

## Urban Water Infrastructure Design in the Climate Change Context: Advances and Challenges in Modeling of Extreme Rainfall Processes

Conception des ouvrages hydrauliques urbains dans le contexte des changements climatiques : avancées et défis dans la modélisation des processus de précipitations extrêmes

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### RÉSUMÉ

Il est nécessaire d'évaluer les impacts possibles des changements climatiques sur la pluie de conception pour améliorer la conception des ouvrages hydrauliques urbains. Cette pluie de conception est couramment estimée à partir des relations intensité-durée-fréquence (IDF) en un site donné. Par conséquent, l'élaboration de ces relations dans le contexte des changements climatiques a été reconnue comme l'une des tâches les plus difficiles de la pratique actuelle de l'ingénierie. Le principal défi est de savoir comment établir les liens entre les projections données par les modèles climatiques à l'échelle globale et les pluies extrêmes observées en un site. Si ces liens pouvaient être établis, les conditions de changement climatique projetées par ces modèles pourraient alors être utilisées pour prédire les variations des pluies extrêmes locales et des caractéristiques de ruissellement associées. Ainsi, différentes approches de mise à l'échelle ont été proposées pour décrire ces liens. Par conséquent, l'objectif principal du présent article est de fournir un aperçu de certains progrès récents et des lacunes des méthodes de mise à l'échelle existantes. En particulier, une procédure innovante de mise à l'échelle statistique a été élaborée pour modéliser les processus de pluies extrêmes pour diverses échelles temporelles en se basant sur le modèle de valeur extrême généralisée d'invariance d'échelle. Les résultats d'une application numérique utilisant des données de pluies extrêmes provenant de 39 stations à travers le Canada et des outputs de 21 modèles climatiques ont indiqué la précision et la fiabilité de la méthode de mise à l'échelle proposée.

### ABSTRACT

There exists an urgent need to assess the possible climate change impacts on the design storm for improving the design of urban water infrastructures. This design storm is commonly estimated from the intensity-duration-frequency (IDF) relations at the location of interest. Consequently, the derivation of IDF relations in the climate change context has been recognized as one of the most challenging tasks in current engineering practice. The main challenge is how to establish the linkages between the climate projections given by climate models at global/regional scales and the observed extreme rainfalls at a given local site. If these linkages could be established, then the projected climate change conditions given by climate models could be used to predict the resulting changes of local extreme rainfalls and related runoff characteristics. Hence, different downscaling approaches were proposed to describe these linkages. Therefore, the overall objective of the present paper is to provide an overview of some recent progress and shortcomings of existing downscaling methods. In particular, an innovative statistical downscaling procedure was developed for modeling extreme rainfall processes over a wide range of temporal scales using the scale-invariance Generalized Extreme Value (GEV) model. Results of an illustrative application using historical extreme rainfall data from 39 stations located across Canada and simulation outputs from 21 climate models have indicated the accuracy and reliability of the proposed scale-invariance GEV downscaling method.

### KEYWORDS

Design storm, Climate change, Downscaling methods, IDF relations, Urban infrastructure design.

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## 1 INTRODUCTION

Extreme rainfalls for short time scales (less than one day) are commonly used for estimating the “design storm” for the design of various urban infrastructures. More specifically, the design storm is computed from the “intensity-duration-frequency” (IDF) relations, which provides extreme rainfall intensities for various durations and return periods at a given site of interest (Willems et al. 2012; CSA 2019). In current engineering practice, the IDF relations are derived based on statistical frequency analyses of available annual maximum (AM) rainfall series for different durations. However, these AM rainfall records for sub-daily durations are often limited or unavailable at the location of interest while those for the daily scale are widely available. Hence, it is necessary to develop new methods for modeling extreme rainfall processes over a wide range of time scales such that information related to sub-daily extreme rainfalls could be inferred from the available daily extreme rainfalls.

Furthermore, climate change has been recognized as having a profound impact on the hydrologic cycle. In particular, the intensity and frequency of extreme storm events in most urban regions in Canada might be likely increased in the future. Hence, there exists an urgent need to assess the possible climate change impacts on these extreme events for improving the design of urban water infrastructures. The main challenge is how to establish the linkages between the daily climate change projections at coarse-grid global/regional scales given by Global/Regional Climate Models and the observed extreme rainfalls at finer time scales for a given local site. If these linkages could be established, then the projected climate change conditions given by climate models could be used to predict the resulting changes of local extreme rainfall and related runoff characteristics.

