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A web-based tool for the development of Intensity Duration Frequency curves under changing climate

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ABSTRACT

Intensity Duration Frequency (IDF) curves are among the most common tools used in water resources management. They are derived from historical rainfall records under the assumption of stationarity. Change of climatic conditions makes the use of historical data for development of IDFs for the future unjustifiable. The *IDF_CC*, a web based tool, is designed, developed and implemented to allow local water professionals to quickly develop estimates related to the impact of climate change on IDF curves for almost any local rain monitoring station in Canada. The primary objective of the presented work was to standardize the IDF update process and make the results of current research on climate change impacts on IDF curves accessible to everyone. The tool is developed in the form of a decision support system (DSS) and represents an important step in increasing the capacity of Canadian water professionals to respond to the impacts of climate change.

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Software availability

Name of software: IDF_CC
Developers: the authors
Year first available: 2015
Hardware required: A web based tool available for public use: www.idf-cc-uwo.ca
Cost: Free
Software and source code: They are released under the rules of the Canadian Water Network which allow for liberal use of the software

1. Introduction

Rainfall IDF curve information describes the frequency of extreme rainfall events for a variety of durations and intensities. An example extracted from Environment Canada, the national agency responsible for the development and dissemination of IDF curves in Canada, is shown in Fig. 1.

Rainfall IDF curves are used for a number of water management applications in Canada, including the design of major and minor stormwater management systems, sanitary sewers, detention ponds, culverts, bridges, dams, pumping stations, roads, and master drainage planning, among other applications (CSA, 2012). For example, typically stormwater management systems are designed to accommodate flows associated with 2–100 year return period events of 10 min–24 h durations (Watt and Marsalek, 2013).

According to the guideline for "Development, Interpretation and Use of Rainfall Intensity-Duration-Frequency (IDF) Information: A Guideline for Canadian Water Resources Practitioners" developed by Canadian Standards Association (CSA, 2012), the major reasons for increased demand for rainfall IDF information can be summarized as follows: (i) as the spatial heterogeneity of extreme rainfall patterns becomes better understood and documented, a stronger case is made for the value of "locally relevant" IDF information; (ii) as urban areas expand, making watersheds generally less permeable to rainfall and runoff, many older water systems fall increasingly into deficit, failing to deliver the services for which they were designed – understanding the full magnitude of this deficit requires information on the maximum inputs (extreme rainfall events) with which drainage works must contend; and (iii) climate change will likely result in an increase in the intensity and frequency of extreme precipitation events in most regions in the

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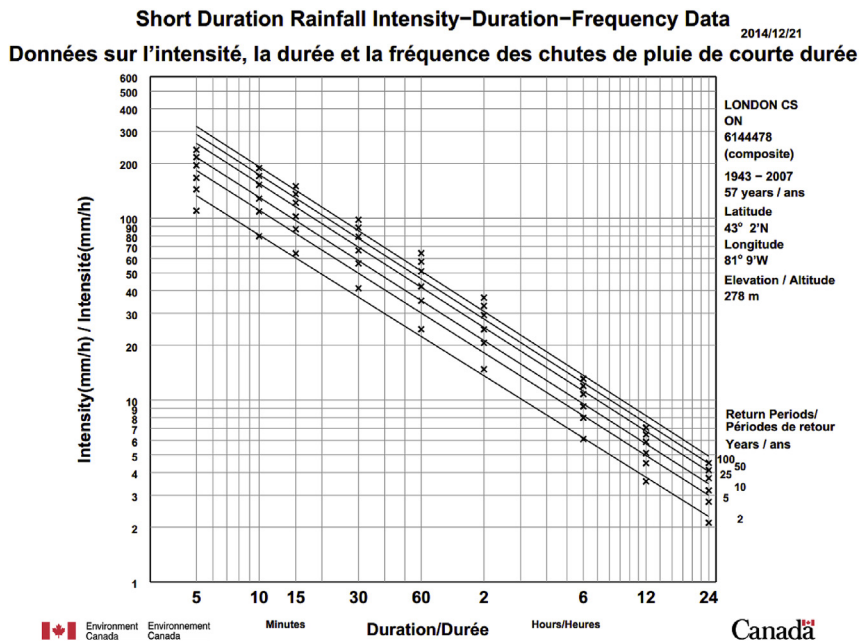


Fig. 1. An example of rainfall IDF curve - Toronto Pearson Int Airport (Environment Canada, 2015).

future (Trenberth, 2011).

One of the climate change impacts is intensification of the global hydrologic cycle, causing increased intensity of wet and dry extremes and accompanying floods and droughts (see for example Warren and Lemmen, 2014). For example in Canada from 1948 to 2012, annual mean temperatures have increased by 1.7 °C with observed trends in extreme rainfall more unclear (Bush et al., 2014). Many studies have suggested that climate change will have considerable impacts on extreme rainfall and associated management of water infrastructure (Cheng et al., 2014; Eum and Simonovic, 2011; Mladjic et al., 2011; Mailhot et al., 2010; Katz, 2010; Cunderlik and Simonovic, 2005; among others).

There has been a notable increase in damages associated with extreme rainfall events in urban municipalities (Insurance Bureau of Canada, (2015a,b). Some examples of the potential impacts of extreme rainfall events on Canada's large urban centres include: (a) Toronto July 8, 2013 - roughly 126 mm of rain fell over a 2-h period generating a total of $1.019 billion (2014 CAD) in losses to the Canadian insurance industry; Toronto August 19, 2005 - resulting in $732 million in losses to the insurance industry (2014 CAD) (Insurance Bureau of Canada, 2015a); and many other urban municipalities across the country, including Calgary, Saskatoon, Winnipeg, London, Burlington, Ottawa, Montreal and Moncton (Sandink, 2015).

Accessibility of data and information to assess adaptation options and availability of technical resources to implement adaptation options has been identified as a barrier to climate change adaptation (Crabbe and Robin, 2006). In addition, much of the work on the impacts of climate change on design standards has been conducted in the academia with limited availability of research to practitioners. Political factors may also inhibit application of design standards that reflect increasing intensity and frequency of extreme events. Further, there exists a level of uncertainty associated with future climate projections, creating difficulty in application of results. The issue is further aggravated by the presence of various uncertainties associated with GCM models and emission scenarios.

As a result of changing conditions, IDF values will optimally need to be updated more frequently than in the past and climate change scenarios are required in order to inform IDF calculations. In the presence of climate change, the theoretical distribution based on historical observations will be different for future conditions. Very limited information is available on how to bring climate change into the IDF calculations (Cheng and AghaKouchak, 2014; Hassanzadeh et al., 2014; Peck et al., 2012; Solaiman and Simonovic, 2011; Prodanovic and Simonovic, 2007; Mailhot et al., 2007) and even less how to implement updated IDF curves in practice (Sandink et al., 2016).

The rainfall "Intensity-Duration-Frequency under Climate Change" (*IDF_CC*) tool was designed to address this gap. The authors and supporting agencies believed that a freely available, computerized IDF update tool would aid in the selection of effective climate change adaptation options at the local level, advancing the decision making capabilities of municipalities and watershed management authorities.

The following sections of the paper provide a detailed description of the tool and methodological components implemented for the calculation of IDF curves under climate change. The description of the *IDF_CC* implementation follows. The next section provides a detailed guide for *IDF_CC* tool use. The paper ends with the discussion of lessons learned in the process and provides some conclusions based on the up-to-date use of the tool by general public.

2. *IDF_CC* tool description - methodology

This section presents the methodology used in the development of the *IDF_CC* tool. For complete information on all background methods used to generate IDF curves based on historical and GCM data, the user can consult the *IDF_CC* tool Technical Manual (Srivastav et al., 2014a). The manual is directly accessible through the tool as an active part of the help menu.

2.1. Intensity-duration-frequency curves

The typical establishment of rainfall IDF curves involves three

steps. First, a probability distribution function (PDF) or a cumulative distribution function (CDF) is fitted to each group comprised of the data value for any specific duration. Tipping bucket rain gage instruments are usually used to collect precipitation that corresponds to different time intervals (5, 10, 15 and 30 min and 1, 2, 6, 12 and 24 h). The maximum rainfall intensity for each time interval is related with the corresponding return period from the cumulative distribution function. For a given return period T (usually 2, 5, 10, 25, 50 and 100 years), the cumulative frequency F can be expressed as:

$$F = 1 - \frac{1}{T} \tag{1}$$

or

$$T = \frac{1}{1 - F} \tag{2}$$

If the cumulative frequency is known, the maximum rainfall intensity can be determined using an appropriate theoretical distribution function (such as Generalized Extreme Value (GEV), Gumbel, Pearson Type III, etc). The *IDF_CC* tool adopts Gumbel distribution for fitting the annual maximum precipitation (AMP) across Canada. The parameter estimation for the selected distributions is carried out using the method of moments. Recent analyses of data over the US, Australia and southern Europe indicate that Gumbel distribution doesn't always fit the data well. It is strongly suggested that the choice of distribution should be made to fit local conditions the best.

2.1.1. Gumbel distribution

The Gumbel distribution is recommended and widely used as the standard distribution by Environment Canada for all precipitation frequency analyses in Canada. The Gumbel distribution for annual extremes can be expressed as:

$$Q_t = \mu + K_T \sigma \tag{3}$$

where Q_t is the exceedance value, μ and σ are the population mean and standard deviation of the annual extremes; T is return period in years; and K_T is calculated according to:

$$K_T = \frac{\sqrt{6}}{\pi}\left[0.5772 + ln\left[ln\left(\frac{T}{T-1}\right)\right]\right]. \tag{4}$$

2.1.2. Parameter estimation

A common statistical procedure for estimating distribution parameters is the use of a maximum likelihood estimator or the method of moments. Environment Canada uses, and recommends the use of the method of moments technique to estimate the parameters of the Gumbel distribution (Hog et al., 1989). The *IDF_CC* tool uses the method of moments to calculate the parameters of the Gumbel distribution. In the case of the Gumbel distribution, the number of unknown parameters is equal to the mean and standard deviation of the sample mean. The first two moments of the sample data are sufficient to derive the parameters of the Gumbel distribution in equation (3).

