Optimal rainfall temporal patterns for urban drainage design in the context of climate change

V.-T.-V. Nguyen, N. Desramaut and T.-D. Nguyen

ABSTRACT

The main objective of the present study is to propose a method for estimating an optimal temporal storm pattern for urban drainage design in southern Quebec (Canada) in the context of climate change. Following a systematic evaluation of the performance of eight popular design storm models for different typical urban basins, it was found that the Canadian Atmospheric Environment Service (AES) storm pattern and the Desbordes model (with a peak intensity duration of 30 min) were the most accurate for estimating runoff peak flows while the Watt model gave the best estimation of runoff volumes. Based on these analyses, an optimal storm pattern was derived for southern Quebec region. The proposed storm pattern was found to be the most suitable for urban drainage design in southern Quebec since it could provide accurate estimation of both runoff peak flow and volume. Finally, a spatial-temporal downscaling method, based on a combination of the *spatial* statistical downscaling SDSM technique and the *temporal* scaling General Extreme Value distribution, was used to assess the climate change impacts on the proposed optimal design storm pattern and the resulting runoff properties.

Key words | climate change impacts, design storms, extreme rainfalls, generalized extreme value distribution, statistical downscaling methods

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INTRODUCTION

The urban drainage systems were historically designed to discharge stormwater as rapidly as possible from occupied area. Hence, hydrological considerations were mostly restricted to the sizing of conduits and therefore the main design purpose was usually based on the sole estimation of runoff peak flows to be expected with some relative frequency. A typical example of this concept is the Rational Method that has been overwhelmingly used for several decades for sizing sewer conduits. However, new demands by society for better environmental control increase the complexity of sewer systems and then induce the need for more realistic procedures to simulate the rainfall-runoff process. Nowadays, some existing procedures can transform nonlinearly more realistic input rainfall hyetographs into complete output storm hydrographs at different points of interest in the drainage system. Therefore, the temporal pattern of the rainfall hyetograph, commonly called "design rainfall" or "design storm", which are required as input for these models, constitutes a major component in the application of these new methods for the design of urban drainage networks.

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The main difficulty related to the determination of a suitable storm pattern for design purposes has been confirmed by the availability of various synthetic design storm models developed and used around the world (Natural Environment Research Council 1975; Arnell *et al.* 1983; ASCE Urban Water Resources Research Council 1983). The Chicago model was the first developed in US by Keifer & Chu in (1957), and it was followed by other alternatives such as the pattern proposed by Sifalda (1973), Pilgrim & Cordery (1975), Desbordes (1978), Yen & Chow (1980), and the balanced model suggested by the US Army

Corps of Engineers (1982). In Canada, the two popular patterns were respectively suggested by the Atmospheric Environmental Service (Hogg 1980) and by Watt *et al.* (1986). However, in practice there are no accepted guidelines regarding how to select an appropriate design storm for a particular study site. In view of these issues, a systematic evaluation of various existing design storms has been carried out in order to determine the most suitable temporal rainfall patterns for urban drainage network design in southern Quebec region (Peyron *et al.* 2005). More specifically, the performance of the eight popular design storm models mentioned above has been assessed based on their accuracy in the estimation of runoff peak flows and volumes as compared to those values given by a set of historical rainfall events. The selection of runoff peak flow and volume are of particular interest since these two runoff parameters are important for the sizing of sewer pipes and the design of water storage systems such as retention basins. Indeed, it was found that the Canadian AES design storm pattern and the model developed by Desbordes in France with a peak intensity duration of 30 min were the most accurate for estimating runoff peak flows while the synthetic storm established by Watt *et al.* (1986) gave the best runoff volume estimates. However, most of the existing design storms, such as the Chicago pattern, were initially developed for the estimation of peak flows, but they are often used in practice for the design of retention basins as well. Hence, the most efficient temporal rainfall pattern should be able to estimate accurately both runoff peak flow and volume. Therefore, an optimal design storm model for southern Quebec has been developed to provide an accurate estimation of both runoff peak flow and volume (Peyron *et al.* 2005).

