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Updated rainfall intensity duration frequency curves for the City of London under the changing climate

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Executive summary

The main focus of this study is the update of rainfall IDF curves for the City of London under the conditions of changed climate. Predicted future climate change impacts for Southwestern Ontario include higher temperatures and increases in precipitation, leading to an intensification of the hydrologic cycle. One of the expected consequences of change is an increase in the magnitude and frequency of extreme events (e.g. high intensity rainfall, flash flooding, severe droughts, etc.). Changes in extreme events are of particular importance for the design, operation and maintenance of municipal water management infrastructure. Management of municipal water infrastructure (sewers, storm water management ponds or detention basins, street curbs and gutters, catchbasins, swales, etc) is based on the use of local rainfall Intensity Duration Frequency (IDF) curves developed using historical rainfall time series data. Annual extreme rainfall is fitted to a theoretical probability distribution from which rainfall intensities, corresponding to particular durations, are obtained. In the use of this procedure an assumption is made that historic hydro meteorological conditions can be used to characterize the future (i.e., the historic record is assumed to be stationary). This assumption is not valid under changing climatic conditions. Potential shifts in extreme rainfall at the local level demand revisions of the existing water infrastructure management regulations as well as changes in design practices.

The objective of this report is to assess the change in IDF curves for use by the City of London under changing climatic conditions. This assessment is completed using (a) only data collected at the London Airport (b) for the period 1961 - 2002. This is all the information that is available from the Environment Canada (EC).

An original methodology is developed in this study to update the rainfall intensity duration frequency (IDF) curves under changing climatic conditions. A non-parametric K-Nearest Neighbour weather generator algorithm operating on a daily time step is used to synthetically create long time series of weather data. The weather generator algorithm is developed to employ data collected by the Environment Canada for use in IDF analysis, including eight for-the-day-maximums of 5, 10, 15, 30 minutes, 1, 2, 6 and 12 hour, along with daily rainfall time series. The weather generator uses (a) a sophisticated shuffling mechanisms to produce synthetic data similar to the observed record; and (b) a perturbation mechanism that pushes the simulated data outside of their historic bounds, thereby generating sequences of extreme rainfall that are likely, but not yet been observed.

Two climate scenarios are used in the analysis: (i) historic climate change scenario (that reshuffles and perturbs the observed data), and (ii) wet scenario (that modifies the observed record according to Global Circulation Model simulation outputs and then uses this data as the weather generator input). Results of the study include tabular and graphical presentation of updated IDF curves for the London Airport. Results are generated for return periods of 2, 5, 10, 25, 50, 100 and 250 years.

The study presents the results of three simulations that differ in the historic input data. The first simulation analysis is based on the original London Airport data set for the period 1961 – 2001 obtained from the EC (eight for-the-day-maximums of 5, 10, 15, 30 minutes, 1, 2, 6 and 12 hour, and daily rainfall time series). Due to limitations of the original data set in correctly representing daily rainfall, the second simulation analysis is based on the combination of the original for-the-day-maximums for the period 1961 – 2002 (eight for-the-day-maximums of 5, 10, 15, 30 minutes, 1, 2, 6 and 12 hour) with hourly data collected at London Airport. Since the hourly data set also had some deficiencies, the third simulation analysis is performed that used the same combination of input data as the second analysis with modifications added to the last three years of observations. *It is recommended that the modified data set be used for drawing conclusions of the study.*

The simulation results indicate that rainfall magnitude will increase under climate change for all durations and return periods. The outputs of the study indicate that: (i) the rainfall magnitude will be different in the future, (ii) the wet climate scenario reveals significant increase in rainfall intensity for a range of durations and return periods, and (iii) the increase in rainfall intensity and magnitude may have major implications on ways in which current (and future) municipal water management infrastructure is designed, operated, and maintained. *Our recommendation is that the current IDF curves should be revised to reflect the potential impact of climate change.*

Results of comparison between the updated IDF curves for modified data set indicate small difference between the historic and wet climate change scenarios. This difference ranges between 0.1% and 12.2% with average value of approximately 4.5%. *Therefore the recommendation is to proceed with potential revisions of the standards using the historic climate change scenario.*

Comparison between the updated IDF curves for modified data set (historic climate change scenario) and the EC IDF curves shows a difference that ranges between 10.7 % and 34.9% with average value of approximately 21%. *Based on this comparison our recommendation to the City of London is to proceed with change of IDF curves in the range of 20%.* Detailed economic analyses should be performed to justify the necessary investment that this change will require.

Keywords: Intensity-Duration-Frequency (IDF) curves, climate change impact modelling, weather generation algorithm, synthetic generation of rainfall.

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1.0 Introduction and background

1.1 The problem of climate change at the municipal level

Increased industrial activity during the last century and a half has increased concentration of carbon dioxide in Earth's atmosphere. This has in turn initiated large scale atmospheric processes resulting in change of global temperature and precipitation (among other variables). Changes in Earth's climate system can disrupt the delicate balance of the hydrologic cycle and can eventually lead to increased occurrence of extreme events (such as floods, droughts, heat waves, summer and ice storms, etc.). For municipalities, changed frequency of extreme events (such as intense rainfall, heavy winds and/or ice storms) are of particular importance as adequate procedures, plans and management strategies must be put in place to deal with them (Mehdi et al., 2006).

Two ways of reducing vulnerability to adverse impacts of climate change are: (a) adaptation – to anticipate possible impacts and develop adaptation strategies; (b) mitigation – to reduce the rate of carbon dioxide release into the atmosphere. Reducing climate change vulnerability means that municipal decision makers and stakeholders need to understand climate change impacts, and develop suitable measures to deal with them in the future. The report by Mehdi et al. (2006) outlines a number of important points regarding why municipal decision makers need to consider climate change. The main point is that *"even small shifts in climate normals will have potentially large ramifications for existing infrastructure."* Further, the report states that climate change *"will affect municipalities large and small, urban and rural, and have positive and negative consequences for the various type of municipal infrastructure, e.g., roads and bridges; natural systems, e.g., watersheds and forests; and human system, e.g., health and education"* (Mehdi et al., 2006, p. 7).

The main focus of this study is on the possible impacts resulting from changes in extreme rainfall (consequence of changed climatic conditions) at the municipal level. Significant change in extreme rainfall demands revisions of storm water management strategies, guidelines and design practices, as well as alteration of municipal infrastructure design standards. In some cases changing hydro-climatic conditions may also require upgrading, retrofitting, rebuilding, or even constructing additional water management infrastructure.

The current design standards are based on historic climate information and required level of protection from natural phenomena. For example, a dyke designed to resist a 100 yr flood event will, if rainfall magnitude increases, provide significantly lower level of protection (Prodanovic and Simonovic, 2006). With changing climate, it is necessary to thoroughly review and/or update the current design standards for municipal water management infrastructure in order to prevent the possibility of future infrastructure performing below its designed level.

The objective of this research project is to provide data and information necessary for design guidelines modification in order to take into consideration the impact of changing climatic conditions. Since design standards for municipal water management infrastructure depend on rainfall, information is provided on change in rainfall magnitude and intensity (extreme rainfall events in particular) as a consequence of changed climate. Synthesis of the research findings is presented in the form of intensity-duration-frequency (IDF) curves, for two future climate scenarios.

1.2 Global circulation models

Currently, one of the best ways to study the effects of climate change is to use global circulation models. These models are the current state of the art in climate science. Their aim is to describe the functioning of the climate system through the use of physics, fluid mechanics, chemistry, as well as other sciences. All global circulation models discretise the planet and its atmosphere into a large number of three dimensional cells (Kolbert, 2006, p. 100) to which relevant equations are applied.

Two different types of equations are used in global circulation models - those describing fundamental governing physical laws, and those that are termed empirical (based on observed phenomena that are only partially understood). The former are representations of fundamental equations of motion, laws of thermodynamics, conservation of mass and energy, etc, and are well known; the latter, however, are those phenomena that are observed, but for which sound theory does not exist yet. For most studies that are concerned with the response of a smaller area (such as a city) to a changed climatic signal, the global models are inappropriate because they have spacial and temporal scales that are incompatible with those of a city. One way around this is to still use the global input, but downscale its results appropriately for the area under consideration.

Traditional way of studying the impacts of climatic change for small areas involves downscaling the outputs from global circulation models (temporally and spatially) from which user and location specific impacts are derived. A number of studies have implemented such methodologies, and thus estimated local impacts of climatic change (Coulibaly and Dibike, 2004; Palmer et al., 2004; Southam et al., 1999).

Use of global modeling results with downscaling methods involves a number of uncertainties inherent to this approach. First, the global models have temporal scales that are sometimes incompatible with temporal scales of interest at the local level. The global models are only able to produce monthly outputs with a higher degree of accuracy. This is insufficient for the use at local level where often the interest is in changes in frequency of occurrence of short-duration high-intensity events. Temporal downscaling of monthly global output must therefore be employed, and shorter duration events be estimated, thus compounding uncertainty. Second, spacial scales of global models are also incompatible with spacial scales at the local level. The global models typically have grid cells of 100 km by 100 km, significantly larger than most watersheds (for example, City of London, Ontario covers an area of about 420 km^2). Coarse resolution of global models is inadequate for the representation of many physical processes of interest at the local scales (including extreme rainfall).

1.3 Weather generating models

Weather generating models offer one way of addressing deficiencies of global climate modeling for use at local scales. They are stochastic simulation tools that synthetically create climate information for an area by combining both, local and global weather data. The local data includes historically observed data taken from area weather stations in and around the study area, while the global data includes outputs obtained from global circulation models. The former acts to address the fine spatial and temporal scale needed for impact studies, while the later provides the global direction of change of the climate within the region of interest (wetter, drier, cooler, warmer, etc).

Weather generators can be parametric and non-parametric (for further details see the paper by Sharif and Burn, 2006a). The parametric weather generators are stochastic tools that generate weather data by assuming a probability distribution function and a large number of parameters (often site specific) for the variables of interest. The non-parametric tools do not make distribution assumptions or have site specific parameters, but rely on various shuffling and sampling algorithms. A common limitation of the parametric weather generators is that they have difficulties representing persistent events such as droughts or prolonged rainfall (Sharif and Burn, 2006a, p. 181). The non-parametric weather generators alleviate these drawbacks, and one of them is adopted for use in this project.

The weather generator takes as input historical climate information, as well as inputs from the global circulation models, and generates climatic information for an arbitrary long period of time for the local weather station. Sophisticated algorithms are used to shuffle (and perturb) the historical data, and generate climatic information not observed in the historic record. The perturbation mechanisms are necessary as long records of historic data are often not available (particularly for shorter durations), or if available, contain a large percentage of missing values. Use of perturbation mechanisms assumes that historic data (of short records) does not capture extreme characteristics likely to be observed in longer data sets. Therefore, they are used to push the generated data outside the historic range, thus providing extremes not been previously recorded. Estimation of extreme rainfall from short data records can underestimate critical values used in the design of municipal infrastructure. Using weather generators with perturbation mechanisms and inputs from global circulation models can therefore produce adequate synthetic data with high spacio-temporal resolution.

1.4 Outline of the report

The rest of this report is organized as follows: Section 2 presents the methodology used in the study. It provides technical details regarding (i) rainfall input data; (ii) formulation of climate change scenarios; (iii) daily K-Nearest Neighbour weather generating algorithm; (iv) and the method used to construct the intensity duration frequency curves. Section 3 shows results from the application of the methodology to the City of London. The report in Section 4 ends with concluding remarks and recommendations based on the study findings.

2.0 Methodology

2.1 Input data preparation

The weather generator used in this study requires nine for-the-day-maximum rainfall elements (5, 10, 15, 30 minute, 1, 2, 6, 12 and 24 hour) as input. Three data sets are used:

ORIGINAL DATA SET

Communication with Ontario Climate Center and EC provided the information that this data set is available for the period 1961 – 2001 (DLY03). Data set prior to 1961 is not available in electronic form for the City of London. Data set after 2001 is not available due to the lack of quality control. It is also important to mention that the weather generator model needs complete data sets with as few missing values as possible to work effectively. Available DLY03 data set is purchased from OCC. Table 1 shows all the data elements. This data set is named original data set.

Table 1. The nine elements of DLY03 used as input for the weather generator model

Element Number*	**Description**
125	Greatest amount of precipitation in 5min (0.1mm)
126	Greatest amount of precipitation in 10min (0.1mm)
127	Greatest amount of precipitation in 15min (0.1mm)
128	Greatest amount of precipitation in 30min (0.1mm)
129	Greatest amount of precipitation in 1hr (0.1mm)
130	Greatest amount of precipitation in 2hr (0.1mm)
131	Greatest amount of precipitation in 6hr (0.1mm)
132	Greatest amount of precipitation in 12hr (0.1mm)
010	Total rainfall (0.1mm)

* Element number as provided by the MSC technical documentation website, 2008 (http://www.climate.weatheroffice.ec.gc.ca/prods_servs/documentation_index_e.html)

After the analysis of the obtained data it has been concluded that the Element 010 is not the 24 hr for-the-day-maximum rainfall in all cases. All the rainfall events crossing the boundary of the calendar day (midnight) were not properly captured by this value. Many data points demonstrated values of 12 hr for-the-day-maximum rainfall higher than the values of element 010.

NEW DATA SET

Further consultations with EC revealed that in their practice, the DLY03 data provided for this research are supplemented with hourly data – HLY03 (Table 2). Element 123 is used for longer duration rainfall analysis when the rainfall events cross the calendar day boundary. The moving window procedure is used with hourly data to find the yearly maximum values of rainfall events. For 2-, 6-hr, and 12-hr durations, the annual maximum for each year is compiled from the maximum of either: (a) the maximum of DLY03 daily elements for these elements, or (b) the maximum of the moving 2-, 6- and 12-hr windows calculated from the HLY03 hourly rainfall observations. However, EC practice does not use or need sequence of 24 hr for-the-day-maximum rainfall and therefore this information is not available from them. The hourly data set HLY03 is provided by EC for the period 1961 – 2002.

The weather generator used in this project does need a sequence of 24 hr for-the-day-maximum rainfall. An original procedure has been developed in this work to overcome this problem. Moving window procedure has been implemented with HLY03 data to recreate the necessary data. Maximum 24 hr rainfall events crossing the calendar day boundary are assigned to a calendar day with greater portion of the rainfall event volume. An algorithm is developed for the implementation of this procedure (computer code is provided in Appendix A). Data set created using this procedure is named new data set.

Table 2. The hourly data used as input for the weather generator model

Element Number*	**Description**
123	Hourly Precipitation (0.1mm)

* Element number as provided by the MSC technical documentation website, 2008 (http://www.climate.weatheroffice.ec.gc.ca/prods_servs/documentation_index_e.html)

MODIFIED DATA SET

Further analysis of available data from both sets – DLY03 and HLY03 – revealed another problem. Hourly data set did not include some of the critical rainfall events (like 2000 summer storm). To overcome this problem, data from both sets are combined in the same way as EC is combining them in their IDF analyses: for 2-, 6-hr, 12-hr, and 24-hr durations for-the-day-maximum for each day is compiled from the maximum of either: (a) the maximum of DLY03 daily elements for these durations, or (b) the maximum of the moving 2-, 6-, 12- and 24-hr windows calculated from the HLY03 hourly rainfall observations. This data set is named modified data set.

2.2 Climate change scenarios

Climate change scenarios are in general obtained as outputs of Global Circulation Model (GCM) simulations and do not represent future predictions or forecasts, but simply offer possibilities of what might happen if the future development follows a certain course of action (i.e., continual growth of population, increased carbon dioxide emissions, increased urbanization, etc.). All scenarios for implementation with global circulation models have been standardized in the report by Nakicenovic and Swart (2000).

In this project, the climate change scenario data is obtained from the Canadian Climate Impacts Scenarios group at the University of Victoria, Canada (http://www.cics.uvic.ca). Time series data is obtained for the grid point containing the City of London, for a particular time slice. For this study, the time slice of 2040-2069 is used, representing average climatic conditions for the year 2050. Historic global circulation data, also obtained from the University of Victoria, consists of data for period 1961-1990 and represents the baseline global data. The storyline B2 on the other hand emphasizes local solutions to economic, social and environmental well being; it anticipates diverse technological change towards environmental protection and social equity at regional levels. For further description of the scenarios, the reader is referred to Appendix B.

Two climate change scenarios are selected for this work: (i) **HISTORIC CLIMATE CHANGE SCENARIO**; and (ii) the GCM B21 (named **WET CLIMATE CHANGE SCENARIO**, as it represents future climate conditions that are warmer and wetter than present). The first scenario is selected to describe the possible change that is already occurring as a consequence of existing concentration of greenhouse gases in the atmosphere. This change will continue on, even if all the mitigation measures are introduced immediately (what is considered highly unlikely in the current political environment). The historic climate change scenario simply uses the three sets of London rainfall data as input into the weather generator model to simulate weather episodes similar (but not identical) to those observed in the past. It uses shuffling and perturbation mechanisms, and therefore may produce extreme rainfall values not observed in the historic record. Similar scenario analysis is adopted by Sharif and Burn (2007), and Prodanovic and Simonovic (2007).

The second scenario is selected as a possible case of what the maximum extent of future climate change might look like (specifically extreme rainfall). The wet climate change scenario is constructed in the following manner: global data (baseline and GCM B21 time series) is used to compute monthly change fields between the periods of 1961-1990 and 2040-2069, which are then used to modify the three sets of London rainfall data introduced in the previous section. The climate-modified historic data is then used as input into the weather generator model, which, through shuffling and perturbation, produces long term synthetic sequences of weather data.

The change fields for the wet climate change scenario are computed using the global circulation data as the percent difference from the baseline case of monthly precipitation averaged for all years of output. The wet climate change scenario is formulated by multiplying the three sets of London rainfall data with the monthly percentage change values previously obtained. This means that if the change field for the month of January is +10%, then all January values in the historic record are multiplied by 1.10; similarly, if the change field is -15% for the same month, all historic data is multiplied by 0.85. These locally modified data sets are then used by the weather generator to produce daily and hourly time series for different climates.

Development of future climate change scenarios in this way integrates all available global and local climatic data to produce a range of potential future climatic conditions. The wet climate change scenario is used specifically to test the region's response to flooding, while the historic climate change scenario is used for assessment of already observed changing climate conditions. It is important to point out that both climate scenarios are equally likely. For the purpose of this work the most critical future climate is represented by the wet climate change scenario, and is recommended when dealing with questions regarding the potential change in extreme rainfall magnitude and frequency resulting from climate change. The historic climate change scenario is considered to define the lower boundary of potential climate change and is recommended to be used for identifying the minimum extent of climate change adaptation to be implemented in the region.

2.3 Weather generator

Weather generator algorithms are stochastic simulation tools able to produce large sequences of weather data. They use mathematical algorithms to generate long records of plausible data based on locally observed precipitation patterns. Weather generators are usually classified into: parametric and non-parametric (Sharif and Burn, 2007). The former are stochastic tools that generate weather data by assuming a probability distribution function and a large number of parameters (often site specific) for the variable of interest. The latter do not make distribution assumptions or have site specific parameters, but rely on various sampling algorithms. One limitation of the parametric weather generators is that they have difficulties representing persistent events such as droughts or prolonged rainfall (Sharif and Burn, 2007). The non-parametric versions alleviate these and other drawbacks, and one of them is adopted in this study.

The K-Nearest Neighbour weather generator of Sharif and Burn (2007) takes as input historical climate information and generates climatic information for an arbitrary long period of time. The nearest neighbour algorithm: (a) is capable of modelling non-linear dynamics of geophysical processes; (b) do not require knowledge of probability distributions or variables; and (c) preserves well the temporal and spacial correlation of generated data. All K-Nearest Neighbour (K-NN) algorithms involve selecting a set of data (in our case weather data) that are similar in nature to the time period of interest. In order to generate synthetic data for a desired time period a single value is randomly selected from statistically similar data set.

