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Climate Change Impact on Design Storm and Performance of Urban Storm-Water Management System - A Case Study on West Central Mountain Drainage Area in Canada

Sadik Ahmed and Ioannis Tsanis*

Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada

Abstract

A number of future climate projections indicate a likelihood of increased magnitude and frequency of hydrological extremes for many regions around the world. The urban storm-water management infrastructures are designed to mitigate the effect of extreme hydrological events. Changes in extreme rainfall events will have a significant implication on the design of storm-water management infrastructures. This study assessed the potential impact of changed rainfall extreme on drainage systems in the West Central Mountain drainage area located in Southern Ontario, Canada. First, the design storms for the study area were calculated from observed rainfall data and the North American Regional Climate Change Assessment Program (NARCCAP) climate simulations based on SRES A2 Scenario. Frequency analysis was performed on the annual maximum time series data by using the best fitted distribution among twenty seven distributions. The Pearson chi-square test and Kolmogorov-Smirnov were used to test the goodness of fit of each distribution. The results show that L-moment Pareto distribution was selected the most often for data from six RCM+GCM pairs. Overall increase of storm depth in the future is highest when the distributions were identified by the Kolmogorov-Smirnov test. The design storm depths calculated from the observed and climate model simulated data were used as input into an existing PCSWMM model of the study area for flow simulation and hydraulic analysis for the storm-water management system, specifically storm sewer and detention pond. The results show an increase in design storm depths under projected climatic change scenarios that suggest an update of current standard for designing both the minor system and detention pond in the study area. The assessment results of storm water management infrastructures indicate that performance of the detention pond as well as the storm sewer network will deteriorate under future climate condition.

Keywords: Climate change; Storm-water management; Frequency analysis; Detention pond; Storm sewers; Canada

Introduction

The release of greenhouse gases and aerosols due to anthropogenic activities are changing the amount of radiation coming into and leaving the atmosphere. These are, in turn, changing the composition of atmosphere that may influence temperature, precipitation, storms and sea level. Observed increases in global average air and ocean temperatures, melting of polar ice and significant increases in net anthropogenic radiative forcing revealed that our global climate system is undergoing substantial warming [1]. An increased intense of 'dry and hot' extremes for many regions around the world was revealed by a number of studies on different climate model projections [2-6]. It is well known that increasing temperatures tend to increase evaporation which leads to more precipitation; so the changes in global temperature will have a significant effect on increasing magnitude and frequency of extreme precipitation events. These changes in temperature and precipitation will significantly affect frequency and severity of floods. Therefore, the design standards of storm-water management infrastructure, such as storm-water detention pond, and storm sewer have to adapt to the changing hydrologic process under future climate.

The storm-water infrastructures in an urban area are usually designed based on the rainfall depth calculated employing statistical analyses of observed precipitation data. The rainfall depths are calculated from the historic rainfall time series without considering climate change impact i.e., based on the assumption of a stationary climate. But, the climate is now non-stationary [7,8] because of the anthropogenic force. So, the designing of storm-water management infrastructure based on design storm considering the assumption of non-stationary climate will not be able to manage extreme events in future climate. The importance of developing design standard for addressing the climate change was indicated by many researchers [9-11]. Forsee and Ahmed [12] explored the projected changes in design-storm depths for Pittman watershed in Las Vegas using five NARCCAP data sets, and they showed a significant increase in case of three GCM+RCM pairs. Zhu et al. [13] investigated the potential changes in IDF curve due to climate change impact for six regions in the United States. They found strong regional patterns and increase in the intensity of extreme events under future climate for most of the study sites. Mailhot et al. [14] investigated the climate change impact in IDF curves for Southern Quebec using the Canadian Regional Model projections. The study results show that return period of 2 hour and 6 hour storm events will be approximately halved and return period of 12 hour and 24 hour storm events will decrease by one third. Coulibaly et al. [15] found significant increases in storm depth in 2050s and 2080s in Grand River, Kenora and Rainy River region in Canada by analyzing the storm depth calculated from climate simulations. In most of the studies, frequency analysis was performed on the annual maximum

***Corresponding author:** Ioannis Tsanis, Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada, Tel: 1-905-525-9140; E-mail: tsanis@mcmaster.ca

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precipitation time series by fitting only one to three distributions for design storm depth calculations. For example, the Log-Pearson Type III for NARCCAP future precipitation time series was used by Moglen and Vidal [11], generalized extreme value was used by some studies [12,14], Extreme value type I (EV I) was used by Zhu et al. [13], Gumbel and generalized extreme value were used by Zhu [16]. This study explored the climate change impact on design storm depth calculated by employing frequency analyses of NARCCAP precipitation data sets. In this study, twenty seven distributions were tested for the observed, NARCCAP current and future dataset, and the best among the fitted distribution was used for frequency analysis to calculate design storm depths. Two statistical tests were used to test the goodness of fit at a 95% confidence level. The source of uncertainty involved in climate change impact studies are resulted from climate model projections, the hydrologic model and data downscaling techniques. The main sources of uncertainty, climate model projections, are derived from three main sources: forcing, model response and internal variability [17]. The climate change impact assessment using climate model data should consider multiple scenarios due to uncertainty in climate model projections. NARCCAP data provide several RCM+GCM pairs, and in this study six pairs of climate projection datasets were used for design storm depth calculation. All the NARCCAP dataset are provided at grid scale. One of the main challenges in climate change impact assessment is bridging the gridded climate change projections with the historic observation at meteorological station. A number of dynamical and statistical downscaling methods are available to downscale climate model gridded data at the target point locations [18-22]. A simple method for transposing gridded climate projections to station scale is the use of delta change factor [13]. In some studies delta change factors have been applied to precipitation time series [22-25], and in other studies it has been applied to design storm depth [12,13]. The delta change method was applied to transpose design storm depth calculated from gridded NARCCAP data to Hamilton Airport meteorological station.

The design and operation of urban drainage system is associated with local rainfall characteristics, i.e., design storm depth [23]. The design criteria of the urban drainage management infrastructure must be revised with the consideration of possible impact of climate change [10]. Moglen and Vidal [11] examined the changes in detention basin performance under several climate change scenario at a study location north of Washington, DC, and indicated that in most cases, the performance of detention basin would be inadequate under future climate condition. Forsee and Ahmad [12] also revealed the inadequate performance of detention basin under future climate condition in a watershed in Las Vegas Valley, Nevada. There are other studies showing inadequate performance of storm sewer and combined sewer under future climate condition [23,25,26]. This study investigated the performance of storm water management system at a study location in the City of Hamilton, Canada using several different climate projections. The following section details the study location.

Study Area and Data

Study area

The study area (Figure 1), West Central Mountain drainage area, is a part of Red Hill Creek watershed located in the City of Hamilton, Southern Ontario, Canada. The modeling area is about 525 ha. The climate of Hamilton is humid-continental and characterized by changeable weather patterns. However, its climate is moderate compared with most of Canada. The daily average temperature in this area is 7.9 °C based on the data from 1981 to 2010 at Hamilton Airport,

