Source control as an adaptation measure to climate change for urban drainage systems

Le contrôle à la source comme mesure d'adaptation aux changements climatiques pour les réseaux de drainage urbain

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RÉSUMÉ

Plusieurs études suggèrent que les changements climatiques (CC) auront des impacts sur les intensités et les récurrences des précipitations extrêmes, ce qui pourra potentiellement modifier les paramètres météorologiques à partir desquels les réseaux de drainage ont été conçus. Cet article présente la méthodologie qui a été utilisée pour évaluer, dans le cas du sud de la province de Québec au Canada, les impacts potentiels des changements climatiques sur les paramètres météorologiques de conception des systèmes de drainage urbain et sur les débits et volumes de ruissellement pour des types spécifiques d'occupation du sol. Dans la perspective où un contrôle à la source peut, pour les événements les plus fréquents, compenser pour une part significative les augmentations attribuables aux CC, ce type de mesure ne devrait plus être vu comme une alternative à des approches traditionnelles de drainage mais devrait plutôt être intégré au mode de conception des réseaux, que ces derniers soient existants ou projetés.

ABSTRACT

Many studies suggest that climate change (CC) will have an impact on extreme rainfall frequencies and intensities, thereby potentially modifying relevant meteorological design parameters for sewer networks. This paper presents the methodology that has been used to evaluate, for the southern part of the Province of Québec in Canada, the potential impacts of CC on the meteorological design parameters of urban drainage systems and the associated impacts on the runoff volumes and peak discharges for typical urban land uses. An analysis was also performed to examine how source control measures could be used to mitigate these impacts so that the systems could still provide the adequate level of service and an acceptable risk level. The fact that these source controls could indeed compensate for a large part of the expected increases associated with CC for less intense rainfall events and that they could, in many cases, be easily implemented, reinforces the need to re-evaluate the overall design approaches for the design of stormwater sewer networks. In that perspective, source controls should not be viewed as an alternative to traditional approaches to drainage but should rather become an integral part of urban drainage planning.

KEY WORDS

climate change; Intensity-Duration-Frequency (IDF) curves; source controls; Southern Quebec, urban drainage planning.

1   INTRODUCTION

Urban drainage network hydrologic design is still largely based on statistical analyses of available historical meteorological data, assuming that a design rainfall event of a specific return period will produce runoff parameters (volume and peak discharge) with the same return period. The relevant design information for rainfall is usually synthesized in Intensity-Duration-Frequency (IDF) curves which present, based on past records, rainfall intensities for different durations and frequencies. The development of IDF curves is closely associated with the use of the rational method since the early 1900s.

It is however generally recognized that climate change (CC) could modify relevant design parameters like the extreme rainfall frequencies and intensities (Houghton *et al.*, 2001), these changes increasing in turn the probability that the design capacities of sewer networks be exceeded. In some cases, this situation could have significant impacts that could lead to increased flooding, detention basin overflows and increased combined sewer overflows.

In order to evaluate the potential impacts of CC on urban drainage systems and to define specific approaches that could be used to reduce future vulnerabilities of these systems, a research project was undertaken to address these issues for the region of southern Québec (Canada). This paper discusses the general methodology and presents the results for three main aspects of the study. Firstly, an evaluation of the extreme rainfall in future climate was made, using a regional climate model. IDF curves under the future climate were produced. Secondly, using historic rainfall data for the region, a taxonomy was developed for the observed rainfall temporal patterns and different generic rainfall patterns could therefore be defined. Using finally the rainfall quantities defined by the IDF curves for the future climate and assuming that the temporal rainfall patterns would not significantly change, an analysis was performed to estimate the impacts on peak discharges and runoff volumes. Four generic land uses were considered: 100% imperviousness (roads or parking lots), high density residential (65% imperviousness), low density residential (35% imperviousness) and undeveloped (0% imperviousness). Only the results for the 100% imperviousness and 35% imperviousness will be presented.

The potential benefits associated with different types of source controls will finally be discussed and compared with the increase of peak discharge and runoff volume deduced from the analyses.

2   RAINFALL FOR URBAN DRAINAGE ANALYSIS AND ANTICIPATED CLIMATE CHANGE

Intensity-Duration-Frequency (IDF) curves are extensively used for the design of urban drainage systems. These curves are based on statistical analyses of annual maximum total rainfall over various durations usually ranging from 5 min. to 24 hours. A fundamental hypothesis underlying the use of these curves is that the statistical properties of these series of annual maximum rainfall remain unchanged over time. However, it is now expected, according to actual CC scenarios, that average as well as extreme values of many meteorological variables could possibly change over time due to increasing greenhouse gases (GHG) concentrations.

