Climate Change and Municipal Stormwater Systems


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The School of Engineering at the University of Guelph
Ontario, Canada
2015
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# List of Abbreviations

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<th>Abbreviation</th>
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<tr>
<td>ACASA</td>
<td>Atlantic Climate Adaptation Solutions Association</td>
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<td>AEP</td>
<td>Annual Exceedance Probability</td>
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<tr>
<td>AGCM4</td>
<td>Fourth Generation Atmospheric General Circulation Model</td>
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<td>AMS</td>
<td>Annual Maximum Series</td>
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<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
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<tr>
<td>AOGCMs</td>
<td>Atmosphere-Ocean General Circulation Models</td>
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<tr>
<td>AR5</td>
<td>Fifth Assessment Report (by IPCC)</td>
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<tr>
<td>CanESM2</td>
<td>Earth System Model</td>
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<td>CCCma</td>
<td>Canadian Centre for Climate Modeling and Analysis</td>
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<td>CCDS</td>
<td>Canadian Climate Data and Scenarios</td>
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<td>CGCM4</td>
<td>Fourth Generation Coupled Global Climate Model</td>
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<td>CMIP3</td>
<td>Coupled Model Intercomparison Project, Phase 3</td>
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<td>CMIP5</td>
<td>Coupled Model Intercomparison Project, Phase 5</td>
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<td>CRB</td>
<td>Châteauguay River Basin</td>
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<td>CRCM</td>
<td>Canadian Regional Climate Model</td>
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<td>CSA</td>
<td>Canadian Standard Association</td>
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<td>CTEM</td>
<td>Canadian Terrestrial Ecosystem Model</td>
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<td>EQM</td>
<td>Equidistance Quantile Mapping</td>
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<td>FCM</td>
<td>Federation of Canadian Municipalities</td>
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<td>FSA</td>
<td>Fraser Sewerage Area</td>
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<td>GCMs</td>
<td>General Circulation Models</td>
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<td>GHG</td>
<td>Greenhouse Gas</td>
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<td>GLM</td>
<td>Generalized Linear Models</td>
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<td>ICLEI</td>
<td>International Council for Local Environmental Initiatives</td>
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<tr>
<td>IDF</td>
<td>Intensity-Duration-Frequency</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>LARS-WG</td>
<td>Long Ashton Research Station Weather Generator</td>
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<td>NRB</td>
<td>du Nord River Basin</td>
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<tr>
<td>OCCAR</td>
<td>Ontario Centre for Climate Impacts and Adaptation Resources</td>
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<tr>
<td>OGCM4</td>
<td>Fourth Generation Ocean General Circulation Model</td>
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<td>PIVEC</td>
<td>Public Infrastructure Engineering Vulnerability Committee</td>
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<td>RCPs</td>
<td>Representative Concentration Pathways</td>
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<td>SDSM</td>
<td>Statistical Down Scaling Model</td>
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<td>SRES</td>
<td>Special Report on Emissions Scenarios</td>
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<td>VSA</td>
<td>Vancouver Sewerage Area</td>
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The projected impacts of climate change are of increasing concern to municipalities across Canada. Significant shifts in weather patterns, especially in storm intensities, are expected to bring challenges to all Canadian communities. These challenges include: earlier snowmelt, more frequent extreme rainfall events, sea storm surges, and increased flood risks. As a result, the changes in timing and volume of floods are a major concern for the planning and management of municipal stormwater systems. Flooding is a ‘trigger’ for a range of potential health and other impacts and risks, including: death and injury, damage to sewer systems, sewage overflows/bypasses, contaminated drinking water, damage to solid waste systems, hazardous material spills, flooded basements, and community disruption and displacement. The financial impacts associated with flooding are often staggering:

- The flood impacting the City of Calgary in 2013 affected one-quarter of the Province of Alberta, and caused an estimated $6 billion in damages [1].
- The Red River flood in 2009 and the Assiniboine River flood in 2011 cost the Province of Manitoba over $1 billion [2,3].
- A flash flood hit southern Ontario in July 2013 after 10 cm of rain fell in Toronto in two hours. The flood set a new record as being one of Ontario’s most expensive natural disasters.
- Flooding has affected more than 267 communities in Newfoundland and Labrador since 1950, causing over $262 million in damage.

A quick example to understand the impact of climate change is illustrated in Figure 1, which presents historic (1971–2003), near future (2010–2039), and far future (2070–2099) mean monthly stream flow rates at Shabomeka station, ON (Asnaarhi [4]). It is noted that long-term increases in the temperature of the region will severely affect both snowpack accumulation and snowmelt delivery time.
An assessment of local climate change impacts is needed to understand the risks and potential failures that may occur in the future. Such an assessment is usually conducted by applying future climate projections onto existing infrastructures, to determine if current service capacity is adequate to function as desired under future conditions. If the existing infrastructure fails to serve future conditions, adaptation is required either to increase service capacity or to reduce service demand. Particular to flood risks, the updating of both Intensity-Duration-Frequency (IDF) curves and floodplain maps is of great importance. IDF curves are used to design minor stormwater systems to convey rainfall runoff of five to ten year return period without roadway flooding or damage to residential properties. Floodplain maps are typically delineated according to 20 and 100 year return floods. To account for climate change, IDF curves and floodplain maps need to be periodically updated to allow evaluation of stormwater systems, and to regulate urban development, such as buildings in floodplains.