Recently, climate variability and climate change have been recognized as having a profound impact on the hydrologic cycle at different temporal and spatial scales. The temporal scales could vary from a very short time interval of 5 min (for urban water cycle) to a yearly time scale (for annual water balance computation). The spatial resolutions could be from a few square kilometres (for urban watersheds) to several thousand square kilometres (for large river basins). General Circulation Models (GCMs) have been recognized to be able to represent reasonably well the main features of the global distribution of basic climate parameters, but outputs from these models are usually at resolution that is too coarse (generally greater than 200 km) for many impact studies. Hence, different downscaling methods have been used for downscaling GCM predictions of climate change to hydrologic processes at appropriate space and time scales for hydrological impact studies (Nguyen *et al.* 2006). Of particular importance for the estimation of urban design storms are those procedures dealing with the linkage of the large-scale climate variability to the historical observations of the sub-daily rainfall extremes at a local site.

The present study, a continuation of a previous study by Nguyen *et al.* (2007), proposes therefore an approach that can be used to link the climate change scenarios given by GCMs to the estimation of a design storms at a local site. More specifically, the proposed approach consists of two steps: (i) firstly, a spatial-temporal downscaling method was used to link large-scale climate variables as provided by GCM simulations with the Intensity-Duration-Frequency (IDF) relations at a local site (Nguyen *et al.* 2007); and (ii) secondly, on the basis of the derived IDF relations, different design storm models can be constructed for a given location. The proposed approach was tested using extreme rainfall data available at Dorval Airport station in Quebec (Canada) for the 1961–1990 period and based on the A2 climate change scenario simulation results (denoted by CGCM2A2 and HadCM3A2, respectively) available for the study region provided by the Canadian and UK GCMs for the current 1961–1990 period as well as for future 2020 s, 2050 s, and 2080 s periods. In general, it was found that the IDF curves based on HadCM3A2 simulations for future periods are quite similar to those for the current period while those using CGCM2A2 indicated a large increasing trend in the future. Finally, on the basis of the derived IDF relations, three different design storm models were constructed for the Dorval Airport station and the resulting peak flows and runoff volumes were estimated using the SWMM model for several urban watersheds of different area sizes, shapes, and imperviousness levels. It can be seen that for Dorval Airport location the design storm rainfall intensities and the resulting runoff characteristics derived from the HadCM3A2 displayed a small decreasing change in the future, while those estimated from the CGCM indicated a large increasing trend for future periods.

METHODOOGY

As mentioned above, the proposed downscaling approach consists of two basic steps: (1) a *spatial-temporal downscaling* method to link large-scale climate variables as provided by GCM simulations with sub-daily extreme precipitations at a local site for the construction of the IDF curves at the site of interest; and (2) the construction of design storms based on the estimated IDF relations for current and future periods under different climate change scenarios.

More specifically, the *spatial-temporal downscaling* method is based on the combination of a *spatial downscaling* technique to describe the linkage between large-scale climate variables as provided by GCM simulations with daily extreme precipitations at a local site using the popular Statistical Downscaling Model (SDSM) (Wilby *et al.* 2002) and a *temporal downscaling* procedure to describe the relationships between daily extreme precipitations with sub-daily extreme precipitations using the scaling General Extreme Value (GEV) distribution (Nguyen *et al.* 2002). In particular, the scaling GEV can be used to derive the IDF relationships for extreme precipitations for different durations. Detailed description of this spatial-temporal downscaling method and the derivation of the resulting IDF curves can be found in Nguyen *et al.* (2007).

On the basis of the estimated IDF relations, the impacts of climate change on the design storms and the resulting runoff conditions for an urban watershed can be assessed. In the present study, for purposes of comparison, three different design storm models (Peyron *et al.* 2005) will be used in the assessment of the runoff characteristics for some typical urban areas with different sizes (from 0.4 to 10 hectares), different shapes (square and rectangular) and impervious levels (35%, 65%, and 100%) using the popular SWMM model for describing the rainfall-runoff relations.