The procedure in the K-NN weather generator starts by assembling a historic data set for a station of interest. To produce weather for a new day, all days with similar characteristics are extracted from the historic record, here referred to as the potential set of neighbours. A two week moving window is typically employed, meaning that if the day of interest is January 7, days from January 1 to January 14 (from *N* years of record, but excluding the January 7 value for the current year) are recognized as a potential set of neighbours. Distance between mean value of a weather variable for the current day and the potential set of neighbours is computed via the Mahalanobis distance metric, and sorted from smallest to largest. Out of the sorted potential neighbour set, only the first *K* values are selected for further analysis (where *K* is a function of the number of potential neighbours), meaning that generated weather variable will be close (but not identical) to the current value for the same variable. A random selection of one of the *K* nearest values follows with the closest (or the nearest) potential neighbour having the greatest chance of being selected. The value of the selected neighbour is then used as the value for the day of interest. The above procedure only re-shuffles the historic data, and can be useful in studies requiring extension of historic records, but not for studies of changes in weather patterns. Sharif and Burn (2007) modified the K-NN algorithm to add a perturbation mechanism that will allow newly generated values to be outside of the observed range.

Use of perturbation mechanisms assumes that historic data (typically shorter record) does not capture extreme characteristics likely to be observed in longer records. Therefore, perturbation mechanism is used to push the observed data outside of its historic range, thus generating extremes not been previously recorded. The perturbation is needed because estimation of extreme rainfall from short data records can underestimate values used in the design of critical municipal infrastructure. Using weather generator with perturbation mechanism can therefore produce adequate synthetic data of high spacio-temporal resolution.

The weather generator model, originally developed by Sharif and Burn (2007), is modified in this work. The driving force for the modification is guided by data requirements for the rainfall IDF analysis. The original weather generator model works by using daily weather data (maximum and minimum temperature, precipitation, etc.). However, for rainfall IDF analysis, durations ranging from 5 minutes to 24 hours are needed. In a rainfall IDF study by Prodanovic and Simonovic (2007), daily rainfall values are generated with a weather generator, which are then disaggregated into hourly intervals based on the K-NN approach, while rainfall of shorter durations (ranging from 5 to 30 minutes) are estimated by disaggregating hourly values.

The research performed in this study adopts a modified weather generation methodology to take into account available data of shorter durations. This study uses for-the-day-maximum rainfall time series for 5, 10, 15, 30 minutes, and 1, 2, 6, 12 and 24 hour intervals. Since the for-the-day-maximum rainfall amounts cannot be treated as separate variables, the original weather generation model of Sharif and Burn (2007) cannot be used. An original modification introduced in this project uses 24 hour rainfall totals as the main variable on which the weather generator operates. The potential set of nearest neighbours is selected for the 24 hour rainfall based on the two week moving window, from which a smaller set of *K* nearest neighbours is selected, and then a single value chosen as that day's simulated value. The important difference here is that the model retains the *K* nearest neighbours for all sub-daily elements from the same day as for the 24 hour amounts. This selection mechanism implies that if the 24 hour rainfall of January

8, 1978 is selected by the weather generator model as the resampled value, all sub-daily elements for that day will also be used (i.e., January 8, 1978) as their resampled values.

Many of sub-daily elements contain a large percent of missing data (in case of London approximately 17% of data is missing for durations shorter than 24 hours). Recall that the weather generator cannot be simulated if the historic data record contains missing values. In studies by Sharif and Burn (2007) and Prodanovic and Simonovic (2007) variables used are temperature, precipitation, and rainfall, for which the missing values can easily be estimated if a dense gauge network exists. For daily values of weather variables this is easily performed with any interpolation method (Thiessen Polygon, Inversed Distance Weighting Method, etc.). However, an interpolation method cannot be applied to the sub-daily time series data, as the data in this series represents for-the-day-maximum values that may be recorded at different times during the day. As a result, use of classical interpolation to estimate missing data cannot be applied.

The weather generator is therefore modified to incorporate use of sub-daily data sets containing missing values. Missing sub-daily values do not play a role in the selection of the nearest neighbours (as these are selected based on daily values that can be interpolated), but present a problem in the application of perturbation mechanism. The perturbation mechanism uses conditional standard deviation and bandwidth calculated from the set of *K* nearest neighbours as a means to estimate the degree by how much each value can be perturbed. In the modification of the weather generator this problem is addressed in the following way: *If the selected value for the element has a missing value, the simulated value for that element is not perturbed, but is kept as missing. If the selected element does not have a missing value, only values in its set of K nearest neighbours free of missing values are used to compute the conditional standard deviation and the bandwidth, therefore producing a perturbation for the element in question. The amount of perturbation therefore depends on how many non-missing values the set of K nearest neighbours has, thereby biasing the perturbation results. Investigation of the true extent of this bias is recommended for future research.*

2.3.1 Weather generating procedure

The nine for-the-day-maximum rainfall values for durations of 5, 10, 15, 30minutes and 1, 2, 6, 12, and 24hrs are used as input into the weather generator. In the K-NN algorithm, *p* variables are selected to represent daily weather (such as temperature, precipitation, solar radiation, etc.). Available data consists of *N* years and *T* total number of days in the observed historic record. Let X_t represent the vector of variable values for day *t*, where *t* = 1, 2,...T. A feature vector can be defined in expanded form as:

$$(1) \qquad X_t = (x_{1,t}, x_{2,t}, ..., x_{p,t})$$

In this study only rainfall is used and therefore $p = 1$. Equation (1) is then simplified to the following:

$$(1a) \qquad X_t = (x_{1,t})$$

where

$x_{1,t}$ represents the amount of rainfall on day *t*.

For simplicity, assume that the simulation starts on January 01, and continues to generate synthetic data to December 31 for the entire observed historic record (i.e., for *N* years). If synthetic data is desired for a longer period (i.e., > *N* years) then the weather generator simulation must be run multiple times. The weather generator algorithm is presented below.

1. Initially, a set of values within a temporal window of size w is selected to represent potential neighbours to the current feature value, X_t. For the current year, values which are $\frac{w}{2}$ *before* and $\frac{w}{2}$ days *after* the current day are considered to be neighbours. Notice that the value for the current day is not considered being a neighbour to itself. For all other $(N-1)$ years, $(w+1)$ days are considered neighbours to the current feature value, X_t. In the work of Yates et al. (2003) and Sharif and Burn (2007), w is selected to be 14 days; this is the window size adopted in this study. In other words, if the current day of the simulation is September 17, then all days between September 10 and September 24 are selected of all *N* years of record; excluding September 17 for the current year. This data block of all potential neighbours to the current feature vector is: $L = (w+1) \times N - 1$ days long.

2. Next, the covariance matrix, C_t , for day *t* is computed using a data block of size $L \times p$. For the current case when *p* = 1, the covariance matrix is simply the variance of the nearest neighbour vector ($L \times 1$) represented as follows:

   $$C_t = Var(L) \tag{2}$$

3. The Mahalanobis distance is computed between the value of the current days weather X_t and the values of all neighbours, X_k where *k* = 1, 2, ... , *L*. The distance is computed as follows:

   $$d_k = \sqrt{(X_t - X_k) C_t^{-1} (X_t - X_k)^T} \tag{3}$$

   Where,

   X_t is the value of the current days weather
   X_k is the value of the nearest neighbour
   T represents the transpose matrix operation
   C_t^{-1} represents the inverse of the covariance matrix

Mahalanobis distance is based on correlation between variables by which different patterns can be identified and analyzed. It is a useful way of determining similarity of an unknown sample set to a known one. It differs from Euclidian distance in that it takes into account data correlation, and is scale-invariant, (i.e., not dependent on the scale of measurements). Equation (3) for Mahalanobis distance is simplified for use with only one set of data as follows:

$$d_k = \frac{X_t - X_k}{\sigma} \tag{3a}$$

4. K nearest neighbours are selected out of L potential values for further sampling. Both Yates et al. (2003) and Sharif and Burn (2007) recommend retaining $K = \sqrt{L}$ neighbours for further analysis, which is adopted in this study.

5. The Mahalanobis distance d_k is sorted from smallest to largest, and the first K neighbours in the sorted list are retained (they are referred to as the nearest neighbours). Furthermore, a discrete probability distribution is used to give higher weights to the closest neighbours in order to resample the K nearest neighbours. Each neighbour in data block L is assigned a weight w_k and a probability p_k as follows:

$$w_k = \frac{1/k}{\sum_{i=1}^{K} \frac{1}{i}} \tag{4}$$

where

$k = 1,2, \ldots, K.$

Cumulative probabilities, p_k , are given by:

$$p_k = \sum_{i=1}^{k} w_i \tag{5}$$

Through this procedure the neighbour with the smallest distance gets the largest weight, while the one with the largest distance gets the smallest weight. For the development of this function, see Lall and Sharma (1996). Now there exists a sorted list of K neighbours.

6. Values from the sorted list of K neighbours are selected based on a random number, u. To determine which of the K nearest neighbours is selected as the one to be used for the current day's weather, a uniformly distributed random number $u(0,1)$ is generated. The next step in the algorithm is to compare u to p, calculated previously; note that p exists for each one of the K neighbours. If $u \leq p_1$ then X_1 is selected from datablock L (of the day corresponding to d_1).

Otherwise, if $p_{k-1} \le u \le p_k$ then X_k is selected from the datablock. The day which is selected for use is depended on the 24 hour rainfall element. The day which is selected to be used for the 24 hour current day's weather is then used as the day assigned to all other sub-daily elements. For example, if the current day selects January 11, 1971 from the 24 hour record, then all sub-daily elements (5, 10, 15, 30minutes and 1, 2, 6, 12 hours) will select the January 11, 1971 values as well.

7. This step perturbs the historic resampled data, and therefore generate data outside of the historically observed range. For each variable a non-parametric distribution is fitted to *K* nearest neighbours of step 6 and an estimate is made of conditional standard deviation, σ, and bandwidth, λ. The conditional standard deviation is estimated from the *K* neighbours, while λ is calculated based on the work of Sharma et al. (1997). The following equation is used in this study to estimate the bandwidth:

   (6) $$\lambda = 1.06\sigma K^{-1/5}$$

   The perturbation of the basic K-NN approach is based on the following:

   (a) Let σ be the conditional standard deviation of rainfall computed from the K nearest neighbors. Assume that z_t is a normally distributed random variable with zero mean and unit variance, for day *t*. The new (perturbed) value of rainfall for day *t*, is computed as:

   (7) $$y_t = x_t + \lambda\sigma\ z_t$$

   where

x_t	is the rainfall value obtained from the basic K-NN algorithm (steps 1 to 6);
y_t	is the rainfall value from the perturbed algorithm
λ	is the bandwidth (dependent on the number of samples)
σ	is the standard deviation of the *K* nearest neighbours
z_t	is the random variable for day *t*

   (b) Equation (7) may generate negative values. To prevent negative rainfall a new value of z_t is generated until the rainfall value becomes non-negative.

The steps 1 to 7 of the weather generating model are repeated for all time intervals of the simulation time horizon. Weather generator simulations are performed using all three data sets in spite of the fact that the original data set is not completely adequate for the analyses performed in this study. Input data sets are used with two climate change scenarios in weather generator simulations. The **HISTORIC CLIMATE CHANGE** simulation uses the three sets of observed data (without multiplying them by change fields), and shuffles and perturbs them using the algorithm presented above. The **WET CLIMATE CHANGE SCENARIO** simulation on the other hand, modifies the historic data by applying change fields first, followed by shuffling and perturbation. The simulations for each climate scenario are performed for 126 years (42 years of historic record simulated three times over), producing nine for-the-day-maximum rainfall elements. The weather generator computer code is shown in Appendix C.

2.4 Rainfall intensity duration frequency analysis

IDF analysis is used to capture the main characteristics of point rainfall for shorter durations. Such analysis provides an effective tool for statistically summarizing regional rainfall information, and is often used in municipal storm water management and other engineering design applications. The IDF analysis starts by gathering time series records of different durations (in this study provided by weather generator). After time series data is gathered, annual extremes are extracted from the record for each duration. The annual extreme data is then fit to a probability distribution, in order to estimate rainfall quantities. The most widely accepted probability distribution used in analysis of extreme rainfall statistics is the Gumbel Extreme Value I distribution (also used by MTO, 1997; Vasiljevic, 2007), and is therefore adopted in this study.

The Gumbel probability distribution has the following form (Watt et al., 1989):

$$(8) \qquad x_t = \mu_z + K_T \sigma_z$$

where x_T represents the magnitude of the T-year event, μ_z and σ_z are the mean and standard deviation of the annual maximum series, and K_T is a frequency factor that depends on the return period, *T*. The frequency factor K_T is obtained using the relationship:

$$(9) \qquad K_T = \frac{-\sqrt{6}}{\pi}\left[0.5772 + \ln\left(\ln\left(\frac{T}{T+1}\right)\right)\right]$$

Environment Canada uses this method to estimate rainfall frequency for durations of 5, 10, 15 and 30 minutes, as well as for 1, 2, 6, 12 and 24 hours. The IDF data derived with above method is typically fitted to a continuous function in order to make the process of IDF data interpolation more efficient. For example, 10 yr intensity for duration of 45 min is not readily available in the published IDF data. In order to obtain this information, the Ontario Drainage Management Manual (MTO, 1997) recommends fitting the IDF data to the following three parameter function:

$$(10) \qquad i = \frac{A}{(t_d + B)^C}$$

where *i* is the rainfall intensity (mm/hr), t_d the rainfall duration (min), and *A*, *B*, and *C* are coefficients. After selecting a reasonable value of parameter *B*, method of least squares is used to estimate values of *A* and *C*. The calculation is repeated for a number of different values of *B* in order to achieve the closest possible fit of the data. Details of this procedure are provided in MTO (1997, Chapter 8). After IDF data is fitted to the above function, plots of rainfall intensity vs. duration (for each return period) can be produced.

3.0 Results and analysis

3.1 Rainfall data

Rainfall data used in this research was obtained from EC for 9 elements for the London station in Southwestern Ontario (see Table 3 and Figure 1). Analysis is performed for the period of 1961-2002, 42 years in length.

Table 3. Meteorological Service of Canada rain gauges

Name#	Climate ID	Lat	Lon	Elevation	Annual
London	6144475	43.03	-81.15	278.0	817.9

Data between 01 Jan 1961 – 31 Dec 2002 is used.

The elements have a digital record dating back to 1961 and a paper record exists for some of the elements back to 1943. However, the paper records were not available for this study.

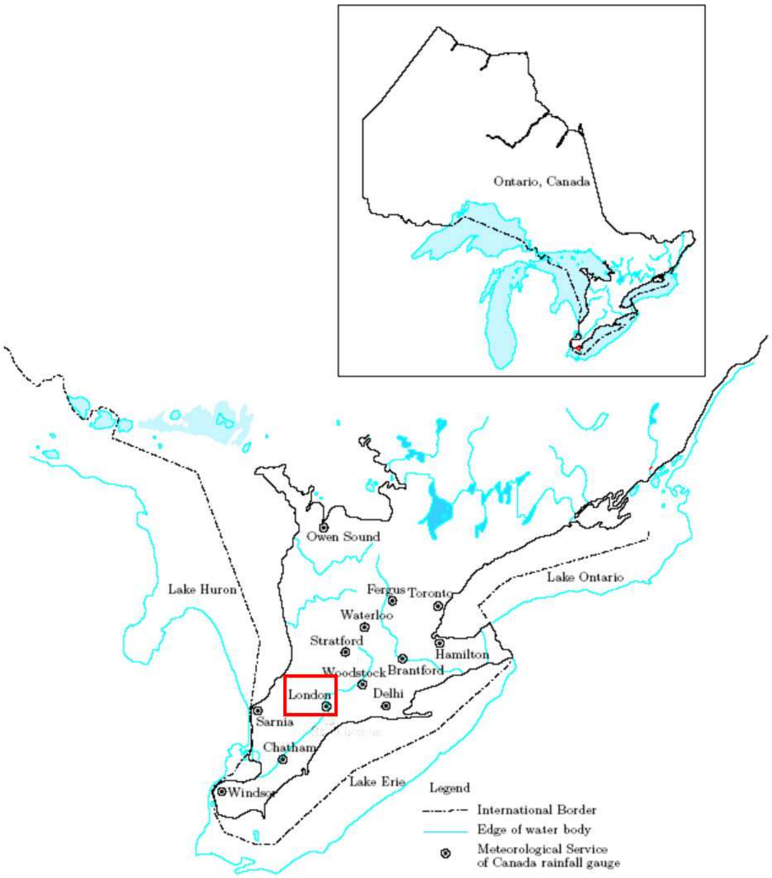


Figure 2: Meteorological station used in the study - MSC ID: 6144475

Rainfall data is used in this study. Three data sets as described in Section 2.1 are used: (i) original data set; (ii) new data set; and modified data set. The **ORIGINAL DATA SET** includes DLY03 data for the period 1961 – 2001. Due to the fact that 24 hr rainfall in this data set is not for-the-day maximum this data is not accurately representing the necessary input. Maximum 24 hr rainfall events crossing the calendar date border are not correctly captured in this data set. The weather generator used in this project does need a sequence of 24 hr for-the-day-maximum rainfall. An original procedure has been developed in this work to overcome the problem with the original data set. Moving window procedure has been implemented with hourly (HLY03) data to recreate the necessary data. Maximum 24 hr rainfall events crossing the calendar day boundary are assigned to a calendar day with greater portion of the rainfall event volume. Data set created using this procedure is named **NEW DATA SET**. Since the hourly data set did not include some of the critical rainfall events (like 2000 summer storm) a new set named **MODIFIED DATA SET** is created in which the event crossing the calendar date border are taken in consideration by selecting either: (a) the maximum of DLY03 daily elements for 2-, 6-, 12- and 24-hr durations, or (b) the maximum of the moving 2-, 6-, 12- and 24-hr windows calculated from the HLY03 hourly rainfall observations.

3.2 Climate change scenarios

Two climate change scenarios are used in this work: (i) **HISTORIC CLIMATE CHANGE SCENARIO**; and (ii) the GCM B21 (named **WET CLIMATE CHANGE SCENARIO**, as it represents future climate conditions that are warmer and wetter than present). The first scenario is selected to describe the possible change that is already occurring as a consequence of existing concentration of greenhouse gases in the atmosphere. This change will continue on, even if all the mitigation measures are introduced immediately (what is considered highly unlikely in the current political environment). The historic climate change scenario simply uses the three sets of London rainfall data as input into the weather generator model to simulate weather episodes similar (but not identical) to those observed in the past. It uses shuffling and perturbation mechanisms, and therefore may produce extreme rainfall values not observed in the historic record.

The second scenario is selected as a possible case of what the maximum extent of future climate change might look like (specifically extreme rainfall). The wet climate change scenario is constructed in the following manner: global data (baseline and GCM B21 time series) is used to compute monthly change fields between the periods of 1961-1990 and 2040-2069, which are then used to modify the three sets of London rainfall data introduced in the previous section. The climate-modified historic data is then used as input into the weather generator model, which, through shuffling and perturbation, produces long term synthetic sequences of weather data.

The change fields for the wet climate change scenario are computed using the global circulation data as the percent difference from the baseline case of monthly precipitation averaged for all years of output (Table 4). The wet climate change scenario is formulated by multiplying the three sets of London rainfall data with the monthly percentage change values previously obtained. This means that if the change field for the month of January is +10%, then all January values in the historic record are multiplied by 1.10; similarly, if the change field is -15% for the same month, all historic data is multiplied by 0.85. These locally modified data sets are then used by the weather generator to produce daily and hourly time series for different climates.

Table 4. Monthly precipitation change fields

Month	CCSRNIES B21
	Wet climate scenario
Jan	17.67
Feb	6.38
Mar	15.07
Apr	22.48
May	24.14
Jun	18.55
Jul	5.03
Aug	7.88
Sep	4.27
Oct	-11.50
Nov	-15.55
Dec	-3.10

Average percent difference from base case for period 2040-2069 using grid cell centered at (43.01, -78.75)

Development of future climate change scenarios in this way integrates all available global and local climatic data to produce a range of potential future climatic conditions. The wet climate change scenario is used specifically to test the region's response to flooding, while the historic climate change scenario is used for assessment of already observed changing climate conditions. It is important to point out that both climate scenarios are equally likely. For the purpose of this work the most critical future climate is represented by the wet climate change scenario, and is recommended when dealing with questions regarding the potential change in extreme rainfall magnitude and frequency resulting from climate change. The historic climate change scenario is considered to define the lower boundary of potential climate change and is recommended to be used for identifying the minimum extent of climate change adaptation to be implemented in the region.

