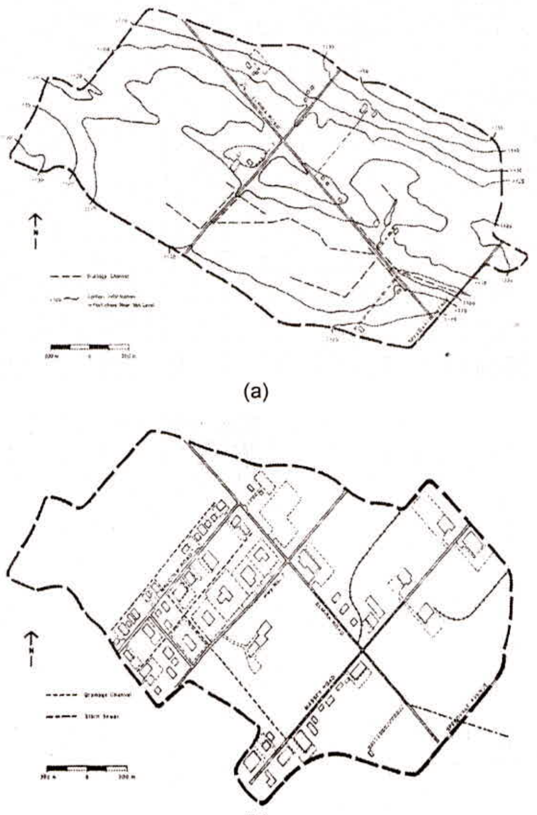
Three gauging stations, Orangeville, Cataract, and Erindale, are selected for the study. The stream flow data for all the gauging stations is downloaded from the Water Survey of Canada, Environment Canada web site. The gauge stations; Orangeville and Cataract fall in the upper watershed and Erindale in the lower watershed. The details of the gauging stations along with the respective watershed area are given in Table 2. Although the stream exhibits monthly variation, there is a cyclic trend to the mean flow, with peak flows occurring between March and April and the low flows occurring between June and September. The mean annual stream flows are 0.6 $m^3 s^{-1}$ at Orangeville, 1.8 $m^3 s^{-1}$ at Cataract, and 8.3 $m^3 s^{-1}$ at Erindale.

Speedvale Watershed

The Speedvale Experimental Basin is a small watershed situated at the northwest of the City of Guelph, Ontario. The climatic conditions are subhumid continental with moderate winters and warm summers. The mean annual precipitation of 840 mm is uniformly distributed throughout the year. The mean temperature for February, the coolest month, is –6.3°C, and for July, the warmest month, is 20.2°C. The primary land use within the watershed prior to 1974 was of mostly agricultural. At that time, the watershed was 199 ha in area (Figure 2(a)). During 1975 and 1976 an extensive servicing program was undertaken by the City of Guelph in the watershed area for the development of industrial zone. The extensive land grading resulted in a change in the watershed boundary, with a net increase of 11 ha (Figure 2(b)). By 1982 approximately 45% of the watershed area was occupied with the development occurring immediately after servicing of the area. A completely new drainage scheme was constructed within the city limits. Conveyance in the lower portion of the system is handled by a large-diameter storm sewer, while the upper portion consists of a network of open drainage ditches as illustrated in Figure 2. The stream flow data (from 1965 to 1982) is available from Water Survey of Canada (Gauge NO.02GA032). Precipitation data for this watershed is available from Atmospheric Environment Service (A.E.S.) from 1966 to 1982. Originally this study was conducted by Cook and Dickinson (1986). The objective of the study was to evaluate the impacts of urbanization on hydrologic response. This paper also discusses the results from this study to evaluate the effect of urbanization on hydrological behavior of the watershed.

Table 2: Details of Gauging Stations Used in the Study

Name	*Gauge Station*	*Period of Data*	*Location*		*Watershed Area, km^2*
Cataract	02HB001	1915–2005	43° 50′ 9″ N	80° 1′ 22″ W	205.00
Erindale	02HB002	1945–1993	43° 32′ 34″ N	79° 39′ 26″ W	795.00
Orangeville	02HB013	1967–2005	43° 53′ 27″ N	80° 3′ 43″ W	62.20



(a)

(b)

Fig. 2: Map of Speedvale watershed showing before and after development of the study area

Streamflow Analysis

The Extreme Value Distributions

The Extreme Value Theory follows one of the three distributions: Gumbel, Fréchet or Weibull. These can be nested into a single parametric representation known as the "Generalized Extreme Value" (GEV) family, and given by,

$$G(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{\frac{-1}{\xi}}\right\} \quad \ldots (1)$$

Where: μ, σ and ξ are the location, scale and shape parameters of the distribution, and

$$\left\{x : 1+\xi\left(\frac{x-\mu}{\sigma}\right) > 0, -\infty < \mu, \xi < \infty; \sigma > 0\right\}$$

Similar to the mean and standard deviation of normal distribution, the location parameter specifies where the distribution is centered and the scale parameter gives its spread and has the same units as the random variable and the shape parameter is dimensionless.

The shape of the GEV distribution assumes three possible types:

1. $\xi = 0$, a light-tailed (or Gumbel) distribution;
2. $\xi > 0$, a heavy-tailed (or Fre´chet) distribution;
3. $\xi < 0$, a bounded (or Weibull) distribution.

The distribution $G(x)$ in equation (1) uses the maxima of blocks of time. Modeling maxima have only limited sample size; poor representation and is wasteful if other data on extremes are available. It is useful to look at excedances over a given threshold instead of simply the maximum/minimum of the data,

$$H(x) = 1 - \left(1 + \frac{x\xi}{\sigma}\right)^{\frac{-1}{\xi}} \quad \ldots (2)$$

Where, $H(x)$ is referred to as the Generalized Pareto Distribution (GPD).

Like the GEV, GPD has the same representation of location and scale. The shape is interpreted as:

1. $\xi = 0$, a light-tailed (or exponential) distribution;
2. $\xi > 0$, a heavy-tailed (or Pareto) distribution;
3. $\xi < 0$, a bounded (or Beta) distribution.

Poisson distribution is a discrete probability distribution that expresses the probability of a number of events occurring in a fixed period of time if these events occur with a known average rate and independently of the time since the last event. When an event becomes rare the occurrence of the events approaches a Poisson Distribution. The Poisson distribution is used to calculate the frequency of extremes, and described as,

$$p(x,\lambda) = \frac{e^{-\lambda}\lambda^{x}}{x!} \text{ forx} = 1, 2, 3 \quad \ldots (3)$$

Where λ is the average number of events in the given time interval.