2.1.3. Spatial interpolation of GCM data

GCM spatial grid size scales are too coarse for the application in updating IDF curves, and usually range above $1.5^\circ \times 1.5^\circ$. Therefore, GCM data has to be spatially interpolated for station coordinates for use in downscaling. The inverse square distance weighting method is applied in the *IDF_CC* tool. The nearest four GCM grid points to the station are used by weighting the precipitation value by the distance between the station and the GCM grid points. In this way the GCM grid points that are closer to the station are weighted more than the grid points further away. The mathematical expression for the inverse square distance weighting method is given as:

$$w_i = \frac{\frac{1}{d_i^2}}{\sum_{i=1}^{k}\frac{1}{d_i^2}} \tag{5}$$

where d_i is the distance between the *i*th GCM grid point and the station, and k is the number of nearest grid points (equal to 4 in the *IDF_CC* tool).

2.2. IDF curves under changing climate

The main assumption in the process of developing IDF curves is that historical series are stationary and therefore can be used to represent future extreme conditions; however under rapidly changing climatic conditions, IDF curves that rely only on historical observations will misrepresent future conditions. Global Climate Modeling (GCM) is one of the best ways to explicitly address changing climate conditions for future periods (i.e., non-stationary conditions). GCM models simulate atmospheric patterns on larger spatial grid scales (usually greater than 100 km) and hence are unable to represent regional scale dynamics accurately. In contrast, regional climate models (RCM) are developed to incorporate the local-scale effects and use smaller grid scales (usually 25–50 km) and require considerable computational time. Both GCM and RCM models have larger spatial scales than the size of most watersheds and provide climate data with insufficient temporal resolution for the computation of IDF curves.

The key input in GCMs for the generation of future conditions includes greenhouse gas emissions. Land-use, energy production, global and regional economies, and population growth also affect future climate scenarios and thus are incorporated into GCMs. The international climate modeling community has adopted four Representative Concentration Pathways (RCP) through the Intergovernmental Panel on Climate Change (Appendix A). These emission scenarios represent a range of climate change impacts, from low to high severity. The most severe impacts are predicted if no climate policy is adopted, while the lowest risks are associated with stringent requirements for climate policy that limit and reduce greenhouse gas emissions (van Vuuren et al., 2011).

According to the IPCC's fifth assessment report (IPCC, 2013), there are 42 GCMs developed by various climate research centres (Table AI.1, Annex I, IPCC, 2013). The *IDF_CC* tool adopts only 22 GCMs out of the 42 listed by the IPCC because: (i) not all the GCMs provide the three selected RCPs for future emission scenarios (i.e., RCP 2.6, 4.5 and 8.5); and (ii) there are some technical issues related to downloading (such as connection to remote servers or repositories) for some GCM models. Currently, the *IDF_CC* tool uses all 22 GCMs that have all the three future emission scenarios available for updating the IDF curves (Appendix B). Many GCMs have multiple runs available that are utilized to eliminate the impacts of initial boundary conditions on a GCM numerical solution procedure. All available runs are used by the *IDF_CC*. The tool applies a skill score algorithm to rank the GCMs provided in the tool. The *IDF_CC* tool adopts a skill score based on quantile regression (QRSS) proposed by Srivastav et al. (2015) to assess the performance of different GCM models available for use within the tool.

Typically, three steps are involved in a climate change impact

analysis process: (1) selection of climate model projections; (2) bias-correction; and (3) downscaling of climate model. Downscaling is a method used to estimate high spatial resolution climate information from low spatial resolution GCM output. Each step of the process offers various approaches widely discussed in the literature. Differences in the approaches of climate change impact assessment studies can be considered as the source of uncertainty associated with future climate projections. Some suggestions for reducing climate change impact assessment process uncertainty are provided in Gaur and Simonovic (2015). Their work also states, for the analyzed region of Canada, that the main source of uncertainty comes from the selection of the appropriate GCM. The second important source, at much lower level, is related to the selection of downscaling method.

The architecture of the *IDF_CC* tool and options selected in its implementation allow for effective consideration of uncertainties involved in updating IDF curves under changing climatic conditions.

2.2.1. Spatial and temporal downscaling of precipitation

The *IDF_CC* tool adopts an original equidistant quantile-matching (EQM) downscaling method for updating IDF curves, developed by Srivastav et al. (2014b). It captures the distribution of changes between the projected time period and the baseline period (temporal downscaling) in addition to spatial downscaling the annual maximum precipitation (AMP) derived from the GCM data and the observed sub-daily data. The quantile-mapping functions are directly applied to annual maximum precipitation (AMP) to establish the statistical relationships between the AMPs of GCM generated precipitation data and sub-daily observed (historical) data rather than using complete daily precipitation records. With respect to modeling complexities, this method is relatively simple and computationally efficient.

Fig. 2 explains the use of the EQM approach by *IDF_CC* tool for updating the IDF curves. The three main steps of EQM method are: (i) establishment of statistical relationship between the GCM generated AMPs and the observed precipitation for a station of interest (referred to as spatial downscaling); (ii) establishment of statistical relationship between the base period GCM AMPs and the future period GCM precipitation data (referred to as temporal downscaling); and (iii) establishment of statistical relationship between steps (i) and (ii) to update the IDF curves for future periods.

The detailed mathematical description of the EQM method is included in Appendix C and can be found in Srivastav et al. (2014a,b).

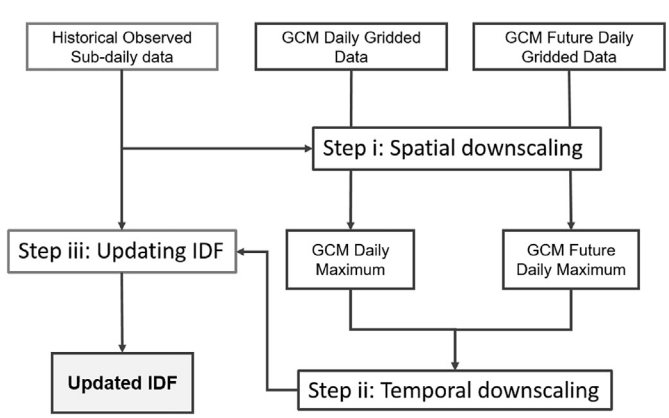


Fig. 2. Schematic representation of the equidistance quantile matching method implementation for updating IDF curves.

2.2.2. Selection of GCM

The *IDF_CC* tool offers multiple GCM choices for updating IDFs for future climate scenarios. The user can select all models (ensemble option) or an individual GCM, and projection period. The 22 models available in the *IDF_CC* Tool are listed in Appendix B. The available range for the time period is 2006–2100. To generate IDF curves that account for climate change, the user has three options: (i) select all models (ensemble option); (ii) select the model with the best skill score; or (iii) select any model from the list according to her/his own preferences. Users are encouraged to experiment with different models due to uncertainties associated with the choice of climate model.

The quantile regression skill score method (QRSS) was implemented within the *IDF_CC* tool to help users select GCMs for the development of future IDF curves. The approach has two main steps: (i) the quantile representation of the data; and (ii) development of the quantile regression lines representing the trends and heteroscedasticity across the quantiles. Therefore, the QRSS captures in the same time the distributional characteristics of the data and the error statistics. The detailed presentation of the QRSS is provided in Appendix D and can be found in Srivastav et al. (2014a, 2015). In order to avoid the risks of claiming a false precision in our ability to distinguish between credible and less credible model choices, which could lead to bad decisions by end users, IPCC typically suggests the use of multi-model ensembles in their uncertainty analysis. Thus, the *IDF_CC* tool provides an option to the user to generate the ensemble of all the 22 GCMs.

3. *IDF_CC* tool implementation

The *IDF_CC* tool was designed as a simple decision support system (DSS) to generate local IDF curve information that accounts for the impacts of climate change. It has been publicly accessible online as of March 1, 2015 at www.idf-cc-uwo.ca. The following section describes the components of the tool as implemented. For details of tool implementation and use, the user can consult the *IDF_CC* tool Users Manual (Schardong et al., 2014). The manual is directly accessible through the tool as an active part of the help menu.

3.1. IDF_CC main components

This section provides a brief description of the three major system components of the *IDF_CC* tool. These components include: (i) the user interface (UI); (ii) the model base; and (iii) the database and GCM file repository (Fig. 3).

3.1.1. User interface

The user interface (Fig. 4) provides for communication between the user and the other two DSS components: model- and database. The major parts of the user interface are: (i) Google Maps API™: the GIS component responsible for map operations; (ii) data manipulation: functionalities that allow users to manipulate stations and data; and (iii) results visualization: functionalities devoted to the presentation of results to the user (tables, equations, interactive graphs). Four different kinds of background maps can be used with the GIS interface: (i) simple background map (shown in Fig. 4); (ii) blue background map; (iii) Google's default background map; and (iv) arterial view background map – NASA imagery. The data input functions are built using *Excel like* spreadsheets with copy and paste functionalities. These characteristics facilitate the manipulation of larger datasets, such as extensive precipitation series. The series can be very easily imported and exported from *Excel* spreadsheets and text files. The same is true for the result screens with friendly

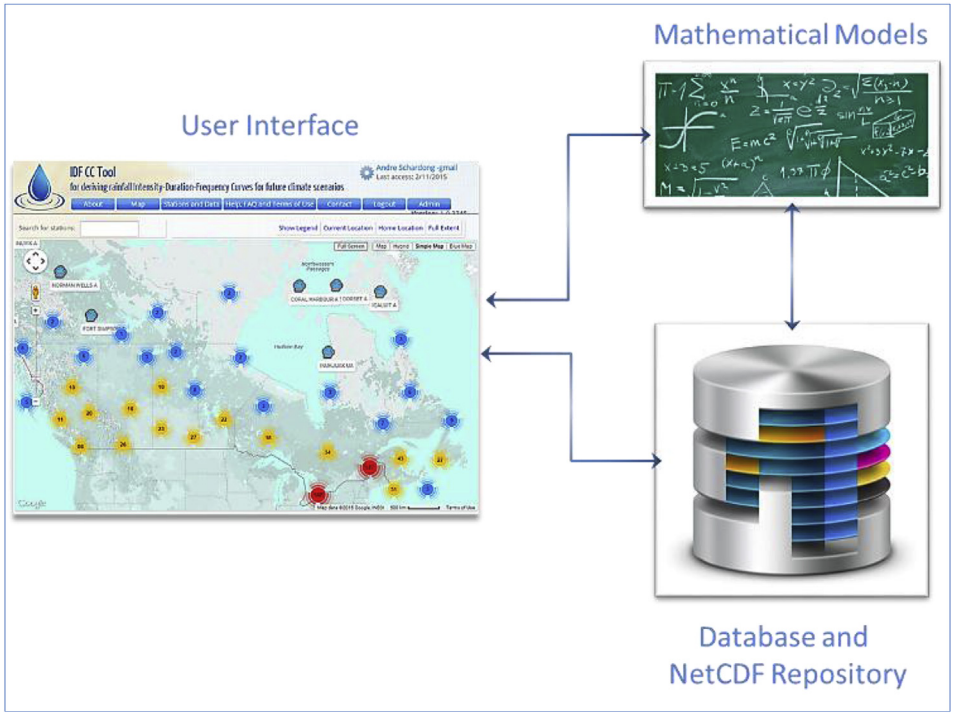


Fig. 3. Major *IDF_CC* tool components.

and interactive graphical presentation of the IDF curves and equations.