3.3 Short duration rainfall under the changing climate

The weather generator has been implemented with three data sets and two climate scenarios. Generated rainfall data is processed to develop updated IDF curves that are compared with existing curves developed by EC (original EC curves are presented in Appendix D). Table 5 shows the intensity duration frequency data obtained using original data set and two climate change scenarios, together with the IDF data produced by EC. Graphical representation of data presented in Table 5 is shown in standard plots, for all scenarios, in Figure 2. Appendix E contains separate plots of intensity and depth duration graphs for different return periods.

Table 5. Summary of IDF curves for the original data set

Historic Climate Change

(**depth** in mm)

	RP (yrs)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	9.9	13.1	15.3	17.9	19.9	21.9
10 min	15.0	20.4	24.0	28.6	31.9	35.3
15 min	18.8	25.7	30.4	36.2	40.6	44.9
30 min	24.9	34.9	41.5	49.9	56.1	62.2
1 hr	29.7	40.3	47.4	56.2	62.8	69.3
2 hr	35.2	47.0	54.9	64.8	72.1	79.4
6 hr	44.1	56.4	64.5	74.7	82.3	89.9
12 hr	48.6	62.4	71.6	83.2	91.9	100.4
24 hr	52.3	70.3	82.3	97.4	108.6	119.7

(**intensities** in mm/hr)

	RP(yrs)					
Duration	2	5	10	25	50	100
5	119.3	157.6	183.0	215.1	238.9	262.6
10	89.9	122.5	144.1	171.4	191.7	211.8
15	75.0	103.0	121.5	144.9	162.3	179.5
30	49.9	69.8	83.1	99.8	112.2	124.5
60	29.7	40.3	47.4	56.2	62.8	69.3
120	17.6	23.5	27.4	32.4	36.0	39.7
360	7.4	9.4	10.7	12.5	13.7	15.0
720	4.0	5.2	6.0	6.9	7.7	8.4
1440	2.2	2.9	3.4	4.1	4.5	5.0

Wet Climate Change

(**depth** in mm)

	RP (yrs)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	11.0	15.4	18.3	21.9	24.7	27.4
10 min	16.6	23.8	28.7	34.7	39.3	43.7
15 min	20.1	28.4	33.9	40.8	45.9	51.0
30 min	25.9	35.9	42.4	50.8	56.9	63.1
1 hr	31.6	43.4	51.3	61.2	68.6	75.9
2 hr	37.9	51.6	60.7	72.1	80.6	89.1
6 hr	46.3	60.3	69.6	81.2	89.9	98.5
12 hr	52.6	68.8	79.5	93.0	103.1	113.0
24 hr	57.4	77.4	90.6	107.2	119.6	131.9

(**intensities** in mm/hr)

	RP(yrs)					
Duration	2	5	10	25	50	100
5	131.6	184.2	219.1	263.2	295.9	328.4
10	99.4	143.0	171.9	208.4	235.5	262.4
15	80.6	113.6	135.5	163.1	183.6	204.0
30	51.8	71.7	84.9	101.5	113.9	126.2
60	31.6	43.4	51.3	61.2	68.6	75.9
120	19.0	25.8	30.3	36.1	40.3	44.5
360	7.7	10.0	11.6	13.5	15.0	16.4
720	4.4	5.7	6.6	7.8	8.6	9.4
1440	2.4	3.2	3.8	4.5	5.0	5.5

EC (1943-2003)

	Return Period (mm)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	9.1	11.9	13.8	16.2	18.0	19.7
10 min	13.0	17.8	21.0	25.0	28.0	30.9
15 min	15.6	21.3	25.1	29.8	33.3	36.8
30 min	20.4	28.2	33.4	39.9	44.8	49.6
1 hr	24.4	35.3	42.5	51.6	58.3	65.0
2 hr	29.6	41.6	49.5	59.6	67.0	74.4
6 hr	36.7	48.2	55.8	65.4	72.5	79.6
12 hr	43.0	54.7	62.5	72.4	79.7	87.0
24 hr	51.3	66.8	77.1	90.0	99.6	109.2

	Return Period (mm/hr)					
Duration	2	5	10	25	50	100
5	109.2	142.8	165.6	194.4	216.0	236.4
10	78.0	106.8	126.0	150.0	168.0	185.4
15	62.4	85.2	100.4	119.2	133.2	147.2
30	40.8	56.4	66.8	79.8	89.6	99.2
60	24.4	35.3	42.5	51.6	58.3	65.0
120	14.8	20.8	24.8	29.8	33.5	37.2
360	6.1	8.0	9.3	10.9	12.1	13.3
720	3.6	4.6	5.2	6.0	6.6	7.3
1440	2.1	2.8	3.2	3.8	4.2	4.6

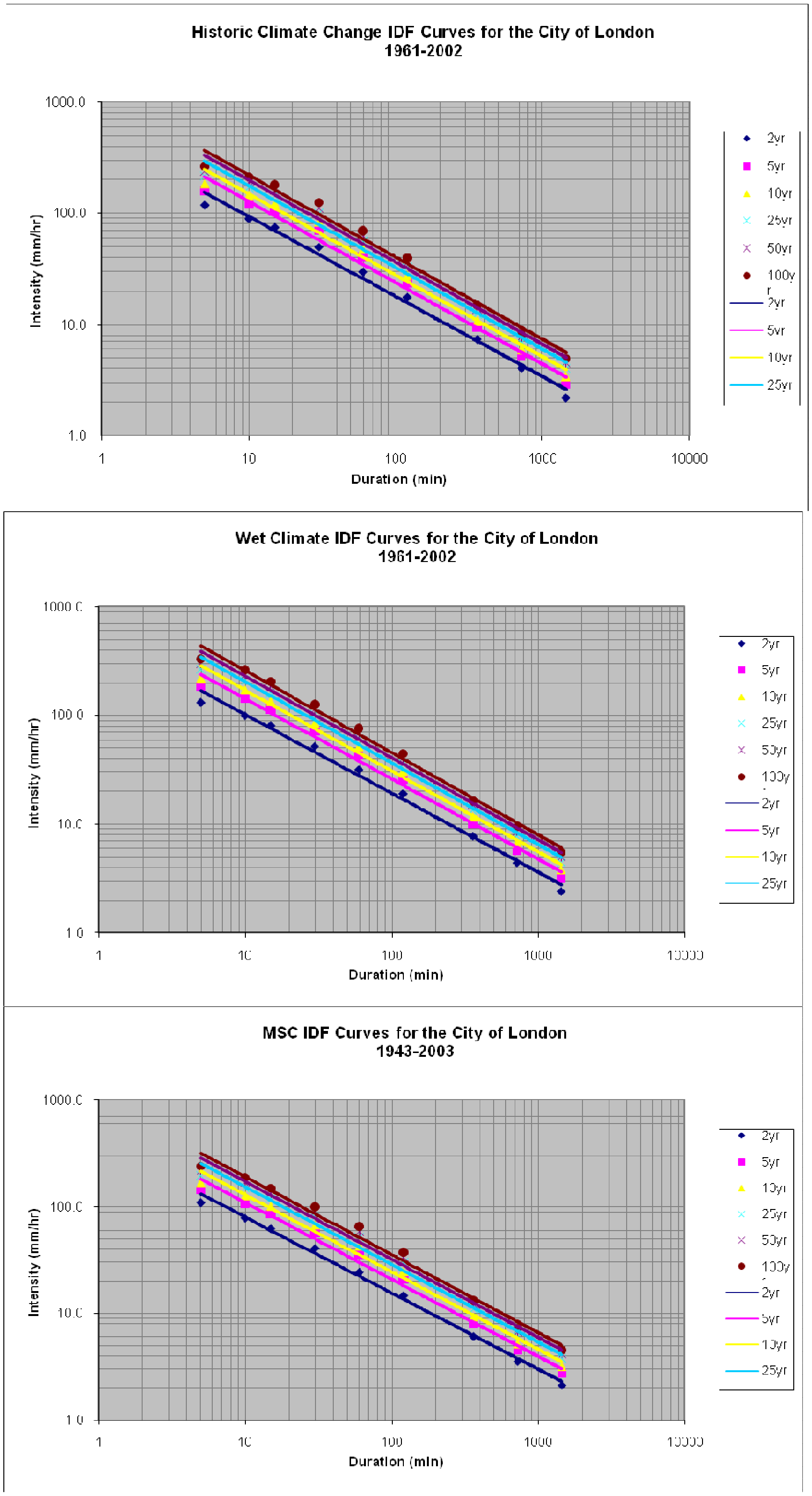


Figure 2. Comparison of IDF curves for the original data set

Table 6 shows the intensity duration frequency data obtained using new data set and two climate change scenarios, together with the IDF data produced by EC. Graphical representation of data presented in Table 6 is shown in standard plots, for all scenarios, in Figure 3. Appendix F contains separate plots of intensity and depth duration graphs for different return periods.

Table 7 shows the intensity duration frequency data obtained using modified data set and two climate change scenarios, together with the IDF data produced by EC. Graphical representation of data presented in Table 7 is shown in standard plots, for all scenarios, in Figure 4. Appendix G contains separate plots of intensity and depth duration graphs for different return periods.

3.3.1 Comparison of IDF results

Updated IDF curves for two climate change scenarios (rainfall intensity) are compared with current EC IDF curves for the City of London as well as between themselves. Relative difference between the curves is determined using the following relationship:

$$(10) \qquad Difference = \left| x_1 - x_2 \right| / ((x_1 + x_2)/2) \times 100$$

Results of the comparison for original data set are shown Table 8 with clear indication of variables used with equation (10). Table 9 shows the results of comparison for the new data set. In Table 10 the comparison results are shown for the modified data set.

The comparison results indicate that rainfall magnitude will increase under climate change for all durations and return periods. The outputs of the study indicate that:

(i) the rainfall magnitude will be different in the future,
(ii) the wet climate scenario reveals significant increase in rainfall intensity for a range of durations and return periods, and
(iii) the increase in rainfall intensity and magnitude may have major implications on ways in which current (and future) municipal water management infrastructure is designed, operated, and maintained.

The comparisons of updated IDF curves for climate change with the IDF curves for London posted by Atmospheric Environment Service of EC reveal that the historic climate change scenario values are up to 35% higher than EC values, while the wet climate scenario produces values up to 42% higher than EC, and up to 23% higher than the historic climate change simulation scenario. These values represent the maximum change among all data sets used in this study.

Table 6. Summary of IDF curves for the new data set

Historic Climate Change

(**depth** in mm)

	RP (yrs)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	10.6	14.4	17.0	20.2	22.6	25.0
10 min	15.9	21.6	25.3	30.0	33.5	37.0
15 min	19.8	27.1	31.8	37.9	42.4	46.8
30 min	26.3	35.8	42.1	50.0	56.0	61.8
1 hr	31.7	43.9	52.0	62.1	69.7	77.2
2 hr	37.3	51.9	61.6	73.8	82.9	91.9
6 hr	45.8	61.4	71.8	84.9	94.6	104.2
12 hr	51.1	67.6	78.6	92.4	102.7	112.9
24 hr	59.2	82.5	97.8	117.3	131.7	146.0

(**intensities** in mm/hr)

	RP(yrs)					
Duration	2	5	10	25	50	100
5	127.0	173.3	204.0	242.8	271.5	300.0
10	95.7	129.5	151.9	180.2	201.2	222.0
15	79.4	108.2	127.4	151.5	169.5	187.3
30	52.5	71.6	84.2	100.1	111.9	123.6
60	31.7	43.9	52.0	62.1	69.7	77.2
120	18.7	26.0	30.8	36.9	41.4	45.9
360	7.6	10.2	12.0	14.1	15.8	17.4
720	4.3	5.6	6.5	7.7	8.6	9.4
1440	2.5	3.4	4.1	4.9	5.5	6.1

Wet Climate Change

(**depth** in mm)

	RP (yrs)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	11.3	16.1	19.2	23.1	26.1	29.0
10 min	17.0	25.0	30.2	36.9	41.8	46.7
15 min	20.7	29.9	36.0	43.6	49.3	54.9
30 min	26.8	38.3	45.9	55.6	62.7	69.8
1 hr	32.2	44.9	53.3	64.0	71.9	79.7
2 hr	39.1	52.7	61.8	73.9	83.1	92.0
6 hr	49.4	65.6	76.3	89.9	99.9	109.9
12 hr	55.8	74.5	86.9	102.5	114.1	125.6
24 hr	61.3	83.7	98.4	117.5	131.9	146.7

(**intensities** in mm/hr)

	RP(yrs)					
Duration	2	5	10	25	50	100
5	136.0	192.8	230.3	277.8	313.0	347.9
10	101.9	149.7	181.4	221.4	251.0	280.5
15	83.0	119.6	143.8	174.4	197.2	219.7
30	53.6	76.6	91.9	111.1	125.4	139.5
60	32.2	44.9	53.3	64.0	71.9	79.7
120	19.6	26.4	30.9	37.0	41.6	46.0
360	8.2	10.9	12.7	15.0	16.7	18.3
720	4.7	6.2	7.2	8.5	9.5	10.5
1440	2.6	3.5	4.1	4.9	5.5	6.1

EC

	Return Period (mm)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	9.1	11.9	13.8	16.2	18.0	19.7
10 min	13.0	17.8	21.0	25.0	28.0	30.9
15 min	15.6	21.3	25.1	29.8	33.3	36.8
30 min	20.4	28.2	33.4	39.9	44.8	49.6
1 hr	24.4	35.3	42.5	51.6	58.3	65.0
2 hr	29.6	41.6	49.5	59.6	67.0	74.4
6 hr	36.7	48.2	55.8	65.4	72.5	79.6
12 hr	43.0	54.7	62.5	72.4	79.7	87.0
24 hr	51.3	66.8	77.1	90.0	99.6	109.2

	Return Period (mm/hr)					
Duration	2	5	10	25	50	100
5	109.2	142.8	165.6	194.4	216.0	236.4
10	78.0	106.8	126.0	150.0	168.0	185.4
15	62.4	85.2	100.4	119.2	133.2	147.2
30	40.8	56.4	66.8	79.8	89.6	99.2
60	24.4	35.3	42.5	51.6	58.3	65.0
120	14.8	20.8	24.8	29.8	33.5	37.2
360	6.1	8.0	9.3	10.9	12.1	13.3
720	3.6	4.6	5.2	6.0	6.6	7.3
1440	2.1	2.8	3.2	3.8	4.2	4.6

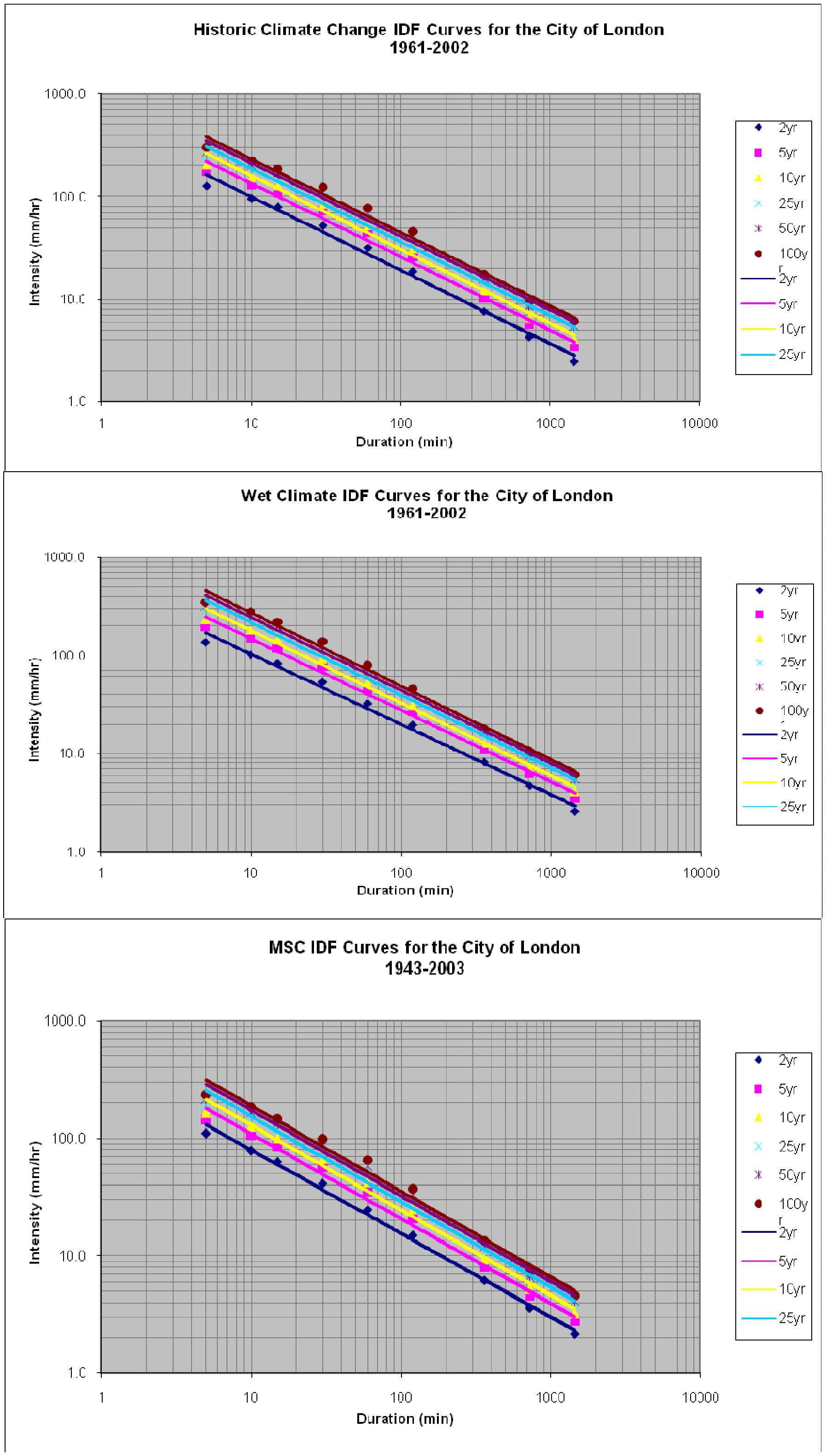


Figure 3. Comparison of IDF curves for the new data set

Table 7. Summary of IDF curves for the modified data set

Historic Climate Change

(**depth** in mm)

	RP (yrs)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	11.0	14.9	17.5	20.8	23.3	25.7
10 min	16.3	23.2	27.7	33.4	37.6	41.8
15 min	19.9	28.6	34.4	41.6	47.0	52.4
30 min	25.4	36.7	44.2	53.7	60.7	67.7
1 hr	30.5	43.7	52.5	63.5	71.8	79.9
2 hr	37.2	52.7	62.9	75.9	85.5	95.1
6 hr	47.0	62.1	72.0	84.6	94.0	103.3
12 hr	53.2	69.8	80.8	94.7	105.1	115.3
24 hr	57.1	78.0	91.9	109.4	122.4	135.3

(**intensities** in mm/hr)

	RP(yrs)					
Duration	2	5	10	25	50	100
5	131.5	178.9	210.3	249.9	279.4	308.6
10	98.0	138.9	166.1	200.3	225.7	251.0
15	79.7	114.4	137.4	166.5	188.0	209.4
30	50.8	73.4	88.4	107.3	121.4	135.3
60	30.5	43.7	52.5	63.5	71.8	79.9
120	18.6	26.3	31.5	37.9	42.8	47.5
360	7.8	10.3	12.0	14.1	15.7	17.2
720	4.4	5.8	6.7	7.9	8.8	9.6
1440	2.4	3.3	3.8	4.6	5.1	5.6

Wet Climate Change

(**depth** in mm)

	RP (yrs)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	11.5	16.1	19.2	23.1	25.9	28.8
10 min	17.3	25.3	30.6	37.4	42.3	47.3
15 min	20.6	29.7	35.7	43.3	49.0	54.6
30 min	26.1	38.8	47.1	57.7	65.6	73.4
1 hr	30.6	43.6	52.2	63.1	71.1	79.1
2 hr	37.0	52.5	62.8	75.9	85.5	95.1
6 hr	47.4	63.4	73.9	87.3	97.1	107.0
12 hr	55.1	72.5	84.1	98.7	109.5	120.2
24 hr	61.4	84.2	99.2	118.3	132.4	146.4