Consequently, in the last decades, different downscaling methods have been developed for establishing these linkages for various impact studies. These downscaling approaches can be grouped into two main categories: dynamical downscaling (DD), based on high resolution regional climate models (RCMs), and statistical downscaling (SD) (Nguyen and Nguyen 2008). In the DD approach, RCMs today can downscale Global Climate Model (GCM) output to resolutions of up to a few kilometers. In the SD methods, statistical models are developed to link large-scale climate predictors to historical observations of the rainfall process at a given location of interest. In particular, SD techniques are quite popular for various types of impact assessment studies since they could be adapted to the specific climatic conditions for a location of interest. However, since DD and SD methods have different associated skills, it is recommended that the best approach for impact and adaptation studies should be based on the combination of these two approaches (CSA 2019).

Canada has significant investments in urban water infrastructures such as storm drainage, and flood control systems. These infrastructures have reduced the vulnerability of the cities, but at the same time could make them more vulnerable to climate extremes, due to the lack of consideration of what might occur when the design criteria are exceeded. Consequently, research on developing innovative approaches for limiting and adapting climate change impacts on urban water infrastructures is highly critical due to substantial investments involved.

In view of the above-mentioned issues, the overall objective of the present research is to focus on the development of a novel statistical modeling method for describing accurately the linkage between global/regional climate change projections to the observed daily and sub-daily extreme rainfalls at a local site. Illustrative applications using climate simulations from different climate models and historical extreme rainfall records available across Canada are presented to indicate the feasibility, accuracy, and robustness of the proposed statistical modeling approach.

## 2 STATISTICAL MODELING OF EXTREME RAINFALL PROCESSES IN THE CLIMATE CHANGE CONTEXT

The proposed statistical modeling approach consists of two steps. The first step is to develop a temporal scale-invariance Generalized Extreme Value (GEV) model for describing the distribution of extreme rainfalls over a wide range of time scales (e.g., from several minutes to one day). The cumulative distribution function (CDF) of the GEV model is given as follows:

$$F(x) = \exp \left[ - \left( 1 - \frac{\kappa(x-\xi)}{\alpha} \right)^{\frac{1}{\kappa}} \right] ; \quad (\kappa \neq 0) \quad (1)$$

in which  $\xi$ ,  $\alpha$ , and  $\kappa$  are the location, scale, and shape parameters, respectively. The quantile  $X_T$  for a given return period  $T$  can be obtained using the following expression:

$$X_T = \xi + \frac{\alpha}{\kappa} \{1 - [-\ln(F(x))]^\kappa\} \quad (2)$$

For a simple scaling process, it can be shown that the parameters of the GEV model for two different time scales  $t$  and  $\lambda t$  are related as follows (Nguyen and Nguyen, 2020):

$$\alpha(\lambda t) = \lambda^\eta \alpha(t) \quad (3)$$

$$\xi(\lambda t) = \lambda^\eta \xi(t) \quad (4)$$

$$\kappa(\lambda t) = \kappa(t) \quad (5)$$

$$X_T(\lambda t) = \lambda^\eta X_T(t) \quad (6)$$

Hence, based on Eqs. (3)-(6), it is possible to derive the GEV distribution of extreme rainfalls for sub-daily scales from those for longer durations.

The second step is to develop the spatial downscaling procedure for linking the global/regional-scale daily climate projections given by climate models to the daily extreme rainfalls at a given local site. Two methods can be used for describing the linkage between the regional extreme rainfalls  $\hat{X}$  and the at-site extreme rainfalls  $X_i$ . The first method is based on the use of the scaling factor  $\eta_i$  as shown by the following equation:

$$X_i(F) = \eta_i \cdot \hat{X}(F) \quad (7)$$

in which  $\eta_i = \mu_i/\hat{\mu}$  is the scaling factor at site  $i$ ;  $\mu_i$  and  $\hat{\mu}$  are the computed sample means of the daily extreme rainfalls at the local site of interest  $i$  and at the grid containing that site, respectively. The second method utilizes a bias correction function  $e(F)$  to correct the differences between the empirical cumulative distribution functions (ECDF) of regional and at-site daily extreme rainfalls as follows (Nguyen and Nguyen 2020):