Peak Over Threshold (pot)/Point Process

This approach combines the number of times at which high-threshold excedences occur by Poisson process (λ) and the number of excess values over the threshold by Generalized Pareto Distribution (μ, σ, and ξ). It is also called Poisson-Generalized Pareto model. The main advantage of the model is that it provides a rich interpretation of extremes that unifies all the previously described models and commonly termed "partial duration series" in hydrologic literature (Kartz, 2002).

Selection of Threshold—The Mean Excess Plot

The mean excess plot was introduced by Davison and Smith (1990). It is a diagnostic plot drawn before fitting any model and gives guidance for choosing appropriate threshold value.

Let the raw data consist of a sequence of measurements $x_1, x_2 \ldots x_n$, and $x_{(1)}, x_{(2)} \ldots x_{(k)}$ represent the subset of data points that exceed a particular threshold, u. Threshold excess is defined by $y_j = x_{(j)} - u$ for $j = 1, 2, 3, \ldots k$. The points are plotted using the x–y coordinates,

$$\left\{\left(u, \frac{1}{n_u}\sum_{i=1}^{n_u}(x_i - u)\right) : u < x_{\max}\right\} \qquad \ldots (4)$$

This plot is called mean excess function/mean residual life plot. From the plot, the threshold is selected by finding the lowest threshold where the mean excess plot is nearly linear taking into account the 95% confidence bounds. The slope of the plot leads to a quick estimate of ξ. An increasing slope indicates $\xi > 0$, a decreasing slope indicates $\xi < 0$, and a constant slope indicates that $\xi = 0$.

Diagnostics Plots

Once the model is run for the respective distribution, a graphic window appears displaying four diagnostic plots, namely probability plot, quantile plot, return level plot and a density estimate plot. The quantile plot compares the model and the data quantiles where as the probability plot compares the two probabilities. Both have the same information expressed in different scale bringing better perception. The return level plot shows the return period against return level with an estimated 95% confidence interval. The density plot is a comparison of the probability density function of the fitted model with a histogram of the data. In the case of perfect fit, the data would line up on the diagonal of the probability and quantile plots; within the confidence interval for the return level plot; density plot aligned with the histogram. Deviations suggest that the model assumptions are invalid for the data plotted.

Return Level-Return Period

The probability of an event in hydrology is calculated by analyzing the series of maximum events called return period. Return period is defined as an annual maximum event has a return period (or recurrence interval) of T years if its magnitude is equaled or exceeded once, on the average, every T years. The reciprocal of T is the excedence probability, 1–F, of the event, that is, the probability that the event is equaled or exceeded in any one year (Philip, 2002). It is more convenient to interpret extreme value models in terms of quantiles or return levels rather than parameter values. The return level is calculated either from GEV or GPD distribution by setting the cumulative distribution function equal to the designed probability/quantile, 1–p; and then solving for the return level.

Flow Duration Curve

A Flow Duration Curve (FDC) is the relationship between any given discharge value and the percentage of time that this discharge is exceeded. FDCs are a potentially important tool for quantifying and studying the effects of urbanization on streams flow, because they respond to changes in a watershed's hydrologic characteristics. It is drawn with stream flow values arranged from highest to lowest (y-axis) and percent excedence (x-axis) at each interval (Fitzgerald, 2000).

Excedence Probability,

$$P = 100 \times [M/(n + 1)] \qquad \ldots (5)$$

Where,

P = the probability that a given flow will be equaled or exceeded (% of time)

M = the ranked position on the listing (dimensionless)

N = the number of events for period of record (dimensionless)

extRemes Software

The software used for the Extreme Value Analysis is Extremes Toolkit[2] ("extRemes"), Weather and Climate Applications of Extreme Value statistics Version 1.57. It is interactive software and facilitates the use of Univariate Extreme Value Theory along with covariates in applications oriented towards problems that involve extremes in Weather and Climate. The "extRemes" software uses maximum likelihood estimation with iterative numeric optimization technique. Parameter estimation by maximum likelihood method maximizes the appropriate likelihood (probability) function of the sample data. It is widely used for large sample sizes; quantifies the standard errors and the uncertainty through confidence bounds. More over covariates can be easily incorporated with MLE that incorporate trends, cycles or actual physical variables (Kartz, 2002). The flow duration curves were made with the Excel spreadsheet with the inbuilt functions.

Dataset for Streamflow

Datasets consist of a set of distribution for different period of time for each gauging station. The parent distribution is the whole data for each of the three gauge stations; Orangeville (02H013), Cataract (02H001):

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[2] Written and maintained by Eric Gilleland, National Center for Atmospheric Research Research pplications Laboratory, 3450 Mitchell Lane, Boulder, CO 80301, USA

and Erindale (02H002); with the reference distribution being the values above threshold for the whole period/season of study. For each station the data were divided into different periods (called study distribution) with sub divisions for the three seasons, namely; spring, winter and summer. The value from the reference distribution is compared with the values of each period to estimate the hydrologic change. The study periods for Orangeville: 1967–1986 and 1987–2005; Cataract 1915–1929, 1930–1944, 1945–1959,1960–1974,1975–1989 and 1990–2005; Erindale: 1945–1960,1961–1976 and 1977–1993. The months chosen for the three seasons are; Spring: February–May; Summer: June – September; Winter: October–January

This research was conducted in two parts: estimation of parent distribution, reference distribution and study distribution with the Extreme Value Theory of POT method, return period–return level of reference and study distribution estimate of the attributes of excedence of annual flow, and flow duration curves. These estimates were analyzed for: change with the reference distribution by performing t-test, the effect of the attributes of excedence with time, change in the low and high flow for different periods and comparison between spring and summer flow duration curves.

IDF Analysis

The basic principles and methodology used for IDF curves in this study are based on the "Handbook of Applied Hydrology" (Chow, 1964), and "Frequency Analysis of Hydrologic Data with Special Application of Rainfall Intensities" (Chow, 1953). The IDF analysis for this study relied primarily on data from 2 climate stations Shand Dam station at Fergus, located in the west, and Pearson station in Toronto, located in the east of the watershed. In this study, the monthly and annual rainfall extremes of 5 min, 10 min, 15 min, 30 min, 60 min, 120 min, 360 min, 720 min, 1440 min, and 2880 min durations were analyzed for two stations. The monthly extreme rainfall data have been available for Pearson and Fergus for the months of April to November for the periods of 1960–2003. Data for the winter months (December to March) were not analyzed because most precipitation during winter is in the form of snow.