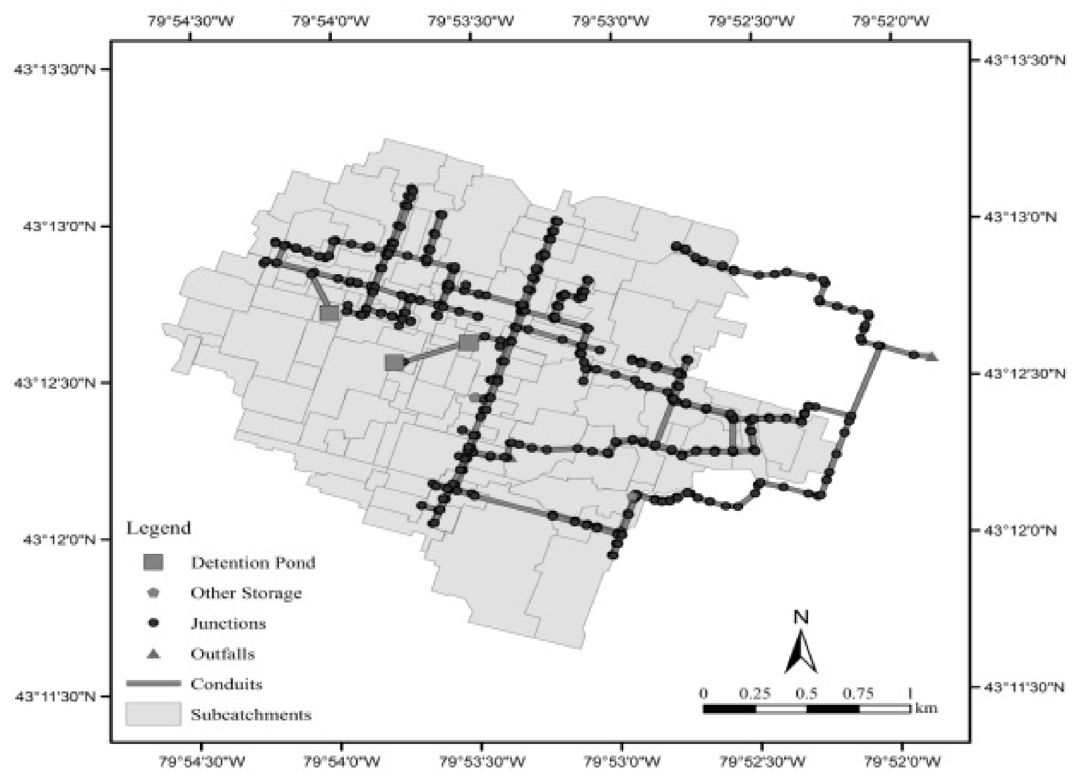

Figure 1: Map of the study area showing the stormwater management infrastructures.

and extreme maximum 37.4 °C and extreme minimum temperature -30 °C were observed on 7 July, 1988 and 16 January, 2004 respectively. The yearly average rainfall and precipitation (rain and snow) are 791.7 mm and 929.8 mm based on data from 1981 to 2010 at Hamilton Airport, and the maximum daily rainfall and precipitation 107 mm were observed on 26 July, 1989. Grillakis et al. [27] analysed observed meteorological data over a twenty year period (1989-2008) from Hamilton Airport to show the interannual trend of precipitation and temperature, and revealed an increase of precipitation 3.5 mm/year and average temperature 0.041°C/year.

Observed meteorological data

The observed hourly rainfall data for 30 years, from 1971 to 2000, were obtained from meteorological station, namely Hamilton Airport meteorological station with latitude and longitude 43 10 25.00 N and 79 56 06.00 W. The hourly rainfall time series of this station was used to calculate the design storm because City of Hamilton uses the design storm calculated from this meteorological station for the study area. This hourly observed precipitation time series was provided by Ontario Climate Center, Environment Canada.

NARCCAP climate data

The climate data sets used in this research were obtained from The North American Regional Climate Change Assessment Program [28-30]. NARCCAP is an international program to produce high resolution climate change simulations covering the conterminous United States and most of Canada. It provides the data sets in order to investigate uncertainties in regional scale projections of future climate and generate climate change scenarios for use in impacts research. The climate data sets are generated by running a set of regional climate models (RCMs) driven by a set of atmosphere-ocean general circulation models (AOGCMs). The AOGCM involves coupling comprehensive three-dimensional atmospheric general circulation models, with ocean general circulation models, with sea-ice models, and with models of land-surface processes. RCM enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales. This study uses the precipitation time series provided by six different RCM+GCM pairs. NARCCAP provides complete data for current and future for these six RCM+GCM pairs, and these six pairs include two pairs of each three RCMs. Table 1 provides the names of the RCMs and GCMs/drivers used in this study.

The spatial resolution of all NARCCAP data sets is 50 km and the temporal resolution of precipitation time series is 3 hour [30]. NARCCAP provides precipitation time series data of time span 33 years for both current (1968-2000) and future (2038-2070) period. First three years of each simulation are spin-up periods [31] and the data of the spin-up period has been discarded. Therefore, the precipitation time series data of time span 30 years for both current (1971-2000) and future (2041-2070) period are actually considered in this study. All the NARCCAP future simulations are driven by a GCM with greenhouse gas and aerosol concentration based on A2 emission scenario described in the Special Report on Emissions Scenarios (SRES) [32]. The A2 scenario was preferred from an impacts and adaptation point of view. Data are stored in the NetCDF files in 2D arrays. The array dimensions are named "xc" and "yc" within the file. The array dimensions (yc, xc) are found from the grid cell maps for each RCMs. The array dimensions (yc, xc) of nearest point of Hamilton Airport for CRCM, HRM3 and RCM3 are (51,100), (57, 105) and (44, 94) respectively.

Methodology

The method used in this study can be described as a two-step procedure. At first an extensive frequency analysis was performed on the observed, NARCCAP current and future period data sets for design storm calculation. Then, the storm information was transformed into runoff and hydraulic information by employing a fully featured urban drainage system modeling tool.

Design storm

Frequency analysis: A design storm can be represented by a value of rainfall depths or intensity (presented by IDF curves) or by a design hyetograph specifying the time distribution of rainfall during a storm. Design storm depths associated with different duration (3 h, 6 h, 12 h and 24 h) and return period (2 yr, 5 yr, 10 yr, 25 yr, 50 yr and 100 yr) were calculated for historic observations at station scale and climate model simulations at grid-scale. Data of the each time series were aggregated into 3-, 6-, 12- and 24 h duration on an annual basis, and the yearly maximum value for each duration was determined from the aggregated time series to generate time series of annual maximum rainfall depth. Frequency analysis was performed on these annual maximum time series data by using the best fitted distribution among twenty seven distribution as shown in Table 2 as well as Extreme Value type 1 (EV1) which is Gumbel distribution. Environment Canada provides the design storm information in the form of IDF curves and uses Gumbel Extreme Value distribution to fit the annual extremes of rainfall for the study area. Therefore, Extreme Value type 1 (EV1) was used for frequency analyses together with the best fitted distribution. Pearson chi-square test and Kolmogorov-Smirnov were used to test the goodness of fit of each distribution. The best fitted distribution is the distribution that attained the highest percentage of a. The percentage value of 'a' for Chi-square test (equation 1) and Kolmogorov-Smirnov (equation 2) are defined by the following two equations:

$$a_{attained} = 1 - x^2(m = k - r - 1, q) \quad (1)$$

$$a_{attained} = 1 - x^2(m, q) \quad (2)$$

where m are the degrees of freedom of chi square test, k is the number of bins used in chi square test, r is numbers of parameters of the distribution and q is the Pearson parameter. Kozanis et al. [33] described the theoretical background of all the tested distributions. The statistical analysis software, Hydrognomon [33], was used to find the best fitted distribution among 27 statistical distributions based on the criteria given in equation 1 and 2 for both observed and climate data.

RCM+GCM Pairs	RCM	GCM/Drivers
CRCM+CCSM	Canadian Regional Climate Model [34]	Community Climate System Model [38]
CRCM+CGCM3	Canadian Regional Climate Model [34]	Third Generation Coupled Global Climate Model [39]
HRM3+GFDL	Hadley Regional Model 3 [35]	Geophysical Fluid Dynamics Laboratory GCM [40]
HRM3+HADCM3	Hadley Regional Model 3 [35]	Hadley Centre Coupled Model, version 3 [41,42]
RCM3+CGCM3	Regional Climate Model version 3 [36,37]	Third Generation Coupled Global Climate Model [39]
RCM3+GFDL	Regional Climate Model version 3 [36,37]	Geophysical Fluid Dynamics Laboratory GCM [40]

Table 1: List of RCM+GCM Data Pairs used in this study.