NUMERICAL APLICATION

To illustrate the application of the proposed approach, a case study is carried out using both global GCM climate simulation outputs and at-site annual maximum (AM) precipitation data available at Dorval Airport raingage station in Quebec (Canada). The selected global GCM climate predictors are given by the CGCM2A2 and HadCM3A2 climate simulations for the 1961–1990 period as well as for some future periods 2020 s, 2050 s, and 2080 s, while the at-site AM rainfall series for durations ranging from 5 min to 1 day used in this study are available only for the 1961–1990 period.

For purposes of illustration, Figure 1 shows the plots of the estimated 5-minute AM precipitations at Dorval Airport

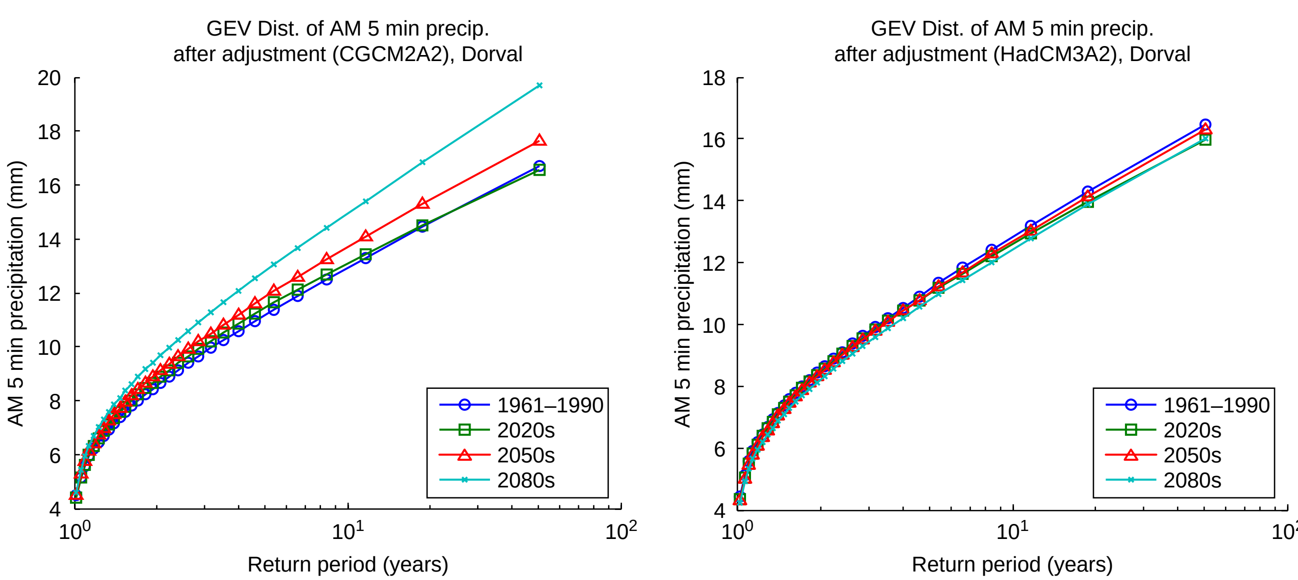

Figure 1 | Probability plots of 5-minute AM precipitations projected from CGCM2A2 and HadCM3A2 scenarios for the 1961–1990 period and for future periods (2020 s, 2050 s, and 2080 s) for Dorval Airport station.

station for the 1961–1990 period and future periods (2020 s, 2050 s, and 2080 s) using the proposed spatial-temporal downscaling method. It can be seen that the HadCM3A2 scenario suggested a small change of AM precipitations in the future, while the CGCM2A2 model indicated a large increasing trend for future periods. Hence, on the basis of the proposed spatial-temporal downscaling method, the IDF curves for the current (1961–1990) period and for future (2020 s, 2050 s, and 2080 s) periods can be derived.