Extreme Value Analysis

Extreme Value Type I (EVI) distribution, also called the Gumbel (1941) distribution or the double exponential distribution, is given as,

$$F(x) = \exp\left[-\exp\left(-\frac{x-u}{\alpha}\right)\right] \quad \dots (6)$$

The parameters are estimated by,

$$\alpha = \frac{\sqrt{6}s}{\pi} \quad \dots (7)$$

$$u = \bar{x} - \gamma\alpha \quad \dots (8)$$

Where, $\gamma = 0.5772157\ldots$ Euler's constant,

$$\bar{x} = \sum x/N \quad \dots (9)$$

$$s = \sqrt{\frac{1}{N-1}\sum\left(x-\bar{x}\right)^2} \quad \dots (10)$$

Frequency Analysis using Frequency Factor

The extreme value, x_T, may be represented by the mean, μ, plus the departure, Δx_T, of the variable from the mean,

$$x_T = \mu + \Delta x_T \quad \dots (11)$$

The departure may be taken as equal to the product of the standard deviation, σ, and a frequency factor, K_T; that is $\Delta x_T = K_T\sigma$. Equation (11) may therefore be expressed as,

$$x_T = \mu + \sigma K_T \quad \dots (12)$$

Since the mean, μ, and the standard deviation, σ, of population can be approximated by mean, $\bar{x}$, and the standard deviation, s, of the sample, Equation (12) may be approximated by,

$$x_T = \bar{x} + K_T s \quad \dots (13)$$

The probability (P) of a recurrence interval of an annual (monthly) maximum value equal to or greater than magnitude, x_T, is given as,

$$P(x \geq x_T) = 1 - P(x \leq x_T) \quad \dots (14)$$

And the recurrence interval, T, is the reciprocal of this probability,

$$T = \frac{1}{P(x \geq x_T)} \quad \dots (15)$$

Substituting Equation (6) and (14) into (15) yields,

$$T = \frac{1}{1-\exp\left[-\exp\left(-\frac{x_T-u}{\alpha}\right)\right]} \quad \dots (16)$$

Transforming, Equation (16) becomes,

$$x_T = u - \alpha \ln\ln\left(\frac{T}{T-1}\right) \quad \dots (17)$$

Substituting Equation (7) and (8) for u and a, Equation (17) becomes Equation (13) and K_T is expressed as,

$$K_T = -\frac{\sqrt{6}}{\pi}\left[\gamma + \ln\ln\left(\frac{T}{T-1}\right)\right] \quad \text{... (18)}$$

This Equation was first derived by Chow (1953) and is used to compute the relationship between the frequency factor and the recurrence interval in Gumbel distribution.

To determine the rainfall amount for any specific return period, the corresponding value of frequency factor, K_T, was calculated using equation (18) and the rainfall amount was estimated using equation (12). To determine the IDF curves of selected stations, annual maximum rainfall data of various durations are analyzed following the previous example. The rainfall depths of specific return period were estimated from the fitted Gumbel distributions and transformed into rainfall intensity (mm h^{-1}) and plotted against the durations (min).

RESULTS AND DISCUSSION

Credit Streamflow

The data for the parent distribution for Orangeville, Cataract, and Erindale showed the abstract information of the range of the flow; Orangeville 0.05–10.30 $m^3\ s^{-1}$; Cataract 0.17–66.8 $m^3\ s^{-1}$; and 0.09–337 $m^3\ s^{-1}$. The high flows show a pattern of increase from Orangville to Cataract to Erindale. On the other hand low flow showed an increasing pattern at Cataract, and decreasing trend at Erindale. The parent distribution is positively skewed for all the stations. The standard deviation (scatter) is quite high for Erindale with the least for Orangeville indicating that the mean of monthly flow for summer and winter period at Erindale has increased steadily which may be due to urbanization. The standard error of location, scale and shape for Cataract: summer (1915–1929), (1930–1944) and winter (1945–1959), Orangeville: summer (1967–2005), (1967–1986), and winter (1967–2005), Erindale: spring (1960–1976), summer (1977–1993) and winter (1960–1976), were found to be zero, indicating that these distributions are a perfect fit to the data and the estimated parameters are accurate.

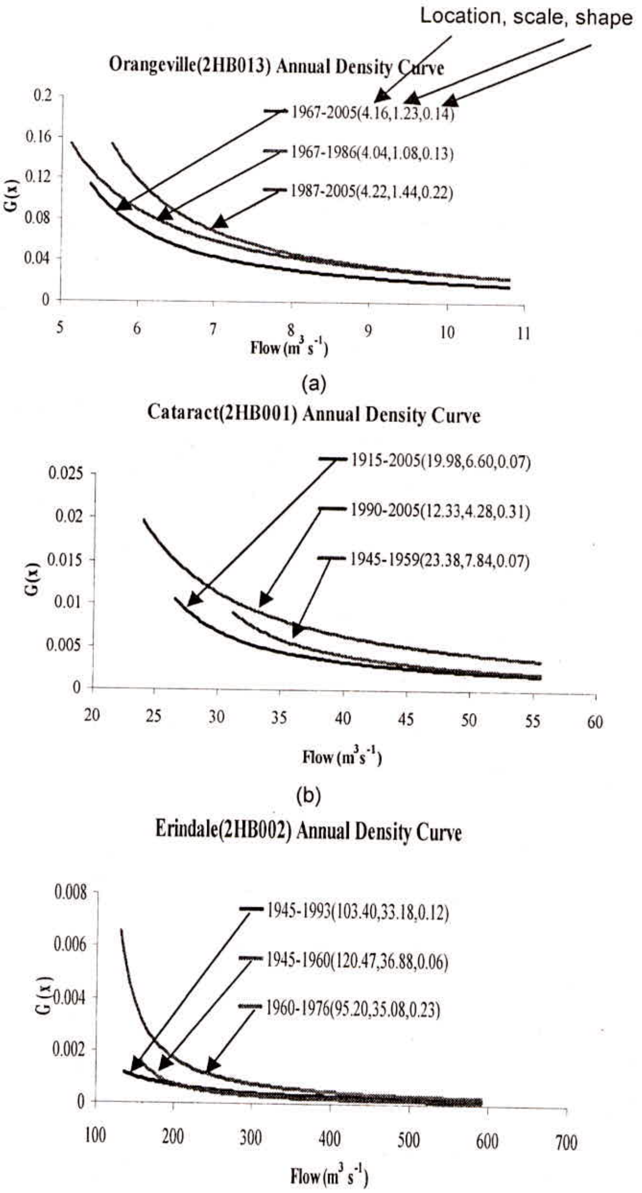
The analysis of the location, scale and shape using annual density curve (Figure 3) with the assumption of stationarity using Extreme Value Theory revealed the failure of stationarity in all cases as the values were different from the reference distribution. The values of the location, scale, and shape; however, do not show any specific trend. This also depicts that there is change in hydrologic regime (Figure 3). Statistical significance was tested by using student t-test by taking the earlier period with the later ones. The t-test incorporates the standard error of each parameter. |t| >1.96 is statistically significant at 5% level. The t-test values in percentage are given in Table 3. These results shows non linear trend. Most of the location and scale factors showed statistical significance but it is either increasing or decreasing. It is also clear from the data in Table 3 that Erindale has more number of observations with >2% significance followed by Cataract and the least for Orangeville. For Orangeville, the number of location, scale, and shape observations with <1% significance are 75%, 25%, and 25%, respectively. This implies that Orangeville has the least hydrologic change whereas Erindale has the highest.

