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Evaluation of the Impact of Rainfall Increases on Runoff in Urban Watersheds

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ABSTRACT

Existing drainage systems, which were already susceptible to degradation, are now facing even greater challenges due to the projected increase of rainfall extremes related to urbanisation and climate change. This could compromise their overall effectiveness. This project aims to develop a novel methodology for assessing the impacts of rainfall increases on urban runoff. The proposed methodology relies on modeling a significant number of artificial urban watersheds using the United States Environmental Protection Agency's (US EPA) Storm Water Management Model (SWMM) software, and the use of rainfall data from different meteorological stations with a variety of durations and frequencies.

Results showed that using a simple increase of 18% in simulated rainfall led to larger relative increases in computed peak flow, with a median variation of 24.7%, and median variations in computed runoff volumes of 18.0%. The dispersion of obtained results depends on the intensity (0.05% to 2.58%), frequency (0.05% to 3.22%), and duration (0.16% to 1.49%) of the rainfall event. This suggests that there is no direct link between the rainfall increase factor and the amount of urban runoff.

A sensitivity analysis (ANOVA) was conducted to evaluate how watershed characteristics influence runoff caused by changing rainfall regimes. It was found that among all the artificial watershed criteria tested, impermeability, area, and slope have a greater influence on calculated peak flow changes under the tested rainfall increases. Additionally, impermeability emerged as the most critical characteristic affecting calculated runoff volume across all stations, although certain stations exhibited variations where soil type played a more prominent role.

This shows that the impacts of climate change could affect watersheds differently depending on their characteristics. This study emphasizes the importance of reducing soil impermeability in the urban water cycle, notably using blue-green infrastructures, to mitigate the impact of climate change on existing urban drainage systems.

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1. INTRODUCTION

The Canadian Infrastructure Report Card (CIRC 2019) has revealed a concerning statistic: around 30% of the country's municipal water assets, such as sewers and culverts, are in very poor, poor, or fair condition. Moreover, drainage infrastructures, which were already susceptible to degradation, are now facing increasing stress related to the impacts of climate change. The current consensus suggests that the increase in anthropogenic greenhouse gas (GHG) emissions will lead to a rise in the global average temperature (IPCC 2023). This global warming will result in various impacts, notably an increase in the frequency and intensity of extreme rainfall events (Douville et al. 2021; Martel et al. 2020; 2021). This situation could put the drainage infrastructure functionality at risk (Mailhot et al. 2007). Such vulnerability can lead to severe consequences, ranging from surface floods to sewage backups. To address these issues, Canadian governments invest billions of dollars annually in infrastructure maintenance to ensure reliability while minimizing future costs (Government of Canada 2023; Kind 2014; Merisalu et al. 2021).

When assessing the needs of drainage infrastructure, it is imperative to consider projected urbanization and future climate change (Bronstert et al. 2002; CSA 2019). Hydrological modeling can play a crucial role as it allows for a better understanding of how a watershed responds to rainfall and provides an efficient and cost-effective means of estimating both current and future runoff patterns.

Modeling runoff under future climate conditions requires the use of historical rainfall data adjusted to account for the impact of climate change. The results of these models provide estimates of both peak flows and runoff volumes, which are essential for developing strategies to adapt to climate change in stormwater management (Rivard 2005).

Hydrological modeling, however, presents significant challenges, particularly when dealing with small urban watersheds. In such cases, the use of sub-daily time steps is essential to accurately capture the fluctuations in runoff (Mailhot et al. 2021). The presence of uncertainties related to the physical characteristics of watersheds and climate change can potentially lead to costly consequences. Several studies have explored the projected impacts of climate change on peak flow and runoff volume over the years using hydrological modeling.