This paper provides an introduction to climate models and projections, as well as models and strategies for updating IDF curves and floodplain maps.

Figure 1. Historic (1971–2003) versus near future (2010–2039), and far future (2070–2099) mean monthly stream flow rates at Shabomeka station (Figure 7 from Asnaarhi [4]).
General Circulation Models (GCMs) are mathematical simulations of the Earth’s atmosphere and/or ocean processes. These processes govern climate variables such as precipitation, wind, cloudiness, ocean currents, air temperature, water temperature, etc. GCMs may contain one or more component models of the atmosphere, ocean, land surface, and/or sea ice.

1.1 HOW DO GLOBAL CIRCULATION MODELS WORK?

Atmosphere-Ocean General Circulation Models (AOGCMs) are coupled models of atmosphere and ocean components, and are considered sufficient for the purposes of guiding adaptation planning in water utilities [5]. Examples of AOGCMs include:

- Had CM3 from the Hadley Centre (UK) [6],
- GFDL CM2 from NOAA’s Geophysical Fluid Dynamics Laboratory (USA) [7], and
- CGCM4/CanCM4 from the Canadian Centre for Climate Modeling and Analysis (CCCma - a division of the Climate Research Branch of Environment Canada) [8].

In AOGCMs, the atmosphere and oceans are divided into horizontal and vertical grids, with spatial resolutions varying from less than one degree to several degrees. The grids are assigned value for an array of climate variables, e.g. wind speed, temperature, humidity, etc.

The driving forces of these models include incoming solar radiation, greenhouse gas (GHG) concentrations, aerosols from volcano eruptions and human activities.

According to CMIP3 (Coupled Model Intercomparison Project, Phase 3) [9], the model will run under pre-industrial values of driving force parameters to “spin up”, and then run with actual historical records (from the late 1800s to present) of driving force parameters to validate
the model. Finally, the model will simulate future climate conditions with provided GHG emission scenarios and other projections of driving force parameters. In addition to CMIP3, CMIP5 will conduct experiments on a decadal scale, which focuses on near-term predictions (10-30 years), in contrast to long-term projection models that project climate responses to climate forcing such as changes in GHG emission and land cover changes. The near-term model includes additional components leading to climate variation such as Pacific Decadal Oscillation and El Niño Southern Oscillation, and investigates the possibility of a comprehensive prediction of climate change [10]. The expectation is that a well-established near-term model will encourage water utilities to plan adaptation strategies for the coming decades.

1.2 WHAT ARE EMISSION SCENARIOS?

One of the driving forces provided to GCMs for simulating future climate are GHG concentrations. Future GHG concentrations are projected based on emission rates and removal rates from the atmosphere. The Special Report on Emissions Scenarios (SRES) [11] produced by the Intergovernmental Panel on Climate Change (IPCC) [12] in 2000 summarized 40 emission scenarios, based on different assumptions for driving forces such as population growth, economic and social development, energy and technology development, agriculture and land use changes, etc. [12]. Four families of emission scenarios, A1, A2, B1, and B2, are schematically indicated in Figure 2, based on the similarity of their assumptions:

- The A1 storyline emphasizes fossil fuel consumption and has the highest GHG emissions. In this future world, there is rapid economic growth, population peaks mid-century (and declines afterwards) and there is rapid introduction of new and more efficient technologies [12].
- The A2 storyline represents a heterogeneous world with a global population that continuously increases, and economic growth that is fragmented and slow [12].
- The world-integrated, ecologically-friendly B1 scenarios have the lowest projected emissions. This storyline is associated with the introduction of clean and resource-efficient technologies.
- The B2 storyline represents a world with a population that is continuously increasing, accompanied by intermediate economic development. Local solutions to economic, social and environmental sustainability are emphasized.
The uncertainties involved in SRES scenarios include: different choices and interpretations of storylines by different authors, translation and quantification of linkage between driving forces and model inputs, differences in methodologies employed for emission projections, as well as the source and quality of data used. There are also inevitable uncertainties such as war, disasters, and environmental collapse that contribute to error within the emission scenarios.

The SRES scenarios have been critiqued in relation to the economic parameters used, natural resource availability and future production expectations [13]. SRES scenarios have been superseded by Representative Concentration Pathways (RCPs) in the fifth assessment report (AR5) by IPCC [14].