	CrcmCcsm				CrcmCgcm3				Hrm3Gfdl				Hrm3Hadcm3				Rcm3Cgcm3				Rcm3Gfdl			
Distribution	3	6	12	24	3	6	12	24	3	6	12	24	3	6	12	24	3	6	12	24	3	6	12	24
Normal						√																		
LogNormal											+,√	+,√												
Galton																								
Exponential										*											√x			
Gamma				+								* x		*										
Pearson III											x		√							x		x		
LogPearson III								*																
Gumbel EV 1 Max		*	x		+	*							+			x	*	+				*		
EV2-Max	+	+							+	+											*			+
Gumbel EV 1 Min							+																	*
Weibull							*																	
GEV Max				√																				
GEV Min	x																							
Pareto								√					* x		+									
L-Moments Normal	√					x		x																
L-Moments Exponential			+											+	*	+			+		+		*	
L-Moments EV1 Max	*	√ x				+																		
L-Moments EV2 Max			*						√*x								+					+		
L-Moments EV1 Min																								
L-Moments EV3 Min																								x
L-Moments GEV Max					√					x										*				√
L-Moments GEV Min			√											√	√	√	x	x				√	x	
L-Moments Pareto				x	*, x		√, x							x	x		√	√	√x	+,√			√	
GEV-Max (k spec.)										√														
GEV-Min (k spec.)								+											*				+	
L-Moments GEV-Max (k spec.)				*							*					*		*						
L-Moments GEV-Min (k spec.)																								

Table 2: Best fitted distribution for NARCCAP data for different duration [Case 1 (current x, future √), case 2 (current *, future +)].

Three sets of storm depths were calculated: (1) Case 1: storm depth with best fitted distribution tested by Chi-square test (2) Case 2: storm depth with best fitted distribution tested by Kolmogorov-Smirnov, and (3) storm depth with Extreme Value type 1 (EV1) distribution.

Delta change factor: The climate models (RCMs) provide gridded data; those are areal average and not point estimates [43]. The systematic difference between climate model simulated and observed precipitation is a problem for using RCMs for hydrological purposes [44]. The storm depth values calculated from the NARCCAP datasets are for grid scale. Delta change factor can be applied to discrete totals i.e., design storm depths [12] to transpose projected future change in climate onto point observation. The assumption in this conversion is that areal-to-point relationships of precipitation remain constant in future climates [14]. The delta change factor application procedure (presented by equations 3, 4 and 5) described by Zhu et al. [13] to adjust the historic station scale intensities/depths to produce future station-scale values for the same duration and return period will be used in this study:

$$I_F^{(g)} = I_H^{(s)}\left[1+\Delta_{F-H}^{(g)}(T,d)\right] \quad (3)$$

$$\Delta_{F-H}^{(g)}(T,d) = \frac{I_F^{(g)}(T,d) - I_H^{(g)}(T,d)}{I_H^{(g)}(T,d)} \quad (4)$$

$$I_F^{(s)}(T,d) = I_H^{(s)}(T,d)\frac{I_F^{(g)}(T,d)}{I_H^{(g)}(T,d)} \quad (5)$$

Where, T and d denote return period and duration respectively, H and F denote historic and future, and s and g denote station and grid respectively.

The point estimates of storm depth for all six RCM+GCM pairs for all three cases are presented in Table 3.

Hydrologic and hydraulic modeling

A large number of hydrological models are used in different countries for different purposes. 'Although hydrological models have been around for quite some time, there is yet to be one exclusive model that can stand apart from the rest and be declared best at modeling in all aspects of the hydrologic system [45]. Considering the urban hydrological and hydraulic modeling capabilities, this study aimed to use PCSWMM 2D Professional, a leading decision support system for US EPA SWMM. PCSWMM also contains a flexible set of hydraulic modeling capabilities used to route runoff and/or external inflows through the drainage system network of natural channels, pipes, storage/treatment units, diversion structures [46]. This study used an existing model, developed using PCSWMM, of the study area. The existing model of the study area was provided by the City of Hamilton. The models that contain proposed detention pond/ storm water management facilities considering the future development are used for minor system/ storm sewer and detention basin performance assessment. The model contains 126 sub-catchments with 172.2 ha impervious area out of 525.06 ha total area. The models used curve number infiltration method and dynamic wave routing method. Three detention pond (pond 1, pond 2 and pond 3) elements were selected for analyses of detention pond performance. The contributing area of pond 1, pond 2 and pond 3 are 44.77 ha (11 sub-catchments, 13.06 ha impervious area), 15.36 ha (8 sub-catchments, 7.7 ha impervious area), 37.63 ha (8 sub-catchments, 13.77 ha impervious area) respectively.

Return Period	Duration (h)	Observed			CrcmCcsm			CrcmCgcm3			Hrm3Gfdl			Hrm3Hadcm3			Rcm3Cgcm3			Rcm3Gfdl		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
2 yr	3	31.1	31	32.5	33.1	34	34.6	35	34.7	37.2	31.9	31.2	33.3	36.8	34.7	38.7	30.8	31.7	35	37.4	38.6	41.2
	6	38.3	37.1	39.5	40	39.3	41.9	43.3	42.4	44.9	41.3	39.7	41.5	37.8	40.2	42.7	42.9	39.1	42.6	42.9	43.1	47.3
	12	43.5	43.8	45.1	44.8	45.8	47.3	52	52.4	52.6	51.1	51	51.2	47.7	47.2	48.4	42.1	46.6	50.7	60.8	52.2	55.7
	24	53.3	50.6	52.4	61.9	58.4	57.9	65.8	57.3	60.9	62.9	59.7	62.4	55	53.2	55.7	62.1	58.4	63.1	62	60	66.5
5 yr	3	42	42.1	46.7	42.9	43.8	48.9	47.2	47.1	55	41.8	42.4	44.7	50	49.2	59.7	44.1	46.5	54.4	60.6	58.3	65.3
	6	52.6	53.7	55.3	53.9	55.9	58.3	60.7	61.8	63.3	52.9	57.4	56.5	55.3	56.7	60.7	58.4	57.6	59.4	65	70.8	72.5
	12	56.9	59.2	61.9	60.1	62.4	64	65.1	69.2	71.4	66.6	68	70.2	64.8	64.5	68.8	61.2	63.4	70	79	80.2	82.7
	24	72	68.7	70.6	80.9	73.7	76.1	85.3	82.5	81.8	86.3	82.3	85.2	78.5	75.4	76.2	83.5	79.8	80.8	93.5	91.8	98.4
10 yr	3	51.1	51.5	56.2	51.7	51.8	58.3	60.1	60.6	67.8	49.9	52	52.4	64.1	65.1	73.9	58	60.4	67.3	79.9	74.9	81.6
	6	63.5	65.9	65.8	65.2	67.9	69	74.1	76	75.8	61.9	69	66.4	71.2	70.1	72.6	68.4	71.6	70.6	85.5	92.2	89.9
	12	68	71	73	72.2	74.4	75	75.9	80.5	83.8	77.7	80.2	82.7	76.7	78.7	82.5	81	80.4	82.7	89.6	101.3	101.3
	24	83.3	82.4	82.7	89.1	85	88	94.2	99.1	95.9	101.1	100	100.4	93.2	91.6	89.9	95.5	95.5	92.5	120	121.1	120.6
25 yr	3	65.6	66.5	68.1	66.3	64.6	69.6	83.6	86.3	83.4	62.3	67.1	61.9	90.6	94.6	91.7	85.3	83.8	83.8	107.8	100.8	102.7
	6	79.2	82	79.1	82.6	83.9	82.5	93.3	94.8	91.5	76	82.1	78.9	95.5	88.2	89.6	81.3	89.9	84.9	121.1	121.1	112.2
	12	85.2	88	87.1	89.4	90.8	88.9	92.8	96.4	99.2	92.5	97.3	98.6	92.8	100.6	99.8	115.4	108.6	98.8	103.5	130	125.3
	24	96.5	102.2	97.9	95.3	103	103	102.8	120.3	113.2	119.1	126.1	119.5	109	113.8	107	107.2	115.9	107.2	161.1	170.7	149.5
50 yr	3	79	80.3	76.9	81	76.5	78.1	107.6	113.1	95.4	73.7	81	68.9	118.4	125.5	104.8	115.3	106.5	95.9	131	124.4	118.1
	6	92.3	94.1	89	98.3	95.5	92.6	109	108.9	103.1	89.3	90.1	88.1	116.7	104.8	100.9	90.6	103.2	95.4	156.6	143.2	129.1
	12	100.7	102.2	97.6	103.4	104.1	99.4	108.2	109.6	110.9	104.5	111.3	110.6	106	120.5	112.8	148.6	134.5	110.9	115.1	152.6	143.4
	24	105.7	118.8	109.2	97.8	119	114.2	108.1	136.3	126.4	132	148.4	133.7	118.7	131.7	119.8	113.9	131.7	118.1	198.1	217.9	171.2
100 yr	3	94.9	99	85.6	99	92.1	86.8	137.5	150.8	107	86.8	100	75.8	154.2	169.3	117.9	157.1	137.4	107.9	156	156.3	133.8
	6	106.7	106.2	98.7	116.8	107.4	102.4	127	123	114.6	105.2	96.5	97.2	140.8	124.7	110.3	99.9	116.3	105.8	202.4	165.3	145.7
	12	118.9	117.9	107.9	118.1	117.9	109.5	126.2	124.5	122.3	117.3	126.7	122.2	120.4	143.7	125.6	190.1	164.9	122.7	128.2	176.1	161.5
	24	114.5	137.1	120.4	98.8	137.6	125.3	112.6	152.7	139.1	144.8	173.4	147.9	126.4	150.8	132.4	119.2	147.7	128.8	241.7	276.1	193.2