Markus et al. (2012) assessed climate change impacts in six suburban watersheds located near Chicago using the Hydrologic Engineering Center – Hydrological Modeling System (HEC-HMS) (Bartles et al. 2022). Their findings highlighted the non-linear relationship between calculated rainfall and simulated runoff, indicating that even minor variations in rainfall could result in significant variations in runoff. Additionally, their research revealed regional heterogeneity in watershed responses to climate change.

A substantial body of research has focused on the United States Environmental Protection Agency's (US EPA) Storm Water Management Model (SWMM) (Rossman and Simon 2022) to evaluate the impacts of urbanization and climate change on urban watersheds. This model incorporates various characteristics, including area, slope, impermeability, surface roughness, and infiltration, into its calculations. Alamdari et al. (2022; 2020; 2017) utilized SWMM to model an urban watershed in Virginia, assessing the impact of climate change and urbanization on future water quantity and quality. Their studies revealed that the combined impact of urbanization and climate change could lead to an increase in simulated runoff of up to 67.6%, nearly four times the projected increase in rainfall.

Mitsova (2014) employed SWMM to conduct a sensitivity analysis on a watershed located in Ohio. Ten different scenarios were evaluated, which involved testing variations in climate projections, soil impermeability, and the use of different levels of low impact development (LID). The simulated results demonstrated that the use of LID techniques could effectively counteract the increase in soil impermeability associated with urbanization growth. Also using SWMM, Thakali et al. (2018) modeled a watershed in Nevada. Their research highlighted the efficacy of incorporating permeable pavement and green roofs, either individually or in combination, as effective measures to mitigate the additional runoff induced by climate change.

Wu et al. (2013) assessed five watersheds located in Iowa, each characterized by varying levels of impervious surfaces. They explored three different scenarios that combined the effects of both climate change and land use change. Their findings showed significant impacts on simulated urban river hydrology, particularly in terms of water quality and peak flows. An 18% increase in simulated rainfall resulted in an average increase of 20.8% in peak flow, considering only the impact of climate change.

Zahmatkesh et al. (2015; 2014) conducted a study on the Bronx River watershed in New York City using SWMM. Their results showed that the simulated increase in extreme rainfall due to climate change would result in higher simulated peak flows and runoff volumes. Additionally, they developed a watershed sensitivity index and found that the slope had the greatest influence on runoff in this watershed.

A study by Nguyen (2013) aimed to assess a statistical downscaling method for estimating the impact of climate change on design rainfall. This study utilized 36 artificial watersheds, varying in terms of area, shape, and impermeability, using the SWMM model to assess the impact of the projected climate change scenarios on simulated peak flows and runoff volumes. The results of the study revealed similar trends regardless of the type of watershed studied.

Coulombe et al. (2022) conducted a study using SWMM on the very small Saint-Régis Watershed located in Quebec to assess climate change adaptation solutions. The results from the SWMM model were incorporated into the technical component of a multi-criteria decision analysis method to rank the best adaptation solutions according to socio-economic, environmental and technical criteria. The study showed that the proposed methodology can be used to select optimal solutions to increase climate resilience.

It is worth noting that while these studies provide valuable insights, they do have their limitations. They were conducted on a relatively small and localized set of local watersheds, each characterized by diverse characteristics and using a limited number of rainfall events. Consequently, generalizing the findings of these studies can be challenging, and doing so may introduce a significant level of uncertainty into their conclusions. Nevertheless, they have demonstrated the existence of a link between rainfall and runoff. It remains important to develop a comprehensive understanding of the nature of this link and the factors influencing urban watershed hydrology within the context of climate change.

The primary objective of this study is to develop a novel methodology for assessing urban runoff in the context of climate change to better understand the influence of rainfall parameters and watershed characteristics on peak flow and runoff volume. To accomplish this, a substantial number of artificial watersheds with various characteristics will be modeled using the SWMM model. The peak flows and runoff volumes of these watersheds will then be simulated using calculated rainfall for different regions, durations, and return periods, with or without considering the impact of climate change on them. This will allow for the assessment of the influence of simulated rainfall parameters, the relative importance of watershed characteristics on runoff, and the disparities between the studied regions concerning peak flow and runoff volume.