In order to investigate how the intensity/frequency of extreme rainfall could change in a future climate, results from the Canadian Regional Climate Model (CRCM, 3.7.1 version), from simulations produced by the Ouranos' Climate Simulations Team as part of the Canadian program of regional climate projections, were used (details on

the model, simulations as well as emission scenarios are given in Plummer *et al*., 2006; the simulation results considered in the present study correspond to simulations ANpr2 (control climate) and ANfr2 (future climate) of Plummer *et al*., 2006). The CRCM simulations are performed over a domain containing most of North America on a 204 x 189 grid at a 45 km resolution.

The two CRCM simulations used in this study cover two periods: one from 1961 to 1990 (control climate) and one from 2041 to 2070 (future climate). CRCM is driven by a simulation from the Canadian Global Coupled Climate Model (CGCM2). For the control climate, Plummer *et al*. (2006) found that simulation results are in agreement with observations, both in terms of regional average seasonal precipitation and inter-annual variation coefficient of the seasonal precipitation. For both models (CRCM and CGCM2), up to 2000, historical levels of GHG were used (1990 for CRCM) while for the future period (2000 to 2100 for CGCM2 and 2041 to 2070 for CRCM), the IPCC SRES A2 scenario was used to define the GHG concentration in the model's atmosphere (Houghton *et al*., 2001). According to historical levels of greenhouse gases, the effective concentration of CO_2 has increased from 408 to 476 ppmv (parts per million by volume) during the 1971-1990 period. For the period 2041-2070, the effective CO_2 concentration is expected to increase from 714 to 950 ppmv according to the selected GHG scenario.

The analysis was performed using the results from the 70 grid-boxes (45 km x 45 km) covering the southern part of the Province of Quebec. May to October maximum 24-, 12-, 6- and 2-hour total rainfalls (the May to October period was considered since rain stations are closed during winter months) were used. Statistical analyses of these extreme rainfall series were performed and event magnitudes at the 2-, 5-, 10- and 25-year return periods were estimated individually for each grid-box for current and future climates. Extreme rainfalls were estimated using the Generalized Extreme Value (GEV) distribution fitted using L-moment method (Hosking and Wallis, 1997).

These were compared afterwards to extreme values estimated using the observed data at 49 stations located in southern Quebec. It should be pointed out that spatial resolution of observed and simulated data are quite different. It is generally recognized that the grid-box rainfall of GCM and RCM has the spatial characteristics of areal averages (Osborn and Hulme, 1997) and, accordingly, CRCM operates in a world drawn using 45 km x 45 km pixels (Fowler *et al*., 2005). Comparison of extreme values estimated using the observed rainfall events and the simulated ones shows that these are coherent with the interpretation of simulated results as spatially averaged rainfall.

A statistical analysis was first performed at the grid-box scale. Regionalization techniques were used to define regional estimates of rainfall extremes (see Hosking and Wallis, 1997 for details about regionalization techniques). These grid-box estimates were then transposed at the station scale using the ratio of grid-box to station estimates in present climate. This approach assumes that this ratio, for a given rainfall intensity at the grid-box scale, will remain unchanged under future climatic condition (details are given in Mailhot *et al*. 2006).

Figure 1 presents the resulting IDF curves in future climate (continuous curves) along with the IDF curves in control climate (dotted curves). The values can be interpreted as average regional estimates over the southern Quebec region. As can be observed, an increase in the total rainfall depth for all durations and all return periods is expected. Maximum absolute increases in total rainfall are obtained for return periods between 5 and 20 years and for 6-hour rainfalls. Expressed in terms of actual rainfall depths, the increases range from 8% to 20%, depending on the return period and duration.
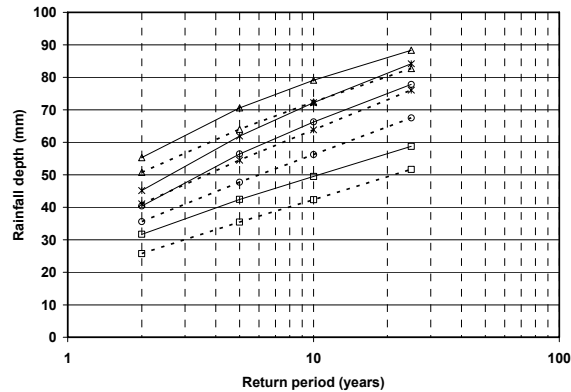
Figure1 IDF curves in control (dotted lines) and future (continuous lines) climates.
Correspondences between the various symbols and durations are as follow: triangles = 24 h.;
crosses = 12 h.; circles = 6 h. and squares = 2 h.