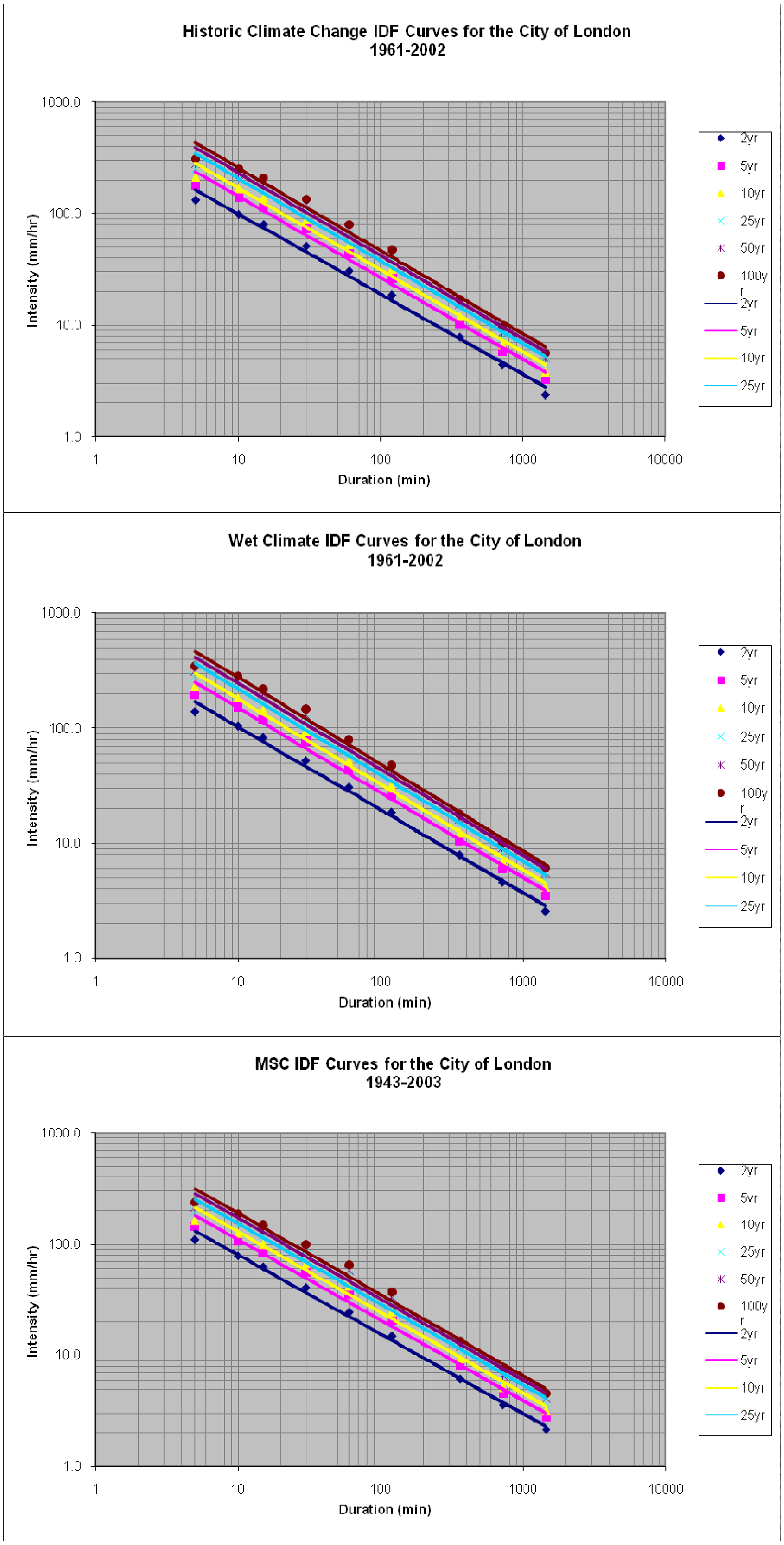
(**intensities** in mm/hr)

	RP(yrs)					
Duration	2	5	10	25	50	100
5	138.1	193.6	230.4	276.8	311.2	345.4
10	103.9	152.0	183.9	224.1	254.0	283.7
15	82.5	118.9	142.9	173.3	195.9	218.3
30	52.3	77.6	94.3	115.5	131.1	146.7
60	30.6	43.6	52.2	63.1	71.1	79.1
120	18.5	26.3	31.4	37.9	42.8	47.6
360	7.9	10.6	12.3	14.5	16.2	17.8
720	4.6	6.0	7.0	8.2	9.1	10.0
1440	2.6	3.5	4.1	4.9	5.5	6.1

EC

	Return Period (mm)					
Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	9.1	11.9	13.8	16.2	18.0	19.7
10 min	13.0	17.8	21.0	25.0	28.0	30.9
15 min	15.6	21.3	25.1	29.8	33.3	36.8
30 min	20.4	28.2	33.4	39.9	44.8	49.6
1 hr	24.4	35.3	42.5	51.6	58.3	65.0
2 hr	29.6	41.6	49.5	59.6	67.0	74.4
6 hr	36.7	48.2	55.8	65.4	72.5	79.6
12 hr	43.0	54.7	62.5	72.4	79.7	87.0
24 hr	51.3	66.8	77.1	90.0	99.6	109.2

	Return Period (mm/hr)					
Duration	2	5	10	25	50	100
5	109.2	142.8	165.6	194.4	216.0	236.4
10	78.0	106.8	126.0	150.0	168.0	185.4
15	62.4	85.2	100.4	119.2	133.2	147.2
30	40.8	56.4	66.8	79.8	89.6	99.2
60	24.4	35.3	42.5	51.6	58.3	65.0
120	14.8	20.8	24.8	29.8	33.5	37.2
360	6.1	8.0	9.3	10.9	12.1	13.3
720	3.6	4.6	5.2	6.0	6.6	7.3
1440	2.1	2.8	3.2	3.8	4.2	4.6


Historic Climate Change IDF Curves for the City of London
1961-2002

Wet Climate IDF Curves for the City of London
1961-2002

MSC IDF Curves for the City of London
1943-2003

Figure 4. Comparison of IDF curves for the modified data set

Table 8. Comparison of IDF results for the original data set

Difference between **Historic** & **Wet** intensities

x_1 --> Wet ; x_2 --> Historic

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	9.8	15.6	18.0	20.1	21.3	22.3
10 min	10.0	15.4	17.6	19.5	20.5	21.3
15 min	7.2	9.8	10.9	11.8	12.4	12.8
30 min	3.9	2.7	2.2	1.8	1.5	1.3
1 hr	6.0	7.4	8.0	8.6	8.9	9.1
2 hr	7.5	9.3	10.1	10.8	11.2	11.5
6 hr	4.9	6.8	7.6	8.4	8.8	9.2
12 hr	8.0	9.7	10.4	11.1	11.5	11.8
24 hr	9.4	9.5	9.6	9.6	9.7	9.7

Difference between **Historic** & **EC** intensities

x_1 --> Historic ; x_2 --> EC

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	8.8	9.9	10.0	10.1	10.1	10.5
10 min	14.2	13.7	13.4	13.3	13.2	13.3
15 min	18.4	18.9	19.0	19.5	19.7	19.8
30 min	20.0	21.3	21.7	22.2	22.4	22.6
1 hr	19.7	13.3	10.8	8.6	7.4	6.4
2 hr	17.3	12.3	10.3	8.3	7.3	6.5
6 hr	18.3	15.6	14.4	13.3	12.7	12.1
12 hr	12.2	13.2	13.6	13.9	14.2	14.3
24 hr	1.9	5.1	6.5	7.9	8.6	9.2

Difference between **Wet** & **EC** intensities

x_1 --> Wet ; x_2 --> EC

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	18.6	25.3	27.8	30.1	31.2	32.6
10 min	24.1	29.0	30.8	32.6	33.5	34.4
15 min	25.5	28.6	29.8	31.1	31.8	32.3
30 min	23.8	23.9	23.9	24.0	23.9	23.9
1 hr	25.6	20.7	18.8	17.1	16.2	15.5
2 hr	24.7	21.5	20.3	19.0	18.5	17.9
6 hr	23.2	22.3	21.9	21.6	21.5	21.3
12 hr	20.1	22.8	24.0	25.0	25.6	26.0
24 hr	11.3	14.7	16.1	17.5	18.3	18.8

Table 9. Comparison of IDF results for the new data set

Difference between **Historic** & **Wet** intensities

x_1 --> Wet ; x_2 --> Historic

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	6.9	10.6	12.1	13.5	14.2	14.8
10 min	6.3	14.5	17.7	20.5	22.0	23.3
15 min	4.5	10.0	12.1	14.1	15.1	16.0
30 min	2.1	6.9	8.7	10.4	11.3	12.1
1 hr	1.5	2.3	2.6	2.9	3.0	3.2
2 hr	4.6	1.5	0.3	0.1	0.3	0.2
6 hr	7.6	6.5	6.1	5.7	5.5	5.3
12 hr	9.0	9.7	10.1	10.4	10.5	10.7
24 hr	3.5	1.4	0.6	0.2	0.1	0.5

Difference between **Historic** & **EC** intensities

x_1 --> Historic ; x_2 --> EC

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	15.1	19.3	20.8	22.1	22.8	23.7
10 min	20.4	19.2	18.6	18.3	18.0	18.0
15 min	23.9	23.8	23.7	23.9	24.0	24.0
30 min	25.1	23.7	23.0	22.6	22.1	21.9
1 hr	26.1	21.7	20.0	18.5	17.8	17.2
2 hr	23.1	22.1	21.8	21.3	21.2	21.0
6 hr	22.0	24.1	25.1	25.9	26.4	26.8
12 hr	17.1	21.1	22.8	24.3	25.2	25.9
24 hr	14.3	21.0	23.7	26.3	27.8	28.9

Difference between **Wet** & **EC** intensities

x_1 --> Wet ; x_2 --> EC

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	21.9	29.8	32.7	35.3	36.7	38.2
10 min	26.6	33.5	36.0	38.4	39.6	40.8
15 min	28.3	33.6	35.6	37.6	38.7	39.5
30 min	27.2	30.4	31.6	32.8	33.3	33.8
1 hr	27.5	24.0	22.6	21.5	20.8	20.3
2 hr	27.7	23.6	22.0	21.4	21.5	21.2
6 hr	29.5	30.6	31.1	31.5	31.8	32.0
12 hr	26.0	30.7	32.6	34.4	35.5	36.3
24 hr	17.8	22.4	24.3	26.5	27.9	29.3

Table 10. Comparison of IDF results for the modified data set

Difference between **Historic** & **Wet** intensities

x_1 --> Wet ; x_2 --> Historic

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	5.0	7.9	9.1	10.2	10.8	11.3
10 min	5.8	9.0	10.2	11.2	11.8	12.2
15 min	3.5	3.8	3.9	4.0	4.1	4.1
30 min	2.9	5.5	6.5	7.3	7.7	8.1
1 hr	0.4	0.2	0.4	0.3	0.3	0.2
2 hr	0.7	0.5	0.1	0.3	0.4	0.3
6 hr	0.9	2.1	2.6	3.0	3.3	3.5
12 hr	3.5	3.8	3.9	4.1	4.1	4.2
24 hr	7.3	7.6	7.7	7.8	7.9	7.9

Difference between **Historic** & **EC** intensities

x_1 --> Historic ; x_2 --> EC

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	18.5	22.4	23.8	25.0	25.6	26.5
10 min	22.7	26.2	27.4	28.7	29.3	30.1
15 min	24.3	29.3	31.1	33.1	34.1	34.9
30 min	21.7	26.2	27.8	29.4	30.1	30.8
1 hr	22.1	21.3	21.0	20.7	20.7	20.6
2 hr	22.6	23.5	23.9	24.1	24.3	24.4
6 hr	24.6	25.1	25.4	25.7	25.8	25.9
12 hr	21.1	24.3	25.6	26.7	27.5	28.0
24 hr	10.7	15.5	17.5	19.5	20.5	21.3

Difference between **Wet** & **EC** intensities

x_1 --> Wet ; x_2 --> EC

Duration	2 yr	5 yr	10 yr	25 yr	50 yr	100 yr
5 min	23.4	30.2	32.7	35.0	36.1	37.5
10 min	28.4	34.9	37.4	39.6	40.8	41.9
15 min	27.8	33.0	35.0	37.0	38.1	38.9
30 min	24.6	31.6	34.1	36.5	37.6	38.6
1 hr	22.5	21.5	21.4	21.0	21.0	20.8
2 hr	23.3	23.9	24.0	24.3	24.7	24.7
6 hr	25.5	27.2	27.9	28.6	29.1	29.3
12 hr	24.6	28.0	29.4	30.7	31.5	32.1
24 hr	17.9	23.0	25.1	27.2	28.3	29.1

4.0 Conclusions and recommendations

4.1 Current water management design standards

Currently, the City of London uses two different IDF curves as standards for water management infrastructure design, operation and maintenance. Conveyance systems are designed based on a curve provided by MacLaren (1962), while most other storm water management facilities are designed using criteria provided by the City of London Sewer Design Standards (2003). The IDF curve in use today for design of conveyance systems has been adopted from a study conducted in 1962, and is based on data from 1950's for the Toronto area.

4.2 Recommended modifications

The rainfall patterns in Southwestern Ontario will most certainly change with the climate change. This report quantifies these changes and their impact on design, operation and maintenance of municipal water management infrastructure (such as roads, bridges, culverts, drains, sewer and conveyance systems, etc). The results presented in previous Section of the report in terms of rainfall intensity duration frequency data for the City of London suggest the need for change of IDF curves used as standards for water management infrastructure design, operation and maintenance in order to take into account potential impact of climate change. New IDF curves represent the best available knowledge at this moment.

Following recommendations are provided on the basis of study results:

(i) In order to include the potential impacts of climate change in management of water infrastructure the City of London is directed to use the modified data set. Data between 2002 and 2009 should be incorporated as soon as they become available.

(ii) Results of comparison between the updated IDF curves for modified data set indicate small difference between the historic and wet climate change scenarios. This difference ranges between 0.1% and 12.2% with average value of approximately 4.5%. Therefore the recommendation is to proceed with potential revisions of the standards using the historic climate change scenario.

(iii) Comparison between the updated IDF curves for modified data set (historic climate change scenario) and the EC IDF curves shows a difference that ranges between 10.7 % and 34.9% with average value of approximately 21%. Based on this comparison our recommendation to the City of London is to evaluate potential change of IDF curves in the range of 20%. Detailed economic analyses should be performed to justify the necessary investment that this change will require.

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Appendix A

Computer code for the development of maximum 24 hr rainfall

The following java code includes the processes used to generate the 24hr duration precipitation file. This program requires the input of element 132 (12hr daily maximum duration file) as well as element 123 (hourly precipitation values) to generate the output; 24hr daily maximums.

The foundation of this program is based on a moving window with a size of 24 (the number of hours in a day). The program incrementally searches using this window across all hours in the ‘current day’. The maximum daily value found using that window is then assigned to the ‘current day’. If the maximum event crosses over into the next day, the value is assigned to the day in which most of the rainfall occurred. The other day is assigned the remainder of the hours. Once the daily value is computed, it is compared to the same day of the 12hr daily precipitation maximum. If the value computed is less than what is specified as the 12hr maximum, then the 12hour maximum value is accepted instead. It is in this way, for the entire record, that the program generates the 24hr precipitation file.

It should also be noted that this program permits a user-specified parameter to process the output into the desirable format. The parameter MISSING_LIMIT allows the user to specify what an acceptable range of missing values is in the hourly data and in turn how many missing values are unacceptable in the input data. Windows which exhibit a greater number of missing values than specified are assigned a value of -999 (missing) in the 24hr output file.

Program:

```
package weathergen;

import java.io.FileNotFoundException;

public class HourlyFormatterWindowVersion3 {
	private static final String TWLEVEHOUR_DATA_FILE =
"Input/London12Hour.txt";
	private static final String INPUT_FILE =
"Input/LondonHourly.txt";
	private static final String OUTPUT_FILES =
	"Output/daily.txt";
	/*
	 * When calculating a daily maximum, if the number of missing
values is greater than or equal
	 * to MISSING_LIMIT then the day will be recorded as missing.
	 */
	private static final int MISSING_LIMIT = 10;

	private static HourlyDataCollection data;
	private static DataCollection twelvehour;
	private static double carryovervalue = 0.0;
```

```
    public static double getTwleveHour(WGDate date, WGTime endtime)
    {
        double sum = 0.0;
        WGTime searchTime = new WGTime(0, 0);
        Double twelve = twelvehour.getPrecipitation(date);

        if(endtime != null) {
            while(!searchTime.equals(endtime))
            {
                Double value = data.getValue(date, searchTime);
                if(value != null) {
                    sum += value.doubleValue();
                }
                searchTime.incmin(60);
            }

            if(twelve != null && twelve.doubleValue() > sum) {
                return twelve.doubleValue();
            }
            return sum;
        }

        if(twelve != null)
            return twelve.doubleValue();
        else
            return -999.9;
    }

    public static double getDailyTotal(WGDate target)
    {
        if(target.year() == 2000 && target.month() == 5 &&
target.day() == 11)
        {
            int testX = 0;
            double testY = 0.0;
            testX++;
            testY += 23.0;
        }
        WGTime endtime = null;
        double max = 0.0;
        double maxday1 = 0.0;
        double maxday2 = 0.0;

        int missingcount = 0;

        for(int i = 0; i < 24; i++)
        {
            WGDate searchDate = new WGDate(target.year(),
target.month(), target.day());
            WGTime searchTime = new WGTime(i, 0);
            double sum = 0.0;

            double sumday1 = 0.0;
            double sumday2 = 0.0;

            boolean nextday = false;
```

```
            for(int j = 0; j < 24; j++)
            {
                Double value = data.getValue(searchDate,
searchTime);
                if(value == null) {
                    if(nextday == false)
                        missingcount++;
                } else {
                    if(nextday == false) {
                        sumday1 += value.doubleValue();
                    } else {
                        sumday2 += value.doubleValue();
                    }

                    sum += value.doubleValue();
                }

                searchTime.incmin(60);

                if(searchTime.hour().intValue() == 0) {
                    nextday = true;
                    searchDate.inc();
                }
            }

            if(sum > max) {
                endtime = new WGTime(i, 0);
                max = sum;
                maxday1 = sumday1;
                maxday2 = sumday2;
            }
        }

        if(carryovervalue > max)
        {
                double ret = carryovervalue;
                carryovervalue = 0.0;
                return ret;
        }

        carryovervalue = 0.0;

        if(maxday2 > maxday1) {
            carryovervalue = max;
            if(missingcount < MISSING_LIMIT)
                return getTwleveHour(target, endtime);
        }
        if(missingcount < MISSING_LIMIT)
        {
            if(target.year() == 2000 && target.month() == 5 &&
target.day() == 11)
            {
                double holy;
                double crap;
                int we = 20;
                we += 50;
            }
```

```
                    double twelve = getTwleveHour(target, null);

                    if(twelve > max)
                          return twelve;
                    return max;
              }
              return -999.9;
        }

        public static void main(String[] args)
        {
              MscFileHourlyDataReader reader = new
MscFileHourlyDataReader();
              OldWGFormatDataReader twlevehourreader = new
OldWGFormatDataReader();
              twelvehour = new HashDataCollection();
              data = new HourlyHashDataCollection();
              OldWGFormatDataWriter writer = new OldWGFormatDataWriter();

              try {
                    twlevehourreader.openFile(TWLEVEHOUR_DATA_FILE,
DataRecord.Element.TWELVEHOUR);
                    reader.openFile(INPUT_FILE);
                    writer.openOutput(OUTPUT_FILES);
              }
              catch(FileNotFoundException e)
              {
                    System.err.println(e.getMessage());
                    return;
              }


        ((HashDataCollection)twelvehour).loadData(twlevehourreader);
              data.loadData(reader);


        ((HashDataCollection)twelvehour).setElement(DataRecord.Element.TW
ELVEHOUR);

              WGDate search = new WGDate(data.getStartDate().year(),
data.getStartDate().month(), data.getStartDate().day());
              WGDate end = new WGDate(data.getEndDate().year(),
data.getEndDate().month(), data.getEndDate().day());
              end.inc();

              final DataRecord.Element element =
DataRecord.Element.DAILY;

              while(!search.equals(end)) {
                    double maximum = getDailyTotal(search);

                    writer.writeRecord(new DataRecord(search, new
Double(maximum), element));

                    search.inc();
              }
```

```
                writer.close();
        }

}
```

Appendix B

IPCC Scenarios

The following is taken from IPCC (2001) and represent four main families of climate change scenarios. The scenarios used in this report are based on B1 and B2.