2. METHODOLOGY

The proposed method for evaluating runoff in the context of climate change using multiple artificial watersheds was developed through the application of various tools, aiming to align with the design methods of urban drainage infrastructure in Quebec. To begin, extreme rainfall time series of different return periods and duration were generated for multiple meteorological stations. A second set of calculated rainfall time series, this time adjusted to account for climate change, was then produced. Then, an algorithm was designed to manipulate the SWMM hydrological/hydraulic modeling software. This enabled modeling a large number of artificial watersheds to evaluate the previously calculated rainfall time series for SWMM simulations. SWMM simulation reports were used to analyze the results through descriptive statistical analyses and an ANOVA sensitivity analysis. All these steps are described in the upcoming subsections.

2.1 Input data

The method first requires rainfall time series as an input variable. There are two types of rainfall time series: continuous and single event. Continuous rainfall time series better account for antecedent moisture conditions (Rivard 2011). However, this paper focuses on artificial extreme rainfall events and does not attempt to simulate real historical events. The antecedent moisture conditions are therefore irrelevant in this study as the event-based simulations were all performed using the same initial conditions to assess the impact of the extreme rainfall event, akin to performing the study using a generic historical simulation before forcing the model with the extreme rainfall events. Also, the use of event-based rainfall time series is required by Quebec regulations (Government of Québec 2023a), and it is also the best way to evaluate rainfall parameters individually.

The rainfall data employed in this study were sourced from meteorological data provided by Environment and Climate Change Canada (ECCC) for 12 meteorological stations located in 12 cities across the province of Quebec in Canada. This approach aimed to capture a wide range of rainfall patterns. Table 1 presents metadata from the selected stations and the Chicago rainfall hyetograph *r* ratios selected for each station.

Table 1 ECCC information on selected meteorological stations.

ID	Latitude	Longitude	Elevation (m)	Years*	Ratio ** (*r*)
7060400	48° 20' N	71° 00' W	159	45	0.42
7080468	46° 43' N	79° 06' W	181	52	0.40
7052603	48° 47' N	64° 50' W	360	26	0.40
710S005	58° 28' N	78° 05' W	26	32	0.40
7113534	58° 06' N	68° 25' W	39	32	0.40
7040813	51° 27' N	57° 11' W	37	28	0.40
702S006	45° 28' N	73° 44' W	32	76	0.45
701S001	46° 48' N	71° 23' W	60	61	0.38
7056480	48° 27' N	68° 31' W	35	25	0.40
7117827	54° 48' N	66° 48' W	517	26	0.40
7047914	50° 13' N	66° 15' W	52	41	0.40
7028124	45° 26' N	71° 41' W	241	32	0.40

** Number of years of recorded rainfall data.*

*** The ratio is used to compute design storm rainfall intensities.*

ECCC provides the equations of least squares-adjusted intensity-duration-frequency (IDF) curves for each return period, interpolated for each duration with two coefficients. However, establishing the rainfall Chicago hyetograph required three parameters (i.e., a, b, and c) (Keifer and Chu 1957). Consequently, MATLAB programming software was employed to extract annual maximum series (AMS) from IDF files provided by ECCC. A rainfall frequency analysis was conducted using the Gumbel distribution, followed by the fitting of IDF curves using a three-parameter regression equation. The intensities obtained this way were like those provided by ECCC.

The return periods (2-, 5-, 10-, 25- 50-, and 100-years) and rainfall durations (1-, 3-, 6-, 12- and 24-hour) studied are those commonly provided by IDF curves and used in the design of urban drainage infrastructure. The selected data all have a minimum recording period of 25 years, reducing the impact from epistemic uncertainty (CSA 2019).

