A Spatial-Temporal Downscaling Approach To Construction Of Rainfall Intensity-Duration-Frequency Relations In The Context Of Climate Change

Van-Thanh-Van Nguyen

Myeong-Ho Yeo

Follow this and additional works at: http://academicworks.cuny.edu/cc_conf_hic

Part of the Water Resource Management Commons

Recommended Citation

Nguyen, Van-Thanh-Van and Yeo, Myeong-Ho, "A Spatial-Temporal Downscaling Approach To Construction Of Rainfall Intensity-Duration-Frequency Relations In The Context Of Climate Change" (2014). CUNY Academic Works.
http://academicworks.cuny.edu/cc_conf_hic/188

This Presentation is brought to you for free and open access by CUNY Academic Works. It has been accepted for inclusion in International Conference on Hydroinformatics by an authorized administrator of CUNY Academic Works. For more information, please contact AcademicWorks@cuny.edu.
A SPATIAL-TEMPORAL DOWNSCALING APPROACH TO CONSTRUCTION OF RAINFALL INTENSITY-DURATION-FREQUENCY RELATIONS IN THE CONTEXT OF CLIMATE CHANGE

VAN-THANH-VAN NGUYEN (1), MYEONG-HO YEO (1)
(1): Department of Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke Street West, Montreal, Quebec, Canada H3A 2K6

This paper proposes a spatial-temporal downscaling approach to construction of the Intensity-Duration-Frequency (IDF) relations at a local site in the context of climate change. More specifically, the proposed approach is based on a combination of a spatial downscaling method to link large-scale climate variables given by General Circulation Model (GCM) simulations with daily extreme precipitations at a site and a temporal downscaling procedure to describe the relationships between daily and sub-daily extreme precipitations based on the scaling General Extreme Value (GEV) distribution. The feasibility and accuracy of the suggested method were assessed using rainfall data available eight stations in Quebec (Canada) and five stations in South Korea for the 1961-2000 period and climate simulations under four different climate change scenarios provided by the Canadian (CGCM3) and the UK (HadCM3) GCM models. Results of this application using data from two completely different climatic regions have indicated that it is feasible to link sub-daily extreme rainfalls at a local site with large-scale GCM-based daily climate predictors for the construction of the IDF relations for the present 1961-1990 period as well as for future periods (2020s, 2050s, and 2080s) under different climate change scenarios. The proposed downscaling method provided therefore an essential tool for estimating extreme rainfalls for various climate-related impact assessment studies for a given region.

INTRODUCTION

The estimation of extreme storms for a given duration and for a selected return period is often necessary for the planning and design of various hydraulic structures. For a site for which sufficient rainfall data are available, a frequency analysis of annual maximum rainfalls can be performed. Results of this analysis are often summarized by “intensity-duration-frequency” (IDF) relationships for a given site, or are usually presented in the form of a “precipitation frequency atlas”, which provides rainfall accumulation depths for various durations and return periods over the region of interest [4]. Several probability models have been developed to describe the distribution of extreme rainfalls at a single site ([1], [11], [12]). Unfortunately, these models are accurate only for the specific time frame associated with the data used. It has necessitated the need for formulating models that could statistically and simultaneously matches
various properties of the rainfall process at different levels of aggregations. Another major advantage of such models is the parsimonious parameterization because these models require a smaller number of parameters for the construction of the IDF curves for rainfall events at all durations [2]. In particular, Nguyen et al. [5] proposed the scaling invariance model based on Generalized Extreme Value (GEV) distribution (called the scaling GEV distribution) to estimate the sub-daily AM rainfall for a given return period from statistical properties of the observed daily AM rainfalls.

Recently, climate change has been recognized to have important impacts on the hydrologic cycle at different temporal and spatial scales. The temporal scales could vary from a very short time interval of 5 minutes to a yearly time scale. The spatial resolutions could be from a few square kilometers (for urban watersheds) to several thousand square kilometers (for large river basins). General Circulation Models (GCMs) have been commonly used to assess these impacts since these models could describe reasonably well the main features of the distribution of basic climate parameters at global scale. However, the coarse-scale outputs from these GCMs are not suitable for hydrological impacts assessment at the regional or local scale. Therefore, several downscaling methods have been developed in order to link large-scale climate variables to local-scale hydrological variables such as precipitation [7].