1.3 REPRESENTATIVE CONCENTRATION PATHWAYS

Representative Concentration Pathways (RCPs) provide projections of climate indicators and GHG emissions directly, rather than starting from projections of socioeconomic processes or emission scenarios. Like their predecessor (SRES scenarios), RCPs are a set of scenarios used by climate modelers [15]. Climate indicators employed in RCPs include GHG concentrations and radiative forcing (which is the difference in solar energy absorbed and solar energy radiated to space by Earth, typically measured at the tropopause, in watts per square meter).

RCPs are superior to SRES assessments in a number of ways. The uncertainties involved in interpreting socioeconomic processes are
avoided in RCPs, since RCPs start directly from GHG concentrations and radiative forcing. Climate policies, as well as mitigation and adaptation policies, are included in RCPs, which make it possible to explicitly explore the associated impacts. RCPs provide detailed and standardized GHG concentrations as inputs for climate models. There are four GHG concentration trajectories in RCPs, namely RCP2.6, RCP4.5, RCP6 and RCP8.5, where the values indicate the radiative forcing by the end of 2100.

- RCP2.6 is a mitigation scenario that assumes emissions of GHG will decline substantially after 2020 due to carbon dioxide removal from the atmosphere and early participation from all main emitters.
- RCP4.5 and RCP6 are two moderate scenarios in which radiative forcing becomes stabilized before 2100. RCP4.5 is similar to the B1 scenario in SRES, while RCP6 assumes application of a range of technologies and strategies for reducing GHG emissions.
- RCP8.5 assumes the least amount of effort in reducing emissions, and serves as a baseline emission scenario (i.e. worst-case scenario). A1FI (A1 scenario emphasis on fossil fuels, Fossil Intensive) from SRES is the counterpart of RCP8.5.

![Figure 3 - Emissions of main greenhouse gases across the four RCPs](image source [16]).
1.4 DOWNSCALING

The spatial resolution of GCMs is usually too coarse to provide features that are important to water utilities. High resolution GCMs are available but require huge computational loads.

Downscaling is an alternative option to high resolution GCMs, where downscaling involves development of regional climate projections. Downscaled climate models are capable of capturing local climate phenomena and processes that are absent in GCMs, such as cloud reflection, convective storms, and mountain-forced circulations. There are two classes of downscaling techniques: statistical and dynamical.

Statistical downscaling techniques develop relationships between observed local climate variables and GCM predictors, and then apply these relationships to future GCM projections to simulate local climate. Examples of statistical downscaling techniques include:

- The Statistical Down Scaling Model (SDSM), which uses multiple linear regression techniques to permit spatial downscaling of daily predictor-predictand relationships [17].
- Long Ashton Research Station Weather Generator (LARS-WG), which is a stochastic weather generator that simulates daily weather time series [18].

Dynamical downscaling is a high resolution climate model over a limited area, which is also known as a Regional Climate Model (RCM). The boundary conditions of RCMs are provided by observations and/or GCM outputs. RCMs outperform GCMs when simulating phenomena that are influenced by topography and small spatial or short temporal extremes.

Uncertainties in statistical downscaling models arise from a variety of sources, including: choice of predictors, estimation of empirical relationships between large-scale predictors and local scale climate variables, potential changes in estimated relationships, and limited data sets.

Uncertainties in RCMs are introduced from the size of domains, the lateral boundary conditions, and the interaction with sea surfaces.
1.5 CLIMATE MODELING AND ANALYSIS IN CANADA

The Canadian Center for Climate Modeling and Analysis (CCCma) [19] has developed a number of climate models for use in studying climate change and variability.

The Fourth Generation Atmospheric General Circulation Model (AGCM4/CanAM4) is the latest model developed for global atmosphere circulation. AGCM4 has 35 vertical layers spanning from sea surface to approximately 50km above sea level, and 64×128 grids for horizontal representation (2.81° square). The model results are provided in the form of CMIP5 experimental outputs, available for atmosphere, land, land ice, and sea ice. Model results can be obtained at different frequencies, ranging from 3 hours to monthly data.

AGCM4 is further coupled with the Fourth Generation Ocean General Circulation Model (OGCM4/CanOM4) to create the Fourth Generation Coupled Global Climate Model (CGCM4/CanCM4). There are 40 vertical layers in OGCM4, and the horizontal resolution is in agreement with AGCM4. Beneath each cell in AGCM4, there are six cells (1.41° in longitude and 0.94° in latitude) in OGCM4. CGCM4 is coupled with the Canadian Terrestrial Ecosystem Model (CTEM), which is a model of terrestrial carbon, to develop an Earth System Model (CanESM2).

The Canadian Regional Climate Model (CRCM)[20] is a dynamical downscaling model developed by CCCma. The latest version, CRCM4.2, is in line with AGCM3, and implements a multi-layer surface scheme to better capture water and energy exchange between the land surface and atmosphere. CRCM4.2 data provided by CCCma are simulations over North-American domains for durations of 1961-2100 and 2041-2070. The models are nested in CGCM3.1/T47 (members #4 and #5) and driven by the A2 emission scenario in SRES. The model has 29 vertical layers and a 45km horizontal grid mesh.
With changing climate, urban infrastructure needs to be designed and managed in a way that ensures performance remains as expected under both current and future climate conditions. GCMs and downscaled projections are too coarse in spatial and temporal resolution to be utilized at the municipal and community level. Intensity-Duration-Frequency (IDF) curves are convenient tools for characterizing point rainfall for short durations and are currently used in the design of drainage infrastructure, the assessment of flood risk, and other management practices. Therefore, IDF curves need to be updated to reflect expected climate change utilizing GCM projections.