The Chicago rainfall hyetograph was selected for this study because it is widely used in engineering design and can be easily applied for all frequencies and rainfall durations. These Chicago storms were derived using *r* ratios, developed by Watt et al. (1986) (see Table 1), and were used alongside the a, b, and c parameters from the three-parameter IDF curve regressions. A 10-minute time step was used for the time series to avoid overestimating peak flows generated by the design storm (MEO 1987). These data were used to generate 60 calculated rainfall time series for each of the 12 cities, for a total of 360 reference calculated rainfall time series.

To streamline the rest of the article, any mention of rainfall refers to calculated rainfall time series rather than observed rainfall data.

2.2 Precipitation increase method

To assess the impacts of climate change, additional rainfall time series were derived from the reference rainfall time series, which included adjustments to account for the effect of climate change. The method used in this study is a simple constant percentage increase with an 18% scaling factor. That was, until recently, the recommended method in the province of Quebec (MELCCFP 2023). The application of this method allows facilitating the comparison between the rainfall increases due to climate change and the projected changes in peak flow or runoff volume. This scaling factor of 18% is applied to all reference rainfall time series, regardless of duration, return period, time horizon, or region. Thus, a total of 720 rainfall time series were considered to account for the impacts of climate change (360 in current and future climates).

2.3 Hydrological model

The US EPA Storm Water Management Model, version 5 (SWMM5) (Rossman and Huber 2015), a widely-used hydrological and hydraulic model to design urban drainage infrastructure in North America, was selected for this study. Developed by the US EPA, the SWMM model simulates the physical processes of the water cycle in urban environments. It receives rainfall time series and transforms raw rainfall into runoff on impervious surfaces, while pervious surfaces infiltrate a portion. The model also accounts for evaporation and is discretized at each time step, allowing the simulation of hydrological variable evolution based on characteristics such as area, slope, imperviousness, surface roughness, and the infiltration model (Rossman and Huber 2015). This choice allows for generating watershed runoff in the form of a sub-daily hydrograph based on temporal rainfall series (CSA 2019).

To supply the SWMM simulation models, the 720 temporal rainfall time series were utilized. An algorithm was developed using the Python programming language in conjunction with the SWMM-API module (Pichler 2022). This module serves as an interface for controlling SWMM, enabling the creation of watersheds with diverse characteristics, and the execution of simulations based on the rainfall time series.

The algorithm developed comprises a series of nested loops. During each iteration, the algorithm creates a watershed with specific characteristics, applies a rainfall time series, generates a SWMM simulation, and produces a report detailing the simulation results. These iterations sequentially modify watershed characteristics and rainfall data, providing a comprehensive exploration of watershed response scenarios. Using this method, 4,860 artificial watersheds (i.e., combinations of watershed characteristics) were modeled for each city analyzed, resulting in a total of 291,600 simulations per city. In total, 3,499,200 simulations were conducted.

For conciseness, any mention of peak flow or runoff volume in this study refers to SWMM simulation results rather than observed peak flow or runoff volume.

2.4 Artificial watersheds characteristics

The watersheds created during each iteration are artificial watersheds. This means they do not represent real watersheds and have no drainage infrastructure. They represent flat surfaces whose characteristics vary from one watershed to another as described below. The use of artificial watersheds allows for the evaluation of a greater variety of urban watersheds. This choice also facilitates the assessment of each watershed characteristic individually, which would not have been possible with a more complex watershed.

The following watershed characteristics were varied to generate the 4,860 artificial watersheds: area, width, slope, impermeability, surface roughness (i.e., Manning's coefficient), and soil type. Table 2 summarizes the discrete values used for each characteristic.

Table 2 Discrete values of each artificial watershed's characteristics.

Area (km^2)	Width	Slope (%)	Impermeability (%)	Manning's Coefficient		Soil class
				Impervious	Pervious	
0.01	Long	0.1	5	0.010	0.05	A
12.5	Square	10.0	25	0.015	0.25	B
25	Wide	20.0	50	0.025	0.50	C
			75			D
			95			

NOTE: All combinations were tested as artificial watersheds, for a total of 4860 watersheds.