In view of the above-mentioned issues, the present study therefore proposes a statistical downscaling (SD) approach to link the climate change scenarios given by GCMs to extreme rainfall event at a local site. More specifically, the suggested approach is based on the combination of a spatial downscaling method for linking large-scale climatic variables provided by GCMs to extreme rainfall for a local site using the statistical downscaling method (SDRain) proposed by Nguyen and Yeo [8] and a temporal downscaling method for describing the relationships between the daily annual maximum precipitation (AMP) and the sub-daily AMPs using the scaling GEV distribution [5]. The proposed spatial-temporal downscaling approach was tested using observed AM precipitation data at eight raingage stations in Quebec (Canada) and five raingage stations in South Korea and climate simulations under four different climate change scenarios provided by the Canadian GCM version 3 (CGCM3) and the UK Hadley Centre Coupled Model 3 (HadCM3) for the current 1961-2000 period as well as for future 2020s, 2050s, and 2080s periods. Results of this numerical application have indicated that it is feasible to establish the relationship between large-scale daily climatic variables provided by GCM simulations and observed daily and sub-daily AMPs at a given location. On the basis of these results, the IDF curves for the current and future periods can be constructed for the different climate scenarios considered.

A STATISTICAL DOWNSCALING APPROACH

As mentioned above, the proposed downscaling approach consists of two basic steps: (i) a spatial downscaling method to link large-scale climate variables as provided by GCM simulations with daily extreme precipitations at a local site using the proposed statistical downscaling model SDRain [8]; and (ii) a temporal downscaling procedure to describe the relationships between daily extreme precipitations with sub-daily extreme precipitations using the scaling GEV distribution [5] for the construction of the IDF curves at the site of interest.

A spatial downscaling method using SDRain
The modeling of the daily precipitation process in the context of climate change (SDRain) involves two components: the modeling of the daily precipitation occurrences and the modeling
of the precipitation amounts [8]. Daily time series of precipitation occurrence is defined by two values \( O_i = 0 \) if day \( i \) dry, \( O_i = 1 \) if day \( i \) is wet. The daily probability \( \pi_i \) of non-zero precipitation for a day \( i \) is formulated as follows:

\[
\ln \left( \frac{\pi_i}{1-\pi_i} \right) = a_0 + a_1 X_1 + a_2 X_2 + \cdots + a_m X_m
\]

(1)
in which \( X_j, j = 1, 2, \ldots, m \), are the significant large-scale climate predictors, and \( a' \)s are the regression parameters. A uniformly distributed random number \( r_i (0 \leq r_i \leq 1) \) is used to determine whether it is a wet or dry day. In addition, the relationship between the local daily precipitation amount \( R_i \) and the large-scale climate predictors \( X_i 's \) is described by the following nonlinear expression:

\[
R_i = \exp \left( b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_m X_m + SE \times \delta_i \right)
\]

(2)
in which \( b' \)s are the regression parameters, and \( SE \) is the standard error in the non-linear regression model, and \( \delta_i \) is a normally distributed random number with the mean of 0 and the standard deviation equal to the Variance Inflation Factor (VIF). The VIF term is used to increase the accuracy in representing the variance of the observed daily precipitation amounts and will be empirically determined using the available data [10].

The daily AMPs are extracted from the downscaled daily precipitation series given by the SDRain for different GCM-based climate scenarios. However, it is expected that these downscaled AMPs are not comparable to the observed values. Hence, a bias-correction procedure is required to improve the accuracy of the downscaled AMPs at a given site. The proposed procedure is described as the follows [8]:

Let

\[
y_{\tau} = \hat{y}_{\tau} + e_{\tau}
\]

(3)
in which \( y_{\tau} \) is the adjusted daily AMP at a probability level \( \tau \), \( \hat{y}_{\tau} \) is the corresponding GCM-SDRain estimated daily AMP and \( e_{\tau} \) is the residual associated with \( \hat{y}_{\tau} \). The residual \( e_{\tau} \) can be computed using the following equation:

\[
e_{\tau} = m_0 + m_1 \hat{y}_{\tau} + m_2 \hat{y}_{\tau}^2 + \varepsilon
\]

(4)
where \( m_0, m_1, \) and \( m_2 \) are the regression parameters, and \( \varepsilon \) is the resulting error term.

**A temporal downscaling method using the scaling GEV distribution**

The GEV distribution has been commonly used to model the AMP series and to construct IDF curves [9]. The cumulative distribution function, \( F(x) \), of the GEV distribution is

\[
F(x) = \exp \left[ -\left( 1 - \frac{\kappa(x - \xi)}{\alpha} \right)^{\gamma} \right]
\]

(5)
in which $\alpha$, $\kappa$, and $\xi$ are the location, scale, and shape parameter, respectively. The $k$-th order non-central moment (NCM), $\mu_k$, of the GEV distribution can be expressed as

$$\mu_k = \left(\xi + \frac{\alpha}{\kappa}\right)^k + (-1)^k \left(\frac{\alpha}{\kappa}\right)^k \Gamma(1+k\kappa) + k \sum_{i=1}^{k} (-1)^i \Gamma\left(z + \frac{\alpha}{\kappa}\right) \Gamma(1+k)$$

(6)

in which $\Gamma(\cdot)$ is the gamma function. Therefore, it is possible to estimate the parameters of GEV distribution using the first three NCMs. The quantiles $X_\tau$ corresponding to a return period $\tau$ can be calculated by the following expression:

$$X_\tau = \xi + \frac{\alpha}{\kappa} \left\{1 - \left[1 - \ln\left(p\right)\right]^k\right\}$$

(7)

where $p$ is the exceedance probability of interest.