2.1  HOW TO UPDATE IDF CURVES?

A commonly used methodology for updating IDF curves is to assume a constant relationship between projected climate variables (e.g. monthly total precipitation, usually downscaled) and short duration rainfall (e.g. 5min daily maximum rainfall). This relationship is calibrated for the current time period with observed rainfall records, and used to project future rainfall quantities. As illustrated in Figure 4, the GCMs simulate both current and future climate variables, labeled as “GCMs Baseline” and “GCMs Projection”. In the real world, historical IDF curves are developed based on the short duration rainfall records. Using the relationship between GCMs baseline and characteristics of historical IDF curves, the IDF curves for future climate can be estimated from GCMs projections.

Case studies have evidenced several approaches to estimate future IDF curves. One approach uses changes in simulated climate variables to project the short duration precipitation time series, and then develop IDF curves from the projected time series. Another approach directly projects the extreme rainfall intensities or IDF curve parameters from simulated climate variables.
2.2 CASE STUDY - WELLAND, ONTARIO (AMEC) [21]

The IDF curves for the City of Welland, Ontario were developed in 1963 based on Buffalo weather data. There are new curves available from Port Colborne, ON which were developed by Environment Canada in 2000. The IDF curves are projected to 2020 and 2050 using 112 GCM outputs from the CMIP3 database. To update the IDF curves, AMEC compared several approaches provided in the technical guide published by the Canadian Standard Association (CSA, PLUS 4013, 2012), and selected an approach which uses Generalized Linear Models (GLM) to relate distributions of short-term precipitation to predictor variables.

In this approach, short-term precipitation (e.g. monthly precipitation maxima) was characterized, employing the Gumbel distribution, in which the location parameter was fit to predictor variables, using a Generalized Linear Model (GLM). The predictor variables considered are: average precipitation, average temperature, and the product of average temperature and average precipitation. GLMs were developed for each month and duration (from 5 minutes to 24 hours), and used to estimate rainfall intensities for return periods from 2 to 100 years. These monthly rainfall intensities were pooled together to derive annual rainfall intensities of different durations and return periods, and then used to generate IDF curves.

Shown schematically in Figure 5 are historical temperatures (T) and precipitations (P) which were adjusted using the difference (Delta) between GCMs simulated baseline and projected T and P. Subsequently, GLMs were used to develop baseline IDF curves from historical T and P, and climate impacted IDF curves from adjusted T and P. The differences (Delta) between the baseline IDF curves and the climate impacted IDF curves were added to the historical IDF curves to estimate projected IDF curves.
Figure 6 displays the increase in rainfall intensities in projected IDF curves for 2020 and 2050, compared to historical IDF curves. Mean values from 112 outputs were used to construct the projected curves. A three to nine percent increase in rainfall intensity is observed from the 2020 IDF curves, and a four to 13 percent increase from 2050, for return periods from two to 100 years. Larger differences between historical and projected IDF curves were observed, when the 90th percentiles of 112 outputs were used to construct IDF curves instead of mean values.

Figure 5 - The “Double Delta” method used to develop IDF curves for Welland, Ontario includes three steps: i) Adjust temperature and precipitation using “delta” of GCM simulations; ii) Generate IDF curves from temperature and precipitation using GLMs; iii) Adjust historical IDF curves using “delta” of IDF curves generated from step ii.
Figure 6. Increases in rainfall intensities in projected IDF curves for Port Colborne, Ontario in 2020 and 2050, compared to historical IDF curves in 2000. Box plots show the median, quartiles, minimum, maximum, and outliers of increases. For example, in a 10min duration storm, a 2% increase is projected from 2000 to 2020, and 4% from 2000 to 2050, averaged out over the return periods from two to 100 years. (Reproduced from Table 8-10 from AMEC [21])
2.3 THE IDF UPDATE TOOL (ICLR - WESTERN UNIVERSITY)

A web-based computerized IDF update tool was developed at the Institute for Catastrophic Loss Reduction, Western University. The objective of the IDF update tool is to standardize the IDF update process and provide the results of current research on climate change, and the impacts of these changes on IDF curves, to all parties. The tool provides IDF tables from multiple runs of each combination of the GCMs and RCP scenarios, which enables users to perform uncertainty analysis. Environment Canada’s IDF tables and curves are provided for selected climate stations as well.