Table 3: Details of Gauging Stations Used in the Study

	t-test Values in %		
Station	*Location*	*Scale*	*Shape*
Cataract			
>2%	65	65	40
1–2%	20	15	35
<1%	15	20	25
Erindale			
>2%	100	75	37.5
1–2%	0	0	37.5
<1%	0	25	25
Orangeville			
>2%	25	25	0
1–2%	0	50	75
<1%	75	25	25

As shape factor is the main parameter to determine the Return Period- Return Level; therefore it is analyzed in detail. According to the Extreme Value Theory, for Beta (Weibull), Exponential (Gumbel), and Pareto (Frechet) distribution, the value of shape factor is <0, 0 and >0, respectively. Generally Pareto distribution fits precipitation, stream flow and economic impact and Beta distribution fits for wind speed, sea level and temperature (Kartx, 2002). None of these distribution followed an Exponential distribution. All the reference distribution follows Pareto distribution showing that it has "long/heavy tail" with the values >0. For heavy tail, the probability density function decays as a power law (decreases at slow rate) than exponential in the upper tail. Except for Erindale-Summer1977–1993, a value of 0.57, all values are between >0 and <0.5.

A distribution with a value >0.5 has an infinite variant. Cataract and Erindale have Beta and Pareto distribution and it could be due to the erratic nature of flow. This type of variation may be because of the impact of high and low flows due to urbanization.



(a)

(b)

(c)

Fig. 3: Annual density curves for various seasons for three stations

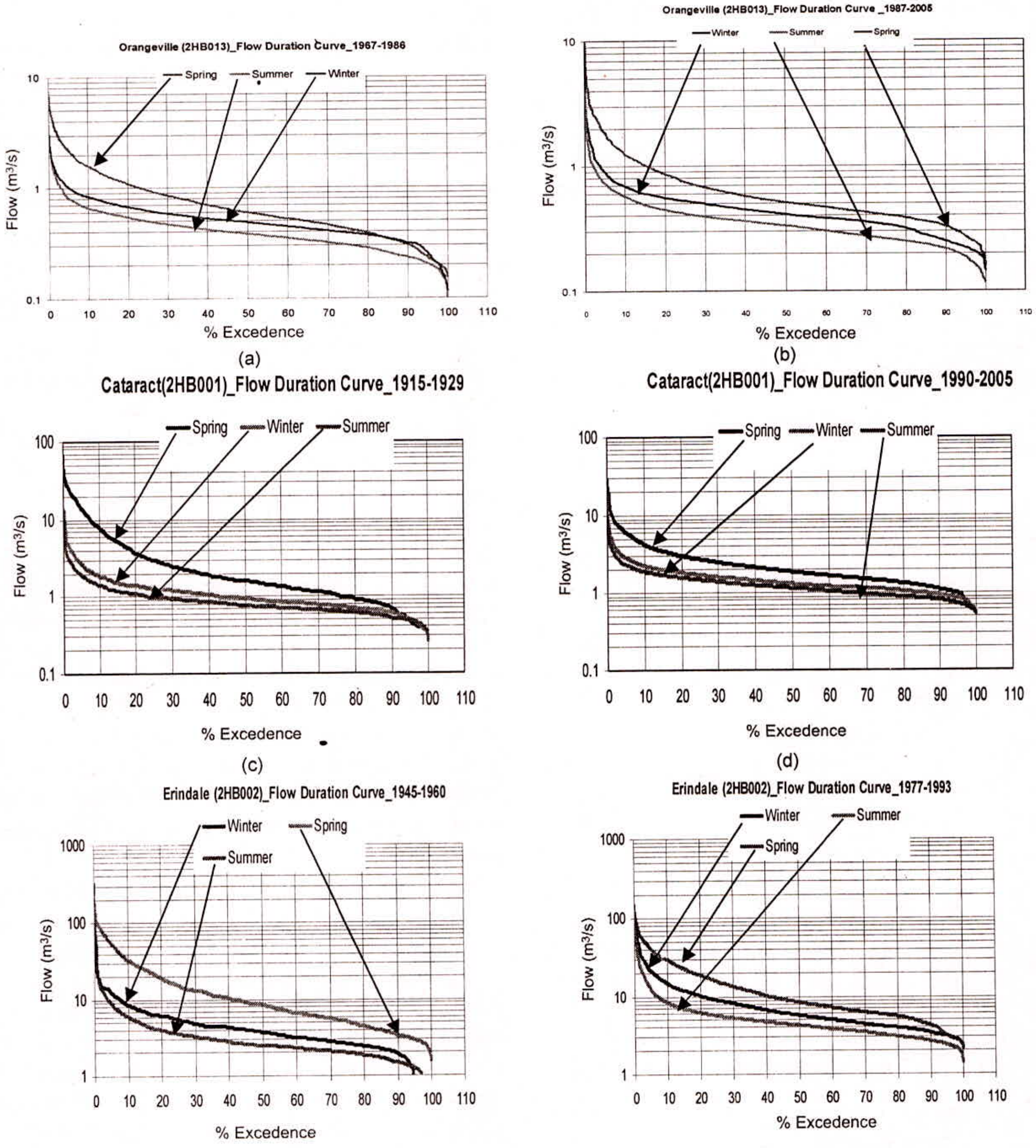
For the Return Period-Return Level of reference and study distribution, the return periods of 2, 5, 10, 15, 10, 25 years of the distribution were set first and then the return level (probability/qantile) for that period was derived from the associated Generalized Pareto Distribution. The confidence interval was set at 95%. In general it is seen that the return levels gradually decreased for higher return periods The 95% confidence bounds widened there by reflecting the inherent uncertainty associated with making inferences far beyond the range of data. The actual and the change with the reference distribution in Return Level for different periods have shifted from the reference distribution; however, there is no linear trend.