Table 3: Design storm depths (in mm) calculated from observed data and NARCCAP future datasets.

Design Storm	Observed	CrcmCcsm	CrcmCgcm3	Hrm3Gfdl	Hrm3Hadcm3	Rcm3Cgcm3	Rcm3Gfdl	Average
24 hr 25 yr for detention pond	102.2	103	120.3	126.1	113.8	115.9	170.7	125
24 hr 5 yr for storm sewer	68.7	73.7	82.5	82.3	75.4	79.8	91.8	80.9

Table 4: Design storm depths (in mm) used for detention pond and storm sewer performance analysis.

The City of Hamilton used 6hour Chicago and 24 hour SCS storm distribution for this study area and found 24 hour SCS distribution to be the governing condition [47]. This study used 24 hour SCS storm distribution for both storm sewer and detention pond performance analysis. The 24 hr -25 yr and 24 hr -5 yr design storm depths (only for case 2, shown in Table 4) were used for detention ponds and storm sewer performance analysis respectively. The last column of the Table 4 provides the average of design storm calculated from six RCM+GCM pairs. A number of hydrologic and hydraulic parameters used by Moglen and Vidal [11] and Berggren et al. [23] as well as other parameter as described in result and discussion section were used for detention ponds and storm sewer performance analysis.

Results and Discussion

Design storm

Design storm depths were calculated for four different duration (3 hr, 6 hr, 12 hr and 24 hr) and six different return periods (2 yr, 5 yr, 10 yr, 25 yr, 50 yr and 100 yr) for observed time series and NARCCAP current and future simulations of six different RCM+GCM pairs. Therefore, a total of 52 (4 observed, 24 NARCCAP current and 24 NARCCAP future) annual maximum time series were used for frequency analysis. The best fitted distribution among twenty seven distributions for NARCCAP current and future datasets are listed in the Table 2. For example, the best fitted distribution for NARCCAP current data in Case 1 was identified by 'x' mark in Table 2 and is GEV Min for CrcmCcsm 3h storm. As two tests were used to test the goodness of fit of each distribution, Table 2 provides 96 selections for 48 NARCCAP datasets. Table 2 shows that L-moment Pareto distribution was selected 14 times (the highest), that is 14.6% of the total selections. Gumbel EV1 Max was selected for 9 times that is 9.4% of the total selection. Therefore, only Gumbel EV1 Max used by different stakeholders for design storm calculation for this study area is not appropriate for climate change impact study. Four distributions namely Galton, L-Momnet EV1 Min, L-Moments EV3 min and L-Moments GEV-Min (k spec.) were not selected as best fitted distribution for any climate data sets. L-moment Pareto distribution was selected 7 times (the highest), for both current and future climate datasets. L-moment Pareto was also selected 12 times (the highest), when Chi-square test was used to test the goodness of fit. Both L-Moment Exponential and Gumbel EV1 Max were selected 7 times (the highest), when Kolmogorov-Smirnov was used to test the goodness of fit. This study identified the best fitted distribution for observed and NARCCAP datasets, and used them for design storm calculation to minimize the uncertainty related to appropriate distribution selections. The design storm depths calculated from observed data and NARCCAP future datasets are presented in Table 3. It is mentionable that the delta change factor was applied on the datasets to get the design storm values for NARCCAP datasets presented in the Table 3. Table 3 shows that there is a significant increase in design storm depths for all six RCM+GCM pairs. Results in the Table 3 also show the overall variability of the design storm depths calculated from the climate data. For example, 3 hr-2 yr storm depths calculated from six RCM+GCM pairs in case 2 are 34, 34.7, 31.2, 34.7, 31.7 and 38.6 mm with mean 34.2 mm and coefficient of variation 7.1%; 3 hr-100 yr storm depths are 92.1, 150.8, 100. 169.3, 137.4 and 156.3 mm with mean 134.3 mm and coefficient of variation 21.4%. The calculated coefficient of variations also show that the variability increases with the increase of return period. The increase in design storm depths under future climate conditions are also shown in the Figure 2. Figure 2 shows the scatterplot of all design storm depths (in Table 3) calculated from observed data and NARCCAP future datasets. The scatterplots in Figure 2 shows that the data are more dispersed from the 45-degree line for higher values. It revealed that the increase of design storm depth under future climate is higher for higher values. It is notable that the higher values may represent storm depths for higher return period or higher duration. The linear trendlines in Figure 2 also shows overall increase of storm depth is higher for case 2 (when distribution were identified by Kolmogorov-Smirnov test) than other two cases, lowest for case 3 (when frequency analysis was performed using Gumbel EV1 Max). Figures 3, 4 and 5 show the difference between design storm depths calculated from observed data and NARCCAP future datasets for different return period and different duration. Here, the positive values refer to an increase of storm depths in future. Visual inspection of these figures revealed that the difference (increase) of design storm depths increase with the increase of return period overall. For example, design storm depths increased by 15.6%, 20%, 22.8% for 24 hr storm of return period 2 yr, 25 yr and 100 yr respectively for case 1, these increase are 14%, 22.3% and 26.2% for case 2, and 16.6%, 19.1% and 20% for case 3. The increasing trend in case 3 is not as significant as other cases; the reason might be that the Gumbel EV1 Max is not the best fitted distribution for most of the datasets for case 3. Considering only the 3 hr and 24 hr duration storm, Figures 3 and 4 shows that the increase is higher for shorter duration with higher return period and also higher for longer duration with lower return period. For example, the increase of storm depths is 38.8% and 22% for 3 hr and 24 hr storm of 100 year return period respectively, 9.9% and 15% for 3 hr and 24 hr storm of 2 year return period respectively for case 1; 35.7% and 26.2% for 3 hr and 24 hr storm of 100 year return period respectively, 10.2% and 14% for 3 hr and 24 hr storm of 2 year return period respectively for case 2. Figures 3 and 4 also show that overall increase of storm depths under future condition is higher in case 2 than that in case 1. Considering this issue and sustainable storm water infrastructure design, the design storm depths calculated in case 2 will be used for investigation of detention pond and storm sewer performance study.