The IDF update tool employs CanESM2 to project future climate, with three RCPs considered. A method called Equidistance Quantile Mapping (EQM) [22] is applied to develop two sets of linear relationships: (i) the sub-daily Annual Maximum Series (AMS) at a climate station and the GCM daily AMS for overlapped time period; (ii) the overlapped GCM daily AMS and the future GCM daily AMS, as shown in Figure 7. These relationships are used to predict future sub-daily AMS, and to derive future IDF curves at the climate station [23].

Figure 7 - Procedure used for the IDF Generation and Update Tool. The two sets of relationships (i and ii) are used to project future sub-daily AMS from GCM future daily AMS, and then to update IDF curves at a climate station.
2.4 CASE STUDY - INFRASTRUCTURE VULNERABILITY TO CLIMATE CHANGE - METRO VANCOUVER

Metro Vancouver conducted a vulnerability assessment for the Vancouver Sewerage Area (VSA) in 2008 [24] and the Fraser Sewerage Area (FSA) in 2009 [25]. Both assessments considered climate projections, including indices for sea level changes, temperature, and precipitation, from the Ouranos reports [26] on climate change scenarios. The VSA vulnerability assessment did not include changes to IDF curves; however, the FSA vulnerability assessment applied adjusted IDF curves developed by Jakob and Lambert [27], which are based on projections developed by Ouranos [26].

The approach applied by Jakob and Lambert [27] to update IDF curves is described herein and shown in Figure 8. For each year of historical data, the total monthly precipitation (P\text{Month}) from October to March was related to the maximum precipitation intensity (P\text{Short}) in the given month, for different durations. A linear relationship between log-transformed values were captured and modeled. Next, using a universal increase of 21% (based on Ouranos [26]) for total monthly precipitation (P'\text{Month}), the monthly maximum precipitation intensity (P'\text{Short}) for the future time period was derived. These monthly maxima were then integrated to obtain the projected annual maximum precipitation intensities for 2041-2070. Finally, the adjusted IDF curves were developed, based on the projected annual maximum series.

**Figure 8 - Procedure used to update IDF curves for the Fraser Sewerage Area [25]**
Flooding is the most frequently occurring natural hazard in Canada. The area submerged during high river flow (the floodplain) is delineated into the floodway and flood fringe. The floodway includes the main channel and the adjacent area where flows are deep, fast, and destructive. The flood fringe is the area outside of the floodway but will be submerged during flooding events. Overland flow is much shallower and lower in velocity than water in the floodway.

3.1 NEED FOR UPDATING FLOODPLAIN MAPS

Management of flood risk is based on floodplain maps (a.k.a. flood risk maps), which are often outdated in Canada. Many insurers are not willing to provide comprehensive flood insurance without an up-to-date floodplain map with climate change effects reflected [28].

According to Environment Canada, causes of flooding in Canada include: snowmelt runoff, rainfall, ice jam, coastal storms, catastrophic outburst, urban runoff, and dam failure. There are also important factors affecting stream flow, including precipitation, drainage basins, and climate [29]. With climate change and urbanization, floods in Canada are expected to be more frequent and more severe in the future. Precipitation is predicted to change in the future; with more intense and sudden rainfall events, flash-floods in small watersheds are expected to be more frequent. In urban areas, when runoff volume exceeds the capacity of the storm sewer system, backup will occur, causing flooding of streets and basements. Urbanization will reduce vegetation cover and increase impervious surfaces, causing high volumes of runoff due to reduced infiltration. Climate change will affect the regime of snowmelt runoff as well - earlier snowmelt will change the timing of flooding, and sudden winter thaw will become more frequent under warmer climate condition. Changes in snow depth and occurrence of heavy rainfall during snowmelt will both affect the volumes of snowmelt flooding. Ice jams are major cause of...
flooding in Canada. The impact on the buildup and breakup of ice jams needs to be assessed to characterize changes in the timing and volumes of flooding.

For coastal municipalities, sea level rise, sea surge, cyclones and hurricanes are all causes of coastal flooding. It is necessary to consider these evolving risks in the delineation of floodplain maps. The outburst from glacier-dammed and moraine-dammed lakes is another cause of flooding. Such flooding should be considered together with glacier retreat. Many causes of flooding are interrelated, and should be jointly considered (e.g. when snowmelt flooding is blocked by ice jams, the flood threat may increase substantially).

3.2 CASE STUDY - HIGH FLOWS IN NEW BRUNSWICK

Fisheries and Oceans Canada analyzed the impact of climate change on flood magnitude of seven catchments in New Brunswick in 2011 [30].

Climate model CGCM3.1 was employed with emission scenarios of B1 and A2 (best and worst) to project climate variables such as temperature and precipitation for the period of 2010-2100. Initially, average monthly discharge was simulated using Artificial Neural Networks (ANN) with input parameters such as maximum and minimum temperature, precipitation, and the month of the year. Then, regression equations were used to predict minimum and maximum daily flows using average monthly discharge. The results indicate that 2-year high flows will increase by 30% and 100-year high flows will increase by 15%.