The conceptual idea of measuring the severity of a flood by studying the frequency and intensity of the flow is examined by calculating the Extreme volatility Index as described by Gangualy (2007). First the Extreme Volatility Ratio was determined by taking the ratio of the return level at 25 years to the 2 years. Then it was normalized to get the Extreme Volatility Index using the formula (1–(1/EVR)) and the value ranges from zero to one. There is an increase in value from the reference distribution; for Cataract from 0.44 to 0.57 i.e., +12.8% (1990–2005); Orangeville from 0.45 to 0.52 i.e., +6.7% (1987–2005). A decrease in value was found for Erindale from 0.48 to 0.40 i.e., –8.13% (1977–1993). The reason may be that these data do not account for records after 1993. As the engineering interpretation for the EVI is the design safety factor, this value forms a factor for any multidisciplinary studies on human life and economics of risk analysis. It is evident that an increase in EVI value would have serious consequences on the infrastructure development, design criteria, urban planning, risk management, and economy.

Figure 4 shows the Flow Duration Curves (FDC) for each season for all three stations. These data were used for comparative study for the high and low regions to understand the pattern and the effect of urbanization. It is expected that the high flow region of the FDC will tend to be higher in later years and the low flow region tends to be lower. More over the summer flow may become closer to spring flow. The difference in flows for the spring and the summer was compared for 10% excedence value. These data show that the high flow and low flow order have reversed for annual and spring for Erindale and Orangeville (Figures 4(a), 4(b), 4(e), and 4(f)). For Cataract, there are some changes in flow but the order is not consistent (Figure 4(c) and 4d). The order of the curves for winter and summer for all the gauging stations remain the same.

Speedvale Study

Table 4 presents the record of annual discharge volume and annual precipitation for the basin. The mean annual discharge volume before development was 5.89×10^5 m^3, compared with 9.44×10^5 m^3 after development (statistically different at the 0.05 level). The mean



(a) (b) (c) (d) (e) (f)

Fig. 4: Flow Durations Curves for various years for three stations

annual precipitation before development was 865 mm, compared with 920 mm after development; however, it was not significantly different. The mean annual runoff coefficients, defined as the ratio of annual discharge to annual precipitation, for after-development period was 0.506, which was significantly greater (1.5 times) than the mean value of the annual runoff coefficient before development. These results clearly show that urbanization has impact on volume of surface flows. In addition, shape of the hydrographs derived for before- and after-development conditions were also used to quantify effect of urbanization on peak flow and the results are presented in Figure 5. There is a significant difference between the hydrographs for these two conditions. The urbanization resulted in a significant decrease in lag time and a significant increase in peak discharge. Also, there is decrease in the length of the time base of the hydrograph. These changes were due to increase in drainage density from 10.8 m/ha to 54.4 m/ha and an increase in impervious area from 1% to 33% as a result of urbanization.

Table 4: Annual Discharge Volume and Annual Precipitation Amount (Cook and Dickinson, 1986)

Year	*Annual Discharge (dam^3)*	*Annual Precipitation (mm)*	*Annual Runoff Coefficient*
Before Development			
1967	705	880	0.403
1968	656	1035	0.319
1969	524	741	0.355
1970	451	854	0.265
1971	473	783	0.304
1972	562	920	0.307
1973	679	913	0.374
1974	662	794	0.419
Mean	589	865	0.343
Std. dev.	92.76	87.83	0.050
After Development			
1977	1000	896	0.529
1978	837	746	0.532
1979	1180	883	0.633
1980	589	803	0.348
1981	641	855	0.355
1982	1415	1045	0.642
Mean	944	871	0.506
Std. dev.	292	93	0.118

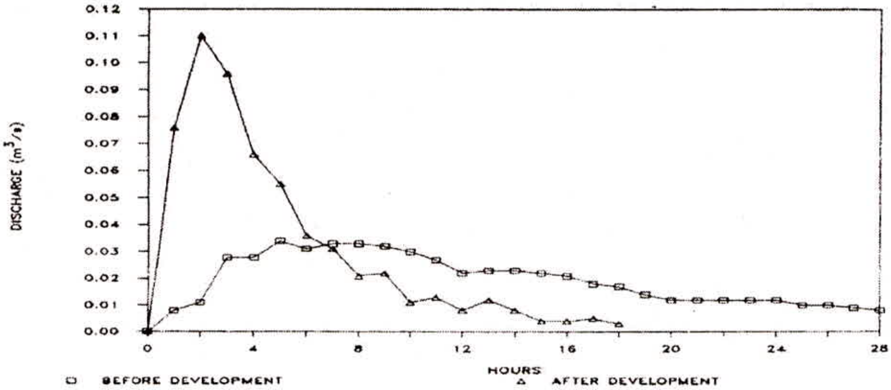


Fig. 5: Effect of urbanization on average unit hydrographs (Cook and Dickinson, 1986)

Rainfall

Spatial Analysis

Figures 6 and 7 show the IDF curves for Pearson and Fergus stations from 1960 to 2003. The rainfall intensities were found to be much higher for most of the intervals for Fergus station when compared with the values for Pearson station. As mentioned earlier that 5 min, 10 min, and 120 min durations data were not available for Pearson station, a direct comparison of various return periods for rainfall intensities of available intervals for both stations are shown in Table 5. It is obvious from the data that Fergus station has much greater rainfall intensity values than those of Pearson values; however, the only exception was for 2 year return period for 15 min and 30 min durations. The percentage difference in the rainfall intensities for various intervals between these two stations varies from 2.8 to –43.8%.

To further evaluate the effect of climate change, if any, the data from Pearson and Fergus stations were divided into two different time intervals (1960 to 1985 and 1986 to 2003). These sets were used separately for calculations of rainfall IDF curves as shown in Figs. 8 to 11. Figures 8 and 9 show the rainfall IDF curves for Pearson and Fergus for the period of 1960–1985. These Figures show that the overall shapes of IDF curves for these two stations are very different for various return periods. For example, 2 year IDF curve for Fergus had similar intensities for 30 min and 60 min intervals. These differences were further examined by computing the percentage change for various durations (Table 6). The analysis showed that Fergus had lower intensities for 15 min and 30 min durations for all the return periods; however, this difference changed for larger intervals for all the return periods. The fluctuations in percentage change for these comparisons were found to be 12.5% to –52.6% (Table 6).