The proposed temporal downscaling method is based on the concept of scale-invariance (or scaling). By definition, a function $f(x)$ is scaling if $f(\lambda x)$ is proportional to the scaled function $f(\lambda x)$ for all positive values of the scale factor $\lambda$. That is, if $f(x)$ is scaling then there exists a function $C(\lambda)$ such that [5][6]

$$f(x) = C(\lambda) f(\lambda x)$$

(8)

It can be readily shown that

$$C(\lambda) = \lambda^{-\beta}$$

(9)

where $\beta$, called a scaling exponent, is a constant for a local site. Hence, the $k$-th order NCMs $\mu_k$ can be expressed as

$$\mu_k (x) = E\left\{f^k (x)\right\} = \alpha (k) x^{\beta(k)}$$

(10)

in which $\alpha(k) = E\left\{f^k (1)\right\}$ and $\beta(k) = \beta k$. Further, for a simple scaling process, it can be shown that the statistical properties of the GEV distribution for two different time scales $t$ and $\lambda t$ are related as follows:

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

(11)

$$\alpha(\lambda t) = \lambda^\beta \alpha(t)$$

(12)

$$\xi(\lambda t) = \lambda^\beta \xi(t)$$

(13)

$$X_\tau (\lambda t) = \lambda^\beta X_\tau (t)$$

(14)

Hence, based on these relationships it is possible to derive the statistical properties of sub-daily AMPs using the properties of daily AMPs. Then, the derived NCMs ($\mu_k$) are used to estimate three parameters of GEV distribution for sub-daily extreme rainfalls. Therefore, the proposed scaling GEV method can be used to construct IDF curves taking account of climate-related impacts on extreme rainfalls.
NUMERICAL APPLICATION

To illustrate the application of the proposed spatial-temporal downscaling approach, a case study is carried out using both global GCM climate simulation outputs and at-site AMP data available at eight raingage stations in Quebec (Canada) and five stations in South Korea for the 1961-1990 period. The selected global GCM predictors are based on the outputs from two GCMs (the Canadian CGCM3 and the UK HadCM3) for the current 1961-2000 period as well as for some future periods 2020s, 2050s, and 2080s under four different climate change scenarios (A1B and A2 for CGCM3 and A2 and B2 for HadCM3). The at-site AMP series for durations ranging from 5 minutes to 1 day were used in this study, and data for the 1961-1990 period were used for model calibration and data for the remaining 1991-2000 period were for validation purposes.

The proposed spatial downscaling method SDRain was used to generate 100 daily precipitation series and to provide the daily AMP amounts for a local site under the four selected climate scenarios. After performing the bias correction based on Equations (3) and (4), the adjusted daily AMP values were then used for estimating the sub-daily AMPS at a site using the proposed temporal downscaling procedure based on the scaling GEV distribution. On the basis of these results, the IDF relations for the current and future periods for different climate scenarios at a given location were constructed.

For purposes of illustration, Figure 1 shows the achievement of a very good agreement between the adjusted mean of GCM-downscaled AMP amounts and the observed at-site values given by HadCM3-A2 for Dorval and Seoul stations after making the bias-correction adjustment using the fitted second-order functions [Equation (4)]. Table 1 shows the improved agreement (smaller relative root mean square error) between the adjusted downscaled AMPS and the observed values as compared to the unadjusted downscaled AMP amounts for all stations for the validation 1991-2000 period. Hence, it can be seen that the derived bias-correction function from the data for the 1961-1990 calibration period could improve the accuracy of the GCM-based downscaled AMPS for other time periods in the future.

![Figure 1. Quantile-Quantile plot of observed daily AMPs and simulated values given by HadCM3-A2 for the calibration 1961-1990 period before and after bias correction for Dorval and Seoul stations. Blue diamonds denote the quantiles before bias-correction, and red circles represent values after bias-correction.](image)

To examine the temporal scaling properties of the AMP series, graphical analyses were carried out for all stations using the first three NCMs. For purposes of illustration, Figure 3 shows the scaling relationships with respect to all duration for Dorval station. The log-linearity of NCMs shows two distinct scaling regimes: from 5 minutes to 30 minutes and from 30 minutes to daily. In addition, the linearity of the scaling exponents β(k) against the order of NCMs of AM precipitation for Dorval as shown in Figure 4 has indicated that the AMP data at
Dorval station can be described by a simple scaling model. Hence, it is possible to estimate the NCMs (and the parameters of the GEV distribution) of AMPs for shorter durations using the AMP data for longer time scales within the same scaling regime. Figure 5 shows the comparison between the observed and estimated AMPs by traditional and scaling GEV distributions for 1 hour for Dorval and Seoul stations. It can be seen that the quantiles derived from the daily AMPs using the established scaling relationships agree very well with those values given by the traditional fitted GEV distribution as well as with the observed values. Similar results were found for other duration and stations.