3.1.2. Modelbase

The *IDF_CC* tool mathematical models provide support for the calculations required to develop the IDF curves based on the historical data and to incorporate GCM output data into IDF curves. The following provides a list of models included in the model base of the *IDF_CC* tool:

- Statistical analysis algorithms: statistical analysis is applied to fit the selected theoretical distribution to both historical and future precipitation data. The distribution applied by the tool is Gumbel, which is fitted using method of moments (Srivastav et al., 2014a, Sections 2.1.1 and 2.1.2)
- Optimization algorithm: an algorithm used to fit the analytical relationships (equations) to the IDF curves. For each return period (T) an equation is fitted using differential evolution (DE) optimization algorithm introduced by Storn and Price (1997). This algorithm is used to find the coefficients of the IDF equation by minimizing the sum of the root square errors between the IDF curve and equation calculated values.
- IDF update algorithm: the equidistant quantile matching (EQM) algorithm is applied to the IDF updating procedure. This algorithm combines historical precipitation data with data from the GCM models to develop the IDF for future periods (Srivastav et al., 2014a, Section 2.2.1).
- GCM model skill score algorithm: the quantile regression skill score (QRSS) algorithm is applied for the selection of the GCM model from the 22 models available with the *IDF_CC* tool. The scores are updated when the station is created and the daily precipitation data is provided or updated. If the daily precipitation is not available the scores will not be calculated. For stations with calculated skill scores, the GCMs will be ranked accordingly and the score will be presented for each model. The lower the score, the better the rank. If no score is available the models will be listed in alphabetic order.

3.1.3. Database

The database stores user data, information related to stations and their data, and information from GCMs. The database management system (DBMS) used for the tool's database is the latest version of Microsoft Sql Server™ (MSSQL). Data are organized into relational tables to model aspects of reality, such as the availability of stations, their location and precipitation series, to support the calculation of IDF curves by the mathematical models. Besides tables, other important DBMS features used in the tool included: 1) *Views*, which allow the combination of several tables in a relational way and return aggregated data to the user interface; and 2) *Store procedures*, which include functions that provide great flexibility for developers, and are used to insert and recover data very efficiently from the database with less computational burden. The following information is stored in the database:

- User information: to access the *IDF_CC* tool's functionalities, the user must create an account and provide data that are stored in the database, including their name, email, institution/municipality, intent of use and password.
- Repository of the Environment Canada IDF curves: the *IDF_CC* tool's database stores the latest hydro-meteorological station information available from the Environment Canada stations across the country. There are approximately 700 stations throughout the country and roughly 500 of these have at least 10 years of observation data (the minimum length). Only publically available data from the EC stations are stored in the tool's database, including station name, location, coordinates, station ID, sub-daily AMP records and daily precipitation data (where available).

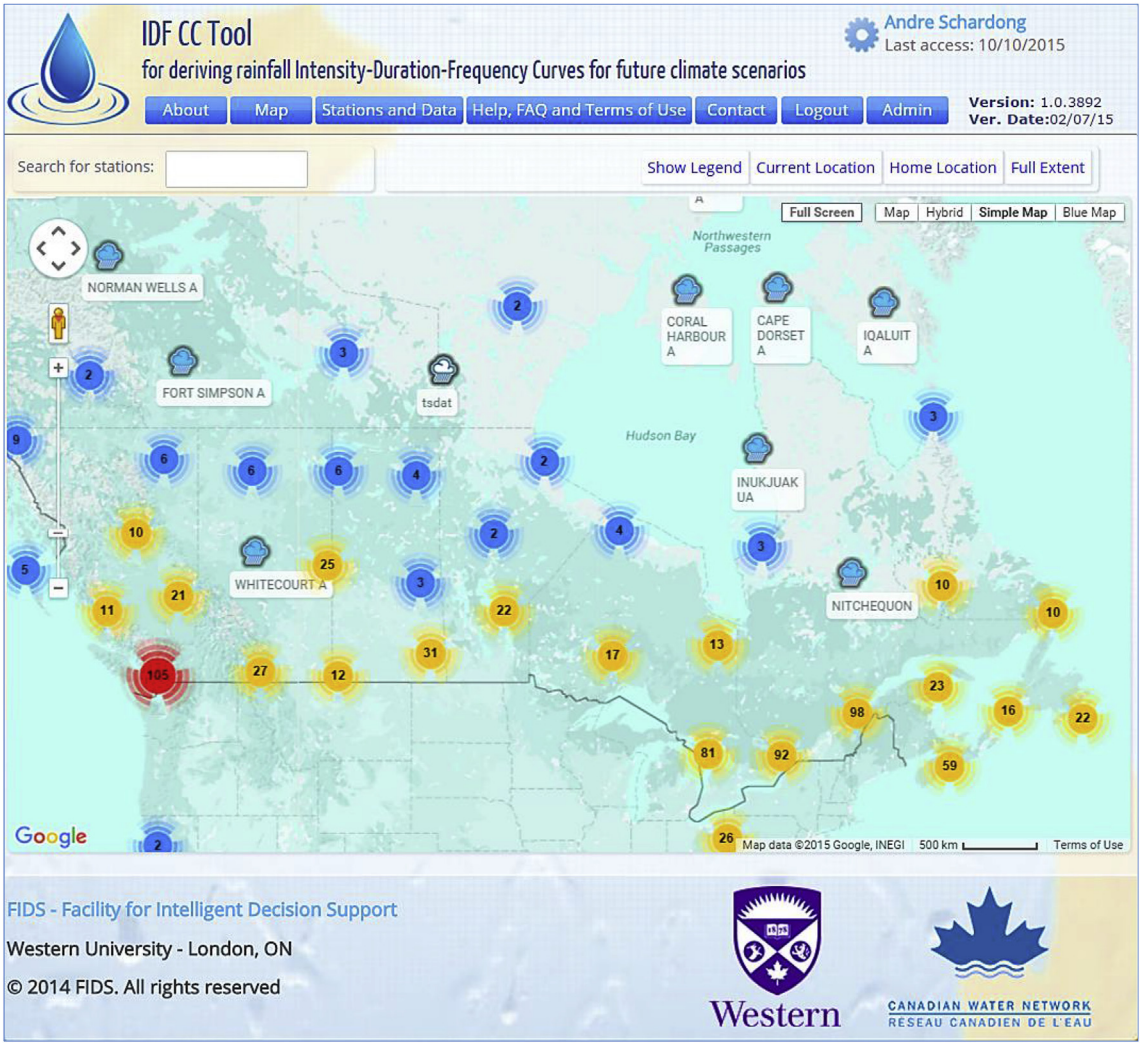


Fig. 4. The *IDF_CC* tool user interface.

- User provided stations and data: any registered user of *IDF_CC* can create stations and provide data for them. The type of data and input options are discussed in Section 4 of the paper. User-created stations can be shared among other users registered with the *IDF_CC* tool. Stations created by users will contain the same basic data as EC stations: name, ID, coordinates and location. The coordinates will allow the tool plot the station on the map with different colors for easier identification. Users are allowed to provide data for their station by including pre-processed sub-daily annual maximum precipitation (AMP) series or raw for-the-day-maximums series. The tool is able to identify the type of data provided and process the IDF curves calculation accordingly. There are several sub-daily durations that the user can choose from: 5, 10, 15, 20 and 30 min, 1, 2, 3, 6, 12, 18 and 24 h.
- Global Climate Models (GCM) output files: original GCM outputs are usually available in the netCDF format that is widely used for storing climate data. The direct use of netCDF with the web-based *IDF_CC* tool is not computationally efficient and would require a very large storage space. Therefore, the netCDF files are converted into a MSSQL database format that is more efficient for use with the tool's algorithms. The GCM data is available in a gridded format, meaning that for each grid point several precipitation series are available. These points cover the globe and are represented by a pair of coordinates (longitude and latitude). The database structure was created in order to allow the grid points be stored with geographic information and the associated series in tabular form. The selection of the grid points from the GCMs and associated series is done with the use of nearest neighbor query available in MSSQL, which adds to the tool's IDF updating procedure efficiency.
- Miscellaneous files: users can upload files that are related to a specific station. The files are also stored in the database and can be either text documents, spreadsheets and/or pdf files.

Data from GCMs stored in the database require up to 20 gigabytes of storage space. Data from hydro-meteorological stations, which is much less demanding, take up to 500 megabytes of server space. The miscellaneous files associated with the EC and user created stations require approximately 200 megabytes of storage space. Space required to store data from the stations is dynamic, and grows as users create new stations, input data series and upload files. Furthermore, space required to store GCM data will increase if new models became available and are included in the database.

3.2. IDF_CC technical implementation details

The tool was conceived as a web-based decision support system without the need for installation files, and is not operating system dependent. It was built for compatibility with major web-browsers and is mobile friendly. The major scientific/technical challenges associated with developing the *IDF_CC* tool were: (i) to create computationally efficient method for downscaling GCM data and updating IDF curves; and (ii) addressing complexity associated with large output files procedures by GCMs. The former was address by the implementation of the Equidistant Quantile Matching algorithm (EQM, Srivastav et al., 2014a) and the second, by converting GCM output series (netCDF files) into a MSSQL database integrated with the tool. The database that stores GCM data was fine-tuned to provide the necessary data series for the tool's mathematical models very efficiently. As a result, the updating procedures requires only seconds, even when the GCM ensemble option is selected.

The mathematical models and functions of the tool were written using the objected oriented C# language, which is part of Microsoft.Net Framework™. This programming language provides the required features to implement the EQM algorithm and all other codes used throughout the tool. The user interface uses a rich combination of technologies: Microsoft ASP .Net, HMTL5 (HyperText Markup Language version 5), CCS3 (Cascading Style Sheets, version 3), JavaScript, jQuery Framework and Google Maps API in order to support the GIS capabilities. A dedicated Windows based server is used to host the tool. The server is capable of handling up to 50 users at a time without significant loss of efficiency. The server is equipped with 16 GB ram memory and a 4-core Xeon processor.