As mentioned previously, Peyron *et al.* (2005) have performed a critical assessment of the accuracy of different design storm models used in various countries in the estimation of runoff peaks and volumes for urban watersheds located in the Dorval Airport region. It was found that the design storm proposed by Desbordes (1978) is the most accurate for estimating the runoff peaks and the model by Watt *et al.* (1986) is the most appropriate for computing the runoff volumes, while the optimal model developed by Peyron *et al.* (2005) can provide an accurate estimation of both of these runoff characteristics. Figure 2 shows the IDF relations and the resulting temporal patterns of these three design storm models for different return periods for the current 1961–1990 period.

Similarly, on the basis of the IDF curves for future (2020 s, 2050 s, and 2080 s) periods the corresponding design storm models can be estimated. For purposes of illustration, Figure 3 shows the design storms for the 2080 s period based on the CGCMA2-projected changing climatic conditions. In general, the design storm rainfall intensities for future periods show significant increases but the shape of these storms did not show important changes.

Furthermore, it can be expected that the rainfall intensities of the design storms derived from the IDF curves for the CGCMA2 will show a large increasing trend, especially for the high rainfall intensity values, while those estimated from the IDF relations for the HadCM3A2 will indicate a small decreasing trend. For purposes of illustration, Figure 4 shows the estimated 50-year design storms for Dorval Airport station based on the CGCMA2 and HadCM3A2 climate simulations.

In addition, to study the impacts of the projected climate change scenarios on the peak flows and runoff

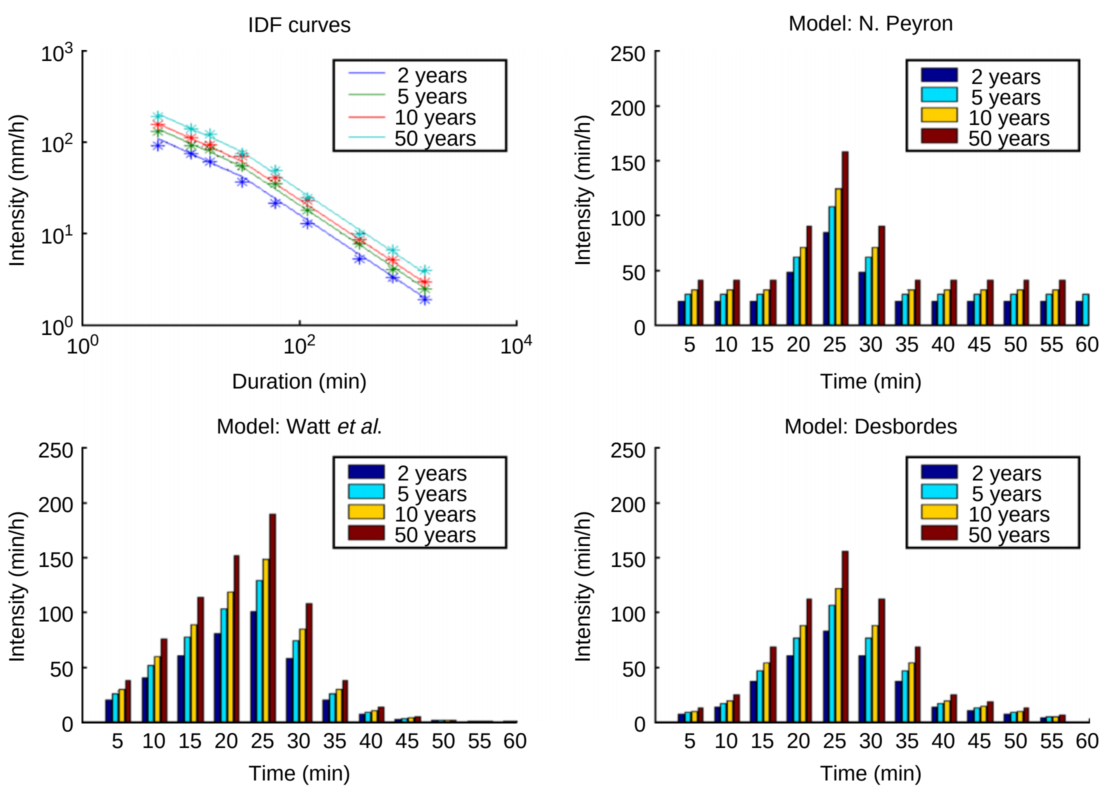

Figure 2 | IDF relations and design storms for the 1961–1990 period for Dorval Airport station.