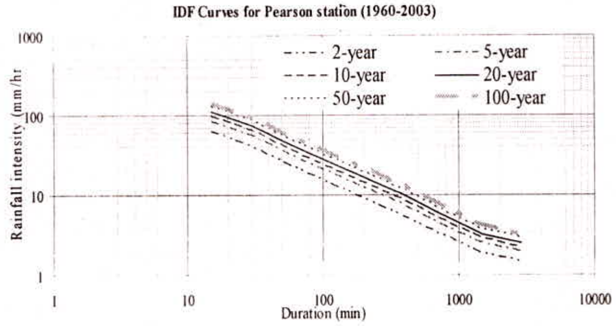


Fig. 6: Rainfall IDF curves for Pearson station

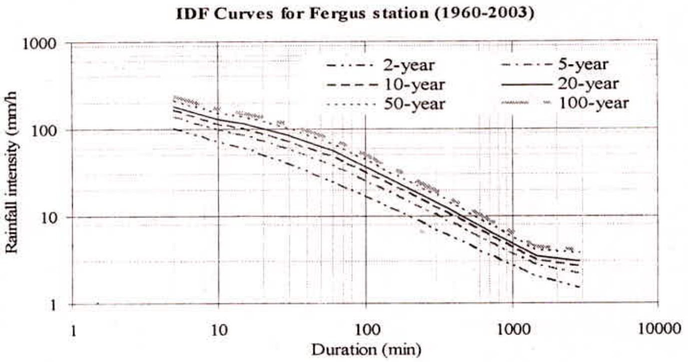


Fig. 7: Rainfall IDF curves for Fergus station

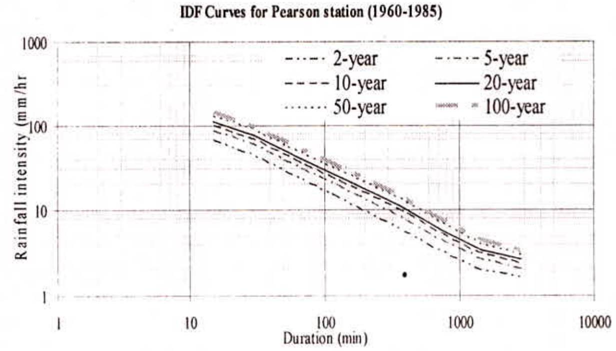


Fig. 8: Rainfall IDF curves from 1960–1985 at Pearson station

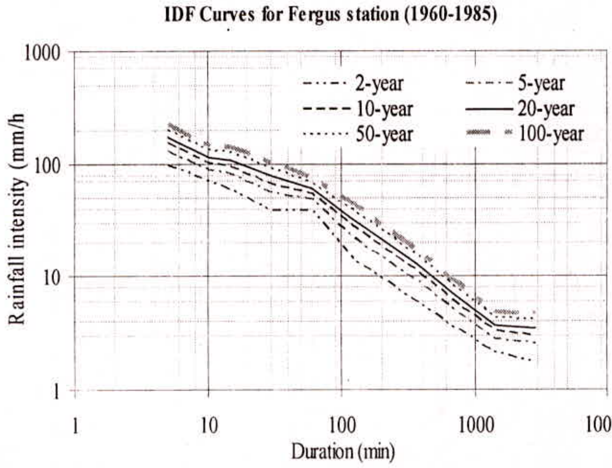


Fig. 9: Rainfall IDF curves from 1960–1985 at Fergus station

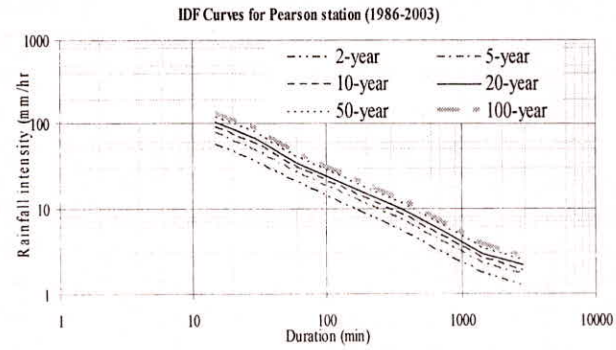


Fig. 10: Rainfall IDF curves from 1986–2003 at Pearson station

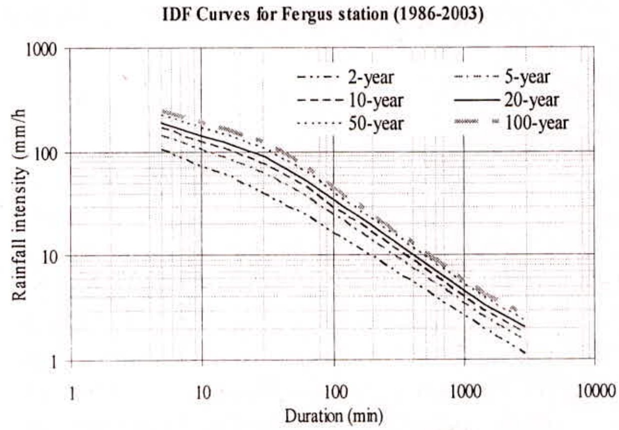


Fig. 11: Rainfall IDF curves from 1986–2003 at Fergus station

Table 5: Comparison of Rainfall Intensity for Pearson and Fergus (1960–2003)

Return Period (yr)	*Duration (min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	2.8^{η}	3.4	–4.0	–5.0	–7.3	–9.4	–0.9
5	–1.7	–6.4	–22.0	–10.6	–9.6	–8.6	–14.2
10	–3.6	–10.5	–29.6	–12.9	–10.5	–8.2	–20.0
20	–4.9	–13.4	–35.2	–14.5	–11.2	–8.0	–24.3
50	–6.3	–16.3	–40.6	–16.0	–11.9	–7.7	–28.7
100	–7.1	–18.0	–43.8	–16.9	–12.3	–7.6	–31.2

$\eta = \{(\text{Pearson - Fergus})/\text{Pearson}\} \times 100$

Table 6: Comparison of Rainfall Intensities for Pearson and Fergus Stations (1960–1985)

Return Period (yr)	*Duration (min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	9.5	12.5	–52.6	0.1	–3.9	–8.2	–8.8
5	6.1	4.4	–43.0	–8.9	–8.3	–7.2	–22.3
10	4.6	0.9	–38.8	–12.6	–10.1	–6.8	–28.5
20	3.5	–1.7	–35.8	–15.1	–11.3	–6.6	–33.1
50	2.4	–4.2	–32.9	–17.6	–12.6	–6.3	–37.8
100	1.7	–5.7	–31.2	–19.0	–13.3	–6.1	–40.6

Similar comparisons were also made for Pearson and Fergus for 1986–2003 data (Figures 10 and 11). These IDF curves show somewhat different results from 1960–1985 data analysis for rainfall intensities for some durations. For example, Fergus station had higher values of rainfall intensities than Pearson for all the durations. Nevertheless, the results were opposite for 48 hours for Fergus station when compared with Pearson station. The percent change for these curves is also shown in Table 7. The data show that the variation in intensities vary widely for various durations and ranged from 11.3% to 67.4%.

Temporal Analysis

The data from these two stations were also used to describe temporal changes in rainfall intensities during the four decades (1960–2003). Therefore, the Pearson data sets for the periods 1960–1985 and 1986–2003 were compared with each other by using the rainfall intensities given in Table 8. These results show that the rainfall intensities for the 1986–2003 period are much less than the rainfall intensities for the 1960–1985 period. It also shows a decline in the rainfall intensities for Pearson in recent years.