3.3. Participation of stakeholders

Stakeholder involvement can serve to increase the quality of decision support systems (DSSs), increase the perceived legitimacy of DSS outputs and also reflects democratic principles. Importantly, stakeholder involvement can help ensure that the outputs of DSSs are used in the decision-making processes.

Specific strategies for stakeholder engagement in the development process for the *IDF_CC* and detailed description of the process and its results are provided in Sandink et al. (2016). The summary of the process is in Table 1.

The stakeholder engagement process applied in the development of the *IDF_CC* tool followed many of the tenants of best practices identified in the literature. While the engagement strategy was generally considered successful, long term funding issues as well as over- and under-representation of some stakeholder groups were weaknesses in the engagement process (Sandink et al., 2016).

4. *IDF_CC* tool use

The *IDF_CC* tool provides precipitation accumulation depths for a variety of return periods (2, 5, 10, 25, 50 and 100 years) and durations (5, 10, 15 and 30 min and 1, 2, 6, 12 and 24 h), and allows users to generate IDF curve information based on historical data, as well as future climate conditions that can inform infrastructure decisions. The *IDF_CC* tool allows users to select multiple future greenhouse gas concentration scenarios (RCPs) and apply results from a selection of 22 GCMs that simulate various climate conditions to local rainfall data. The summary of the procedure for the use of *IDF_CC* tool is illustrated in Fig. 5 (from Sandink et al., 2016). For details on tool use the user can consult the *IDF_CC* tool Users Manual (Schardong et al., 2014). The manual is directly accessible through the tool as an active part of the help menu.

4.1. IDF_CC tool use with historical data

The tool's database stores the latest hydro-meteorological station information available from Environment Canada. There are approximately 700 stations throughout the country and roughly 500 of these have at least 10 years of observation data (the minimum length required to generate reliable IDF curves).

To create IDF curves based on historical data using the tool, users complete the six steps as shown in Table 2. When the user selects a station and the "IDF, historical data" tab from the main menu (shown later in Fig. 9), the *IDF_CC* tool triggers a background calculation process mathematical models in the tool's model base. The steps performed in the background are as follows:

1) Read and organize data from the database for the selected station.
2) Data analysis (ignore negative and zero values) and extraction of yearly maximums.
3) Calculate statistical distribution parameters (Gumbel) using method of moments (see Section 2.1).
4) Calculate IDF (Section 2.1).
5) Fit interpolated equations to the IDF curve using Differential Evolution optimization algorithm (Section 3.1.2).
6) Organize data for display (tables, plots, and equations) (see Figs. 9–11).

4.2. IDF_CC tool use with GCM data

By selecting the "IDF under climate change" tab, the user can generate IDF curves that account for future climate conditions. To generate the updated IDF curves for future climate, the user can select all GCM models (ensemble option) or an individual GCM and projection period (shown later in Fig. 12). There are 22 models available in the *IDF_CC* tool listed in Appendix B. The available time period is 2006–2100.

A skill score procedure is implemented to assist in the selection of a GCM for each station (Section 2.2.2). The CGMs are listed in ascending order according to their skill score, with the best model listed first. In theory, the better the score the more suitable the model is for the particular station. With respect to GCM selection, to generate IDF curves that account for climate change, the user has three options: select all models (ensemble option), select the model with the best skill score, or select any model from the list of GCMs provided in the tool. The users are encouraged to test different models.

To create IDF curves based on the GCM data using the tool, users must complete the nine steps shown in Table 3. The *IDF_CC* tool can apply GCM data in two different ways to obtain the IDFs for future climatic conditions (Fig. 5). The first and more direct way is use of an existing station from Environment Canada as follows: (i) select a station; (ii) calculate the historical IDF (intermediate step) that can be used for comparison with the IDF for the future climatic conditions; and (iii) select the GCM model and projection period and generate the IDF curve for future climatic conditions.

The second way of using the tool for development of IDF curves with GCM data includes one additional step where the user creates her/his own station by providing the necessary station information and precipitation data (for details of creating a station please see Schardong et al., 2014, Section 2.6.1). The remaining steps are the same as those required to create IDF curves based on historical information.

Table 1
Stakeholder engagement strategies for the development of the *IDF_CC* Tool (from Sandink et al., 2016).

Engagement step	Description
Defining the problem/assessing the need	• Early work with City of London and Upper Thames Region Conservation Authority (local watershed management agency) on updating IDF curves and incorporating climate change into IDF curves • Early work with Insurance Bureau of Canada (Canadian P&C insurance industry) on Municipal Risk Assessment Tool, including updating and incorporating climate change into IDF curves for multiple Canadian urban municipalities • Presentation of London and IBC work to technical audiences and municipal and regional decision makers • Audiences identified need for standardized, accessible approach to updating and incorporating climate change impacts into local IDF curves
Project initiation	• Application for Canadian Water Network knowledge mobilization funding required support from practicing community (i.e., municipal stormwater management professionals)
Developing support/partnerships with target stakeholders	• Developing support from multiple urban municipalities for CWN proposal • Support letters received from storm and wastewater management departments at Cities of Toronto, Mississauga, Hamilton, London, Kingston and Region of Peel, Ontario, setting the stage for further collaboration with municipal stakeholders throughout the development process
Early, in-depth collaboration with cities of Toronto and Hamilton	• Collaboration with stormwater management staff from cities of Toronto and Hamilton, Ontario for early and in-depth review of tool methods • Early collaborators provided with the initial iteration of the IDFCC tool to allow testing within their respective stormwater management departments • Meetings and frequent communication by email and phone to allow development team to receive feedback from early collaborators
National workshops	• Three national stakeholder workshops designed to inform, educate and engage stakeholders in draft iterations of the IDFCC tool • Users asked to perform a number of tasks using the DSS and report back to the development team with questions, comments and suggestions for improvement
National webinars	• Two national webinars with large attendance (>200 participants) to inform stakeholder communities • One webinar conducted before workshops, one conducted at end of the project
Publishing *IDF_CC* tool	• Publishing *IDF_CC* tool on the internet, open to all members of public • Providing contact information for questions and feedback about the *IDF_CC* tool • Providing limited support for responding to questions and feedback

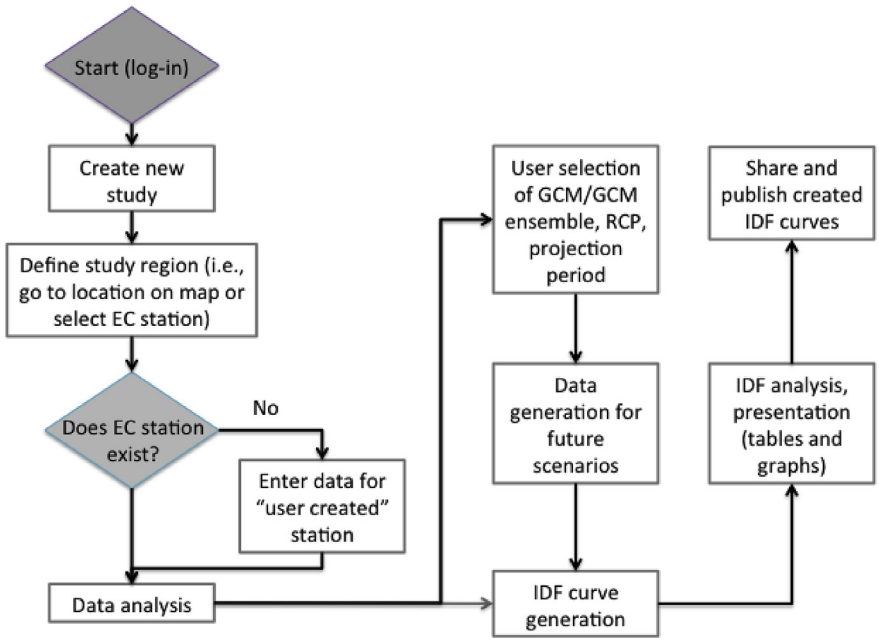


Fig. 5. *IDF_CC* tool use flowchart (after Sandink et al., 2016).

Table 2
Use of the tool to create IDF curves based on historical data.

1.Create a user account
2.Sign into the Tool
3.Select the map option to view a map of all of the available rain stations in the Tool (see Fig. 1).
4.Zoom into the area of their choice.
5.Click on the rain station of interest. After clicking on a station, a window will open that provides rain station information, including the length of the data record.
6.Users will then have the option of viewing an IDF curve based on historical data.

Table 3
Use of the tool to create IDFs from GCM data.

To create IDF curves for future conditions, first follow steps 1 through 5 listed in Table 1. Following these first five steps:
6.Select the "IDF under climate change" tab
7.Select a projection period – the Tool allows user to select a 20 year project period for any time between 2006 and 2100
8.Select a GCM or the GCM ensemble option
9.Press the "Calculate IDF for future" button. The Tool will then automatically downscale GCM results and apply GCM results to the local rain station data.

For generation of IDF curves under future climate conditions, the background computational procedure conducted by the *IDF_CC* tool includes the following steps:

1) Extract precipitation data series from GCM grid points for the selected station (e.g., using Canadian CanESM2 model, 80 series have to be extracted).
2) Organize data and extract yearly maximums.
3) Apply equidistant quantile matching (EQM) downscaling algorithm (Appendix C)
4) Estimate distribution parameters and calculate IDF curves for each future emission scenario (RCPs and their runs).
5) Generate average IDF from the results of step 4 for each RCP.
6) Organize data for display (tables, plots, and equations, uncertainty range plot).

4.3. Details of the IDF_CC tool use

This section provides a detailed description of the main steps for *IDF_CC* tool use illustrated with the tool's interface screen captures. The intention here is to document the process for using the tool and assist the reader in starting to use the publicly available web based tool.

The tool provides the following menu options as shown in Fig. 6:

- About: description of the tool and additional resources.
- Map: this option presents the map and stations from Environment Canada and those created by the user.
- Stations and Data: this menu option opens list of stations created by the user and allows them to select data, upload companion files, share with other users, delete and create stations. This page also allows users to see all stations from Environment Canada, as well as open the IDF screen.
- Help, FAQ and Terms of Use: provides access to help documents including the Users Manual, Technical Manual, and other references, frequently ask questions section – FAQ and terms of use of the *IDF_CC* tool.
- Contact: contact form for sending comments, reporting bugs and issues to tool administrator(s).
- Logout: disconnects the user's session.
- Admin Menu: this item is only available to *IDF_CC* tool's administrator(s).