$$X_i(F) = \hat{X}(F) + e(F) \quad (8)$$

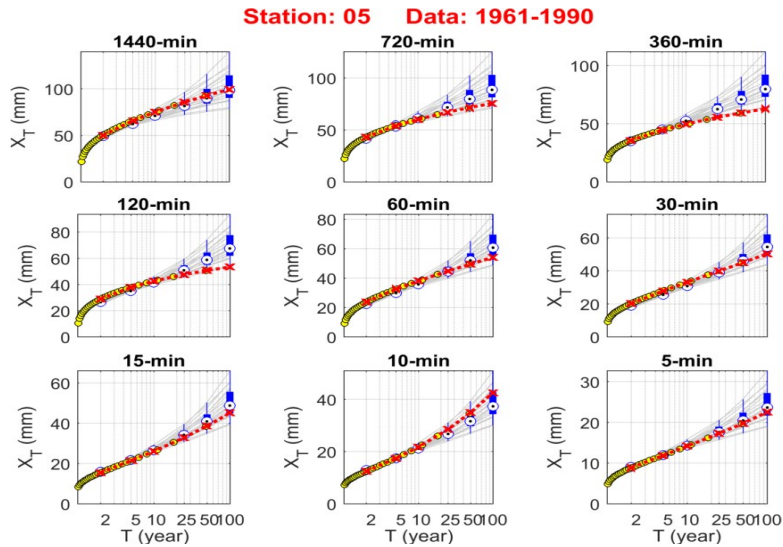
$$e(F) = c_0 + c_1 \cdot \hat{X}(F) + c_2 \cdot [\hat{X}(F)]^2 + \varepsilon \quad (9)$$

where  $X_i(F)$  is the adjusted daily extreme rainfall series at the local site of interest  $i$ ;  $\hat{X}(F)$  is the daily regional extreme rainfall series at the grid containing that site;  $F$  is the cumulative probability of interest;  $e(F)$  is the bias correction function associated with  $\hat{X}(F)$ ;  $c_0$ ,  $c_1$ , and  $c_2$  are the constant coefficients of this function and  $\varepsilon$  is the resulting error term.

### 3 NUMERICAL APPLICATION

In the present study, to assess the feasibility of the proposed statistical modeling method an illustrative application is presented using the available long records (at least 40 years) of annual maximum rainfall data from 74 stations across Canada. These rainfall records consist of different durations ranging from 5 minutes to one day. In addition, the simulation outputs from 21 global climate models under the Coupled Model Inter-comparison Project Phase 5 were selected. These outputs have been statistically downscaled by NASA from the global scales to the regional scale (approximately 25 km x 25 km) for two different scenarios RCP 4.5 and RCP 8.5. In this study, data from 1961 to 1990 were used for calibration, while those from 1991 to 2005 for validation.

In general, as expected it was found that the spatial downscaling using ECDF bias correction shows a better fit than the MEAN method for calibration. However, for validation these two methods provided a comparable performance. After obtaining the daily extreme rainfalls for a given site from the regional values by this spatial downscaling step, the temporal scaling GEV model was used to derive the distributions of sub-daily extreme rainfalls. For purposes of illustration, Figure 1 shows the probability plots of the computed extreme rainfalls  $X_T$  (mm) for different durations for London CS station for the 1961-1990 calibration period. The yellow markers show the empirical CDF using the observed data. The red discontinuous lines and cross markers show the theoretical CDF based on at-site frequency analysis. The gray lines and boxplots show the estimated CDF derived using the scaling GEV model and all 21 climate model outputs. Uncertainty associated with the estimation of the extreme rainfalls is displayed in the form of standard boxplots. It can be seen that the estimated distributions of the sub-daily extreme rainfalls derived from the distribution of daily extreme rainfalls using the scale-invariance GEV model did agree very well with the observed data. Similar results were found for other stations (Nguyen and Nguyen 2020).



**Figure 1.** Empirical and estimated distribution functions of extreme rainfalls  $X_T$  (mm) for different durations for London CS station

## 4 CONCLUSIONS

The present study has introduced a novel statistical modeling approach to the estimation of extreme design rainfalls for a location of interest in the climate change context. The proposed approach consists of two steps. The first step was based on the temporal scale-invariance GEV probability model to represent the distributions of extreme rainfalls over a wide range of time scales (from several minutes to one day) for a given site, and the second step was relied on a spatial downscaling procedure to describe the linkages between regional daily extreme rainfall projections given by climate models and the observed at-site daily extreme rainfalls. Results from an illustrative case study using observed annual maximum rainfall data available at different locations across Canada and climate simulation outputs from 21 different climate models have indicated the feasibility, accuracy, and robustness of the statistical modeling approach developed in this study. In summary, the proposed statistical modeling approach can be used to estimate extreme design rainfalls for the current climate as well as for future climate under different climate change scenarios. This new modeling approach could enhance our understanding of the reliability and uncertainty of climate change projections and their effects in the design of our urban water infrastructures.

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