3.3 CASE STUDY - FLOODPLAIN DELINEATION IN TWO SOUTHERN QUEBEC RIVER BASINS

Two watersheds located in southern Quebec, namely the Châteauguay River Basin (CRB) and the du Nord River Basin (NRB), were modeled to delineate floodplains with projected climate changes in 2020 and 2080 [31]. Nine climate projections were chosen from four GCMs, to preserve uncertainties associated with future climate conditions.

The projected daily temperatures and precipitation time series were used in hydrological models to simulate river responses, and further extract 20-year and 100-year flooding events. The result of NRB is shown in Table 1. Generally, there is a trend toward a decrease in spring peak flow in 2020 (+2% to -12%), and an increase for 2080 (4.3% to 12.5%, except the result simulated with ECHAM4, which indicated a reduction by 23%).
Hydrodynamic models were subsequently used to map the flooding extents. For the Châteauguay River Basin, an increase of 6.3 and 23.4% of the flooded extent was obtained for the 20 and 100-year events, respectively, simulated using CGCM3 and A2 emission scenario. However, the simulation from the ECHAM4 model showed a reduction of 2.6 and 3.1% in flooded area for the 20 and 100-year events, respectively. The variability between climate projections is considerable.

To characterize uncertainties in climate change projections, 20 and 100-year flow values computed from different combinations of GCM and emission scenarios were pooled together, and the 5th, 50th, and 95th quantiles were obtained using frequency analysis. These data were used as HEC-RAS inputs to model flood extents. Figure 9 shows floodplain maps projected for 2080 with different probabilities of exceedance. For example, the 95% exceedance map indicates that a 100-year flood zone in 2080 has a 95% chance to exceed this area.

This case study adopted a probabilistic approach to account for climate-related uncertainties, and to improve flood risk assessments when used in conjunction with flood consequence assessments.

<table>
<thead>
<tr>
<th>Return Period</th>
<th>Control</th>
<th>CGCM3</th>
<th>HADCM3</th>
<th>ECHAM4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizon 2020</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>100-Year</td>
<td>360</td>
<td>367</td>
<td>342</td>
<td>335</td>
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<tr>
<td>20-Year</td>
<td>301</td>
<td>290</td>
<td>271</td>
<td>265</td>
</tr>
<tr>
<td><strong>Horizon 2080</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100-Year</td>
<td>360</td>
<td>378</td>
<td>405</td>
<td>276</td>
</tr>
<tr>
<td>20-Year</td>
<td>301</td>
<td>314</td>
<td>323</td>
<td>232</td>
</tr>
</tbody>
</table>

*Table from Laforce et al. [31]

Table 1. Spring peak floods flow rates (m3/s) of the NRB at station 040110 (drainage area = 1,170 km2) corresponding to A2 GHG emission scenario.
3.3 CASE STUDY - FLOOD RISK MAPS UPDATED IN NEWFOUNDLAND AND LABRADOR

Flood risk mapping in Newfoundland and Labrador delineates the floodway as zones where floods have a return period of 20 years (5% chance of exceedance in any single year) and the flood fringe where the risk of flooding is once in 100 years (1% chance of exceedance in any single year). Flood risk areas have been mapped for 38 communities and these maps are used for “public information, municipal planning, development control, and the setting of structural design criteria. All proposed developments in flood risk zones are evaluated against potential impacts on water resources, the structures themselves, and the surrounding areas” [32].

Figure 9 - Probabilistic Floodplain Map of the du Nord River in Lachute (control period and 2080 horizon) [31].

Click here to access a website containing a list of all studies associated with flood risk mapping in the province of Newfoundland and Labrador [32].
Flood risk mapping studies are being updated to respond to climate change projections. Some flood risk mapping studies from Newfoundland and Labrador[33] include:

- CBCL Limited conducted a flood risk mapping study for the town of Logy Bay – Middle Cove – Outer Cove in 2012 [34]. The updated IDF curves for the 2050 tri-decadal period, developed by Finnis [35], were used to generate hyetographs and used as an input to the HEC-HMS model to simulate flood flows, and generate 1:20 and 1:100 Annual Exceedance Probability (AEP) flood risk maps for climate change scenarios. This study also updated flood risk maps for existing development conditions and the ultimate development condition.

- AMEC developed flood risk maps (1:20 and 1:100 AEP) for the Corner Brook Stream and Petrie’s Brook, in the Corner Brook area, in 2013 [36]. The flood risk maps were based on both existing and projected climate conditions. IDF curves projected by Finnis [35] were used at Stephenville, while the IDF curves at Deer Lake station were developed by AMEC, using the same “double delta” method as in the City of Welland project. The flood flow magnitudes were simulated in HEC-HMS, and the floodplain extents were simulated in HEC-RAS. In addition to summertime floods, wintertime floods are modeled with ice jam conditions. A similar study for the Goulds and Petty Harbour area were conducted by AMEC as well.