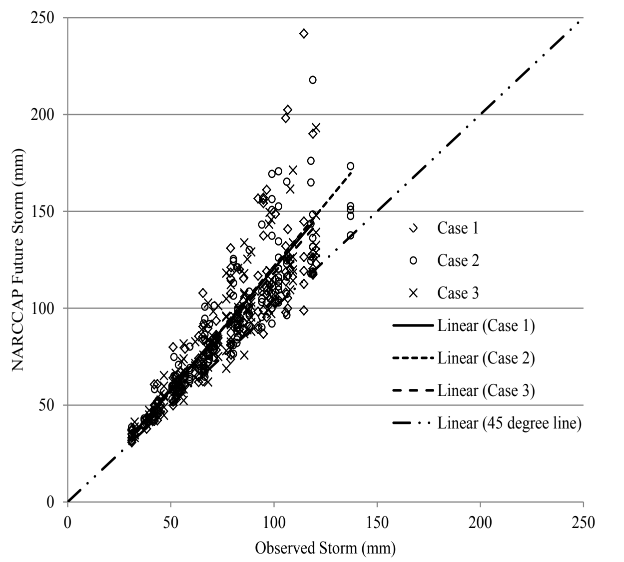

Figure 2: Scatterplot of design storm depths calculated from observed data and NARCCAP future datasets.

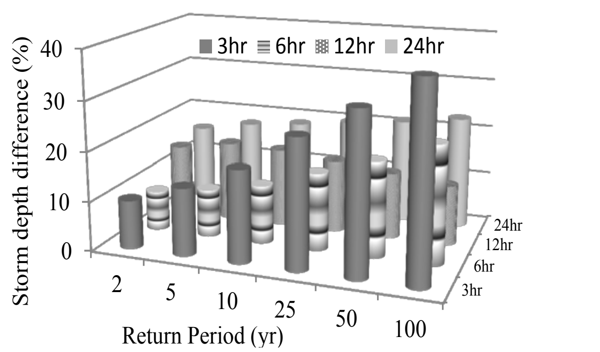

Figure 3: Difference between design storm depths calculated from observed and NARCCAP future datasets for case 1.

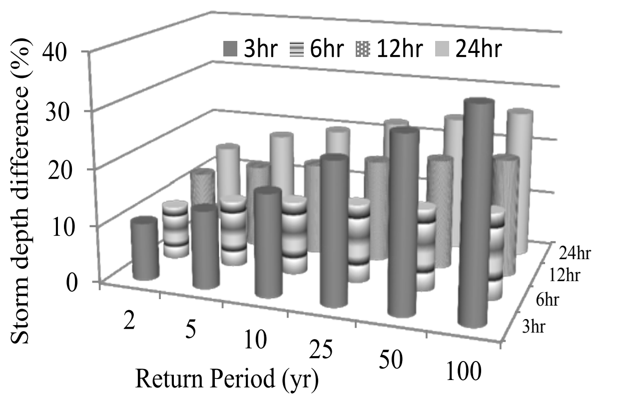

Figure 4: Difference between design storm depths calculated from observed and NARCCAP future datasets for case 2.

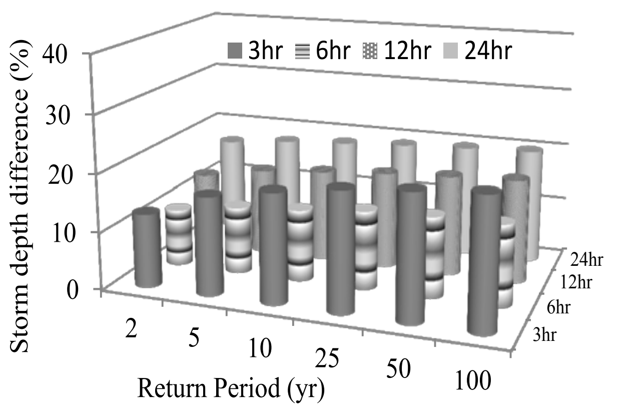

Figure 5: Difference between design storm depths calculated from observed and NARCCAP future datasets for case 3.

Detention pond

The 24 hr 25 yr storm depths listed in the Table 4 were used as input in the PCSWMM model, simulation were performed and the following metrics were collected: Average depth (m), maximum depth (m), maximum total inflow (m^3/s), average volume (1000 m^3), average percent full (%), max volume (1000 m^3), max percent full (%) and max outflow (m^3/s). These metrics for three detention ponds are reported

Features	Metric	Observed	CrcmCcsm	CrcmCgcm3	Hrm3Gfdl	Hrm3Hadcm3	Rcm3Cgcm3	Rcm3Gfdl	Average
Pond 1	Avg Depth (m)	0.64	1	1.06	1.08	1.05	1.05	1.2	1.08
	Max Depth (m)	1.45	1.01	1.11	1.14	1.08	1.08	1.2	1.14
	Max Total Inflow (m^3/s)	9.28	1.01	1.25	1.33	1.16	1.19	1.97	1.32
	Average Volume (1000 m^3)	6.06	1	1.08	1.11	1.05	1.06	1.24	1.1
	Avg Percent Full (%)	31	1	1.1	1.1	1.06	1.06	1.23	1.1
	Max Volume (1000 m^3)	15.35	1.01	1.15	1.19	1.09	1.11	1.27	1.18
	Max Percent Full (%)	79	1	1.14	1.19	1.09	1.1	1.27	1.18
	Max Outflow (m^3/s)	1.2	1.03	1.74	1.99	1.47	1.56	2.44	1.95
Pond 2	Avg Depth (m)	0.34	1.03	1.12	1.15	1.09	1.09	1.38	1.15
	Max Depth (m)	1.59	1	1.11	1.15	1.07	1.08	1.54	1.14
	Max Total Inflow (m^3/s)	4.1	1.01	1.21	1.28	1.13	1.16	1.89	1.27
	Average Volume (1000 m^3)	0.88	1.01	1.11	1.14	1.07	1.09	1.42	1.14
	Avg Percent Full (%)	10	1	1.1	1.1	1	1.1	1.4	1.1
	Max Volume (1000 m^3)	4.84	1.01	1.15	1.21	1.1	1.11	1.81	1.2
	Max Percent Full (%)	53	1.02	1.15	1.23	1.11	1.13	1.83	1.21
	Max Outflow (m^3/s)	1.59	1.03	1.56	1.66	1.37	1.43	2.23	1.66
Pond 3	Avg Depth (m)	0.59	1	1.08	1.12	1.05	1.07	1.27	1.1
	Max Depth (m)	1.62	1	1.14	1.2	1.08	1.1	1.23	1.19
	Max Total Inflow (m^3/s)	8.53	1.01	1.25	1.33	1.16	1.19	1.96	1.31
	Average Volume (1000 m^3)	4.31	1	1.09	1.12	1.06	1.07	1.3	1.12
	Avg Percent Full (%)	26	1	1.12	1.12	1.08	1.08	1.31	1.12
	Max Volume (1000 m^3)	12.7	1.01	1.17	1.25	1.1	1.12	1.29	1.24
	Max Percent Full (%)	77	1.01	1.18	1.26	1.1	1.13	1.3	1.25
	Max Outflow (m^3/s)	1.5	1.03	1.87	2.17	1.53	1.64	2.41	2.11

Table 5: Detention Pond Performance Ratios (Future values normalized by observed performance values) for 24 hr 25 yr design storm.

in Table 5. The third column in the Table 5 shows performance values using the design storm calculated from observed data. All other values in the Table 5 are detention pond performance values for NARCCAP future storm normalized by the values in the column 3. Almost all the performance ratios greater than 1 for all six RCM+GCM pairs and average value indicate that the detention ponds will not perform as expected under future climate. The performance ratios of all eight metrics for RCM3+GFDL are highest among the ratios for all six RCM+GCM pairs, that indicates the worst performance of all detention ponds under RCM3+GFDL future scenario. The performance ratios for RCM3+GFDL models varies from 1.2 for average depth to 2.44 for maximum outflow for pond 1, i.e., average depth increase by 20% and maximum outflow increase by 144% under future climate presented by RCM3+GFDL models. The very high increase in the uncontrolled peak discharge indicates the vulnerability of flooding in the downstream of the detention pond. One model, CRCM+CCSM, among the six pairs shows no change for some metrics and insignificant (only 3% for maximum outflow) change for some metrics for all three ponds. Using the future to present performance ratio greater than 1 (i.e., future condition are greater than present conditions), the increases are observed in 93% of all the metrics for all 3 ponds. Results in the Table 5 show that the performance ratios varies from 1.08 for average depth for pond1 to 2.11 for maximum outflow for pond 3 for average design storm, i.e., average depth increase by 8% and maximum outflow increase by 111% under average future climate condition. The performance ratios varies 1.08-1.95, 1.10-1.66 and 1.10-2.11 for average future climate condition for pond 1, pond 2 and pond 3 respectively, the performance ratio varies 1.2-2.44, 1.38-2.23 and 1.27-2.41 for highest increased 24 hr 25 yr design storm by RCM3+GFDL models.