The selection included minimum, average, and maximum areas, all of which corresponded to relatively small urban watersheds. It is worth noting that applying IDF curves to areas larger than 25 km^2 is not recommended, as per guidelines from the CSA (2019).

Three typical rectangular watershed shapes were established, enabling the evaluation of length-to-width ratios. These shapes included a long watershed with a length (L) twice its width (W), a square watershed with equal width and length, and a wide watershed with a length of half its width. The algorithm computed the width based on these predefined proportions, using the given area value as input. Then the flow length was automatically estimated by the software.

Additionally, slopes were selected to represent urban watersheds with low (0.01%), medium (10%), and high (20%) gradients. This diversity of gradients aimed to reflect the potential variability of hydrological characteristics in urban environments with different topographies.

As discussed earlier, the impermeability of surfaces plays a crucial role in the runoff process. To effectively illustrate this phenomenon, a range of impervious percentages, spanning from very low (5%) to nearly complete impermeability (95%), were selected.

The roughness coefficients for impervious surfaces were selected with minimum (0.010), average (0.015), and maximum (0.025) values, whereas for pervious surfaces, minimum (0.05), average (0.25), and maximum (0.50) values were chosen. These values were sourced from the SWMM user manual by Rossman and Huber (2015), which itself is based on research by McCuen, Johnson, Ragan, and United States Federal Highway Administration (1996).

The Horton infiltration model was chosen to simulate infiltration processes. The parameters used originate from the study by Terstriep and Stall (1974) and are grouped into four hydrological soil classes (i.e., A, B, C, D) from Cronshey and United States Department of Agriculture (USDA 1986). A brief description of each soil class and the corresponding Horton parameters are presented in Table 3.

Table 3 Soil type classes and corresponding Horton parameters.

Class	Description	*f0* (mm/h)	*fc* (mm/h)	*k* (1/h)
A	Sand, loamy sand, or sandy loam	254.0	25.4	2.0
B	Silt loam or loam	203.2	12.7	2.0
C	Sandy clay loam	127.0	6.4	2.0
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay	76.2	2.5	2.0

2.5 ANOVA sensitivity analysis

A global sensitivity analysis was conducted based on the decomposition of the ANOVA sensitivity analysis, originally introduced by Fisher (1920). The primary aim of this analysis is to evaluate the influence of the model's input parameters on its output variables (Bucci 2021; Aryal et al. 2019). The input parameters are the artificial watershed characteristics as described previously, and the output variables under study are the peak flow and runoff volume.

The MATLAB library Anovan (The MathWorks, Inc. 1994), which is an *n*-way ANOVA, was then employed to conduct the sensitivity analysis. This analysis allowed for the calculation of the portion of variance explained by each input parameter of the model, while also accounting for interactions between them. Additionally, it quantified the proportion of residual variance, contributing to a comprehensive assessment of parameter sensitivity

3. RESULTS

3.1 Analysis of the influence of rainfall parameters

A descriptive analysis was conducted to better understand the relationship between rainfall and runoff in the context of climate change. This analysis considered the three main characteristics of rainfall: intensity, duration, and frequency. Peak flow and runoff volume were evaluated based on these three parameters. Figure 1 illustrates the median variation of peak flow and runoff volume between historical and increased rainfall of 18% to account for climate change for the studied meteorological stations.