Table 1 Values of relative root mean square errors (RRMSE) for the daily AMPs without and with bias correction for the validation 1991-2000 period.

<table>
<thead>
<tr>
<th>Site</th>
<th>without bias correction</th>
<th>with bias correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorval</td>
<td>0.126</td>
<td>0.122</td>
</tr>
<tr>
<td>Bagotville</td>
<td>0.222</td>
<td>0.198</td>
</tr>
<tr>
<td>Gaspe</td>
<td>0.109</td>
<td>0.122</td>
</tr>
<tr>
<td>Goosebay</td>
<td>0.213</td>
<td>0.223</td>
</tr>
<tr>
<td>Kuujjuag</td>
<td>0.281</td>
<td>0.292</td>
</tr>
<tr>
<td>Kuujjuari</td>
<td>0.421</td>
<td>0.415</td>
</tr>
<tr>
<td>Mont Joli</td>
<td>0.217</td>
<td>0.178</td>
</tr>
<tr>
<td>Natashquan</td>
<td>0.129</td>
<td>0.141</td>
</tr>
<tr>
<td>Seoul</td>
<td>0.564</td>
<td>0.546</td>
</tr>
<tr>
<td>Incheon</td>
<td>0.403</td>
<td>0.376</td>
</tr>
<tr>
<td>Daegu</td>
<td>0.265</td>
<td>0.255</td>
</tr>
<tr>
<td>Pusan</td>
<td>0.285</td>
<td>0.297</td>
</tr>
<tr>
<td>Gwangju</td>
<td>0.144</td>
<td>0.109</td>
</tr>
</tbody>
</table>

Figure 3. Log-log plots of Non-central Moments (NCMs) of the first three orders against several durations for Dorval station.

Figure 4. Plot of the scaling exponents $\beta(k)$ against the order of NCMs of AM precipitation for Dorval.

The proposed spatial-temporal SD was used to construct IDF curves for stations located in the selected study areas under four different climate change scenarios (HadCM3 A2 & B2 and CGCM3 A1B & A2) for the current (1961-1990) and future periods (2020s, 2050s, and 2080s). For purposes of illustration, Figure 6 shows the plots of daily and 30-minute AM precipitations at Dorval station for the 1961-1990 period and future periods (2020s, 2050s, and 2080s) using the proposed spatial-temporal downscaling method. It can be seen that both CGCM3 and HadCM3 suggested increasing trends of AM precipitations for future periods under the four selected climate change scenarios. In addition, changes of AM precipitations in the future given by the CGCM3 are more pronounced than changes given by the HadCM3.
CONCLUSIONS

A spatial-temporal downscaling approach was proposed in the present study to describe the linkage between large-scale climate variables for daily scale to AM precipitations for daily and sub-daily scales at a local site. The feasibility of the proposed downscaling method has been tested based on climate simulation outputs from two GCMs (CGCM3 and HadCM3) under different climate scenarios and using available AMP data for durations ranging from 5 minutes to 1 day at eight raingage stations in Quebec (Canada) and five stations in South Korea for the 1961-2000 period. Results of this numerical application has indicated that it is feasible to link daily large-scale climate variables to daily AMPs at a given location using a second-order bias-correction function. Furthermore, it was found that the AMP series in Quebec (Canada) and in South Korea displayed a simple scaling behaviour. Based on this scaling property, the scaling GEV distribution has been shown to be able to provide accurate estimates of sub-daily AM.
precipitations from GCM-downscaled daily AMP amounts. Therefore, it can be concluded that it is feasible to use the proposed spatial-temporal downscaling method to describe the relationship between large-scale climate predictors for daily scale given by GCM simulation outputs and the daily and sub-daily AMPs at a local site. This relationship would be useful for various climate-related impact assessment studies for a given region.

Finally, the proposed downscaling approach was used to construct the IDF relations for a given site for the 1961-1990 period and for future periods (2020s, 2050s, and 2080s) using climate predictors given by the CGCM3 and HadCM3 simulations. In general, it was found that AM precipitations at a local site downscaled from the HadCM3 displayed a smaller change in the future, while those values estimated from the CGCM3 indicated a large increasing trend for future periods. This result has demonstrated the presence of high uncertainty in climate simulations provided by different GCMs.

REFERENCES