Figure 6 presents the time series plot of inflow, outflow, storage volume and depth for detention pond 1. These time series data were produced by inputting design storm depth from observed data and average (listed in Table 4) of design storm from 6 RCM+GCM pairs. Figure 6 shows that maximum inflow increased from 9.28 m^3/s for observed to 12.21 m^3/s for NARCCAP average that is an increase of 32%. The outflow from the pond increased from 1.198 m^3/s for observed to 2.331 m^3/s for NARCCAP average, i.e., the controlled peak flow will be increased by 95% under future average climate condition. Figure 6 shows that the maximum storage volume and maximum depth will increase by 18% and 14% respectively. The maximum values obtained from the simulated time series, the maximum storage volumes are 15347 m^3 and 18175 m^3, and the maximum depths are 1.45 m and 1.65 m for observed and NARCCAP average respectively.

Storm sewer

The 24 hr - 5 yr storm depths listed in the Table 4 were used for storm sewer performance analysis. These design storm depths with SCS storm distribution was inputted in the PCSWMM model. Then, a number of hydraulic parameters were obtained from the PCSWMM generated status files. The parameters, maximum water level and pipe flow ratio, used by Berggren et al. [23] for measuring hydraulic impact were calculated. Pipe flow ratio is the ratio of the actual maximum flow rate and the flow rate when the pipes were running full in the system.

At the outset, the number of nodes flooded and surcharged observed/baseline scenario and future climate were compared. The number of node flooded and surcharged for 24 hr - 5 yr SCS storm are presented in Table 6. Flooding refers to all water that overflows a node, and surcharge occurs when water rises above the crown of highest conduit. There was only one node flooded under present climate condition. The number of flooded node increased under future climate condition ranging from 4 for CRCM+CCSM models to 72 for RCM3+GFDL models, and 17 for average design storm calculated from 24 hr 5 yr design storm of 6 RCM+GCM pairs. There were 58 nodes surcharged for observed/baseline condition, these numbers increased

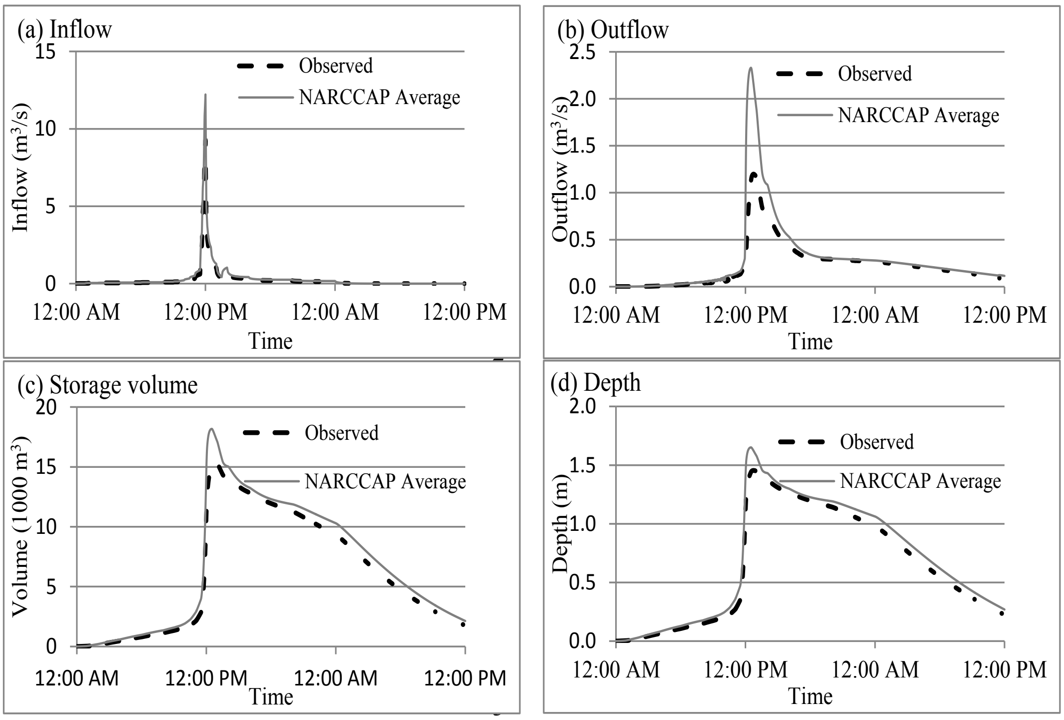

Figure 6: Plots showing time series of inflow, outflow, storage volume and depth from 25 year return period storm for detention pond 1 (observed/baseline values obtained using storm depths calculated from observed data).

Features	Observed	CrcmCcsm	CrcmCgcm3	Hrm3Gfdl	Hrm3Hadcm3	Rcm3Cgcm3	Rcm3Gfdl	Average
Node Flooded	1	4	22	18	15	15	72	17
Node Surcharged	58	92	146	143	98	125	189	131

Table 6: Number of node flooded and surcharged.

Features		CrcmCcsm	CrcmCgcm3	Hrm3Gfdl	Hrm3Hadcm3	Rcm3Cgcm3	Rcm3Gfdl	Average
Max Water Level	mean difference (m)	0.42	1.28	1.27	0.57	0.97	2.6	1.07
	mean difference (%)	26	79	79	36	60	162	66
Pipe Flow ratio	mean difference	0.08	0.2	0.2	0.1	0.16	0.31	0.18
	mean difference (%)	10	25	25	13	20	39	23

Table 7: Difference between the observed/baseline scenario and future climate for maximum water level and pipe flow ratio.

under future climate with the smallest for CRCM+CCSM models which are 92, the largest for RCM3+GFDL models which is 189, and 131 nodes will be surcharged for average future climate condition.

Then, The difference between the observed/baseline scenario and future climate for maximum water level and pipe flow ratio are presented in Table 7. The mean difference between the observed/baseline scenario and future climate for maximum water level at all the nodes varies from 0.42 m for CRCM+CCSM models and 2.62 m for RCM3+GFDL, and the difference between observed and climate average is 1.07, i.e., the maximum water level increase on an average of 26% for CRCM+CCSM models, 162% for RCM3+GFDL models and 66% for average design storms under future climate. Similarly, The mean difference between the observed/baseline scenario and future climate for pipe flow ratios varies from 0.08 m for CRCM+CCSM models and 0.31 m for RCM3+GFDL, and the difference between observed and climate average is 0.18, i.e., the pipe flow ratios increase on an average of 10% for CRCM+CCSM models, 39% for RCM3+GFDL models and 23% for average design storms under future climate.