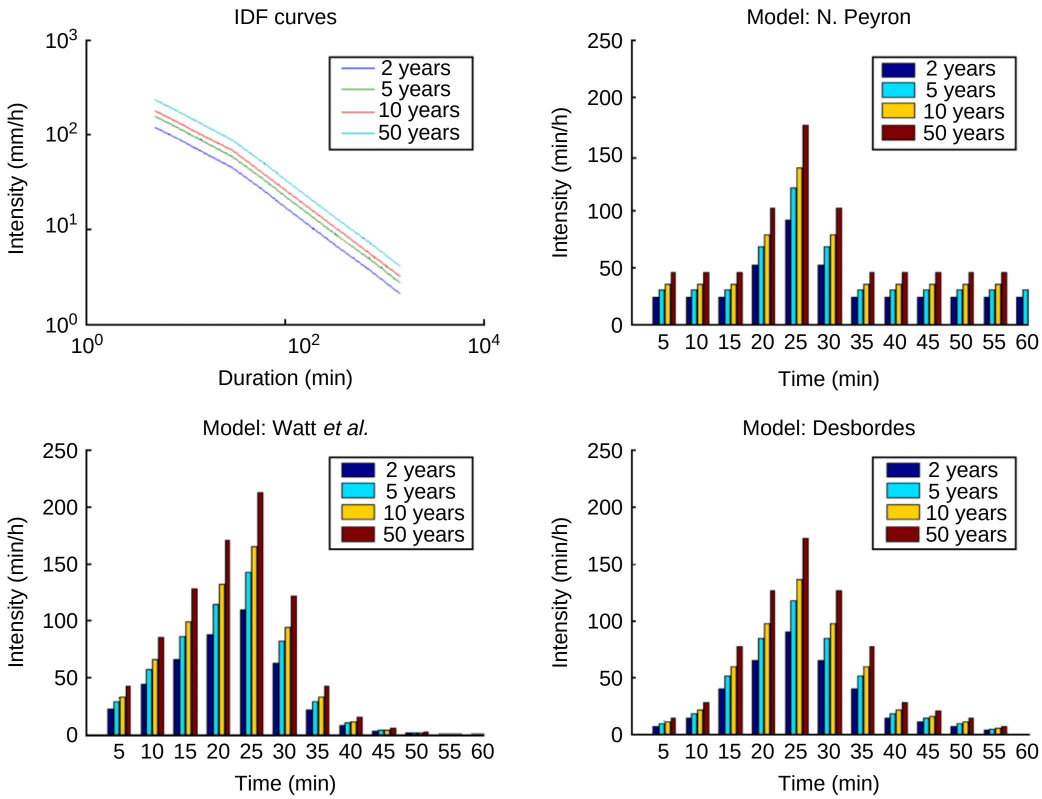

Figure 3 | IDF relations and design storms for the 2080s period for Dorval Airport station based on CGCMA2 climate change scenario.

volumes and to explore the design storms sensitivity, the analyses were carried out for a set of hypothetical basins that possess widely varying physiographic characteristics. The basins were patterned after some typical urban basins located in residential development in Quebec (Canada). More specifically, these basins were chosen based on the three main characteristics that affect directly the properties of the runoff process: the basin shape, the basin size, and the basin imperviousness level. Runoff simulations based on the SWMM model were then conducted to evaluate the influence of these basin characteristics on the performance of the different design storm models.