3   ANALYSIS OF CLIMATE CHANGE IMPACTS FOR URBAN DRAINAGE NETWORKS

3.1   Rainfall taxonomy

A rainfall event is characterized by various parameters that can have different impacts depending on the drainage element being analyzed and on the type of land use. As described by Adams and Papa (2000), a drainage system comprises different components that respond to specific characteristics of rainfall events: transport elements like pipes are generally more sensitive to rainfall intensity and duration, as these two parameters affect more directly the peak discharge. Storage elements like retention basins and infiltration devices are, on the other hand, more influenced by the rainfall quantities, its duration, the inter-event period and other internal rainfall characteristics. The land use being analyzed is also important to consider, as a surface with 100% imperviousness will admittedly react differently than a low density residential area. In the first case, the short and very intense event will likely control whereas, in the other case, a longer event, with the peak closer to the end of the rainfall, could be more critical. A classification of the types of rainfall event should therefore take into account these elements.

For the second part of the study, a data base of 199 historical rainfall events covering the period from 1943 to 1994 for the Dorval Airport station in Montréal was used to classify the different events. Following the approaches defined by Huff (1967) in the U.S., and Hogg (1982) in Canada, the rainfall temporal patterns were thereafter categorized in different quartiles depending on when the most important rainfall depth were recorded (Figure 2). Normalized mass curves were then created resulting in families of rainfall temporal patterns for each quartile. Different profiles were also created for each quartile corresponding to different probability of exceedance of total rainfall depth.

Design rainfall events could thereafter be determined by using rainfall depths for given durations, as defined by the IDF curves.
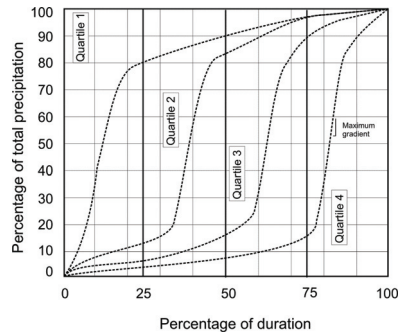
Figure 2 Classification of rainfall events.

3.2 Development of rainfall temporal patterns for future climate

The hydrologic responses (runoff volumes and peak discharges) for the 199 historical rainfall events were evaluated with SWMM (Stormwater Management Model; Huber and Dickinson, 1988) for the typical urban land uses previously defined. Statistical analyses of runoff volumes and peak discharges simulated using historical rainfall events were then performed. Finally, different temporal patterns were tested for each land use to determine which temporal patterns and percentages of exceedance would provide the best fit to the statistically estimated runoff volumes or peak discharges of a given return period. For example, for a parking lot (100% impervious), a duration of 1 hour with the temporal pattern of quartile 1 and a 65% exceedance gave the best fit for the peak discharge whereas a duration of 6 hours with the temporal pattern of quartile 1 and a 50% exceedance gave the best fit for the runoff volume. Figure 3 gives an example of the results for a parking lot with a 0.5 ha area. For a low density residential area (35% imperviousness), the best fit was obtained with a rainfall with quartile 4 temporal pattern and a 50% exceedance for the discharge and a quartile 3 (return periods 1 in 2 y. to 10 y.) and 4 (return periods 1 in 10 y. and rarer) (50% exceedance) for the runoff volume.

Once the temporal patterns were selected for each generic land use, the last step was finally to use the rainfall depth given by the IDF curves in future climate and to come up with design rainfall events for the future conditions. This approach is based on the hypothesis that rainfall profiles of extreme events (spatial and temporal profiles) will not change in future climate. The change in runoff volume and peak discharge could therefore be evaluated by simulation for each land use.
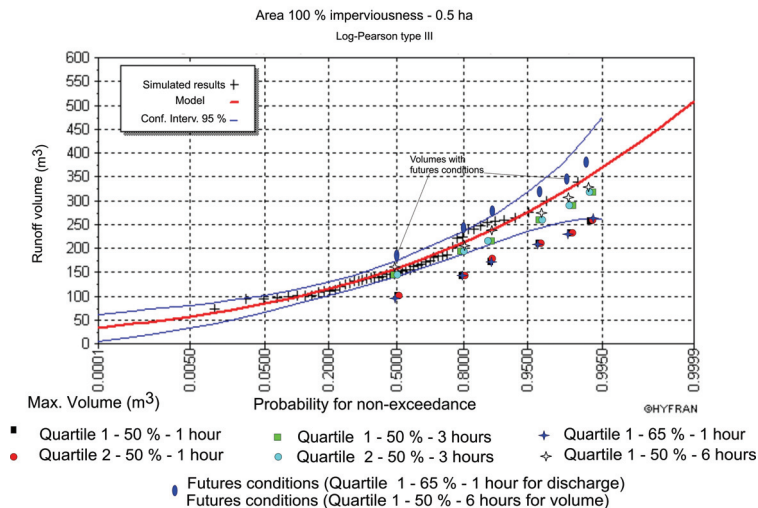
Figure 3 Results of the SWMM simulations for the selection of the more appropriate rainfall temporal pattern for the runoff volume for a parking lot (100% imperviousness).