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other story lines.

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid- century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 story lines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Appendix C

Weather generator computer code

Introduction

The Weather Generator (WG) program is designed to use the observed historical record of rainfall data from a single station. The WG uses this as input to generate synthetic rainfall data for *N* number of years of the observed historic record. If more than *N* years of synthetic rainfall are required, the WG must be run multiple times. The WG functions by first establishing a data block of nearest neighbour values to the current day. New values are selected from this block and then weighted according to their Mahalanobis Distance. A random number is generated and then compared to the probability of selecting each neighbouring value. This random number is used as a perturbation mechanism pushes the data out of its historical boundaries. The output is a record of *N* years of synthetic rainfall data.

Preprocessing

There are a few preparatory steps to follow before running the Weather Generator program. Following these guidelines will help avoid production of obscure and inaccurate results and minimize program crashes.

Prepare Weather Generator input files in the recommended format before using them as input (see Formatting Weather Generator Input Files). The class PrePocessing.java can be used to process the input files, format them and output them as new files.

If change fields are required for a particular scenario then they are applied here. The mainScenarios.java file will apply the change fields for the Wet scenario.

Modify the parameters at the beginning of the Main.java function in order to manipulate the WG simulation and specify the appropriate input and output files.

Weather Generator

Run the Main.java WG class. There will be an equal number of output files produced from the WG as there were input files. The specified output directory contains these files.

Postprocessing

After running the WG program, the output files are in the same format as the input files only now the rainfall values have been shuffled and perturbed. These nine output elements are then submitted to a PostProcessing.java class which extracts the annual maximum rainfall values and then fits the values to a Gumbel probability distribution function and outputs an IDF table.

Due to the length - over 150 pages - this Appendix does not list the weather generator computer code. It is available upon request from Prof. S.P. Simonovic.

Appendix D

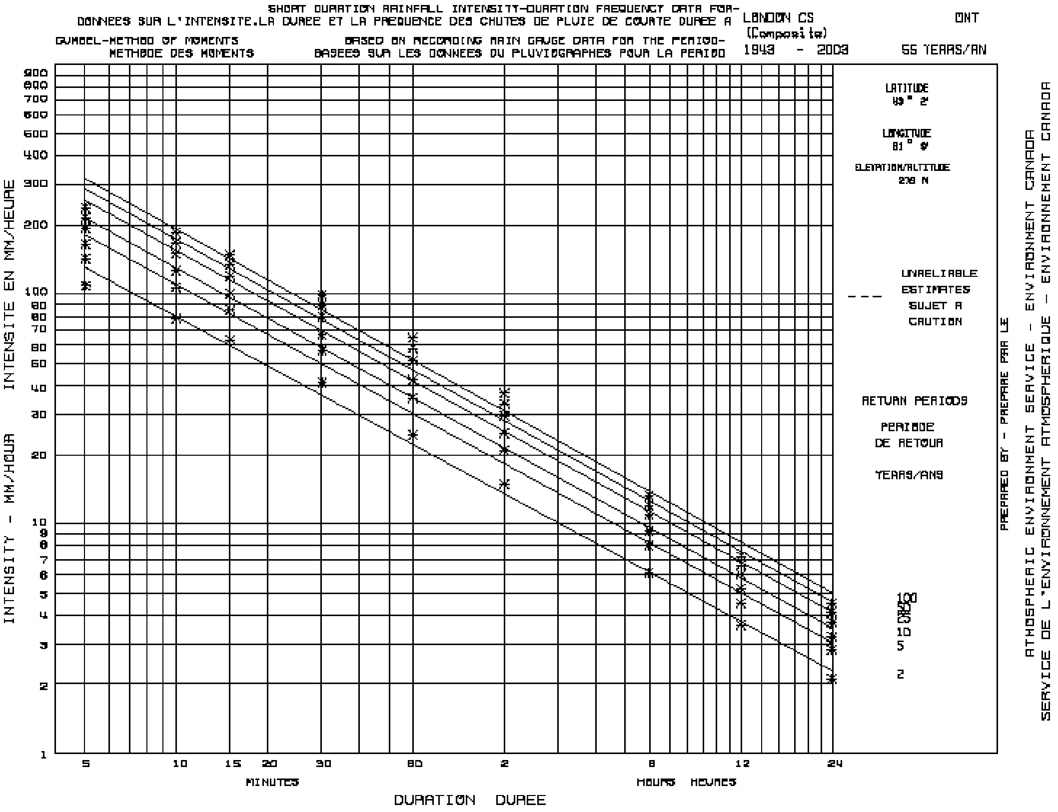
MSC IDF information for London from 2001

```
                           ATMOSPHERIC ENVIRONMENT SERVICE
                     SERVICE DE L"ENVIRONNEMENT ATMOSPHERIQUE

                    RAINFALL INTENSITY-DURATION FREQUENCY VALUES
                      INTENSITE, DUREE ET FREQUENCE DES PLUIES

                            DATA INTEGRATION DIVISION
                      LA DIVISION DU TRAITEMENT DES DONNEES

                GUMBEL - METHOD OF MOMENTS/METHODE DES MOMENTS - 2001

*******************************************************************************

         TABLE 1         LONDON A                 ONT                6144475

         LATITUDE 4302       LONGITUDE  8109       ELEVATION/ALTITUDE  278  M
*******************************************************************************
         YEAR   5 MIN 10 MIN 15 MIN 30 MIN   1 H    2 H    6 H   12 H   24 H
         ANNEE

          1943   18.3   24.1   26.2   36.3   51.1   53.8   53.8   56.1   78.7
          1944    7.6    8.1   11.2   15.2   21.1   34.3   47.0   51.8   56.1
          1945    6.6    9.7   12.7   17.3   19.3   25.4   34.3   39.4   47.8
          1946   13.2   14.5   15.5   29.7   48.3   60.5   61.5   61.5   83.3
          1947   10.9   19.3   23.9   29.2   29.2   29.2   40.9   43.2   46.7
          1952    7.9   12.7   15.2   28.7   30.5   30.5   38.4   39.9   74.2
          1953   15.7   24.6   36.8   56.9   83.3   83.3   83.3   83.3   83.3
          1954   10.9   12.7   17.0   21.6   29.2   32.8   39.1   52.6   78.0
          1955    6.6    9.1   11.2   14.2   14.7   17.3   32.5   44.2   51.1
          1956    9.1   10.7   11.7   16.8   20.1   35.3   40.4   42.7   53.8
          1957    6.3    9.4   12.4   16.5   26.2   28.2   35.6   47.5   55.6
          1958    7.6    9.7   11.2   15.7   16.5   18.5   29.2   39.1   39.9
          1959    8.6   10.9   13.0   15.5   23.4   39.6   50.3   50.5   50.5
          1960    9.1   12.7   16.8   27.7   28.2   38.9   39.9   42.4   46.7
          1961   11.4   20.1   23.9   29.0   39.9   43.2   43.4   43.4   43.4
          1962    8.6   16.5   17.0   17.0   18.8   26.7   29.0   34.8   35.1
          1963    5.6    7.9    9.1   10.4   10.4   11.4   21.3   21.3   23.9
          1964    7.9   10.9   14.2   19.0   23.9   32.3   38.1   59.2   67.3
          1965    5.6   10.4   11.7   14.2   18.3   21.1   29.0   38.4   43.7
          1966    8.4    8.4    8.9   14.2   19.3   27.4   43.9   52.6   52.6
          1967    7.9   11.9   12.2   19.3   20.6   22.4   33.5   37.3   41.4
          1968   10.4   13.2   16.0   24.6   28.7   32.3   53.1   67.6   84.6
          1969    6.9   10.2   13.5   15.7   15.7   18.5   27.4   39.9   47.5
          1970   10.9   13.0   16.5   17.0   21.1   22.1   23.9   33.3   36.8
          1971    8.9   15.0   22.4   32.5   39.1   42.7   42.7   42.7   42.7
          1972   14.5   20.1   22.9   22.9   34.3   40.6   58.4   59.7   62.5
          1973    7.4    9.4   13.5   17.0   17.8   19.6   31.5   40.4   52.1
          1974    4.8    7.9    9.1   10.9   13.2   22.4   29.2   30.2   35.3
          1975    9.1   12.4   15.2   18.5   21.1   21.1   27.9   30.5   30.5
          1976   18.5   26.9   27.7   29.2   30.5   30.7   37.8   40.9   50.0
          1978    6.6   10.9   14.2   14.4   14.4   14.4   23.5   27.3   29.6
          1979   19.2   33.5   37.6   45.9   46.0   46.0   46.6   65.4   68.2
          1980   11.5   20.6   27.8   30.6   32.5   32.6   37.7   47.1   61.7
          1981   10.1   12.5   13.2   13.2   16.2   26.7   35.0   37.5   43.5
          1982    6.8   10.8   15.1   22.2   24.6   28.6   35.4   36.8   37.6
          1983   13.5   23.4   29.5   37.6   41.1   41.1   47.0   55.8   64.4
          1984    9.8   10.6   14.5   27.4   27.8   43.5   50.8   56.0   69.7
```

```
      1985    8.3   10.9   13.7   22.8   29.0   35.1   43.2   56.8   65.0
      1986   12.4   22.7   24.2   24.5   30.6   42.2   43.8   49.7   89.1
      1987    6.7    9.4   11.0   13.2   14.3   17.7   27.2   44.5   56.5
      1988    7.9   11.2   15.5   18.2   18.3   26.9   33.0   41.9   61.6
      1989    8.7   10.9   13.5   23.3   25.7   25.8   25.8   34.0   34.8
      1990   11.9   16.7   18.7   30.4   35.1   37.9   41.6   54.1   75.5
      1991    9.7   11.6   13.9   17.5   20.6   22.0   28.1   32.2   32.2
      1992    6.5   11.5   15.9   20.9   35.0   45.2   51.8   58.6   76.3
      1993    9.4   14.3   15.1   19.1   21.9   25.0   28.5   30.7   49.2
      1994    7.5   11.3   12.1   16.8   20.6   33.2   38.9   40.3   46.5
      1995    8.2   11.3   12.6   15.8   21.8   28.0   37.8   45.0   56.1
      1996    9.4   15.8   17.9   26.1   39.2   68.1   82.7   83.5   89.0
      1997   10.6   17.0   19.6   21.8   21.8   24.8   31.1   33.9   33.9
      1998   12.6   14.7   15.8   17.6   20.4   20.4   20.4   20.4   33.0
      1999    7.3   11.2   11.8   12.7   13.3   19.0   25.9   26.1   32.9
      2000   11.5   15.3   17.6   23.0   30.6   40.6   42.7   59.2   82.8
      2001    6.3    7.9   10.6   13.2   13.4   14.0   24.0   35.0   41.2
      NOTE:-99.9 INDICATES MSG DATA
                 DONNEES MANQUANTES

     # YRS.   54     54     54     54     54     54     54     54     54
     ANNEES
       MEAN   9.6   13.9   16.7   21.9   26.4   31.9   38.9   45.2   54.2
    MOYENNE
  STD. DEV.   3.2    5.4    6.4    8.8   12.3   13.5   13.0   13.3   17.5
 ECART-TYPE
       SKEW   1.29   1.55   1.58   1.67   2.16   1.48   1.49    .76    .42
DISSYMETRIE
   KURTOSIS   4.74   5.50   5.48   7.03  10.57   6.43   6.38   4.07   2.29
   KURTOSIS


                           WARNING / AVERTISSEMENT
          YEAR 1953 HAD VALUE GREATER THAN 100 YEAR STORM.
              EN 1953 L"INTENSITE DE LA PLUIE A DE PASSE
             CELLE POUR UNE PERIODE DE RETOUR DE 100 ANS
            DATA/LA VALEUR =  56.9     100 YEAR/ANNEE =  49.6

                           WARNING / AVERTISSEMENT
          YEAR 1953 HAD VALUE GREATER THAN 100 YEAR STORM.
              EN 1953 L"INTENSITE DE LA PLUIE A DE PASSE
             CELLE POUR UNE PERIODE DE RETOUR DE 100 ANS
            DATA/LA VALEUR =  83.3     100 YEAR/ANNEE =  65.0

                           WARNING / AVERTISSEMENT
          YEAR 1953 HAD VALUE GREATER THAN 100 YEAR STORM.
              EN 1953 L"INTENSITE DE LA PLUIE A DE PASSE
             CELLE POUR UNE PERIODE DE RETOUR DE 100 ANS
            DATA/LA VALEUR =  83.3     100 YEAR/ANNEE =  74.4

                           WARNING / AVERTISSEMENT
          YEAR 1953 HAD VALUE GREATER THAN 100 YEAR STORM.
              EN 1953 L"INTENSITE DE LA PLUIE A DE PASSE
             CELLE POUR UNE PERIODE DE RETOUR DE 100 ANS
            DATA/LA VALEUR =  83.3     100 YEAR/ANNEE =  79.6

                           WARNING / AVERTISSEMENT
          YEAR 1979 HAD VALUE GREATER THAN 100 YEAR STORM.
              EN 1979 L"INTENSITE DE LA PLUIE A DE PASSE
             CELLE POUR UNE PERIODE DE RETOUR DE 100 ANS
            DATA/LA VALEUR =  33.5     100 YEAR/ANNEE =  30.9

                           WARNING / AVERTISSEMENT
```

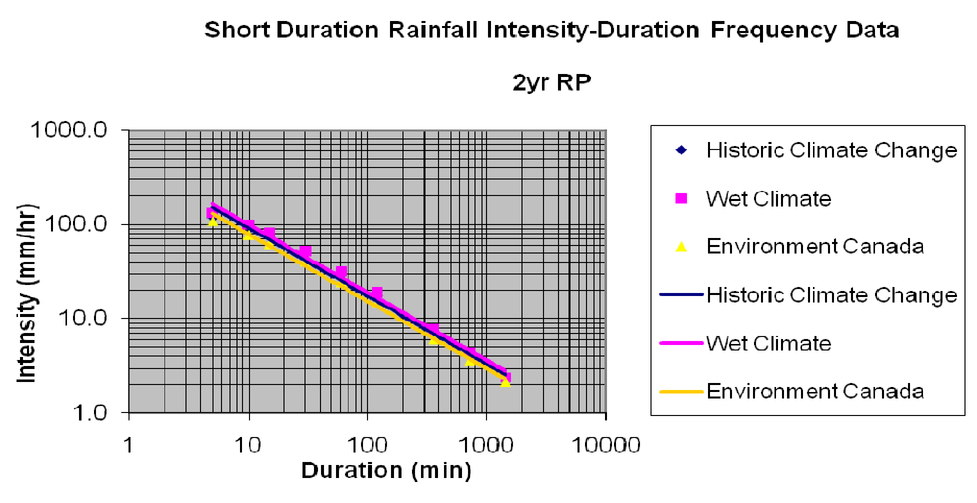
```
              YEAR 1979 HAD VALUE GREATER THAN 100 YEAR STORM.
                  EN 1979 L"INTENSITE DE LA PLUIE A DE PASSE
                 CELLE POUR UNE PERIODE DE RETOUR DE 100 ANS
                DATA/LA VALEUR =  37.6     100 YEAR/ANNEE =  36.8

                               WARNING / AVERTISSEMENT
              YEAR 1996 HAD VALUE GREATER THAN 100 YEAR STORM.
                  EN 1996 L"INTENSITE DE LA PLUIE A DE PASSE
                 CELLE POUR UNE PERIODE DE RETOUR DE 100 ANS
                DATA/LA VALEUR =  82.7     100 YEAR/ANNEE =  79.6



         NOTE: -99.9 INDICATES LESS THAN 10 YEARS OF DATA AVAILABLE
                INDIQUE MOINS DE 10 ANNEES DE DONNEES DISPONIBLES
                           ATMOSPHERIC ENVIRONMENT SERVICE
                     SERVICE DE L"ENVIRONNEMENT ATMOSPHERIQUE

                        RAINFALL INTENSITY-DURATION FREQUENCY VALUES
                          INTENSITE, DUREE ET FREQUENCE DES PLUIES

                GUMBEL - METHOD OF MOMENTS/METHODE DES MOMENTS - 2001
 ******************************************************************************

         TABLE 2         LONDON A                ONT                6144475

         LATITUDE 4302       LONGITUDE  8109       ELEVATION/ALTITUDE  278  M
 ******************************************************************************

                              RETURN PERIOD RAINFALL AMOUNTS (MM)
                           PERIODE DE RETOUR QUANTITIES DE PLUIE (MM)

        DURATION    2        5        10       25       50       100   # YEARS
         DUREE    YR/ANS   YR/ANS   YR/ANS   YR/ANS   YR/ANS   YR/ANS  ANNEES
         5 MIN     9.1     11.9     13.8     16.2     18.0     19.7      54
        10 MIN    13.0     17.8     21.0     25.0     28.0     30.9      54
        15 MIN    15.6     21.3     25.1     29.8     33.3     36.8      54
        30 MIN    20.4     28.2     33.4     39.9     44.8     49.6      54
          1 H     24.4     35.3     42.5     51.6     58.3     65.0      54
          2 H     29.6     41.6     49.5     59.6     67.0     74.4      54
          6 H     36.7     48.2     55.8     65.4     72.5     79.6      54
         12 H     43.0     54.7     62.5     72.4     79.7     87.0      54
         24 H     51.3     66.8     77.1     90.0     99.6    109.2      54

            RETURN PERIOD RAINFALL RATES (MM/HR)-95% CONFIDENCE' LIMITS
    INTENSITE DE LA PLUIE PAR PERIODE DE RETOUR (MM/H)-LIMITES DE CONFIANCE DE
 95%


        DURATION  2 YR/ANS  5 YR/ANS 10 YR/ANS 25 YR/ANS 50 YR/ANS 100 YR/ANS
         DUREE
         5 MIN     108.6     143.0     165.8     194.5     215.8     237.0
                 +/-  9.5  +/- 16.0  +/- 21.7  +/- 29.2  +/- 34.9  +/- 40.7
         10 MIN     77.8     106.6     125.7     149.9     167.7     185.5
                 +/-  8.0  +/- 13.5  +/- 18.2  +/- 24.5  +/- 29.3  +/- 34.2
         15 MIN     62.4      85.2     100.2     119.3     133.4     147.4
                 +/-  6.3  +/- 10.6  +/- 14.3  +/- 19.3  +/- 23.1  +/- 26.9
         30 MIN     40.8      56.4      66.8      79.9      89.6      99.2
                  +/-  4.3  +/-  7.3  +/-  9.8  +/- 13.3  +/- 15.9  +/- 18.5
           1 H      24.4      35.3      42.5      51.6      58.3      65.0
                 +/-  3.0  +/-  5.1  +/-  6.8  +/-  9.2  +/- 11.0  +/- 12.9
           2 H      14.8      20.8      24.8      29.8      33.5      37.2
                 +/-  1.7  +/-  2.8  +/-  3.8  +/-  5.1  +/-  6.1  +/-  7.1
```