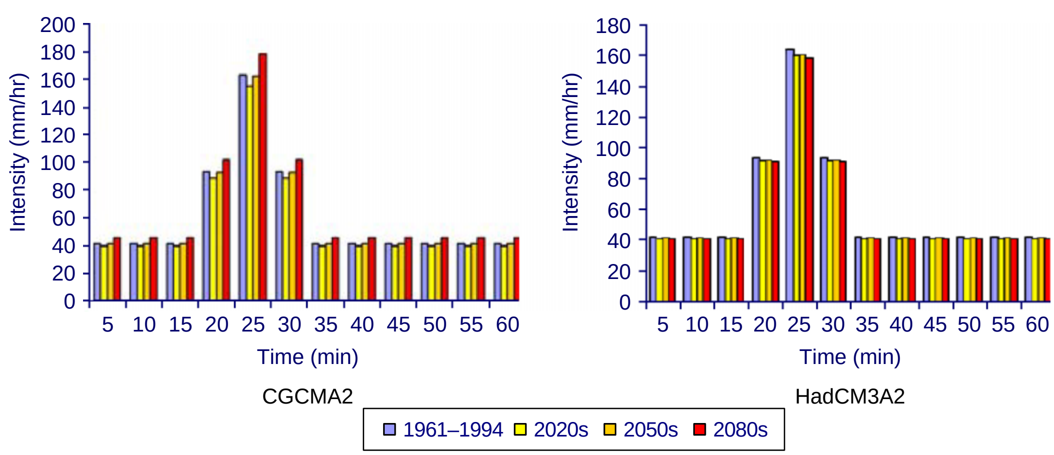

Figure 4 | Temporal patterns of a 50-year Peyron design storm model for current and future periods based on CGCMA2 and HadCM3A2.