Table 7: Comparison of Rainfall Intensities for Pearson and Fergus (1986–2003)

Return Period (yr)	*Duration (min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	–8.4	–12.5	–21.8	–13.1	–12.4	–11.2	11.3
5	–14.7	–26.9	–41.7	–13.4	–11.9	–11.3	7.8
10	–17.3	–32.8	–50.5	–13.5	–11.6	–11.3	6.3
20	–19.1	–36.9	–57.0	–13.6	–11.4	–11.3	5.1
50	–20.9	–40.9	–63.5	–13.6	–11.3	–11.3	4.0
100	–21.9	–43.3	–67.4	–13.7	–11.2	–11.3	3.3

Table 8: Temporal Analysis of Two Data Sets, (1960–1985)^a and (1986–2003)^b, for Change in Intensities at Pearson Station

Return Period (yr)	*Duration(min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	13.7$^{\alpha}$	19.3	18.1	10.6	8.7	9.7	21.0
5	9.9	16.1	20.0	12.3	10.1	12.4	19.3
10	8.3	14.7	20.8	12.9	10.7	13.5	18.5
20	7.1	13.7	21.4	13.4	11.1	14.4	17.9
50	5.9	12.7	21.9	13.8	11.4	15.2	17.3
100	5.2	12.1	22.3	14.1	11.7	15.6	17.0

a = 1960–1985, b = 1986–2003, $\alpha = \{(a-b)/a\} \times 100$

Table 9 shows similar analysis for Fergus station (by dividing the data in two sets, 1960–1985 and 1986–2003). The analysis showed that smaller durations (15 min and 30 min) rainfall events have much higher intensities for 1986–2003 period than the intensities for the 1960–1985 period. However, the intensities were opposite for longer duration events (60, 120, 360, 720, 1440, and 2880 min). Overall, the data (Tables 8 and 9) show that rainfall intensities have decreased in recent years for Pearson station. On the other hand, for Fergus station, rainfall intensities for longer duration storms have substantially decreased in recent years. In addition, these analyses show that these stations do not have similar change in rainfall pattern (depth/intensity) over the last few decades.

Dickinson (1976) performed the analysis for monthly rainfall extremes of 5-. 10-, 15-, 30-, 60-, 120-, 360-, 720-, and 1440- min durations for the Pearson station. The method was almost similar to the one used in this study except that Dickinson (1976) assumed that the monthly extreme probability distributions for rainfall amounts occurring in specific durations are independent and derived the annual extreme distribution from the monthly data. This study share same results such as the Gumbel distribution represents monthly and annual rainfall extreme data equally well. Also, the rainfall depths of 2 year -30 min and 100 year -30-min storms at Pearson are estimated from the annual extreme value distributions and compared with results from previous study performed by Dickinson (1976) (Table 10). The differences between rainfall depth results from this study and Dickinson (1976) study are acceptable at this station.

Seasonal Analysis

The data from these two stations were also analyzed to examine seasonal changes in rainfall depth over the last four decades (1960–2003). Therefore, the data sets were rearranged on seasonal basis. The monthly extreme rainfall depths were divided in spring (March, April, May), summer (June, July, August), and fall (September, October, November) for 1960–1985 and 1986–2003 periods. Tables 11 to 13 show the seasonal rainfall depths for Pearson station. The spring analysis

Table 9: Temporal Analysis of Two Data Sets, (1960–1985)^a and (1986–2003)^b, for Change in Intensities at Fergus Station

Return Period (yr)	*Duration(min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	−3.4$^{\alpha}$	−3.8	34.6	−1.2	1.3	7.2	35.6
5	−10.0	−11.4	20.7	8.7	7.1	9.1	39.2
10	−12.7	−14.3	14.1	12.2	9.4	9.9	40.6
20	−14.6	−16.3	9.1	14.6	11.0	10.5	41.5
50	−16.5	−18.1	4.0	16.7	12.5	11.1	42.4
100	−17.6	−19.2	0.8	17.9	13.3	11.5	42.9

a = *1960*–1985, b = 1986–2003, $\alpha = \{(a-b)/a\} \times 100$

Table 10: Rainfall Depths Compared with Results from Previous Study

Station	*30 min, 2 year storm*			*30 min, 100 year storm*		
	Previous Study (mm)	*This Study (mm)*	*Difference (%)*	*Previous Study (mm)*	*This Study (mm)*	*Difference (%)*
Pearson	19.00	20.34	7.05	49.00	47.06	–3.96

Table 11: Seasonal Analysis (Spring)‡ of Two Data Sets, (1960–1985)^a and (1986–2003)^b, for Change in Rainfall Depth at Pearson Station

Return Period (yr)	*Duration(min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	–13.3$^{\alpha}$	–14.0	–17.1	–14.3	–15.2	–15.6	15.2
5	–24.8	–18.6	–22.1	–18.9	–12.9	–18.9	11.8
10	–28.8	–20.3	–24.0	–20.7	–12.0	–20.2	10.5
20	–31.5	–21.3	–25.3	–21.9	–11.4	–21.1	9.6
50	–33.9	–22.3	–26.5	–23.0	–10.8	–22.0	8.8
100	–35.3	–22.8	–27.2	–23.7	–10.5	–22.4	8.3

‡ Spring = March, April, May
a = 1960–1985, *b* = 1986–2003, α = {(*a*–*b*)/*a*} × 100

Table 12: Seasonal Analysis (Summer)‡ of Two Data Sets, (1960–1985)^a and (1986–2003)^b, for Change in Rainfall Depth at Pearson Station

Return Period (yr)	*Duration (min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	7.3$^{\alpha}$	12.3	13.1	12.9	15.5	17.4	25.3
5	9.0	14.5	15.2	12.7	15.2	17.2	21.8
10	9.5	15.2	16.0	12.7	15.1	17.1	20.6
20	9.9	15.7	16.4	12.6	15.1	17.0	19.7
50	10.2	16.1	16.9	12.6	15.0	17.0	18.9
100	10.4	16.3	17.1	12.6	15.0	17.0	18.5

‡ Summer = June, July, August
a = 1960–1985, *b* = 1986–2003, α = {(*a*–*b*)/*a*} × 100

Table 13: Seasonal Analysis (Fall)‡ of Two Data Sets, (1960–1985)^a and (1986–2003)^b, for Change in Rainfall Depth at Pearson Station

Return Period (yr)	*Duration(min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	–10.1$^{\alpha}$	–15.4	–12.3	–22.9	–18.0	–6.9	3.4
5	–3.2	–9.7	–8.2	–30.1	–26.5	–13.4	9.3
10	–0.9	–7.9	–6.9	–32.6	–29.4	–15.6	11.2
20	0.6	–6.7	–6.0	–34.3	–31.4	–17.1	12.4
50	1.9	–5.6	–5.2	–35.8	–33.1	–18.5	13.4
100	2.6	–5.0	–4.7	–36.6	–34.1	–19.2	14.0

‡ Fall = September, October, November
a = 1960–1985, *b* = 1986–2003, α = {(*a*–*b*)/*a*} × 100

in Table 11 showed that the rainfall depths were much greater for all durations except 2880 min duration for 1986–2003 period when compared with 1960–1985 period. These results also show an increase in rainfall depths in spring in recent years for Pearson. However, the analysis of summer season indicates a prominent decline in rainfall depths for 1986–2003 years (Table 12). Contrary to summer results, the pattern of rainfall depth in fall for 1986–2003 years is similar to spring for Pearson station (Table 13). This analysis also indicates an increase in rainfall depths for fall for all durations except for 2880 min duration.