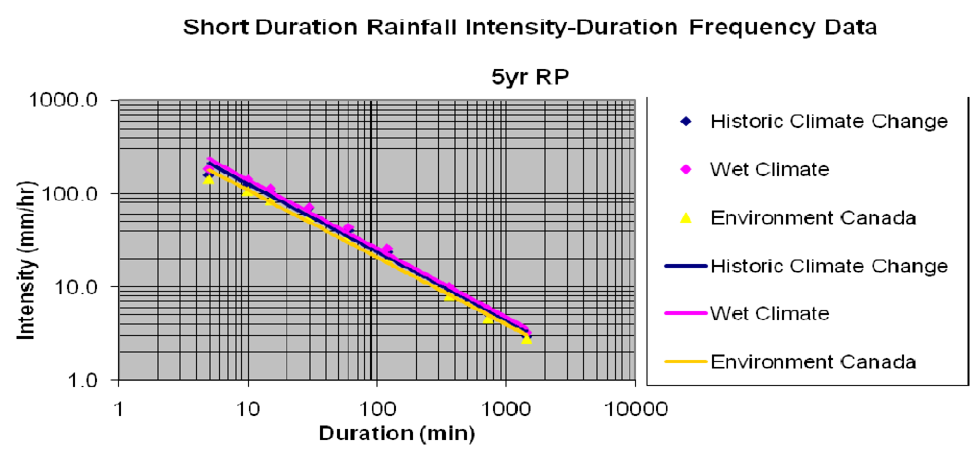
```
           6 H        6.1       8.0       9.3      10.9      12.1      13.3
                 +/-   .5  +/-   .9  +/-  1.2  +/-  1.6  +/-  1.9  +/-  2.3
          12 H        3.6       4.6       5.2       6.0       6.6       7.2
                 +/-   .3  +/-   .5  +/-   .6  +/-   .8  +/-  1.0  +/-  1.2
          24 H        2.1       2.8       3.2       3.8       4.2       4.5
                 +/-   .2  +/-   .3  +/-   .4  +/-   .5  +/-   .7  +/-   .8


                          ATMOSPHERIC ENVIRONMENT SERVICE
                       SERVICE DE L"ENVIRONNEMENT ATMOSPHERIQUE

                    RAINFALL INTENSITY-DURATION FREQUENCY VALUES
                      INTENSITE, DUREE ET FREQUENCE DES PLUIES

                GUMBEL - METHOD OF MOMENTS/METHODE DES MOMENTS - 2001

*******************************************************************************

         TABLE 3         LONDON A                 ONT                6144475

         LATITUDE 4302       LONGITUDE  8109       ELEVATION/ALTITUDE  278  M
*******************************************************************************

         INTERPOLATION EQUATION / EQUATION D"INTERPOLATION: R = A * T ** B
                 R = RAINFALL RATE / INTENSITE DE LA PLUIE (MM /HR)
                 T = TIME IN HOURS / TEMPS EN HEURES


             STATISTICS               2 YR   5 YR  10 YR  25 YR  50 YR 100 YR
            STATISTIQUES              ANS    ANS    ANS    ANS    ANS    ANS


           MEAN OF  R                37.8   51.4   60.3   71.7   80.1   88.4
           MOYENNE DE R
            STD. DEV. R               37.7   50.2   58.6   69.1   77.0   84.8
           ECART-TYPE
           STD. ERROR                 8.4   14.5   18.6   23.7   27.5   31.3
           ERREUR STANDARD
           COEFF. (A)                22.2   30.0   35.2   41.7   46.6   51.4
            COEFFICIENT (A)
           EXPONENT (B)             -.712  -.721  -.725  -.728  -.730  -.732
           EXPOSANT (B)
            MEAN % ERROR               7.8   10.4   11.5   12.5   13.1   13.5
           % D'ERREUR
```

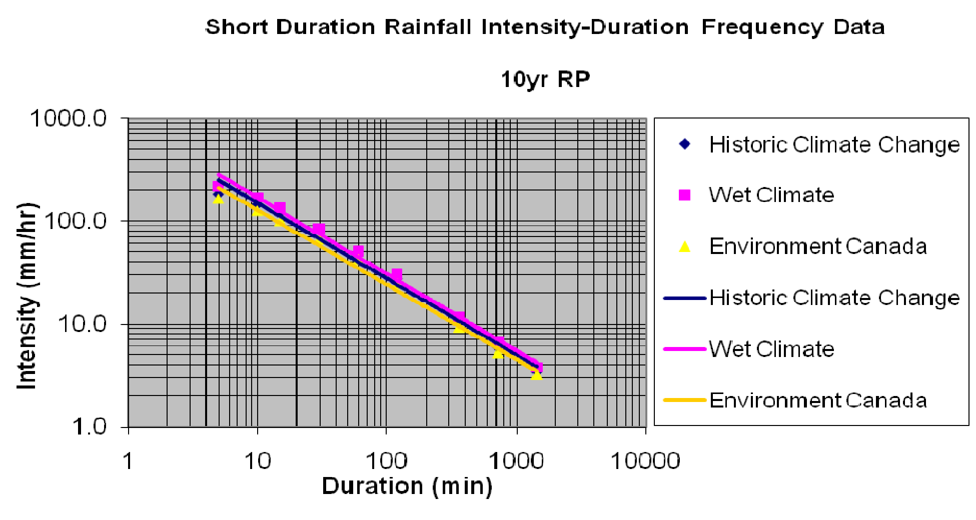

SHORT DURATION RAINFALL INTENSITY-DURATION FREQUENCY DATA FOR-
DONNEES SUR L'INTENSITE,LA DUREE ET LA FREQUENCE DES CHUTES DE PLUIE DE COURTE DUREE A
LONDON CS
(Composite)
ONT
GUMBEL-METHOD OF MOMENTS
METHODE DES MOMENTS
BASED ON RECORDING RAIN GAUGE DATA FOR THE PERIOD-
BASEES SUR LES DONNEES DU PLUVIOGRAPHES POUR LA PERIOD
1943 - 2003
55 YEARS/AN
LATITUDE
43° 2'
LONGITUDE
81° 9'
ELEVATION/ALTITUDE
278 M
UNRELIABLE ESTIMATES
SUJET A CAUTION
RETURN PERIODS
PERIODE DE RETOUR
YEARS/ANS
100
50
25
10
5
2
INTENSITY - MM/HOUR
INTENSITE EN MM/HEURE
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
5
10
15
20
30
60
2
6
12
24
MINUTES
HOURS HEURES
DURATION DUREE
PREPARED BY - PREPARE PAR LE
ATMOSPHERIC ENVIRONMENT SERVICE - ENVIRONMENT CANADA
SERVICE DE L'ENVIRONNEMENT ATMOSPHERIQUE - ENVIRONNEMENT CANADA

Appendix E

Comparison of IDF curves for the original data set

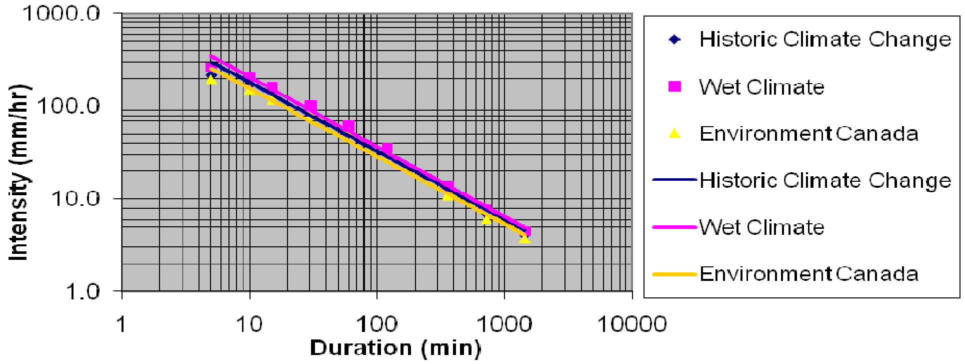






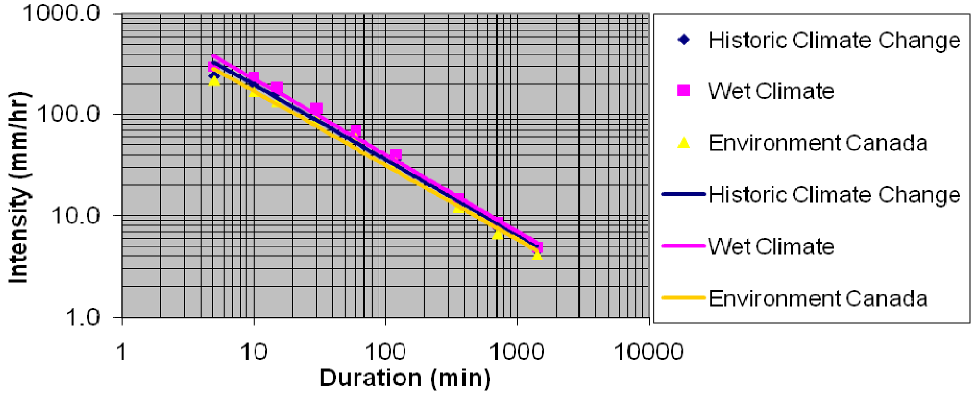
Short Duration Rainfall Intensity-Duration Frequency Data

25yr RP



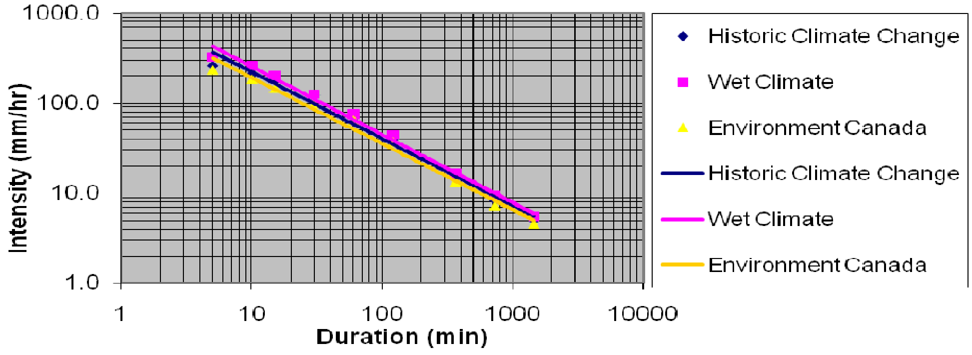
Short Duration Rainfall Intensity-Duration Frequency Data

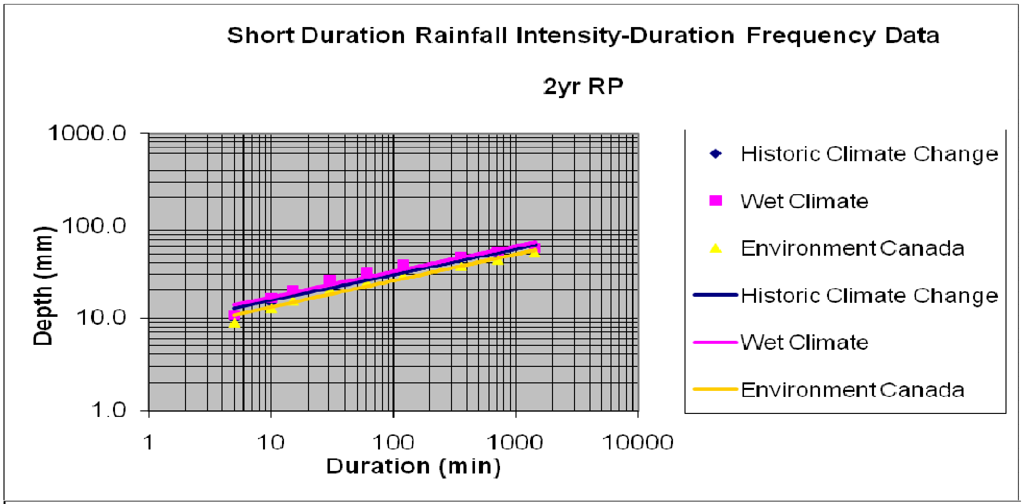
50yr RP

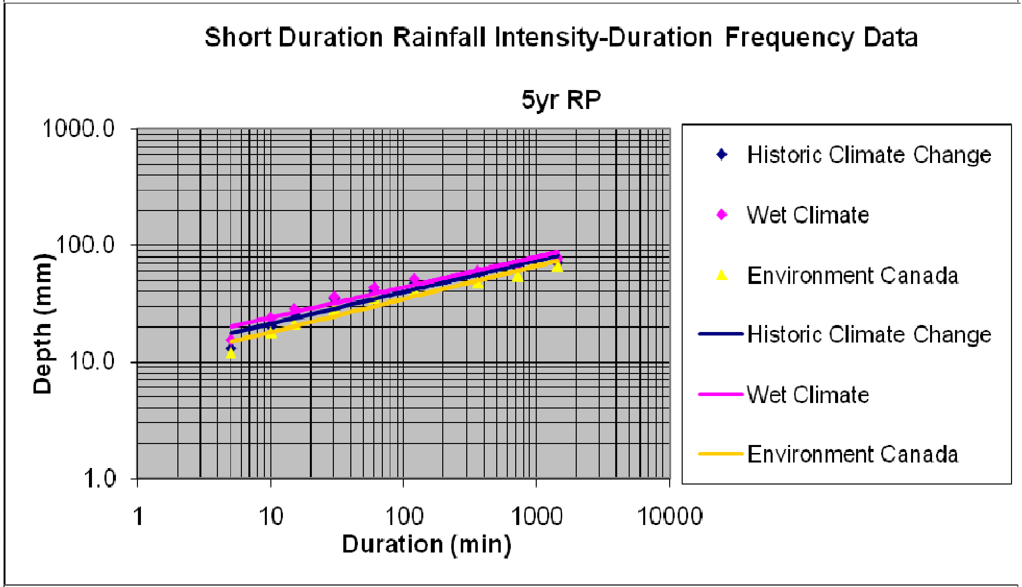


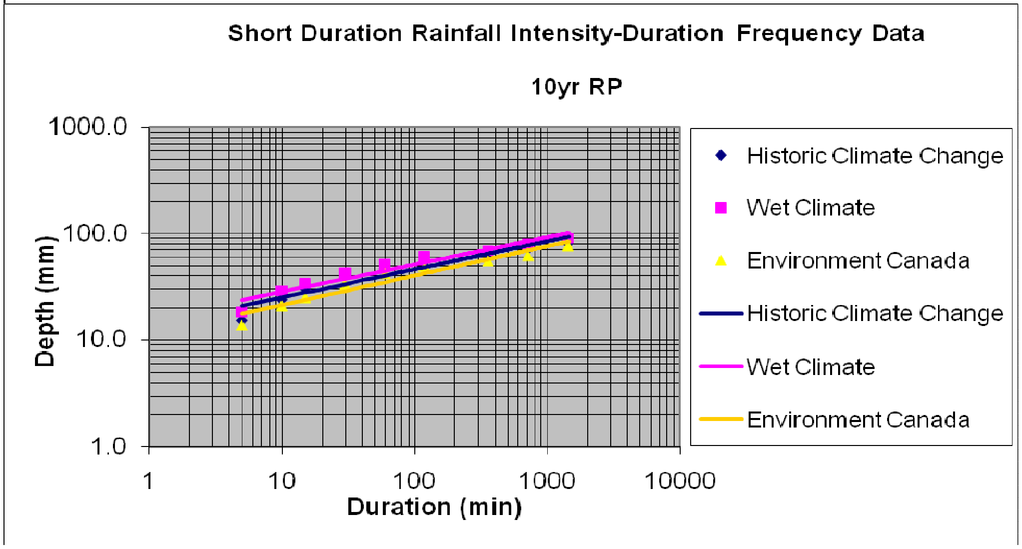
Short Duration Rainfall Intensity-Duration Frequency Data

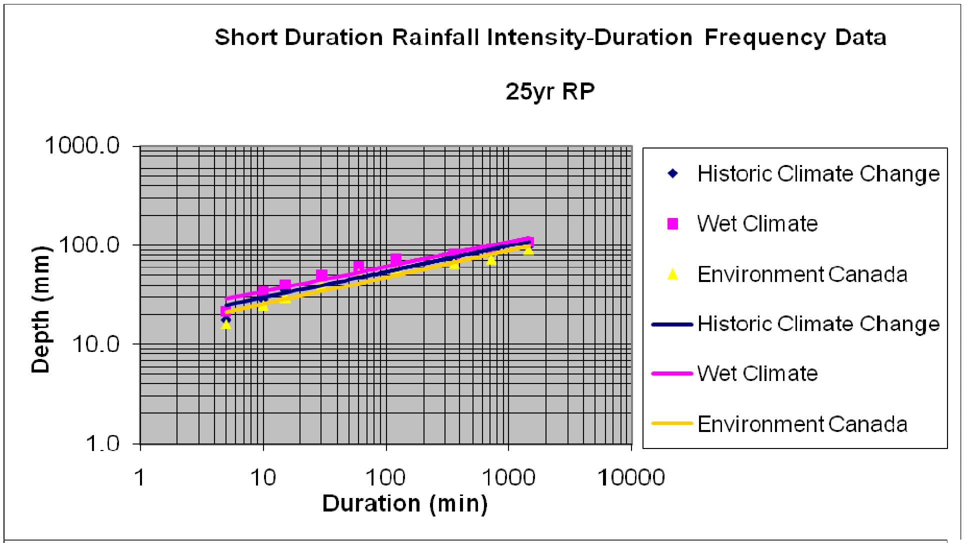
100yr RP

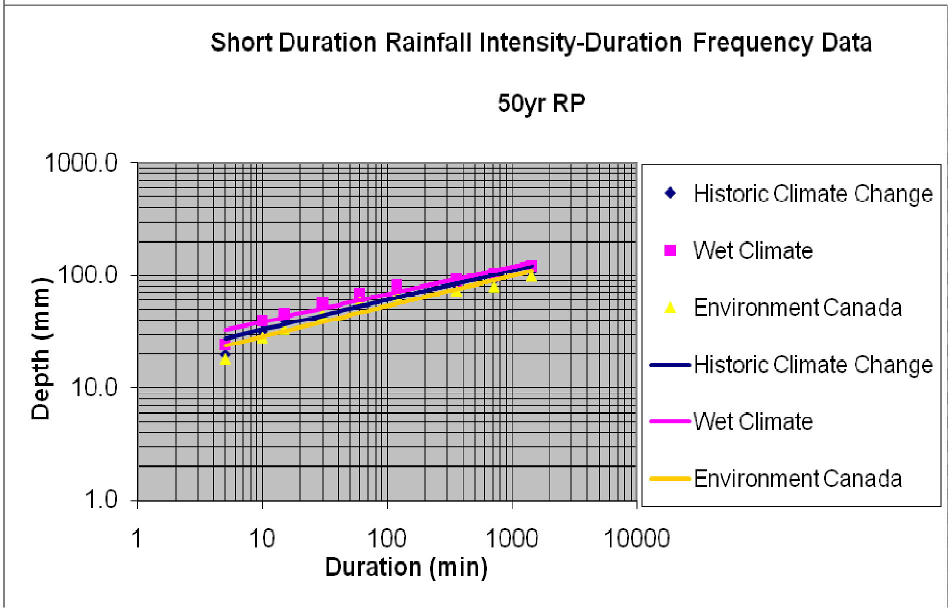


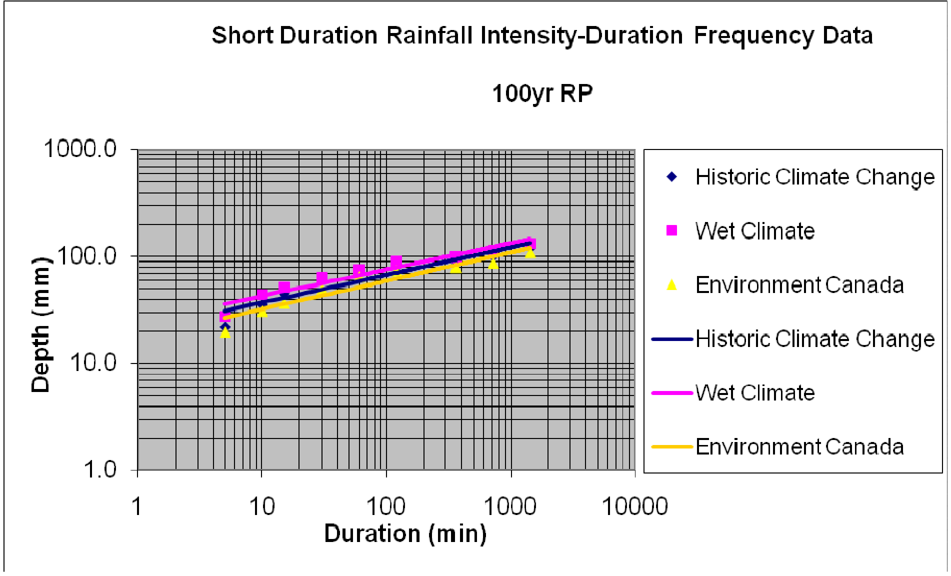

Short Duration Rainfall Intensity-Duration Frequency Data
2yr RP
Depth (mm)
1000.0
100.0
10.0
1.0
1
10
100
1000
10000
Duration (min)
Historic Climate Change
Wet Climate
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada