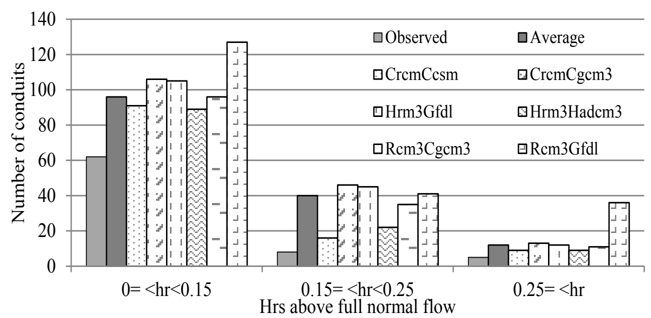

Figure 7: Number of conduits above full normal flow for 5 year return period storm.

Figure 7 presents the number of conduits above full normal flow and Figure 8 presents the number of conduits for capacity limited. These numbers for the observed/baseline period and future period are categorized for three durations: 0=<hr<0.15, 0.15=<hr<0.25 and 0.25=<hr. The numbers are always higher for all categories for all six

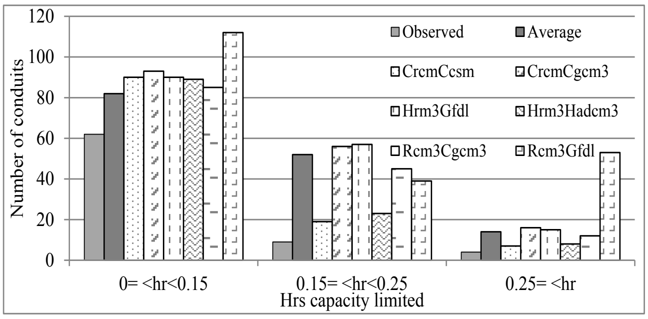

Figure 8: Number of conduits for capacity limited for 5 year return period storm.

RCM+GCM models. The number of conduits above full normal flow and for capacity limited for RCM3+GFDL are the highest among the six RCM+GCM pairs for durations 0=<hr<0.15 and 0.25=<hr.

The higher numbers are observed for CRCM+CGCM and HRM3+GFDL models for second category. The numbers of conduits above full normal flow are 62, 8 and 5 for observed and 96, 40 and 12 for future average climate for three categories, i.e., the numbers increase by 55%, 400% and 140%. The numbers of conduits for capacity limited are 62, 9 and 4 for observed and 82, 52 and 14 for future average climate for three categories, i.e., the numbers increase by 32%, 477% and 250%.

Figure 9 shows the spatial distribution of number of nodes flooded, number of nodes surcharged and pipe flow ratio, and it contributes to the understanding of most vulnerable locations in the study area under future climate condition.

Conclusions

This study explored the potential impact of climate change on the design storm depths and consequent effect on the performance of detention pond and storm sewer network under future climate condition at a study area located in the City of Hamilton, Ontario, Canada.

The best fitted distribution among twenty seven distributions for observed and NARCCAP datasets for design storm calculation were identified in this study. The precipitation time series provided by six different RCM+GCM pairs were used in frequency analysis; two statistical tests were used to test the goodness of fit of each distribution. The delta change factor was used to convert the storm depths calculated from gridded data to station scale values. The results show that there is an overall significant increase of design storm depths for all six RCM+GCM pairs. The visual inspection of scatter plots revealed that the increase of design storm depths under future climate condition is higher for higher values. Visual inspections also revealed that increase of design storm depths also increase with the increase of return period overall. The results also show overall increase of storm depths in future is higher in the case when distributions were identified by Kolmogorov-Smirnov test. The design storm depths calculated using the distribution identified by Kolmogorov-Smirnov test are suggested to use for investigation of stormwater management infrastructure performance study for sustainable infrastructure design.

The 24 hr - 25 yr and 24 hr - 5 yr design storm depths were inputted in the PCSWMM model for analyses of detention pond and storm sewer network performance respectively under future climate condition. The deteriorated performance of three detention ponds were indicated by the performance ratio calculated from eight metrics. The time series plot of inflow, outflow, storage volume and depth also shows increase of the metrics. Results also indicate the worst performance of all detention ponds under RCM3+GFDL future scenario. A number of hydraulic parameters were used to assess the system capacity, and all the parameters show deteriorated performance under future climate condition. Similar to detention pond, the worst performance of the storm sewer network were observed under RCM3+GFDL future scenario. Overall, the urban drainage management infrastructures designed based on current climate condition will not be able to cope with the increased design storm depth under future climate condition. The findings of this study would encourage municipalities and other stakeholders for considering climate change impact in planning and

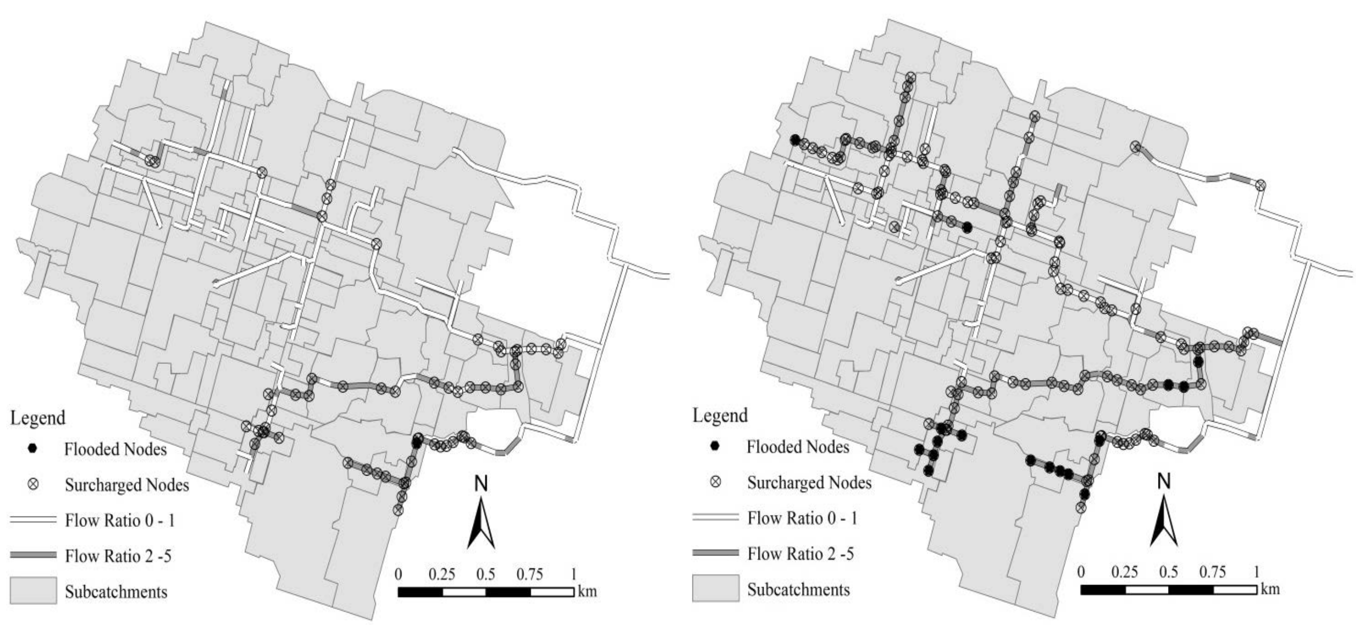

Figure 9: Flooded and surcharged nodes, and pipe flow ratio for observed/baseline (to the left) and future NARCCAP average (to the right) for 5 year return period storm.

designing of drainage management infrastructures to ensure that they will work effectively in future.