- HATCH updated flood risk maps for the community of Shearstown in the Town of Bay Roberts in 2012 [37]. The rainfall-runoff process was modeled in HEC-HMS and the 1:20 and 1:100 AEP flood flows were modeled in HEC-RAS to evaluate flood extents. Climate change impacts on flood flows were assessed by using projected extreme rainfalls (12 hours duration) for the time periods of 2010-2039, 2040-2069, and 2070-2099. These changes in precipitation were cited from Lines [38], which used two GCMs (CGCM2 and HadCM3) to simulate the B2 emission scenario in Atlantic Canada. A similar study for Stephenville Crossing/Black Duck Siding area was conducted by HATCH in 2012 as well.
A variety of strategies can be implemented to adapt to Canada’s changing climate.

Engaging Municipalities

As discussed in the Climate Ready Water Utility final report [39], local municipalities are encouraged to participate in the following activities when developing climate change action plans:

- Local climate research: with cooperation from local municipalities, climate scientists can customize downscaled climate impact data as an input for local utility models, and provide vulnerability analysis suited to local conditions.

- Vulnerability assessments: evaluate how water systems are susceptible to climate impacts. A top-down quantitative approach employs downscaled climate projections as inputs to local hydrologic and hydraulic models to simulate a range of water system responses, and hence identify gaps between current and future service levels. In response to these shortcomings, the local municipality should develop strategies to reduce identified vulnerabilities, such as expanded capacity and service flexibility as well as alternative service options.

- Long-term planning: there is a need to transition from stationary planning to scenario-based planning methods, to better address uncertainties involved in climate change projections. A stationary planning method often focuses on a single forecast of future conditions, based on historic records. This method is suitable for a design life of ten or 20 years. However, when looking at the long-term, GCMs, downscaling
techniques, and emission scenarios (or representative pathway assumptions) all introduce uncertainties into climate projections, and result in a range of future condition scenarios, which should be treated as equally plausible. Therefore, good planning practices should evaluate the robustness of alternative strategies, and identify projects that make infrastructure resilient to all, or at least many of the potential scenarios.

Adaptation Strategies for Stormwater Utilities

In 2013, Bolivar-Phillips reviewed adaptive stormwater management strategies for the City of Ottawa to consider adapting to climate change impacts [40]. The report identifies a series of examples representing the various methods that can be used to update IDF curves, including:

- The City of Guelph IDF update in 2007,
- The City of London and the University of Western Ontario’s IDF update in 2007.
- Ontario Ministry of Transportation’s IDF Update and Web Tool (which was the first of its kind in Canada - employing the latest Environment Canada data available at 125 meteorological stations across Ontario to determine rainfall intensities for any location in the province) [41].
- Development of Future IDF curves for Welland, ON (2012)

The report also provides an overview for conducting risk and vulnerability assessments (e.g. Welland’s stormwater infrastructure assessment, conducted in February 2012 [42]). The report reviews a variety of adaptation measures, including: modeling tools which integrate stormwater management adaptation, failure modes and fast recovery techniques in infrastructure design, green streets with “Silva cells” to retain stormwater, green infrastructure and LIDs, stormwater management facilities, and operational measures (e.g. real time radar and rain gauge analysis tools to predict flood risks and identify operational options).
Resources and Tools for Adaptation Planning

The Federation of Canadian Municipalities (FCM) summarizes the basic knowledge that exists, relating to adaptation resources, to aid municipalities in planning for and responding to climate change [43]. A large range of topics is covered, including:

- **Adaptation Basics** (e.g. what is adaptation, why is it important, and what are the potential effects?)
- **Archived webinars** detailing climate change impacts, adaptation strategies and greening cities (made available by the Alliance for Resilient Cities - Clean Air Partnership) [44].
- **Guidebooks and online courses** for adaption planning and conducting risk assessments, including:
  - “Partners for Climate Protection - Municipal Resources for Adapting to Climate Change” (prepared by ICLEI - Local Governments for Sustainability and the FCM through the Green Municipal Fund) [45]
  - “From Impacts to Adaptation: Canada in a Changing Climate” (prepared by the Climate Change Impacts and Adaptation Division of Natural Resources Canada) [46].

Additional valuable resources include:

- **ICLEI’s Adaptation Library** - a publicly accessible and searchable collection of community-related products and tools for adaptation programs, providing relevant information related to local climate change adaptation to community and municipal users [47].
- **Public Infrastructure Engineering Vulnerability Committee’s (PIVEC) Engineering Protocol** - consisting of a five step process for analyzing the engineering vulnerability of an individual infrastructure to current and future climate parameters such as extreme rainfall. PIVEC’s website [48] contains a series of case studies using the engineering protocols (e.g. an assessment of the City of Nelson’s (BC) stormwater management system (conducted by Focus Engineering [49])).
• **Canadian Climate Data and Scenarios (CCDS)** website - allows users to download GCM outputs from IS92a, SRES and AR4 (IPCC Fourth Assessment Report) as 20-year, 30-year or user-defined averages or as time series from 2010 to 2100 (model results from the CMIP5 archive employed in the IPCC 5th Assessment are expected to be made available soon) [50].