Short Duration Rainfall Intensity-Duration Frequency Data
5yr RP
Depth (mm)
1000.0
100.0
10.0
1.0
1
10
100
1000
10000
Duration (min)
Historic Climate Change
Wet Climate
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada


Short Duration Rainfall Intensity-Duration Frequency Data
10yr RP
Depth (mm)
1000.0
100.0
10.0
1.0
1
10
100
1000
10000
Duration (min)
Historic Climate Change
Wet Climate
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada

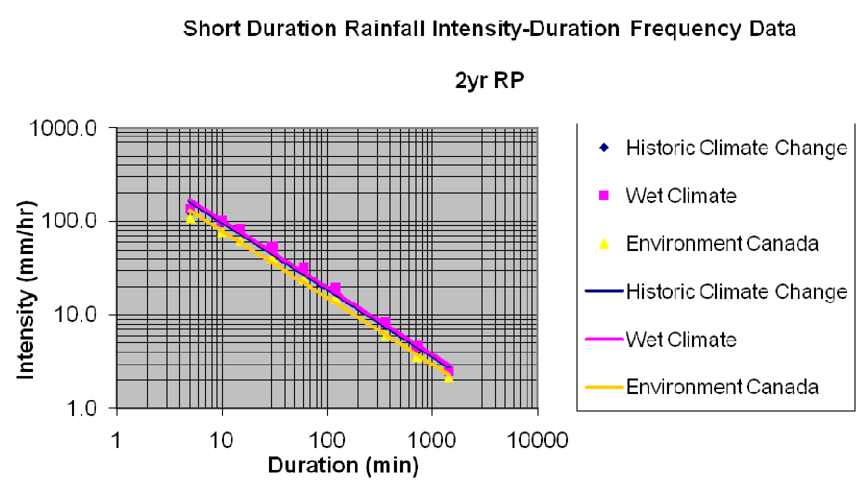

Short Duration Rainfall Intensity-Duration Frequency Data
25yr RP
Depth (mm)
1000.0
100.0
10.0
1.0
1
10
100
1000
10000
Duration (min)
◆ Historic Climate Change
■ Wet Climate
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada

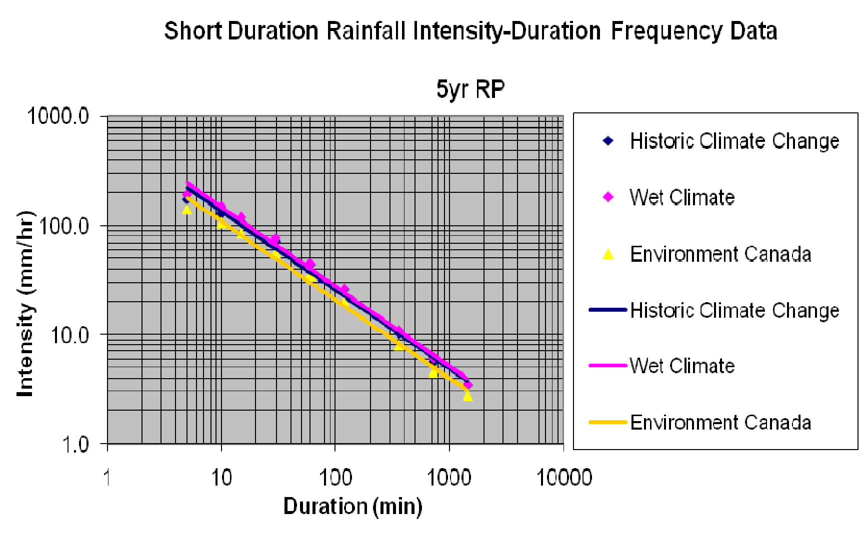

Short Duration Rainfall Intensity-Duration Frequency Data
50yr RP
Depth (mm)
1000.0
100.0
10.0
1.0
1
10
100
1000
10000
Duration (min)
◆ Historic Climate Change
■ Wet Climate
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada

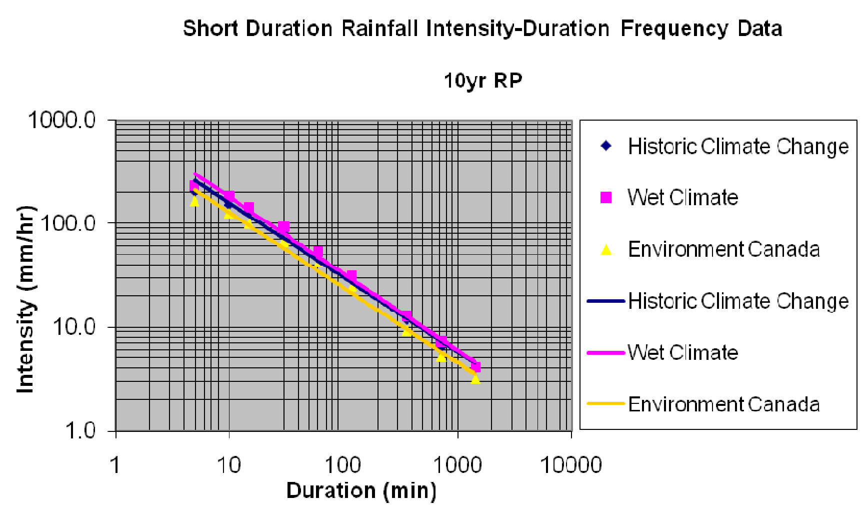

Short Duration Rainfall Intensity-Duration Frequency Data
100yr RP
Depth (mm)
1000.0
100.0
10.0
1.0
1
10
100
1000
10000
Duration (min)
◆ Historic Climate Change
■ Wet Climate
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada

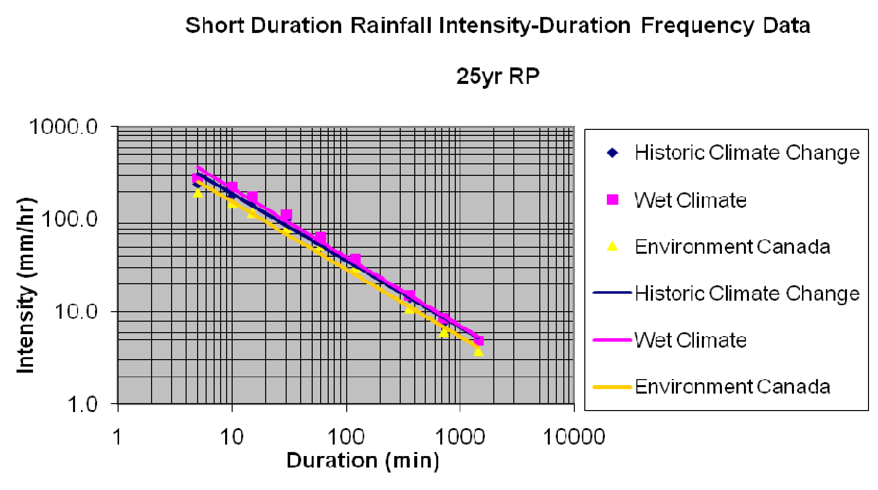
Appendix F

Comparison of IDF curves for the new data set





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Intensity (mm/hr)
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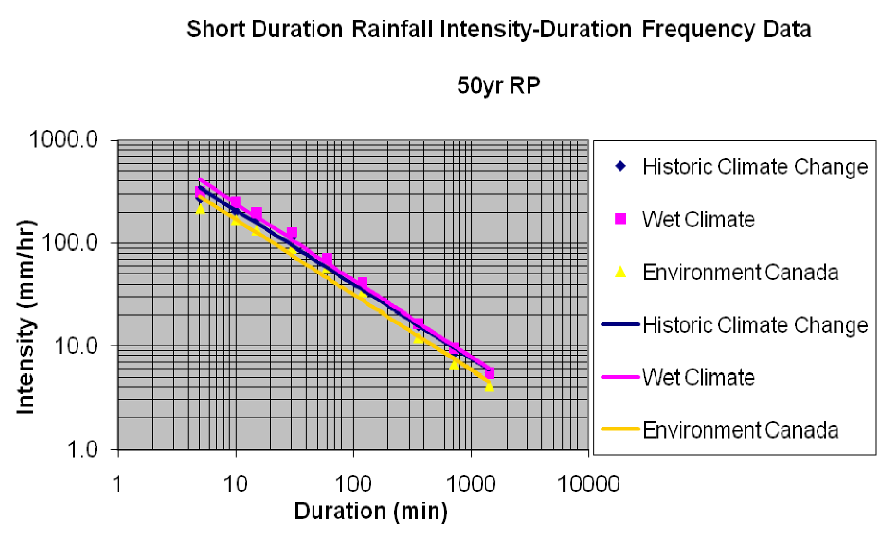
Duration (min)
Historic Climate Change
Wet Climate
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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Duration (min)
Historic Climate Change
Wet Climate
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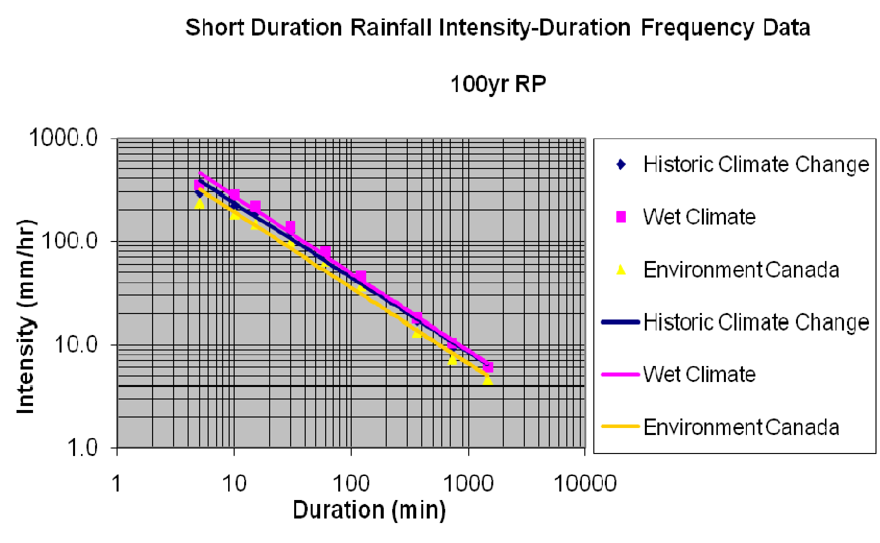
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Duration (min)
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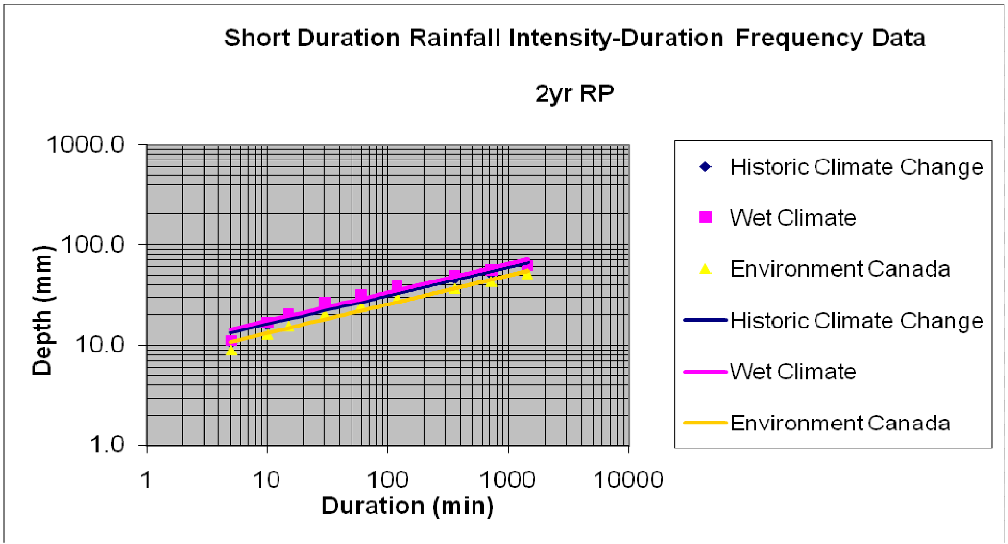
Wet Climate
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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Duration (min)
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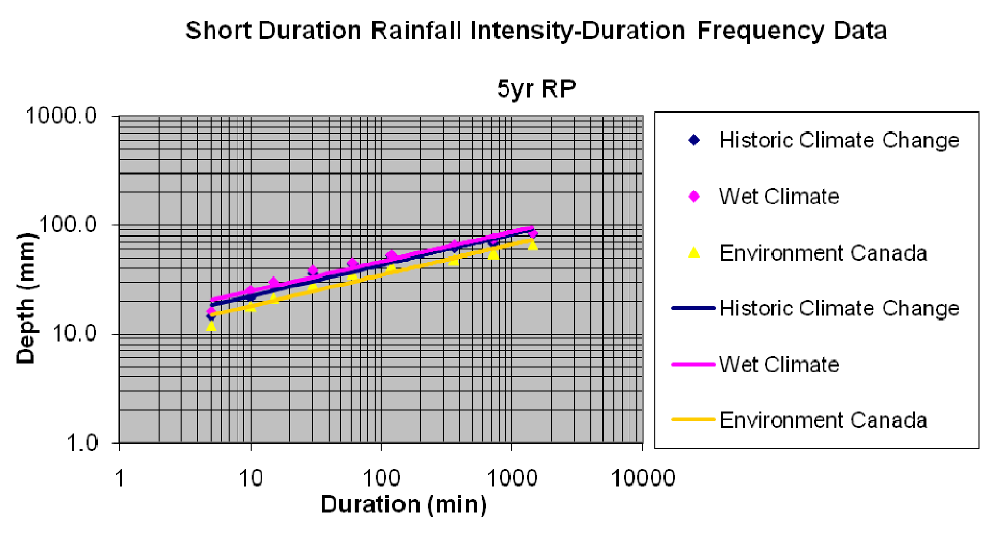
■ Wet Climate
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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Duration (min)
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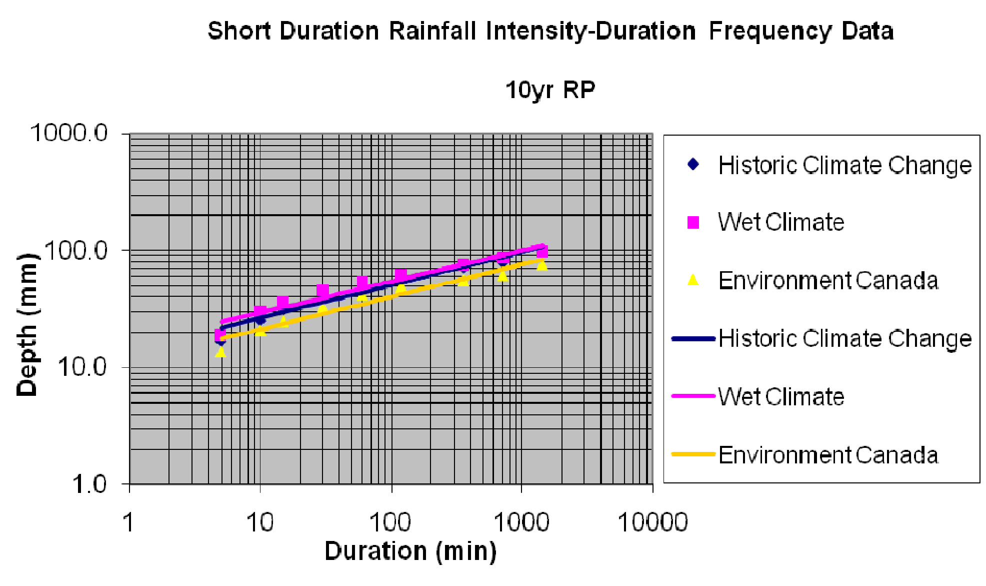
◆ Wet Climate
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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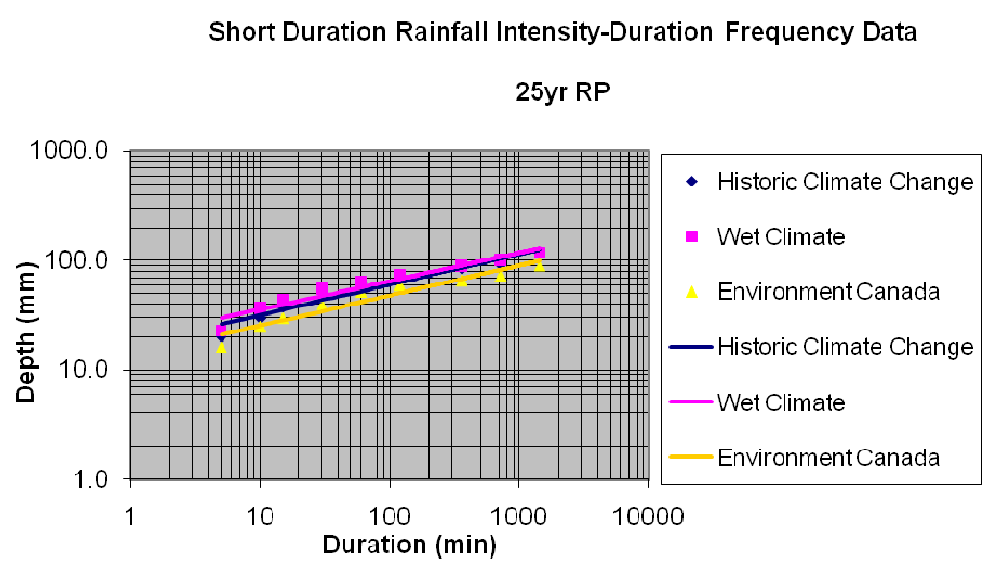
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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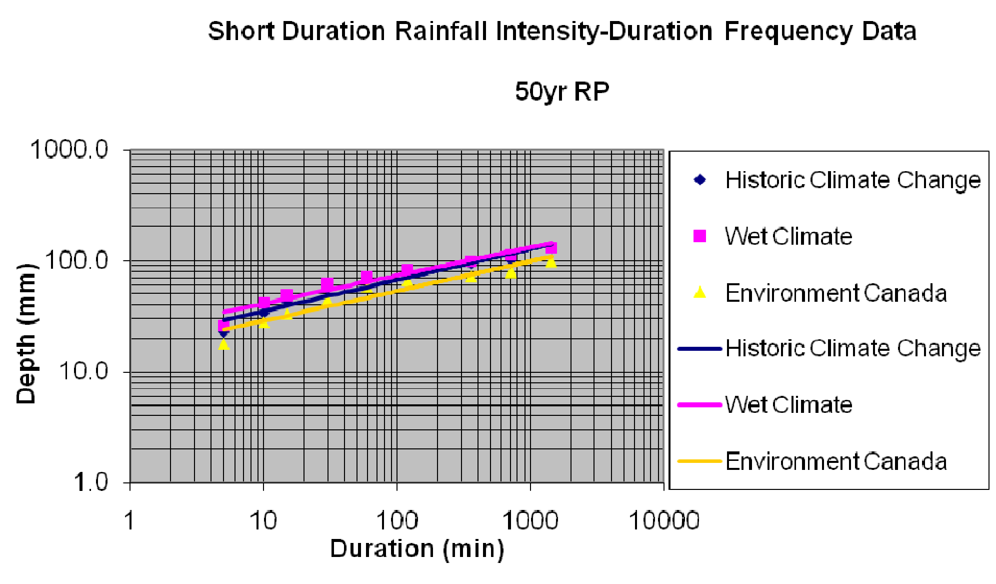
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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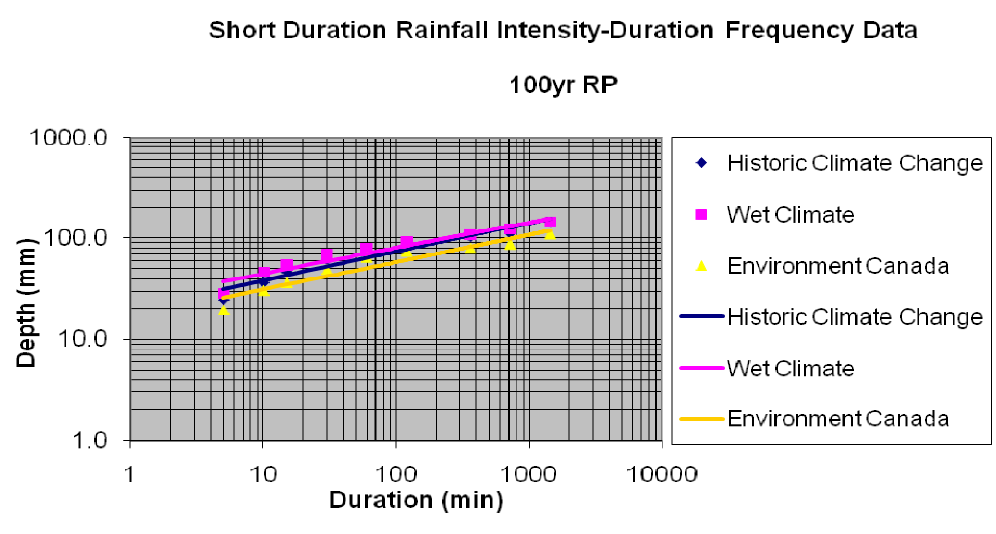
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Duration (min)
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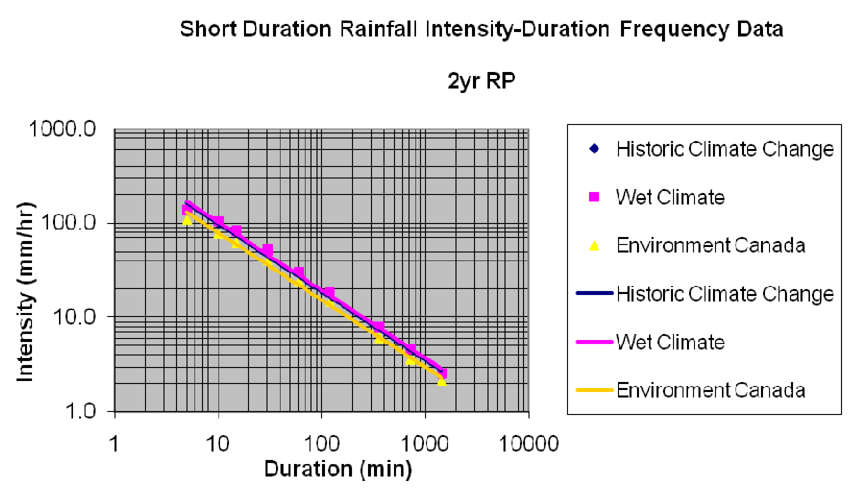
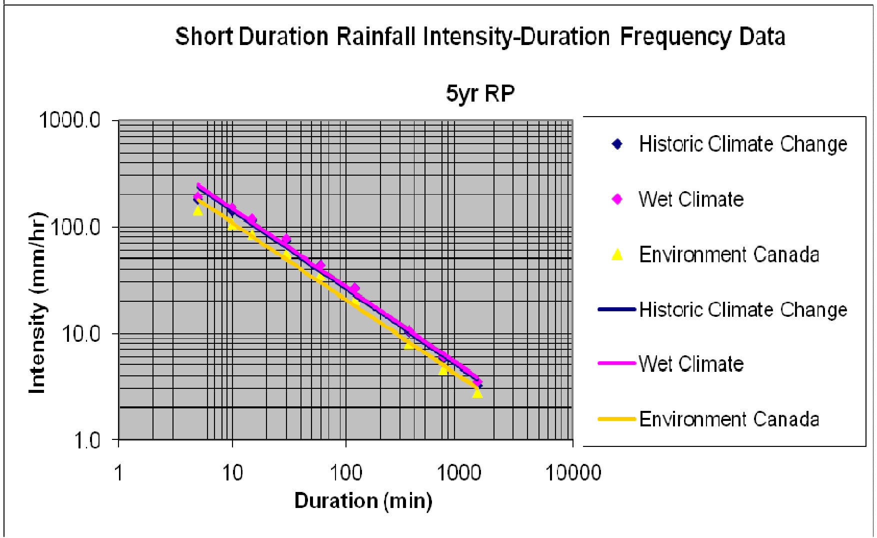
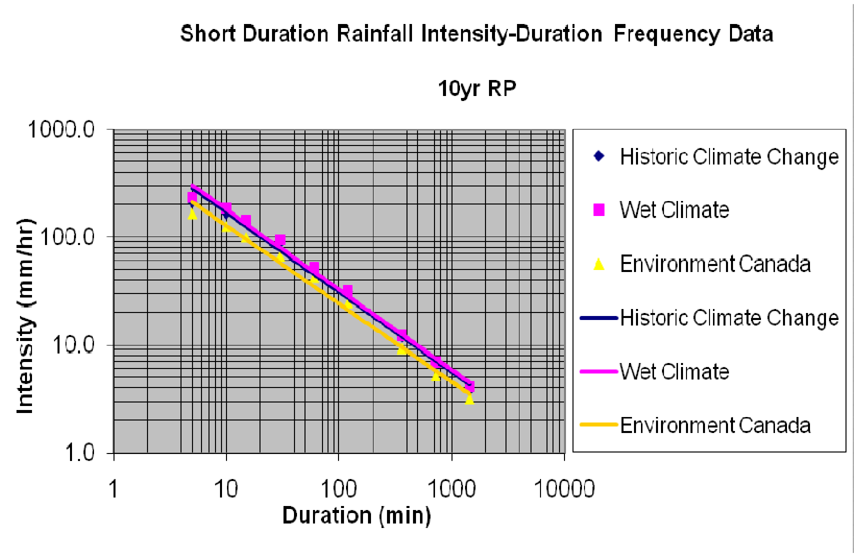
Wet Climate
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada