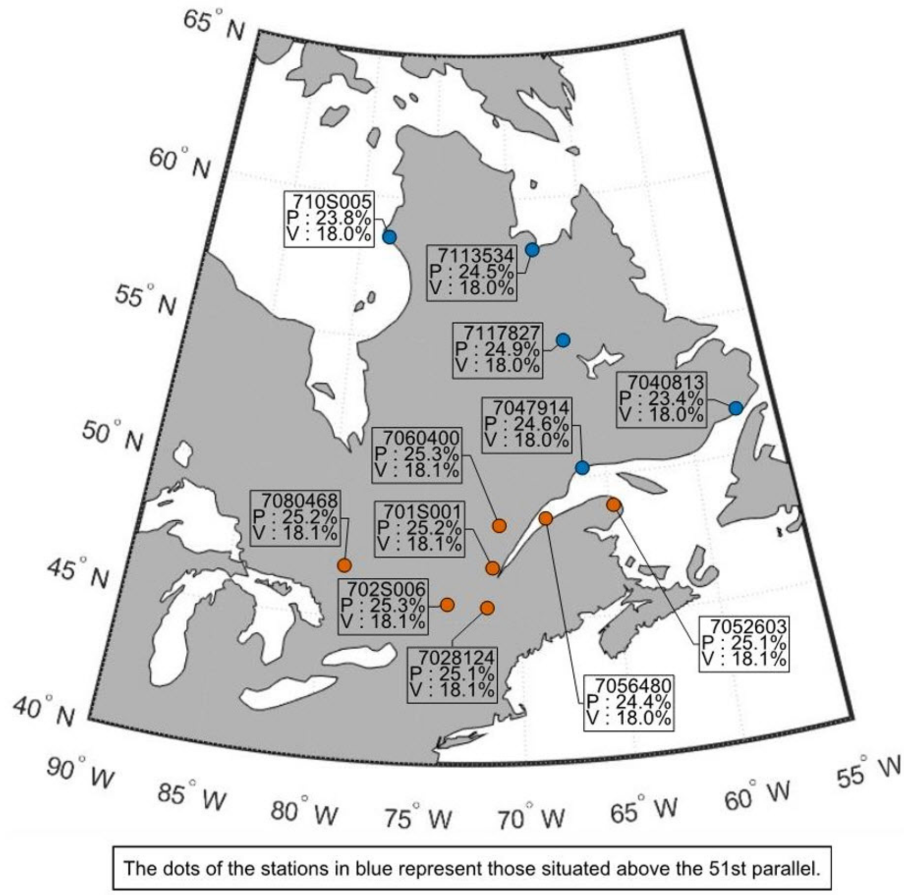

Figure 1 Median variation in peak flow (P) and runoff volume (V) between historical and increased rainfall to account for climate change, according to the meteorological station.

The blue stations represent those located in northern Quebec (above the 51st parallel), and the orange ones represent those situated in southern Quebec (below the 51st parallel). All meteorological stations that represent IDF curves with different intensities experience an increase in runoff volume by a median value of approximately 18%. However, this value is exceeded for peak flow, with the additional 18% aimed at addressing climate change impacts.

Rainfall intensity

The first variable examined is rainfall intensity, which exhibits variations depending on the meteorological station under study. Each station presents a unique set of IDF curves derived from its recorded historical rainfall data. The peak flow and runoff volume variation between historical and increased rainfall for each meteorological station are presented in Figure 2.