3.3   Analysis of impacts for different land uses

Table 1 summarizes the percentage of increase for peak discharges and runoff volumes, using the temporal patterns under actual and future conditions.

Land use	Parameter	Return period			
		2	5	10	100
Parking lot	Rainfall	23 (for Q) 13.5 (for V)	19.7 (for Q) 18.2 (for V)	17 (for Q) 17.8 (for V)	13.8 (for Q) 15.3 (for V)
	Q	21.2	24.8	22.8	16
	V	14.3	18.9	18.6	15.8
Low density residential	Rainfall	23	20	17	14
	Q	33.3	37.9	32	24.1
	V	49.0	35.6	26.7	21.1

Q = peak discharge; V = runoff volume.

Table 1. Percentage of increase for rainfall and runoff parameters for different land uses.

4   SOURCE CONTROLS AS AN ADAPTATION MEASURE TO CLIMATE CHANGE

The last part of the study examined if source controls could be used or adapted to compensate for the increases that could be associated with CC, both for runoff volumes and peak discharges. For parking lots, where source control is already common, the estimated increases in discharge for the future climate varied from 44 L/s/ha (2-year return period) to 90 L/s/ha (100-year return period). For the runoff volumes, the corresponding increases are respectively of 14.3% and 15.8%. For existing sewer networks where source control is already in place, these values could be used to identify how these can be adapted and the possible impacts of increasing

runoff volumes considering the available retention volumes. On the other hand, for a projected development where actual IDF curves are used for the design, these values could be used to take into account future conditions, with most probably marginal effect on costs.

For residential areas, recent studies have looked at the potential benefits that could provide different source controls. A first study, MWLAP (2002), was based on continuous runoff simulation and investigated different combinations of source controls. These included absorbent landscaping (300 mm deep), on-lot infiltration, green roofs and on-street infiltration. Figure 4 shows the results for different combinations and, although these are obviously site-specific, it demonstrates that runoff volume and peak discharge reductions comparable to the ranges of values shown in Table 1 are possible, at least for return periods more frequent than 1 in 5 year.
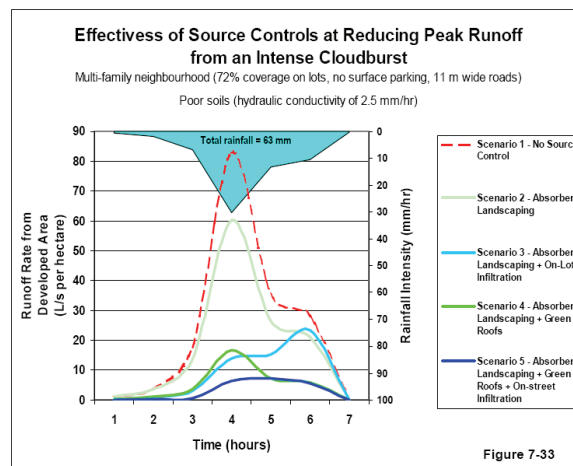

Figure 4 Global benefits for different source controls (MWLAP, 2002).

Table 2 is extracted from another study (Watt *et al*., 2003) and gives possible benefits associated with other types of control. Once again, based on theses results obtained with simulations using a calibrated model, it appears possible to compensate the anticipated increases for existing sewer networks. Obviously, for new projects, the increases could be included in the overall design.

Case	Runoff Volume (10^3 m^3)[1]	Peak Discharge (m^3/s)[1]	Time to Peak Discharge (min)[1]
Present Rainfall (24.5 mm)	1.9	1.5	22
Present Rainfall + 15% (28.2 mm)	2.3	1.7	22
Roof Disconnection (Full Roof)	1.4 (-39%)	1.0 (-39%)	22 (no change)
Roof Disconnection (Back Roof Only)	1.8 (-20%)	1.4 (-18%)	22 (no change)
Increased Surface Storage	1.8 (-19%)	1.5 (-14%)	22 (no change)
Install ICDs (orifice induced ponding)	2.3 (no change)	1.5 (-12.5%)	26 (+18%)

[1]percent change values relative to 'Present Rainfall+15% case

Table 2 Potential benefits for different source controls (Watt et al., 2003).

5   CONCLUSION

The increases in runoff volume and peak discharge that could be anticipated due to CC have been evaluated for different generic land uses. Although there is uncertainty associated with the methodology used to derive future design storms, significant increases are obtained. Evaluation of potential benefits that could be associated with source controls of various types, when compared with the increases due to CC, indicated that these could certainly be considered to mitigate the potential impact of CC, at least for the more frequent events. These findings suggest that source controls and micro-management should be integrated in a more general way into the design of stormwater systems, in order to provide or maintain the generally expected level of service.

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