After creating a user account and logging in, the *IDF_CC* tool allows users to select their location of interest by zooming in on the map as shown in Fig. 7. Alternatively, users may search for and select a local Environment Canada hydro-meteorological station using a text search box (Fig. 8). Users have the option of selecting one of the 700 pre-loaded EC hydro-meteorological stations and creating and entering data for their own "user created" stations.

Users are able to view IDF curves based on the historical records for pre-loaded and user created stations using the tool, in both table (Fig. 9) and plot formats (Fig. 10). Users are also able to view interpolation equations (Fig. 11) used for generating IDF curves based on historical Environment Canada or user entered rain station data.

The IDF curves can be developed using (a) historical data or (b) GCM projected data. For the development of IDF curves based on the GCM projections (Fig. 12) the user can select a combination of projection period (any 20 year period between 2006 and 2100), one of 22 GCMs for which data has been stored in the database or median results from an ensemble of the 22 GCMs. The results for each GCM model are automatically provided for three future emission scenarios (RCP2.6, RCP4.5 and RCP8.5). A "skill score" is also provided as an accessible assessment of the ability of particular GCMs to provide the most representative projections for the hydro-meteorological station under consideration (Srivastav et al., 2015). Users are encouraged to generate multiple future IDF scenarios using different combinations of GCMs or the GCM ensemble option.

Outputs for IDF curves based on future climate scenarios are provided in tabular and graphical formats, similar to the approach shown in Figs. 9–11. Tables and graphs are automatically generated that provide results for each of the three available RCPs. Results are provided for 5 min to 24 h durations, and for 1 in 2 to 1 in 100 year return periods. In addition a comparison graph can be generated to quickly assess the impact of different RCPs on outputs for a particular station (Fig. 13). All the results, including plots and tables, can be exported for use outside of the tool. Users also have the option of exporting future IDF results in *csv* file format for analysis outside of the tool. Exported future IDF results contain outputs reflecting analysis from all 22 GCMs, GCM model runs and RCPs available within the tool.

Exported results from the tool provide for easy additional analyses required by the users. One of the major issues in the use of the tool is how to address and communicate the uncertainty associated with the choice of GCMs (Gaur and Simonovic, 2015). The flexible tool architecture provides the users with the opportunity to make a choice among using ensemble of GCMs, using one GCM of choice or using GCM recommended by skill score analysis. In order to illustrate the level of uncertainty associated with various choices, an additional feature is available within the *IDF_CC* tool – presentation of the Box plot generated from running all available GCMs, for each emission scenarios using all available model runs. Fig. 14 shows a Box plot graph of the 2 year return period IDF curve for the London (Ontario) station and RCP2.6. Selected presentation effectively communicates the extent of uncertainty associated with the developed IDF curve and can be used by the user in the follow up decision making process.

Fig. 6. *IDF_CC* tool main menu options.

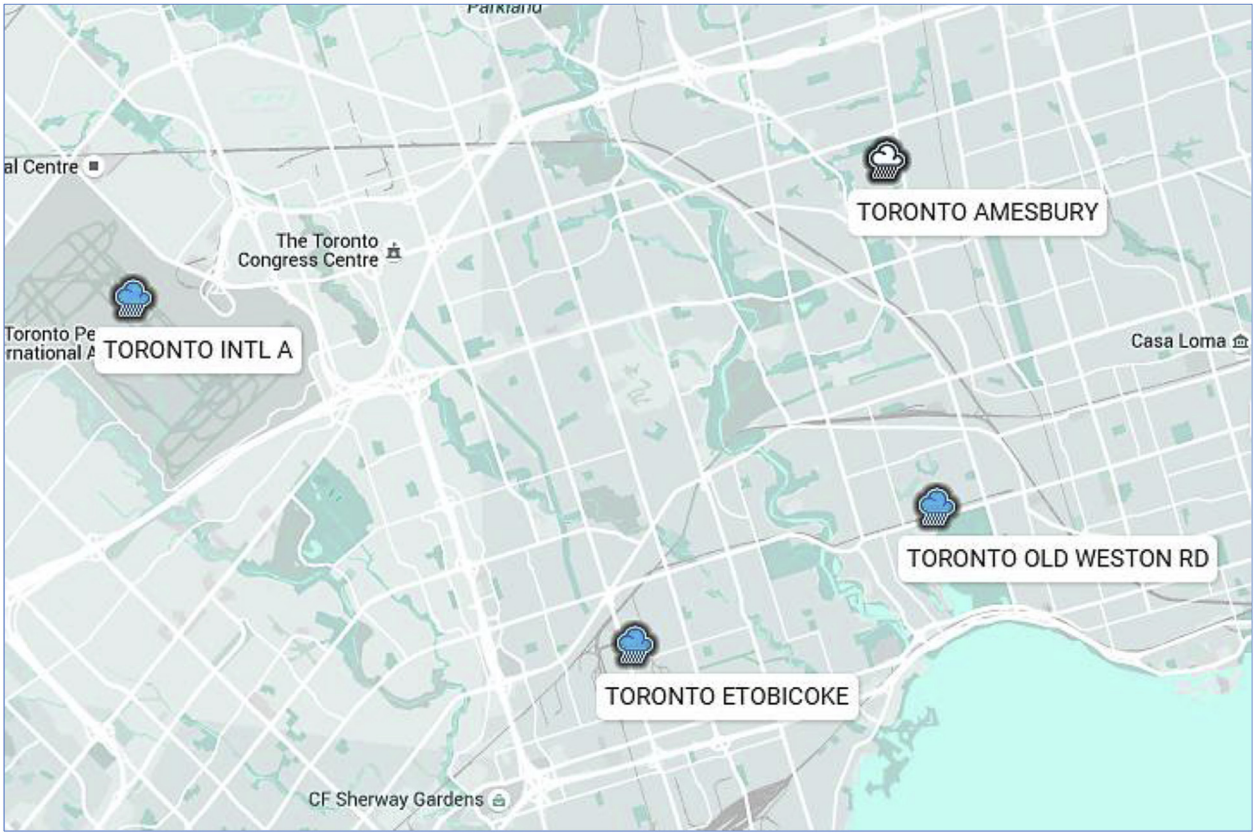


Fig. 7. Stations map: Environment Canada (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

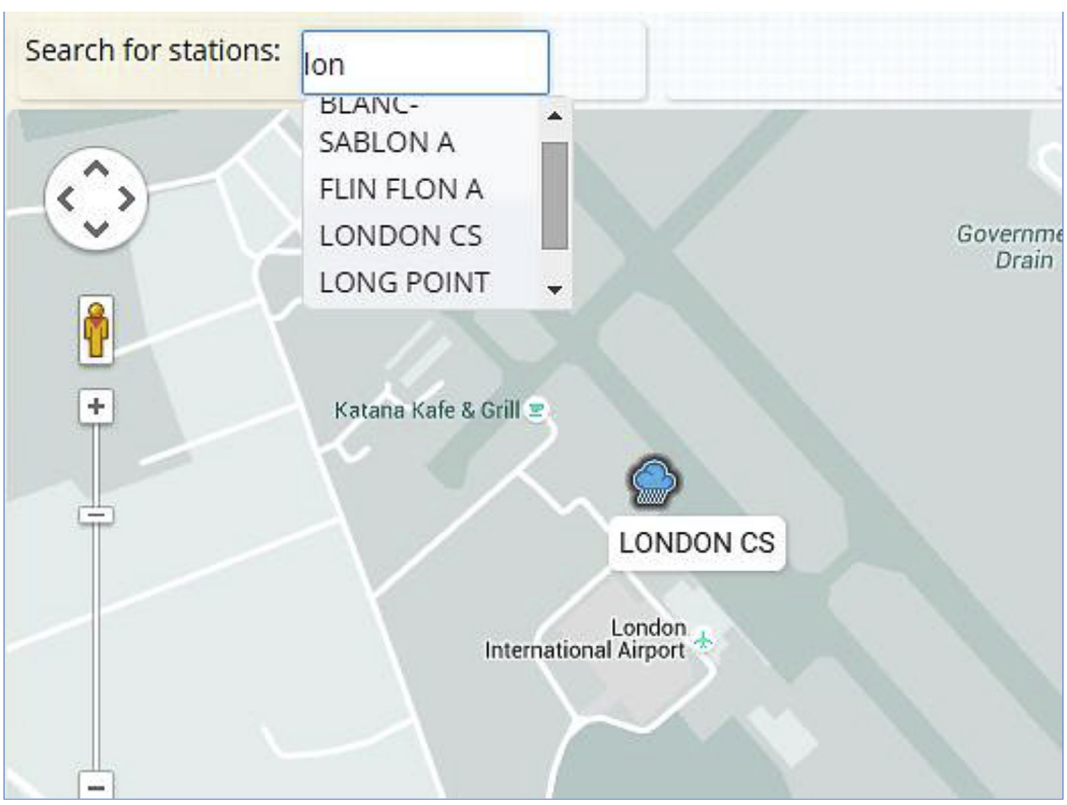
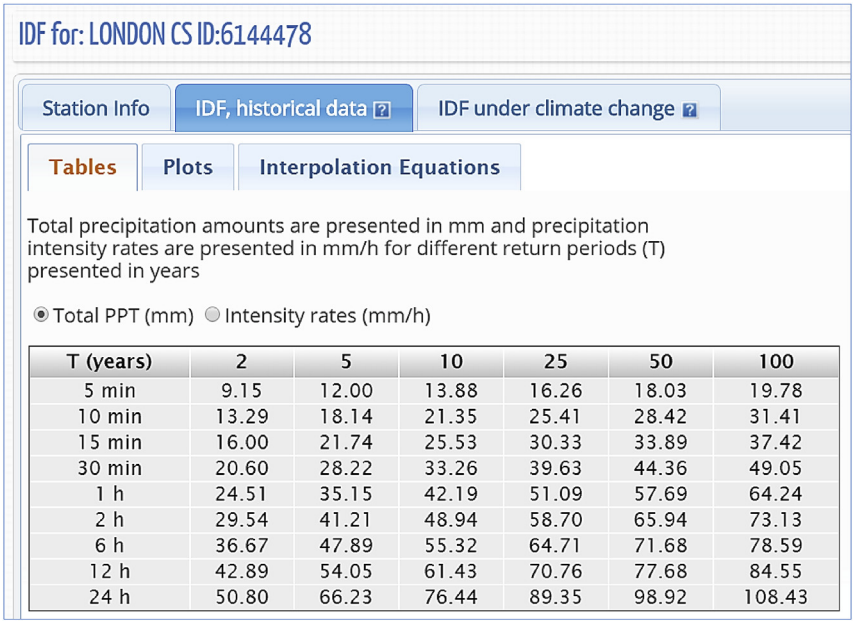


Fig. 8. Text box search for station and user provided (in green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



T (years)	2	5	10	25	50	100
5 min	9.15	12.00	13.88	16.26	18.03	19.78
10 min	13.29	18.14	21.35	25.41	28.42	31.41
15 min	16.00	21.74	25.53	30.33	33.89	37.42
30 min	20.60	28.22	33.26	39.63	44.36	49.05
1 h	24.51	35.15	42.19	51.09	57.69	64.24
2 h	29.54	41.21	48.94	58.70	65.94	73.13
6 h	36.67	47.89	55.32	64.71	71.68	78.59
12 h	42.89	54.05	61.43	70.76	77.68	84.55
24 h	50.80	66.23	76.44	89.35	98.92	108.43

Fig. 9. Total precipitation IDF table.