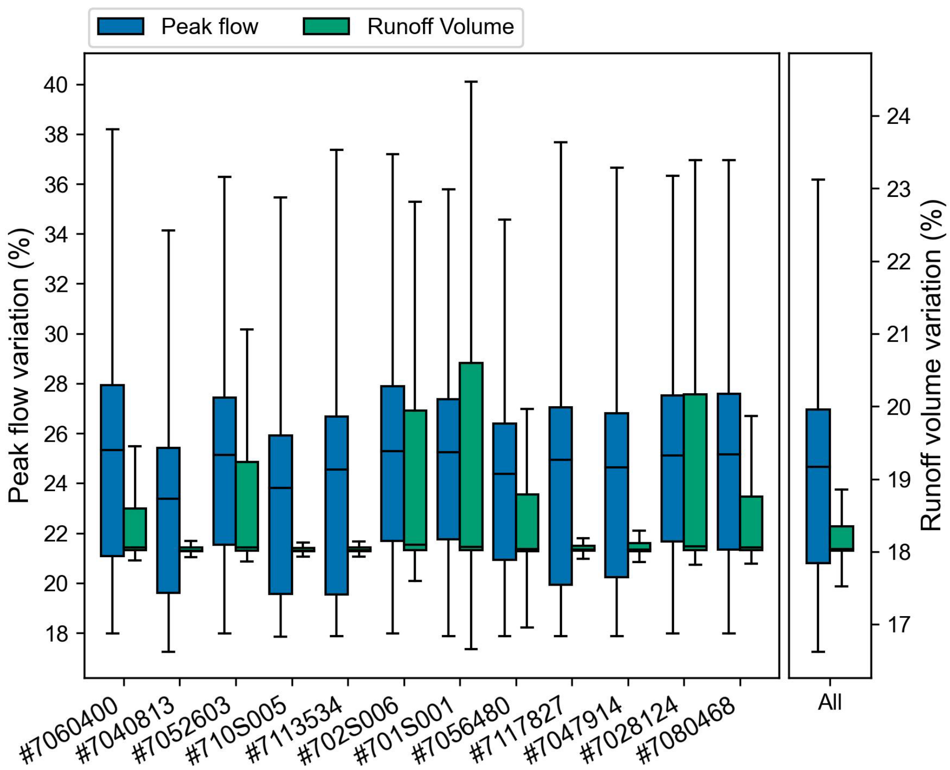

Figure 2 Variations in peak flow and runoff volume between rainfall events for current and future climate for each meteorological station.

Although the rainfall increased by 18%, the increase in peak flow exceeds this, ranging from 23.4% (station #7040813) to 25.3% (station #7060400). The overall median value for all meteorological stations is 24.7%. This represents an average difference of +6.7% from the rainfall increase factor of 18%.

The stations with the greatest variations in peak flow are located south of the 51st parallel. This southern area of Quebec is characterized by a cold and humid continental climate, resulting in a higher amount of rainfall, with 75% of it occurring as rainfall throughout the year (Government of Québec 2023b). The northern area of Quebec (above the 51st) is, in contrast, characterized by a subpolar continental climate, bringing less rain as it occurs over a shorter period due to lower temperatures (Government of Québec 2023b). An examination of the IDF curves of meteorological stations has confirmed that historical rains from the stations in the southern area of Quebec generate higher rainfall intensities than the others.

A Kruskal-Wallis analysis was conducted to compare differences between mean variations of peak flow in regards of the stations. The results of this test, as illustrated in Figure 3, showed significant differences between the sample means, except for two stations: #7052603 and #7080468. These two stations, the first located in the city of Gaspé, and the other at the Témiscamingue dam, do not seem to exhibit similarities that could explain this result.

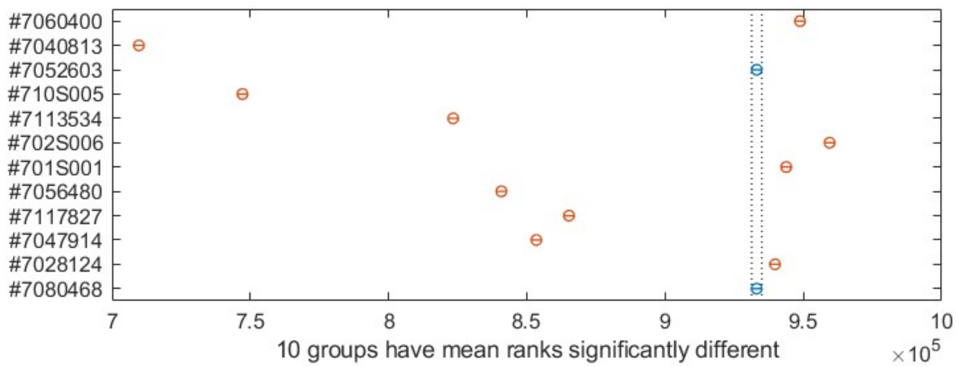

Figure 3 Multiple comparisons of mean ranks of peak flow between stations.