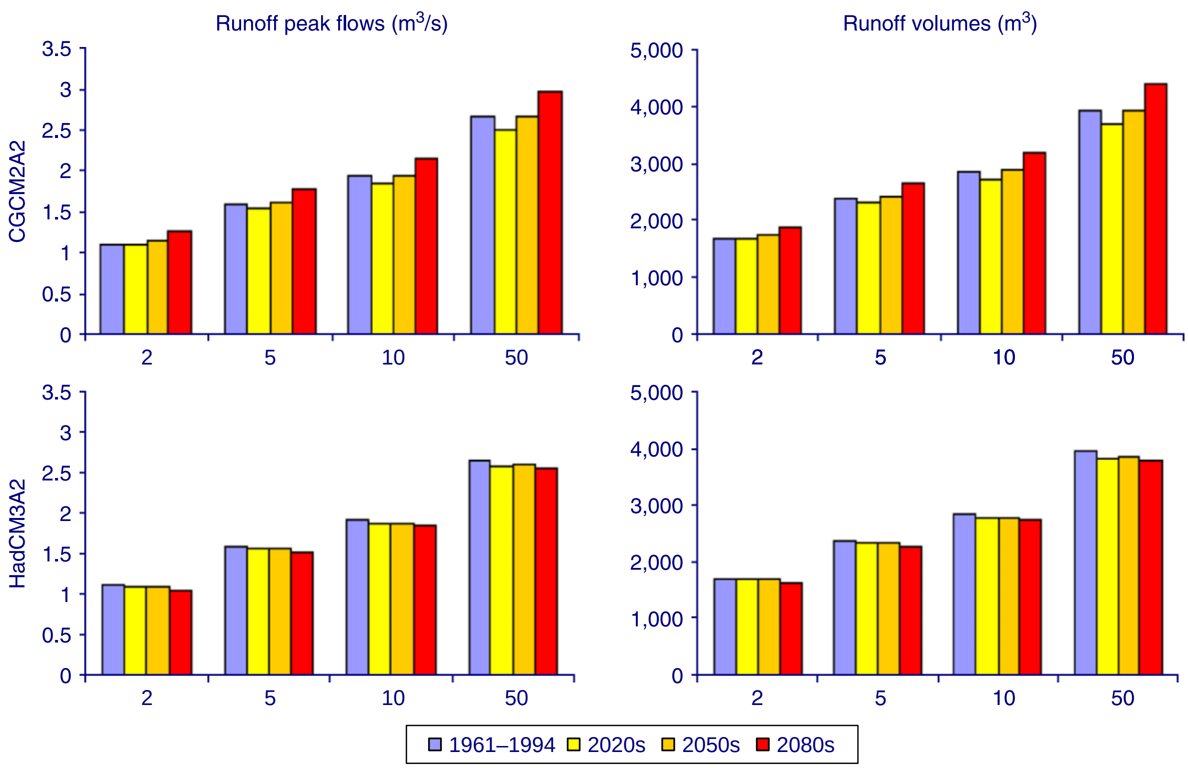

Figure 5 | Peak flows and volumes from a square 10-hectare residential area with 65-percent imperviousness for current and future periods.

The basin shapes considered in this paper represent the most common forms for parking lots, multi-residential and typical residential areas in Quebec (Canada). Square basins and rectangular basins with a ratio of the length over the width equal to 2 and 4 define regular parking lots and multi-residential areas. For such basin configurations, outlets are located in the center of the watershed as commonly designed in practice. The shape of typical residential basins for the Montreal City (Quebec, Canada) is also rectangular, but established from the observation that cross-streets are approximately 300 m apart. The outlet is in this case placed at the bottom left corner of the rectangular shape. The major difference between the various shapes is the width parameter, which represents the drainage length. In addition, different percentages of imperviousness are examined for each basin shape. Imperviousness values of 35, 65 and 100% are respectively commonly assigned to residential, multi-residential and parking lots. The present study focuses on small urban areas, up to 10 hectares. Hence, area sizes of 0.4, 0.75, 1, 2, 5 and 10 hectares are assigned to each basin shape, except for the typical residential basins where the size of 0.4 hectare is not considered because this size is not realistic for such a basin. Finally, the present study is restricted to basins with a fixed slope of 1% since it represents a typical condition for urban watersheds in southern Quebec.

For purposes of illustration, Figure 5 shows the impact of the projected climate change scenarios on peak flows and volumes for a typical 10-hectare square area with a 65-percent impervious surface. In general, the increasing trends in flow characteristics were found for CGCMA2 and the decreasing trends were observed for HadCM3A2. Similar results were found for other areas of different sizes, shapes, and impervious conditions considered in the present study as mentioned above.

CONCLUSIONS

A systematic evaluation of various existing synthetic design storms has been carried out (Peyron *et al.* 2005) to identify the most suitable rainfall temporal pattern for urban drainage network design in southern Quebec region. It was found that the accuracy of each design storm model depends on the runoff parameter considered. Indeed, the Canadian AES model and the model developed by Desbordes in France with peak intensity duration of 30 min were the most accurate for estimating runoff peak flows, whereas the Canadian Watt storm pattern gave the best runoff volume estimates. However, no existing model could provide an accurate estimation of both runoff peak flow and volume. On the basis of this assessment, an optimal design storm pattern was developed for southern Quebec region to provide accurate estimates of both runoff peak flow and volume.

Furthermore, a statistical downscaling method was proposed in the present study for estimating the design storms at a location of interest in the context of climate change. The proposed downscaling approach was used to construct the IDF relations and the resulting design storms for Dorval Airport for the 1961–1990 period and for future periods (2020 s, 2050 s, and 2080 s) using climate predictors given by the HadCM3A2 and CGCM2A2 simulations. It was found that AM precipitations downscaled from the HadCM3A2 and the resulting design storm rainfall intensities displayed a small decreasing change in the future, while those values estimated from the CGCM2A2 indicated a large increasing trend for future periods. Similar trends were found for flows characteristics of typical urban areas with different sizes, shapes, and imperviousness levels. This result has demonstrated the presence of high uncertainty in climate simulations provided by different GCMs. Further studies are planned to assess the feasibility and reliability of the suggested downscaling approach using other GCMs and data from regions with different climatic conditions.

Finally, it should be noted that the estimation of the design storms in this study was based mainly on the analysis of particular climatic and rainfall conditions and urban drainage characteristics in southern Quebec region. However, the methodology used for the derivation of these design storms can be applied to any other regions having sufficient climate and hydrologic data.

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