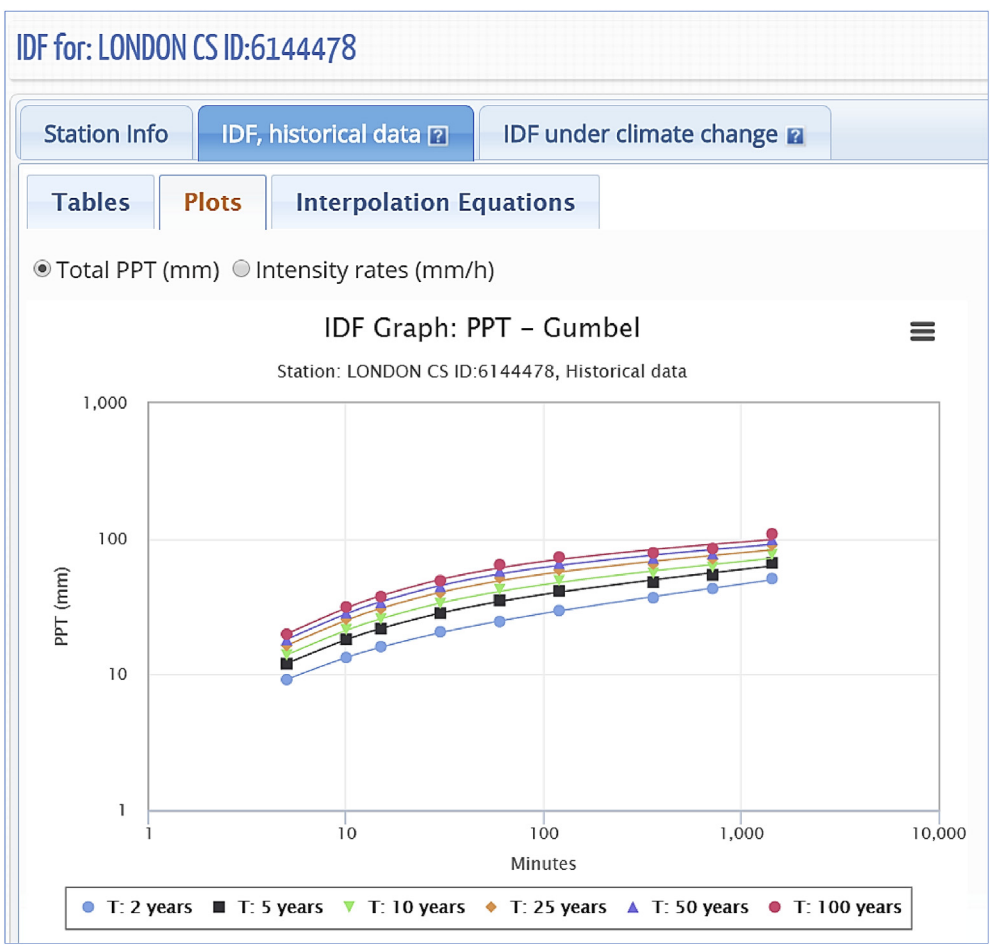
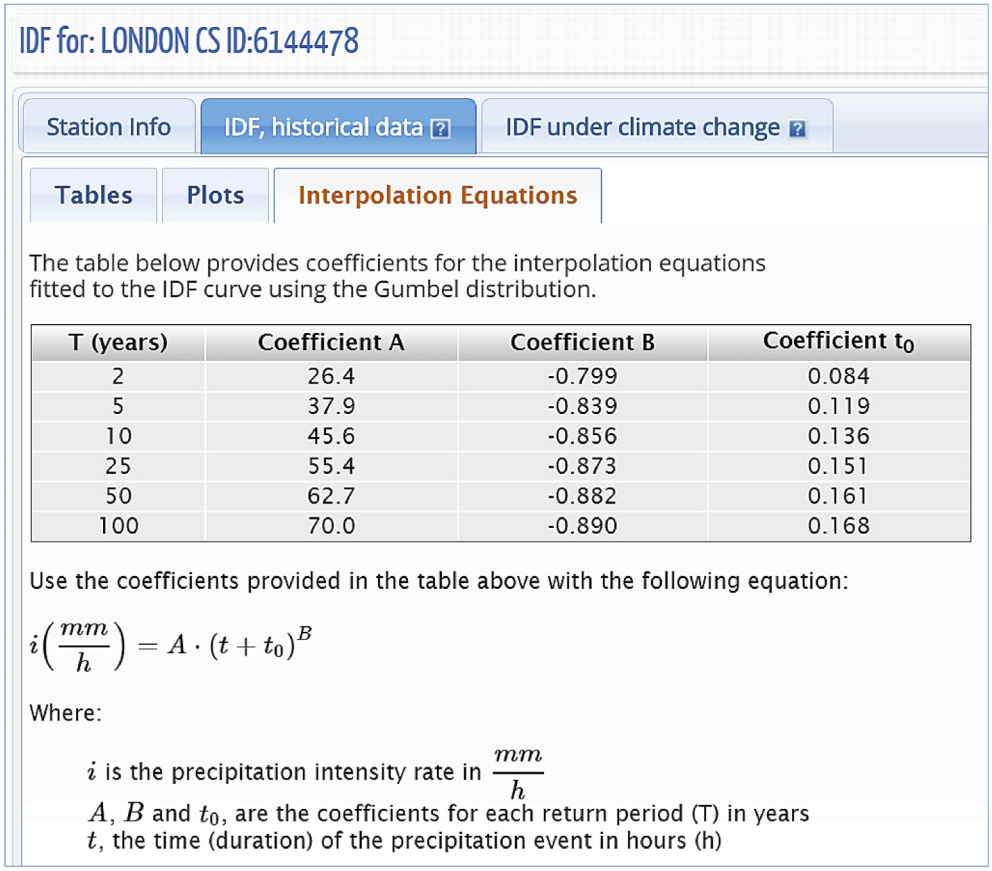


Fig. 10. Total precipitation IDF graphs.



T (years)	Coefficient A	Coefficient B	Coefficient t_0
2	26.4	-0.799	0.084
5	37.9	-0.839	0.119
10	45.6	-0.856	0.136
25	55.4	-0.873	0.151
50	62.7	-0.882	0.161
100	70.0	-0.890	0.168

Fig. 11. Fitted IDF equation.

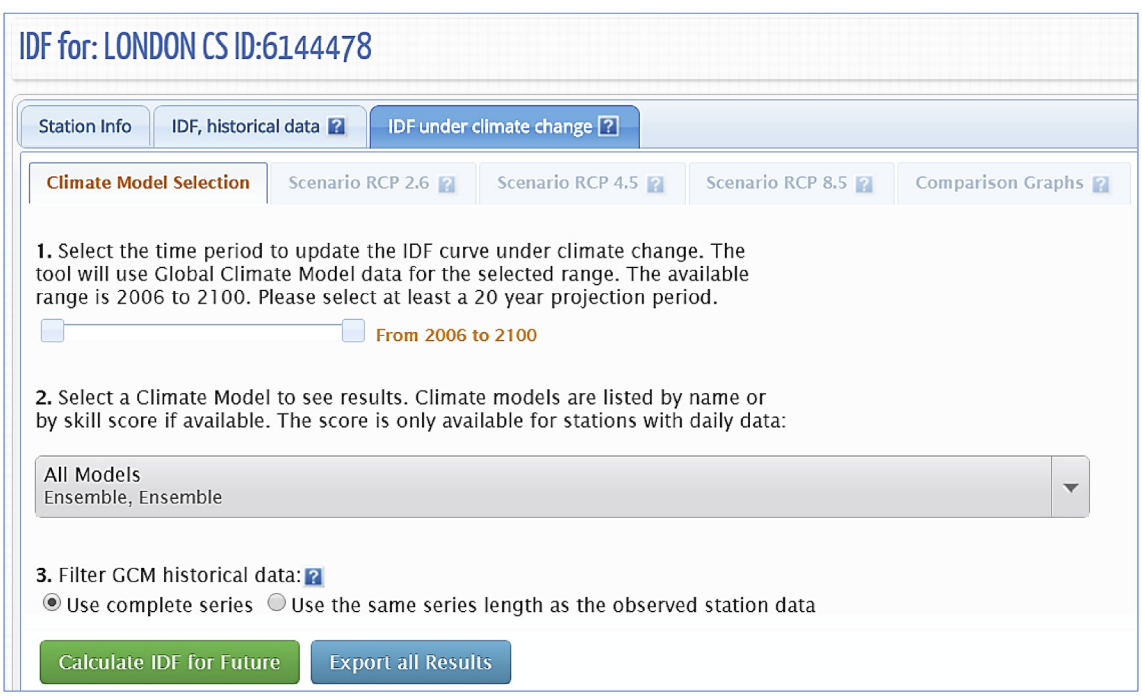


Fig. 12. Screen for selection of the GCM model and time period.

Fig. 13. A comparison graph showing IDF curves for various RCPs and GCM model ensemble.

5. Conclusions

There are many implications of extreme rainfall events, including issues related to water quality, infrastructure management and public safety. Older subdivisions have not been designed to accommodate extreme rainfall events, and increasing urbanization is creating more impervious surfaces. Inadequate infrastructure investment and maintenance further increases exposure of urban communities to flooding. Rainfall intensity-duration-frequency (IDF) curves are used for a number of water management applications in Canada, including the planning, design, operation and maintenance of stormwater management systems, wastewater systems, stormwater detention ponds, culverts, bridges, dams, pumping stations, roads and master drainage planning.

IDF curves have traditionally been developed based on the assumption of stationarity (use of historical data to develop statistics that give an indication of the likelihood of future extreme rainfall events). However, it is widely acknowledged that climate conditions of the past are no longer indicative of future climate, calling into question the reliability of this assumption.