Many more resources are available at provincial levels, including:

• **The Ontario Centre for Climate Impacts and Adaptation Resources (OCCAR)**: provides information on the impact of climate change and adaptation resources for researchers and stakeholders [51]. OCCAR’s website contains a large number of links to climate data, datasheets, case studies, tools and frameworks (e.g. CCME’s Tools for Climate Change Vulnerability Assessments for Watersheds - prepared in 2013 [52]).

• **Atlantic Climate Adaptation Solutions Association (ACASA)**: a non-profit organization that was formed to coordinate project management and planning for climate change adaptation initiatives in Newfoundland and Labrador, Prince Edward Island, Nova Scotia and New Brunswick (supported through the Regional Adaptation Collaborative - a joint undertaking between Atlantic provinces and Natural Resources Canada, regional municipalities and other partners) [53]. Some select resources that are available on the ACASA’s website include:
  • “An Atlas of Climate Change for the Island of Newfoundland - derives from regional models in the North American Regional Climate Change Assessment Project” [54]. This is a report prepared to provide a “best-guess” at the climate Newfoundland can expect by mid-century. Although there can be considerable uncertainty with forecasting, the projections can provide reasonable guidance for short-term adaptation planning.
  • “It’s Time to Prepare Now - 7 Steps to Assess Climate Change Vulnerability in Your Community” – prepared by the Government of Newfoundland and Labrador with funding support through Natural Resources Canada’s Regional Collaborative Adaptation Program [35].
  • “Inland Flood Risk Mapping and Modeling for the Hillsborough River Basin, PEI” [55] – “from 2010 to 2012 three different rainfall events dropped 90 mm of rain in Charlottetown PEI, consequently overwhelming the stormwater drainage systems”. This particular project produced flood risk mapping and modeling for the Hillsborough River basin and provided recommendations that could guide infrastructure design and land use planning.
• **British Columbia’s Climate Action Toolkit**: provides a medium for sharing the latest news, best practices, practical advice, information and strategic guidance to help local governments in BC successfully adapt to a changing climate [56]. The website provides links to valuable resources such as:

  - “Stormwater Planning - A Guidebook for British Columbia” [57]. Rain gauge data for BC indicates changing precipitation frequency, intensity and duration in contrast to mid-20th century levels. Research has indicated that these changes in precipitation are the direct result of climate change. The stormwater planning guidebook provides an introduction to integrated stormwater management, and indicates how integrated stormwater management can be achieved at both the planning and site levels (using case study experience drawn from various local governments and developers in BC). Various strategies and the steps required to start or fund an integrated stormwater management plan or program are also covered in the guidebook.

  [Click here to access a presentation describing the flood risk mapping work for the Hillsborough River Basin [56].]

  [Click here to access BC’s Climate Action Toolkit [57].]
This document focused on the impact of a changing climate - particularly changes in extreme rainfall and associated implications on IDF curves and floodplain maps. The document introduces procedures by which general circulation models and methodologies for updating IDF curves and floodplain maps can be used as starting points for municipalities to assess climate change impacts and adaptation strategies.

The case studies presented herein aim to demonstrate a variety of available methods to characterize climate change impacts, and to provoke thinking about appropriate protocols for municipalities. The tools and resources for adaptation planning can aid municipalities in obtaining further information and guidance specific to their geographic area.

Many case studies employed CMIP3 projections, which are based on GHG emission scenarios. The next generation of GCM projections in CMIP5 uses representative concentration pathways and will provide projections on a decadal scale. Climate change adaptation strategies in Canada should move beyond CMIP3 and take advantage of CMIP5 (e.g. CGCM4 and CanESM2). This requires collaboration of academics and consultants to transfer the latest climate projections to accessible hydrologic and hydraulic data for municipalities.

Many municipalities want to have available, future IDF curves and use their existing skills to design infrastructure to be resilient to “this” future. However, even with the most sophisticated model, the updated IDF curves have substantial uncertainties. One approach is to simulate a range of different future conditions and IDF curves, and select the adaptation strategies that increase water system resilience in the face of all, or many, of the potential scenarios.
In addition to changes in extreme rainfall and temperatures, floodplain maps are subject to changes in snowmelt timing, coastal storms, and land use modifications. Updating floodplain maps based solely on IDF curves is not sufficient due to additional climate change impacts. Further research into confounding variables such as snowmelt, sea level rise, and land use modifications is required.

Technical guidance exists for updating IDF curves, such as CSA, PLUS 4013, 2012; however, application of such guidance is optional. Many practitioners use different models and apply the updated IDF curves regardless of model efficiency. A compulsory protocol, or a centralized database of updated IDF curves can aid in quality control and significantly increase confidence in climate change adaptation planning.


11. Intergovernmental Panel on Climate Change. https://www.ipcc.ch


47. ICLEI, Adaptation Library. http://www.adaptationlibrary.com
51. Ontario Centre for Climate Impacts and Adaptation Resources. http://www.climateontario.ca