The precipitation pattern at Fergus station were also examined for seasonal analysis by dividing the data in two sets (1960–1985 and 1986–2003 periods) and then computing rainfall depths for spring, summer, and fall months (Table 14 and 16). The spring analysis results for Fergus given in Table 14 show that the durations

Table 14: Seasonal Analysis (Spring)‡of Two Data Sets, (1960–1985)^{a} and (1986–2003)^{b}, for Change in Rainfall Depth at Fergus Station

Return Period (yr)	*Duration(min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	-11.2^{α}	–8.0	–15.9	–7.8	–9.0	6.2	28.1
5	–16.7	–15.4	–18.5	–7.1	–11.1	5.7	28.2
10	–18.4	–18.0	–19.4	–6.8	–11.9	5.4	28.3
20	–19.6	–19.7	–19.9	–6.7	–12.4	5.3	28.3
50	–20.6	–21.3	–20.4	–6.5	–12.9	5.2	28.4
100	–21.1	–22.2	–20.7	–6.4	–13.1	5.1	28.4

‡ Spring = March, April, May

a = 1960–1985, b = 1986–2003, $\alpha = \{(a-b)/a\} \times 100$

Table 15: Seasonal Analysis (Summer)‡ of Two Data Sets, (1960–1985)^{a} and (1986–2003)^{b}, for Change in Rainfall Depth at Fergus Station

Return Period (yr)	*Duration(min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	24.3^{α}	23.9	21.7	30.2	31.9	38.0	59.2
5	28.5	27.5	26.2	33.8	36.4	38.7	63.7
10	30.1	28.8	27.8	35.1	38.0	39.0	65.0
20	31.1	29.7	28.9	35.9	39.1	39.2	65.9
50	32.1	30.5	29.9	36.7	40.1	39.3	66.7
100	32.7	31.0	30.4	37.1	40.6	39.4	67.1

‡ Summer = June, July, August

a = 1960–1985, b = 1986–2003, $\alpha = \{(a-b)/a\} \times 100$

Table 16: Seasonal Analysis (Fall)‡ of Two Data Sets, (1960–1985)^{a} and (1986–2003)^{b}, for Change in Rainfall Depth at Fergus Station

Return Period (yr)	*Duration(min)*						
	15	*30*	*60*	*360*	*720*	*1440*	*2880*
	Difference (%)						
2	23.1^{α}	17.5	3.7	23.1	17.5	38.2	53.7
5	20.4	13.1	4.9	26.4	23.6	40.6	52.0
10	19.5	11.5	5.4	27.7	25.9	41.4	51.4
20	18.9	10.5	5.7	28.5	27.4	42.0	51.0
50	18.3	9.5	5.9	29.3	28.8	42.5	50.7
100	18.0	9.0	6.1	29.7	29.6	42.8	50.5

‡ Fall = September, October, November

a = 1960–1985, b = 1986–2003, $\alpha = \{(a-b)/a\} \times 100$

from 15 min to 720 min have greater rainfall depths for 1986–2003 period compared to 1960–1985 period. However, the rainfall depths were opposite for longer durations (1440 and 2880 min). In addition, the rainfall depths for summer and fall were totally different from spring season. Also, Tables 15 and 16 show that rainfall depths have decreased in recent years (1986–2003) compared to previous years (1960–1985). Overall, rainfall depths have increased in spring and decreassed in summer for both stations. On the other hand, for the fall period results showed a decrease in rainfall depth for the Fergus and Pearson stations.

CONCLUSIONS

The stream flow (1915–2005) and rainfall patterns (1960–2003) for the Credit River Watershed were studied to investigate the change in hydrological regime due to urbanization and climate change. The conclusions drawn from the study are:

- There is relative change in the mean and standard deviation of the stream flow with the reference distribution for all three stations. The statistics of both the annual and seasonal distribution showed that the mean, median and standard deviation flip flopped over time.
- Analysis of location, scale and, shape parameters indicated that streamflow data either followed Beta or Pareto distribution. Also, stationarity of Extreme Value Theory failed in all the cases. Results from this analysis also showed a non linear trend and statistically significant change for most of the location and scale parameters. A t-test on the data from the earlier and later years of streamflow showed that Erindale has the maximum number of parameters with greater than 2% significance followed by Cataract. This is a clear indication of urbanization. As Orangeville has the least change; therefore, this change could be taken as a reference point to segregate the effect of climate change.
- Analysis of Return Level-Return Period showed a change in the return level with the reference distribution with non linear trend. The Extreme Volatility Index has increased for Cataract (0.44) and Orangeville (0.45) depicting a high return level. Also, the pattern of high flow and low flow has changed, and the summer flows in all three gauging stations have become closer to the spring flow.
- The FDC analysis showed that except for Orangeville, the order of high flow and low flow curves changed positions with time. The effect of urbanization was tested by taking the relative changes in flow during summer and spring season which showed a reduction of 0.07 $m^3 s^{-1} yr^{-1}$.
- The values of IDF curves for various recurrence intervals for the Fergus station were found to be much higher than the IDF values of the Pearson station. The percentage difference in rainfall intensities between these two stations for various intervals varied from 2.8% to –43.8%.
- The analyses to evaluate temporal changes in rainfall intensities for these stations showed that the rainfall intensities were much lower for all durations for 1986–2003 period when compared with the intensities from 1960–1985 period. Overall, it can be concluded that rainfall intensities have decreased in recent years for Pearson station. For Fergus station, only longer duration intensities have been decreased in recent years.

It can be concluded from the study that rainfall pattern in the watershed showed a reduction in recent years; however, streamflow peaks have increased as compared to previous years, specially for the areas which are urbanized or developing continuously with time. Therefore, effect of urbanization on streamflow is obvious and shows a prominent effect on hydrologic regime of the watershed.

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