Climate change will result in intensification of the global hydrologic cycle, causing increased intensity of wet and dry extremes and accompanying floods and droughts (Warren and Lemmen, 2014). One of the most significant expected impacts of climate change in Canada is an increase in the intensity and frequency of extreme weather events. This means that infrastructure built to manage 1-in-100 year rainfall events based on existing IDF curves may only be able to manage 1-in-30 year events in the future (Peck et al., 2012). The result will be infrastructure that will not perform as intended, creating considerable economic implications for existing and planned water management infrastructure across Canada.

The process of updating and incorporating climate change impacts into local IDF curves is highly technical. The lack of locally relevant climate change impact information has been noted as a challenge that is difficult to overcome in many municipalities, including those with very high adaptive capacity. The *IDF_CC* tool was designed to allow water managers, municipal infrastructure professionals, provincial and federal government agencies, researchers, consultants and non-profit groups to quickly develop estimates related to the impact of climate change on IDF curves for almost any local rain monitoring station in Canada.

The rainfall "Intensity-Duration-Frequency under Climate Change" (*IDF_CC*) tool has been designed and implemented as a freely available, computerized IDF update tool that aids in the selection of effective climate change adaptation options at the local

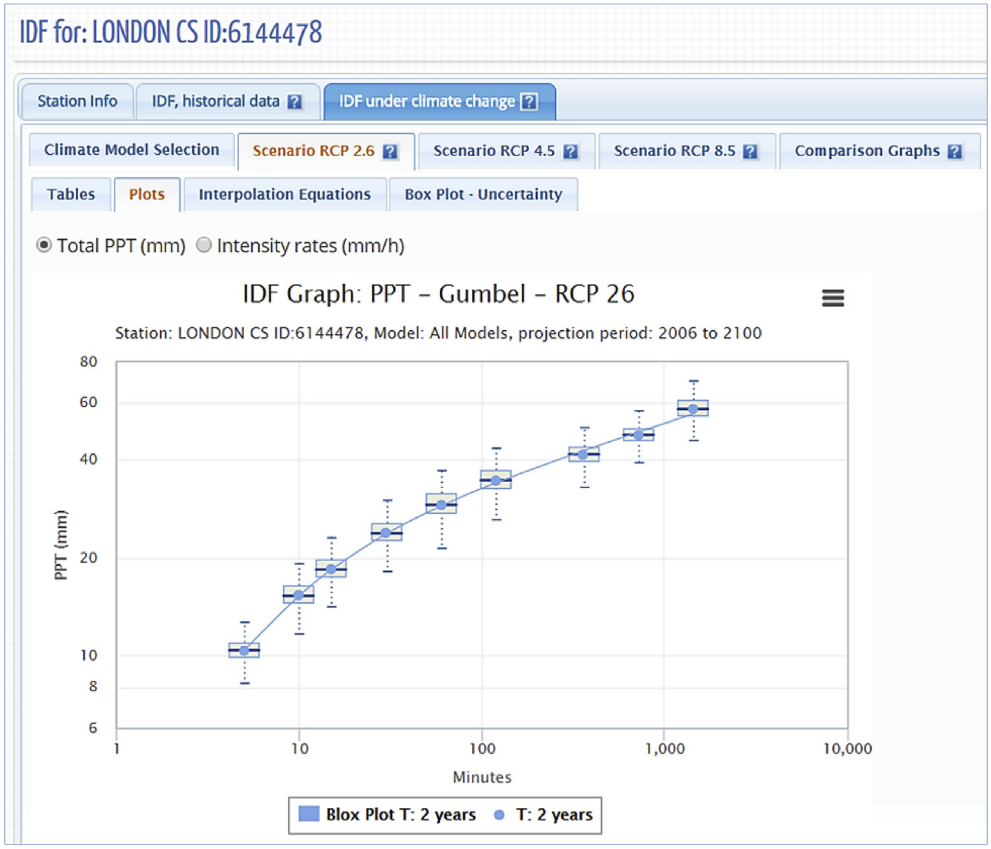


Fig. 14. A Box plot of uncertainty analysis of the 2 year IDF curve for London station and RCP2.6.

level. The tool can be accessed through the project website: www.idf-cc-uwo.ca. It has been made public on March 1, 2015 and currently is being used by more than 277 registered users (as of August 2015).

Since the publication of the tool in March of 2015 a number of observations (lessons learned) have been made:

1. The "knowledge mobilization" orientation and support for stakeholder involvement (partnership) is a strong point of the *IDF_CC* tool design. The number of participants in the process (webinars, workshops and direct communications) indicates a high relevance and usability of the tool for a large, national stakeholder community.
2. Flexible design architecture of the tool allows for easy modification, improvement and/or evolution of the knowledge (models and procedures) incorporated in the tool.
3. The *IDF_CC* was developed for Canada. However, the design concept and procedures used in the development can be easily implemented at any other location. The team members were already involved in discussions for the development of similar tools for Taiwan, China and Brazil.
4. The quality of the IDF curves is strongly correlated with the quality of the available data. Therefore, any improvement in data availability and quality will be reflected in the quality of IDF curves developed using the tool.
5. The *IDF_CC* tool was primarily developed for municipal stakeholders. It was the great surprise to the development team that representatives from private consulting firms dominated the stakeholder involvement process used in the development of the tool. Furthermore, private consultants currently comprise the majority of registered tool users.
6. Project funding was available only for the development of the tool. Lack of funds (a) to continue monitoring the tool's use, (b) to provide the assistance in the tool use, (c) to allow updating the tool's data- and model bases, and (d) to support adaptation of the tool into activities of Canadian water management community, is the main shortcoming of the presented work.

While many municipalities and water managers across Canada understand the need to update IDF curves to reflect the impacts of climate change, there has been limited support available up to now. The *IDF_CC* tool represents an important step in significantly increasing the capacity of Canadian water management professionals to respond to the impacts of climate change.

Acknowledgments

Funding provided by the Canadian Water Network (grant KA2013-5 to the first author) and the Institute for Catastrophic Loss Reduction for the development of this project was greatly appreciated. Collaboration with several municipal water management professionals from the cities of Toronto and Hamilton, notably David Kellershohn and Nahed Ghbn, was invaluable. Finally, the authors would like to thank the professionals who are currently using the tool, attended the workshops and participated in the webinars for their thoughtful feedback on the *IDF_CC* tool.

Appendix A. Description of RCPs.

RCP	Description	CO_2 concentration (ppm) equivalent	Pathway	Scenario severity
2.6	A peak in radiative forcing of approximately 3 W/m^2 before 2100, declining to 2.6 W/m^2 by 2100. Also referred to as RCP3PD (Representative Concentration Pathway 3 Peak-Decline).	Peak of ~490 and then decline by 2100	Peak and decline	Lowest
4.5	Stabilization at 4.5 W/m^2 by 2100 without overshoot.	650 (stabilized after 2100)	Stabilization without overshoot	Medium-low
6.0	Stabilization at 6 W/m^2 by 2100 without overshoot.	850 (stabilized after 2100)	Stabilization without overshoot	Medium-high
8.5	Rising pathway resulting in 8.5 W/m^2 by 2100. Radiative forcing continues to rise beyond 2100.	>1370 in 2100	Rising	Highest

Appendix B. List of GCM models included with the *IDF_CC* tool.

Country	Centre acronym	Model	Centre name	Number of runs (*)	GCM resolutions (Lon. vs Lat.)
China	BCC	bcc_csm1_1	Beijing Climate Center, China Meteorological Administration	1	2.8 × 2.8
China	BCC	bcc_csm1_1 m	Beijing Climate Center, China Meteorological Administration	1	
China	BNU	BNU-ESM	College of Global Change and Earth System Science	1	2.8 × 2.8
Canada	CCCma	CanESM2	Canadian Centre for Climate Modeling and Analysis	5	2.8 × 2.8
USA	CCSM	CCSM4	National Center of Atmospheric Research	1	1.25 × 0.94
France	CNRM	CNRM-CM5	Centre National de Recherches Meteorologiques and Centre Europeen de Recherches et de Formation Avancee en Calcul Scientifique	1	1.4 × 1.4
Australia	CSIRO3.6	CSIRO-Mk3-6-0	Australian Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence	10	1.8 × 1.8
USA	CESM	CESM1-CAM5	National Center of Atmospheric Research	1	1.25 × 0.94
China	LASG-CESS	FGOALS_g2	IAP (Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China) and THU (Tsinghua University)	1	2.55 × 2.48
USA	NOAA GFDL	GFDL-CM3	National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamic Laboratory	1	2.5 × 2.0
USA	NOAA GFDL	GFDL-ESM2G	National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamic Laboratory	1	2.5 × 2.0
United Kingdom	MOHC	HadGEM2-AO	Met Office Hadley Centre	1	1.25 × 1.875
United Kingdom	MOHC	HadGEM2-ES	Met Office Hadley Centre	2	1.25 × 1.875
France	IPSL	IPSL-CM5A-LR	Institut Pierre Simon Laplace	4	3.75 × 1.8
France	IPSL	IPSL-CM5A-MR	Institut Pierre Simon Laplace	4	3.75 × 1.8
Japan	MIROC	MIROC5	Japan Agency for Marine-Earth Science and Technology	3	1.4 × 1.41
Japan	MIROC	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology	1	2.8 × 2.8
Japan	MIROC	MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology	1	2.8 × 2.8
Germany	MPI-M	MPI-ESM-LR	Max Planck Institute for Meteorology	3	1.88 × 1.87
Germany	MPI-M	MPI-ESM-MR	Max Planck Institute for Meteorology	3	1.88 × 1.87
Japan	MRI	MRI-CGCM3	Meteorological Research Institute	1	1.1 × 1.1
Norway	NOR	NorESM1-M	Norwegian Climate Center	3	2.5 × 1.9

*Number of runs for precipitation data. Models might have multiple runs in order to eliminate the impact of initial conditions on model performance.

Appendix C. Description of the EQM downscaling method.