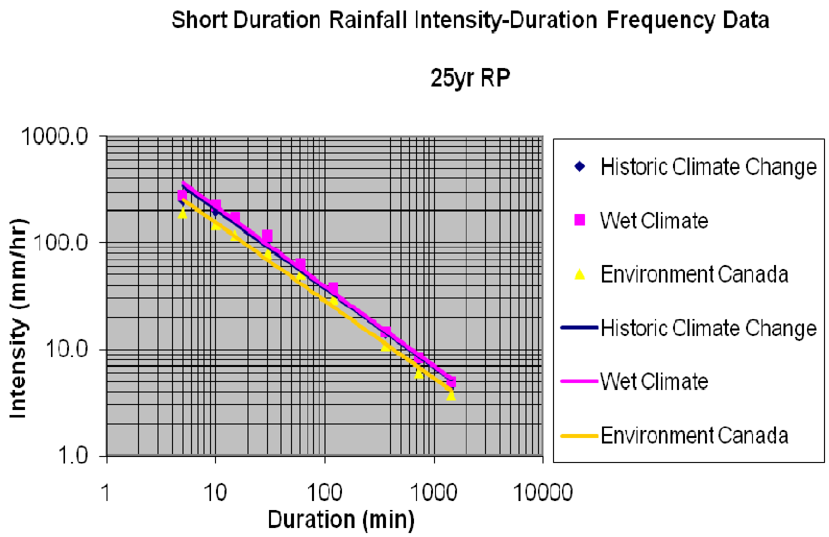
Appendix G

Comparison of IDF curves for the modified data set





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Intensity (mm/hr)
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100.0
10.0
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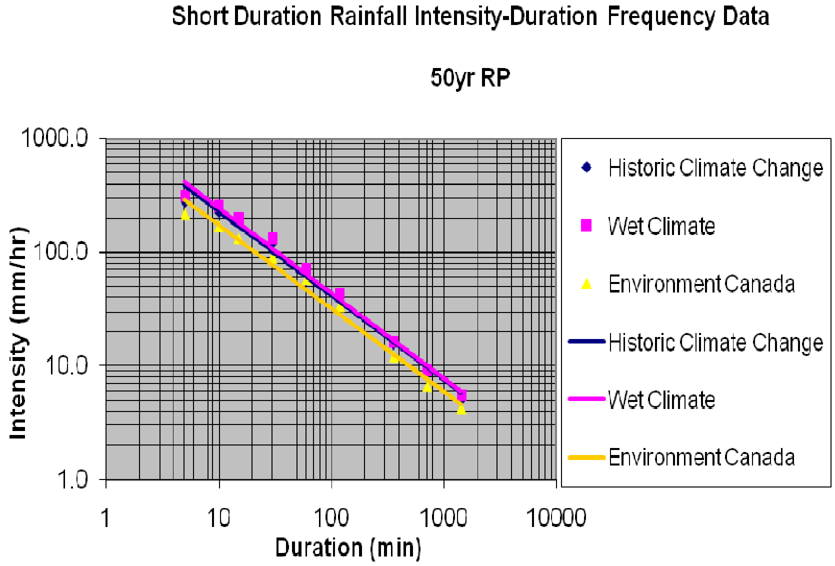
10000
Duration (min)
◆ Historic Climate Change
■ Wet Climate
▲ Environment Canada
— Historic Climate Change
— Wet Climate
— Environment Canada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10.0
1.0
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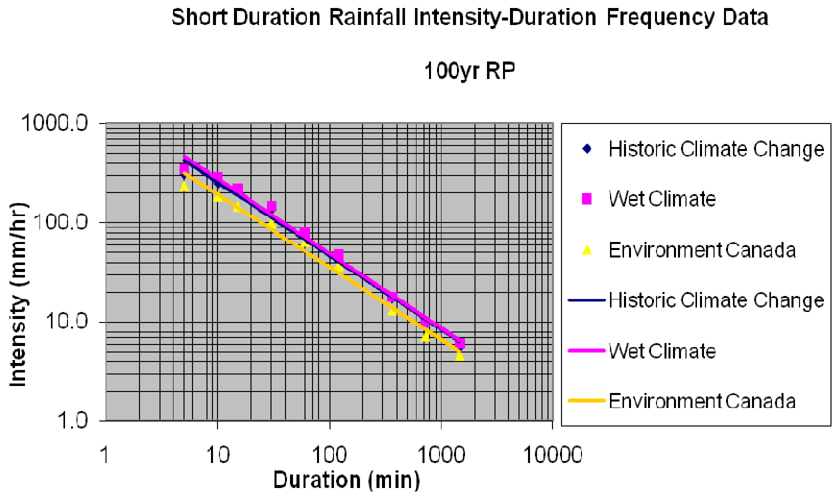
Duration (min)
◆ Historic Climate Change
■ Wet Climate
▲ Environment Canada
— Historic Climate Change
— Wet Climate
— Environment Canada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Duration (min)
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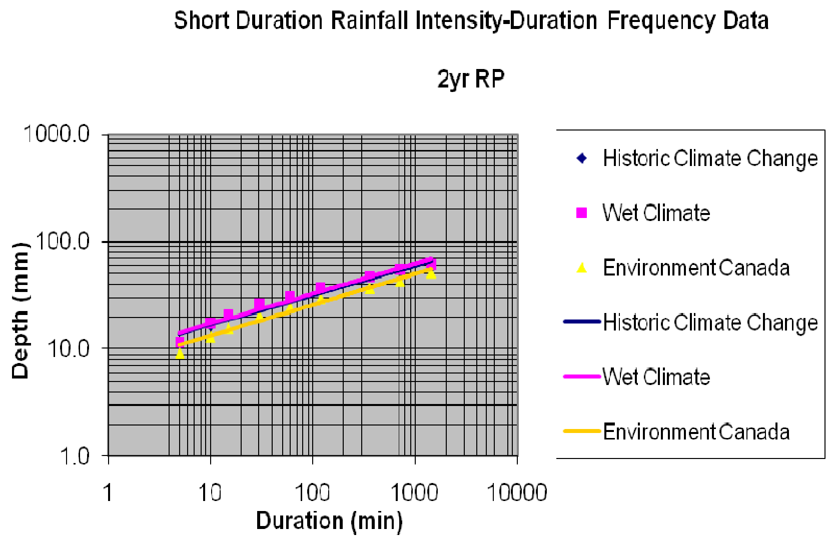
■ Wet Climate
▲ Environment Canada
— Historic Climate Change
— Wet Climate
— Environment Canada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Depth (mm)
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Duration (min)
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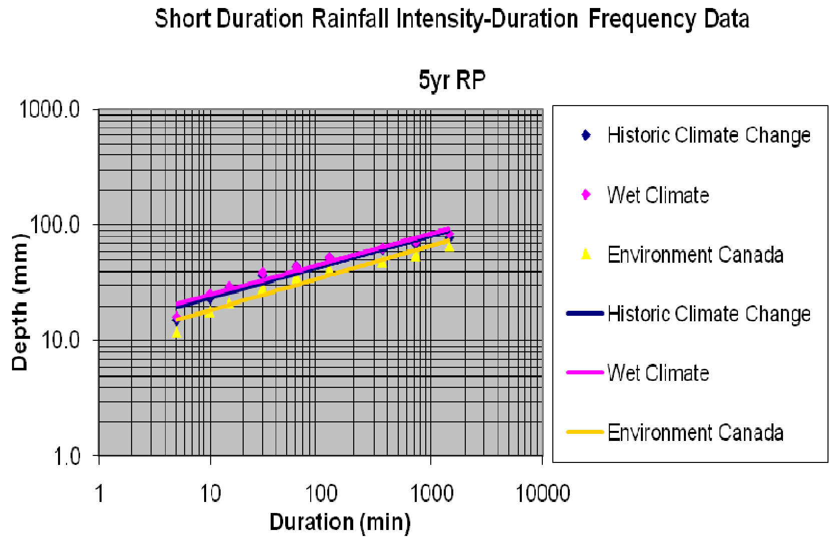
■ Wet Climate
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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Duration (min)
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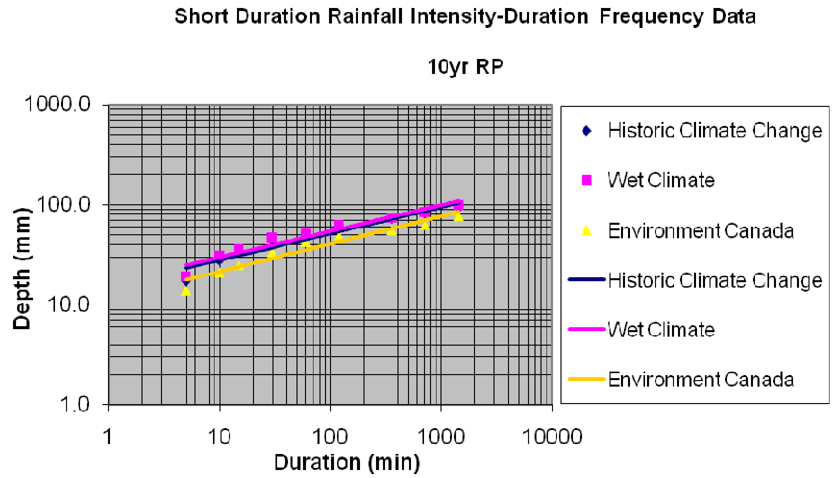
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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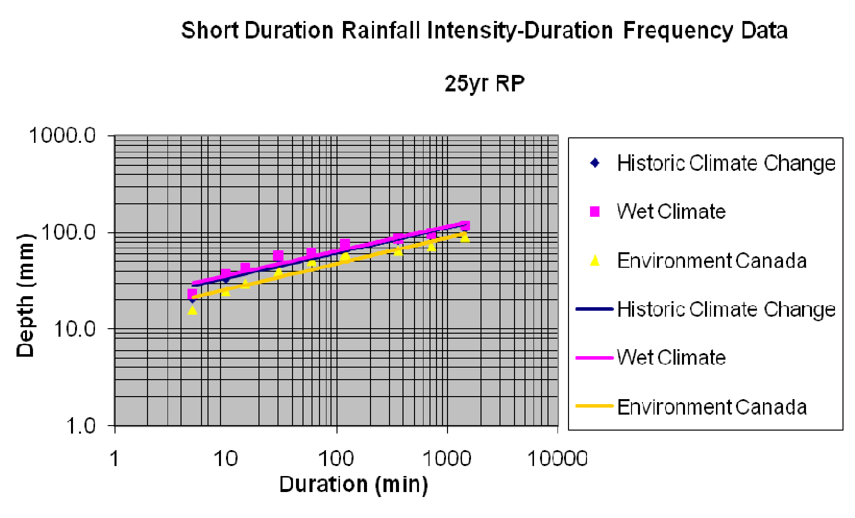
Duration (min)
◆ Historic Climate Change
■ Wet Climate
▲ Environment Canada
Historic Climate Change
Wet Climate
Environment Canada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Duration (min)
Historic Climate Change
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Historic Climate Change
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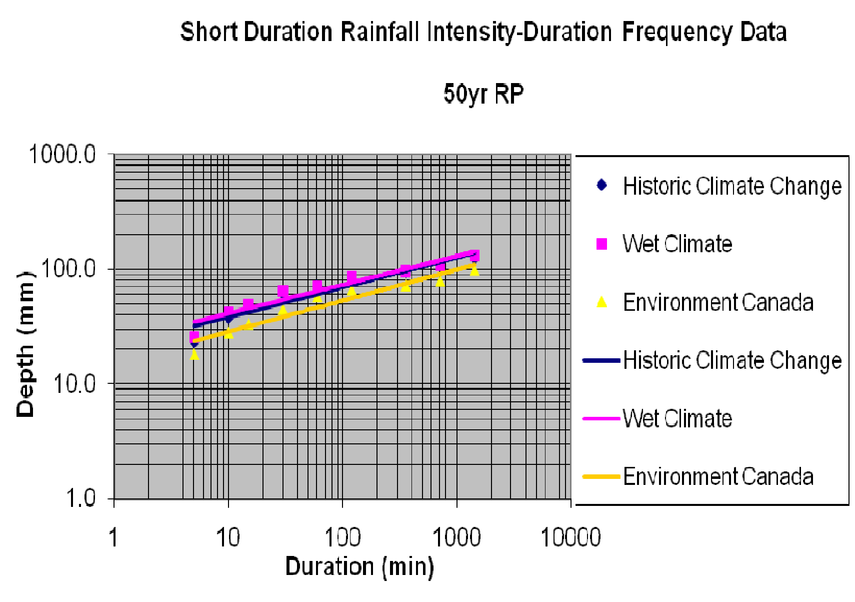
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Historic Climate Change
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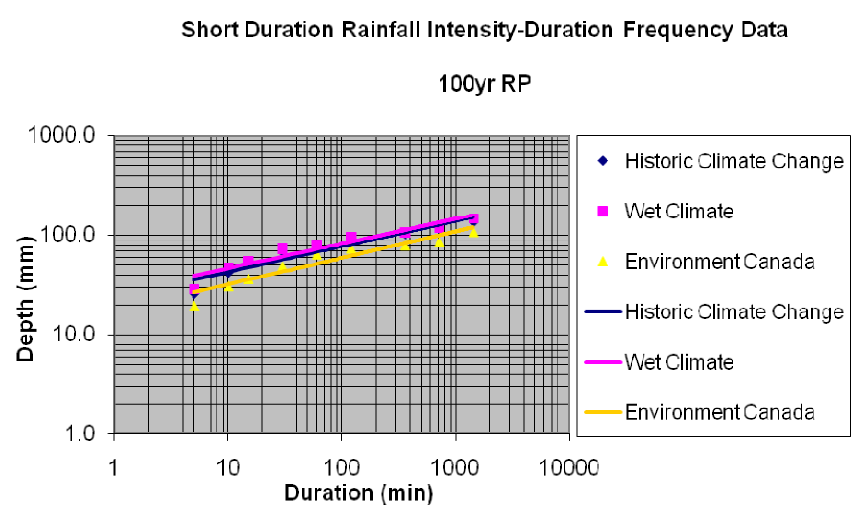
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Duration (min)
Historic Climate Change
Wet Climate
Environment Canada
Historic Climate Change
Wet Climate
Environment Canada

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