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References

1. IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri PK, Meyer LA (eds.) IPCC, Geneva, Switzerland, pp: 151-175.
2. Beniston M, Stephenson DB, Christensen OB, Ferro CAT, Frei C, et al. (2007) Future extreme events in European climate: an exploration of regional climate model projections. Climatic Change 81: 71-95.
3. Christensen JH, Christensen OB (2003) Climate modelling: severe summertime flooding in Europe. Nature 421: 805-806.
4. Kundzewicz ZW, Radziejewski M, Pinskwar I (2006) Precipitation extremes in the changing climate of Europe. Climate Research 31: 51-58.
5. Semmler T, Jacob D (2004) Modeling extreme precipitation events-a climate change simulation for Europe. Global and Planetary Change 44: 119-127.
6. Tsanis IK, Koutroulis AG, Daliakopoulos NI, Jacob D (2011) Severe climate-induced water shortage and extremes in Crete: A letter. Climatic Change 106 (4): 667-677.
7. Brown C (2010) The end of reliability. J Water Resour Plann Manage 136: 143-145.
8. Karla A, Ahmad S (2009) Using Oceanic-atmospheric oscillations for long lead time streamflow forecasting. Water Resour Res 45(3): DOI:10.1029/2008WR006855.
9. Guo YP (2006) Updating rainfall IDF relationships to maintain urban drainage design standard. J Hydrol Eng 11 (5): 506-509.
10. Mailhot A, Duchesne S (2010) Design criteria of urban drainage infrastructures under climate change. J Water Resour Plann Manage 136 (2): 201-208.
11. Moglen GE, Vidal GER (2014) Climate change impact and storm water infrastructure in the Mid-Atlantic region: design mismatch coming. J Hydrol Eng 19 (11): DOI:10.1061/(ASCE)HE.1943-5584.0000967.
12. Forsee WJ, Ahmad S (2011) Evaluating urban storm-water infrastructure design in response to projected climate change. J Hydrol Eng 16 (11): 865-873.
13. Zhu J, Stone MC, Forsee W (2012) Analysis of potential impact of climate change on intensity-duration-frequency (IDF) relationships for six regions in the United States. J Water and Climate Change 3 (3): 185-196.
14. Mailhot A, Duchesne S, Caya D, Talbot G (2007) Assessment of future change in intensity-duration-frequency (IDF) curves for Southern Quebec using the Canadian Regional Climate Model (CRCM). J Hydrol 347: 197-210.
15. Coulibaly P, Shi X (2005) Identification of the effect of climate change on future design standards of drainage infrastructure in Ontario. Highway Infrastructure Innovation Funding Program, Ministry of Transportation of Ontario, Canada.
16. Zhu J (2013) Impact of climate change on extreme rainfall across the United States. J Hydrol Eng 18 (10): 1301-1309.
17. Deser C, Phillips A, Bourdette V (2012) Uncertainty in climate change projections: the role of internal variability. Climate Dyn 38: 527-546.
18. Dibike YB, Coulibaly P (2005) Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. J Hydrol 307 (1-4): 145-163.
19. Fowler HJ, Blenkinsop S, Tebaldi C (2007) Linking climate change modeling to impacts studies: Recent advances in downscaling techniques for hydrological modeling. Int J Climatol 27 (12): 1547-1578.
20. Kalra A, Ahmad S (2011) Evaluating changes and estimating seasonal precipitation for Colorado River Basin using stochastic nonparametric disaggregation technique. Water Resour Res 47: W05555.
21. Praskievicz S, Chang HJ (2009) A review of hydrological modeling of basin-scale climate change and urban development impacts. Progress in Physical Geography 33 (5): 650-671.
22. Prudhomme C, Reynard N, Crooks S (2002) Downscaling of global climate models for flood frequency analysis: Where are we now? Hydrol. Processes 16 (6): 1137-1150.
23. Berggren K, Olofsson M, Viklander M, Svensson G, Gustafsson A (2012) Hydraulic Impacts on Urban Drainage Systems due to Changes in Rainfall Caused by Climatic Change. J Hydrol Eng 17 (1): 92-98.
24. Olsson J, Berggren K, Olofsson M, Viklander M (2009) Applying precipitation model climate scenarios for urban hydrological assessment: A case study in Kalmar City, Sweden. Atmos Res 92 (3): 364-375
25. Semadeni-Davies A, Hernebring C, Svensson G, Gustafsson L (2008) The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. J Hydrol 350: 100-113.
26. Fortier C, Mailhot A (2015) Climate change impact on combined sewer outflows. J Water Resour Plann Manage 141(5), DOI:10.1061/(ASCE)WR.1943-5452.0000468.
27. Grillakis MG, Koutroulis AG, Tsanis IK (2011) Climate change impact on the hydrology of Spencer creek watershed in Southern Ontario, Canada. Journal of Hydrology 409: 1-19.
28. Mearns, L.O., et al. (2007), updated 2012. The North American Regional Climate Change Assessment Program dataset, National Center for Atmospheric Research Earth System Grid data portal, Boulder, CO. Data downloaded 2014-07-07. [DOI:10.5065/D6RN35ST].
29. Mearns LO, Gutowski WJ, Jones R, Leung LY, McGinnis S, et al. (2009) A regional climate change assessment program for North America. EOS, 90: 311-312.
30. NARCCAP (2013) North Americal Regional Climate Change Assessment Program. <http://www.narccap.ucar.edu/> (January 26, 2013).
31. Mailhot A, Beauregard I, Talbot G, Caya D, Biner S (2012) Future changes in intense precipitation over Canada assessed from multi-model NARCCAP ensemble simulations. Int J Climato 32: 1151-1163.
32. Nakicenvoic N, Davidson O, Davis G, Grübler A, Kram T, et al. (2000) Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press Cambridge, 599.
33. Kozanis S, Christofides A, Efstratiadis A (2010) Scientific documentation of the hydrogram software version 4, Athens, pp 173.
34. Music B, Caya D (2007) Evaluation of the hydrological cycle over the Mississippi River Basin as simulated by the Canadian regional climate model (CRCM). J Hydrometeor 8: 969-988
35. Jones R, Noguer M, Hassell D, Hudson D, Wilson S, et al. (2004) Generating high resolution climate change scenarios using PRECIS. Met Office Hadley Center. Exter p 40.
36. Elguindi N, Bi X, Giorgi F, Nagarajan B, Pal J, et al. (2007) RegCM Version 3.1 User's Guide, Trieste, Italy. <https://users.ictp.it/RegCNET/regcm.pdf> (July 9, 2015)
37. Giorgi F, Marinucci MR, Bates GT (1993) Development of second generation regional climate model (RegCM2) I: boundary layer and radiative transfer processes. Mon Weather Rev 121: 2794-2813.
38. Collins WD, Bitz CM, Blackmon ML, Bonan GB, Bretherton CS, et al. (2006) The community climate system model version 3 (CCSM3). J Climate 19: 2122-2143.
39. Flato GM (2005) The Third Generation Coupled Global Climate Model (CGCM3). <http://www.ec.gc.ca/ccmac-cccma/default.asp?n=1299529F-1> (August 9, 2015).
40. GFDL GAMDT (2004) The new GFDL global atmospheric and land model AM2-LM2: Evaluation with prescribed SST simulations. J Climate 17: 4641-4673.
41. Gordon C, Cooper C, Senior CA, Banks H, Gregory JM, et al. (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16: 147-168

42. Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parameterizations in the Hadley Centre climate model-HadAM3. Climate Dynamics 16: 123-146.

43. Chen C, Knutson T (2008) On the verification and comparison of extreme rainfall indices from climate models. J Clim 21 (7): 1605-1621.

44. Leander R, Buishand TA (2007) Resampling of regional climate model output for the simulation of extreme river flows. J Hydrol 332: 487- 496.

45. Sharma M (2009) Comparison of downscaled RCM and GCM data for hydrologic impact assessment M.A.Sc. Thesis, Dept. of Civil Engineering, McMaster University, Hamilton, Ontario, Canada.

46. James W, Rossman LA, James WRC (2010) User's guide to SWMM 5, 13th edition. CHI, Guelph, Ontario, Canada.

47. City of Hamilton (2011) West central mountain drainage assessment supplemental capacity analysis and SWM sizing Mewburn and Sheldon neighbourhoods." AMEC Environment and Infrastructure, Burlington, Ontario, Canada.