The steps involved in the algorithm are as follows:

(i) Extract sub-daily maximums from the observed data at a given location (i.e., maximums of 5min, 10min, 15min, 1hr, 2hr, 6hr, 12hr, 24hr precipitation data):

$$X_{\max}^{STN} = \begin{bmatrix} X_{1,\max}^{STN,5\min} & X_{1,\max}^{STN,10\min} & \cdots & X_{1,\max}^{STN,24hr} \\ X_{2,\max}^{STN,5\min} & X_{2,\max}^{STN,10\min} & \cdots & X_{2,\max}^{STN,24hr} \\ X_{3,\max}^{STN,5\min} & X_{3,\max}^{STN,10\min} & \cdots & X_{3,\max}^{STN,24hr} \\ \vdots & \vdots & \vdots & \vdots \\ X_{N,\max}^{STN,5\min} & X_{N,\max}^{STN,10\min} & \cdots & X_{N,\max}^{STN,24hr} \end{bmatrix} \quad (1)$$

where $X_{i,\max}^{STN,j}$ represents the maximum sub-daily precipitation at a

station (STN) for jth duration in ith year; and N is the total number of years.

(ii) Extract daily (24hr) maximums for the historical base period from the selected GCM model

$$X_{\max}^{GCM} = \begin{bmatrix} X_{1,\max}^{GCM} \\ X_{2,\max}^{GCM} \\ X_{3,\max}^{GCM} \\ \vdots \\ X_{N,\max}^{GCM} \end{bmatrix} \tag{2}$$

where $X_{i,\max}^{GCM}$ represents the maximum daily precipitation from GCM model in ith year and N is the total number of years (the same time span from the historical/observed data is used).

(iii) Extract daily maximums from the RCP Scenarios (i, (iii) Extract daily maximums from the RCP Scenarios (i.e., RCP2.6, RCP4.5, RCP8.5) for the selected GCM model:

$$X_{\max}^{GCM,Fut} = \begin{bmatrix} X_{1,\max}^{GCM,RCP26} & X_{1,\max}^{GCM,RCP45} & X_{1,\max}^{GCM,RCP85} \\ X_{2,\max}^{GCM,RCP26} & X_{2,\max}^{GCM,RCP45} & X_{2,\max}^{GCM,RCP85} \\ X_{3,\max}^{GCM,RCP26} & X_{3,\max}^{GCM,RCP45} & X_{3,\max}^{GCM,RCP85} \\ \vdots & \vdots & \vdots \\ X_{N_F,\max}^{GCM,RCP26} & X_{N_F,\max}^{GCM,RCP45} & X_{N_F,\max}^{GCM,RCP85} \end{bmatrix} \tag{3}$$

where $X_{\max}^{GCM,Fut}$ represents the maximum daily precipitation for the future scenarios considered; and N_F is the total number of years considered for future time period.

(iv) Fit a probability distribution to the daily maximums from GCM model (each of the sub-daily maximum series for the observed data and daily maximums for the future scenarios):

$$PDF^{GCM} = f\left(\theta^{GCM} \Big/ X_{\max}^{GCM}\right) \tag{4}$$

$$PDF_j^{STN} = f\left(\theta^{STN,j} \Big/ X_{\max}^{STN,j}\right) \tag{5}$$

$$PDF^{GCM,Fut} = f\left(\theta^{GCM} \Big/ X_{\max}^{GCM,Fut}\right) \tag{6}$$

where PDF stands for probability distribution function, f () is the function, θ is the parameter of the fitted distribution.

(v) The cumulative probability distribution of the GCM and the sub-daily series are equated to establish a statistical relationship between them and obtain GCM modeled sub-daily series $Y_{\max,j}^{GCM}$ using the principle of quantile based mapping. This is *spatial downscaling* of the data from the GCM daily maximums to observed sub-daily maximums:

$$Y_{\max,j}^{STN} = CDF\left(\left(invCDF\left(X_{\max}^{GCM} \Big/ \theta^{GCM}\right)\right) \Big/ \theta^{STN,j}\right) \tag{7}$$

where $Y_{\max,j}^{STN}$ is statistically downscaled sub-daily maximum series for jth duration; CDF stands for cumulative probability distribution function; and invCDF stands for inverse CDF.

(vi) Establish a similar quantile-mapping statistical relationship that models the change between the current GCM maximums and future GCM maximums. This is *temporal downscaling* of the data from the projected GCM simulations of daily maximums to baseline GCM daily:

$$Y_{\max}^{GCM,Fut} = CDF\left(\left(invCDF\left(X_{\max}^{GCM} \Big/ \theta^{GCM}\right)\right) \Big/ \theta^{GCM,Fut}\right) \tag{8}$$

where $Y_{\max}^{GCM,Fut}$ is quantile matching between the baseline period and the projection period.

(vii) Find an appropriate function to relate $Y_{\max,j}^{STN}$ and $X_{\max}^{GCM}$. Literature suggests that in most cases the relation is observed to be linear. It is evident from the Gumbel CDF that it results in a linear equation when equating the two CDFs. It is important to note that there is no guarantee that the use of other distribution functions would result in the similar linear first order equations:

$$Y_{\max,j}^{STN} = f\left(X_{\max}^{GCM}\right) \tag{9}$$

$$Y_{\max,j}^{STN} = a_1 \times X_{\max}^{GCM} + b_1 \tag{10}$$

(viii) Find an appropriate function to relate $Y_{\max}^{GCM,Fut}$ and $X_{\max}^{GCM}$:

$$Y_{\max}^{GCM,Fut} = f\left(X_{\max}^{GCM}\right) \tag{11}$$

$$Y_{\max}^{GCM,Fut} = a_2 \times X_{\max}^{GCM} + b_2 \tag{12}$$

(ix) To generate future maximum sub-daily data, combine above equations into:

$$X_{\max,j}^{STN,future} = a_1 \times \left[\frac{X_{\max}^{GCM,future} - b_2}{a_2}\right] + b_1 \tag{13}$$

(x) Generate IDF curves for the future sub-daily data and compare the same with the historically observed IDF curves to obtain the change in intensities.

A MATLAB code for updating the IDF curves using the equidistance quantile matching algorithm is available in Srivastav et al. (2014a).

Appendix D. Description of the QRSS skill score calculation method.

The steps involved in calculation of QRSS are as follows:

Let the historical observed precipitation data X^H, the GCM model data X^G and the quantiles A be represented as:

$$X^H = \left\{x_1^H, x_2^H, \ldots, x_t^H\right\} \tag{1}$$

$$X^G = \left\{x_1^G, x_2^G, \ldots, x_t^G\right\} \tag{2}$$

$$A = \{\alpha_1, \alpha_2, \ldots, \alpha_n\} \tag{3}$$

where the superscript H and G represent historical and GCM model data, respectively; and n is the number of quantiles considered.

For a given quantile level α, the linear quantile function is given as:

$$\widehat{X}^{H,\alpha} = a^{\alpha,H} t + b^{\alpha,H} \quad \forall t = 1, 2, 3, \ldots, T \tag{4}$$

$$\widehat{X}^{G,\alpha} = a^{\alpha,G}t + b^{\alpha,G} \quad \forall t = 1,2,3,\ldots,T \tag{5}$$

where a and b represent the coefficients of linear quantile function as slope and intercept, respectively at αth quantile; t is the time variable; and T is the total time period.

It is expected that the GCM models should be able to generate variable values close to the historical observed data. However, the models are not perfect and exhibit systematic bias and variability in the generation process. The degree of bias between the GCM model data set and the observed data set is calculated as:

$$S_{bias} = \sum_{i=1}^{k} \sqrt{\frac{1}{T}\sum_{i=1}^{T}\left[\widehat{X}_i^{H,\alpha_i} - \widehat{X}^{G,\alpha_i}\right]^2} \tag{6}$$

where k is the total number of quantiles used in the study.

The above equation is simply the root mean square error between the quantile lines of observed and GCM data. The bias at various quantile levels (representing the distributional characteristics of the data) is estimated by using equation (5). In order to address the issue of difference in trends, in this study we propose to use a penalty function, which would assign a penalty to equation (5) whenever the trends are different from the historical observed trends. The similarity of the slopes of quantile lines are calculated using a Student's t-test. The following steps compare the two slopes:

1. To statistically test two slopes are equal, the null hypothesis H_o^α and the alternate hypothesis H_1^α, for a given quantile α is defined as

$$H_o^\alpha : a^{\alpha,H} = a^{\alpha,G} \;\; i.e., \;\; a^{\alpha,H} - a^{\alpha,G} = 0 \tag{7}$$

$$H_1^\alpha : a^{\alpha,H} \neq a^{\alpha,G} \;\; i.e., \;\; a^{\alpha,H} - a^{\alpha,G} \neq 0 \tag{8}$$

2. Assuming that the difference between the two slopes has normal distribution, the test statistics is given as

$$t^\alpha = \frac{a^{\alpha,H} - a^{\alpha,G}}{s_{a^{\alpha,H}-a^{\alpha,G}}} \text{with } (\mathrm{n1} + \mathrm{n2} - 4) \text{ degrees of freedom} \tag{9}$$

where $s_{a^{\alpha,H}-a^{\alpha,G}}$ is the standard error of estimated slopes; n_1 and n_2 is the length of the observed and GCM observed data.

3. The standard error of the slopes is calculated as

$$s_{a^{\alpha,H}-a^{\alpha,G}} = \sqrt{s^2_{a^{\alpha,H}} + s^2_{a^{\alpha,H}}} = s_{res}\sqrt{\frac{1}{s_H^2(n_1-1)} + \frac{1}{s_G^2(n_2-1)}} \tag{10}$$

where s_{res} is the pooled residual variance, which is equal to

$$s_{res} = \frac{(n_1-2)s^2_{res,H} + (n_2-2)s^2_{res,GCM}}{(n_1-2)+(n_2-2)} \tag{11}$$

4. If the value of t in equation is greater than the Student's t-distribution, the null hypothesis is accepted, i.e., the slopes of the observed data and the GCM data for a given quantile are equal. The t-statistics for the given quantile line is simplified as

$$t^\alpha = \begin{cases} 0 \; \textit{if null hypothesis is accepted} \\ 1 \; \textit{otherwise} \end{cases} \tag{12}$$

The effect of the dissimilarity of slopes between the observed data and the GCM data is obtained by multiplying a penalty factor to the overall bias. Equation (6) can be rewritten as

$$SS = S_{bias} \times \xi \tag{13}$$

where ξ is the penalty factor based on t-test and is obtained as

$$\xi = 1 + \frac{1}{k}\sum_{i=1}^{k} t^{\alpha_i} \tag{14}$$

where k is the total number of quantiles lines used in the study.

The skill scores obtained in the equation (8) are normalized using inter-quantile range of the observed distribution, which could provide interpretation of scores in terms of the overall spread of the distribution of observations. The quantile regression based skill scores is given as

$$S_{QR} = \frac{SS}{IQ_H} \tag{15}$$

where IQ_H is the inter-quantile range of the historical observations.

The best GCMs should have the S_{QR} values close to zero.

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