The median variations in runoff volume between historical and increased rainfall ranges from 18.0% (station #7040813) to 18.1% (station #702S006). The overall median variation across all stations is 18.0%, corresponding to the increased rainfall factor. It is noteworthy that the Kruskal-Wallis test showed significant differences in mean variations among all stations. This can be attributed to diverse distributions observed from one station to another, as shown in Figure 2. The interquartile range varies between 0.05% and 2.58%. Stations with the largest interquartile ranges are located in the southern part of Quebec, characterized by heavier rainfall.

Rainfall frequency

The second IDF curve variable studied is rainfall frequency. The variation in peak flow and runoff volume between historical and increased rainfall variation is presented in Figure 4.

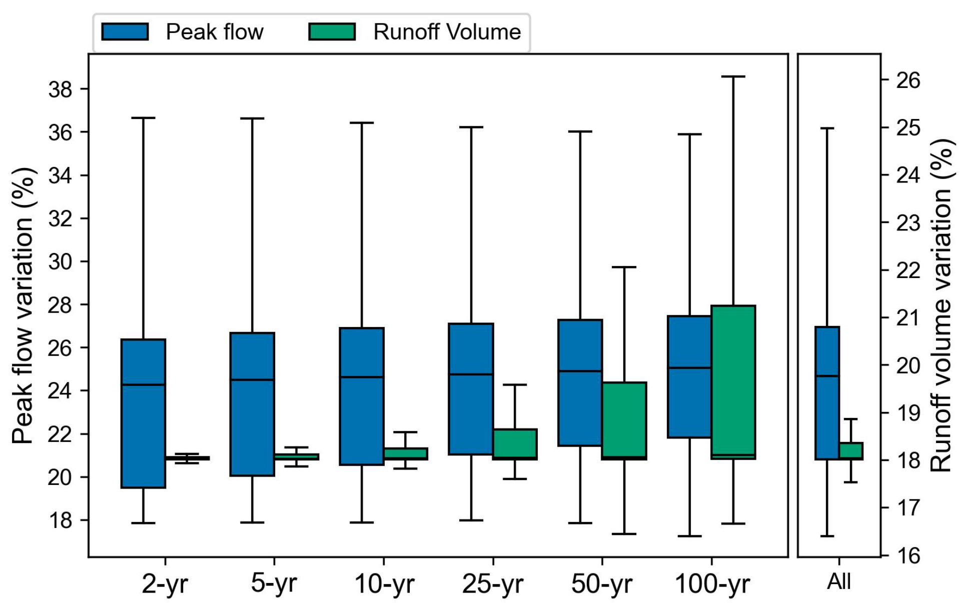

Figure 4 Variations in peak flow and runoff volume between rainfall events for current and future climate for each rainfall frequency tested.

The median variation in peak flow, across all frequencies, remains at 24.7%. However, this value gradually varies between 24.3% (2-year frequency) and 25.0% (100-year frequency) as the rainfall frequency increases. Regardless of the frequency, the variation consistently exceeds the 18% rainfall scaling factor. The Kruskal-Wallis test detects significant differences in mean variations of peak flow across frequencies.

Examining runoff volume, the variation in median volume between historical and increased rainfall for each frequency ranges from 18.0% (2-year frequency) to 18.1% (100-year frequency). The median variation across all periods is 18.0%. The interquartile range varies between 0.05% and 3.22% as the rainfall frequency increases. As for the peak flow, the Kruskal-Wallis test detected significant differences in the average variation across frequencies.

Rainfall duration

The third determining parameter in IDF curves is the rainfall duration. The variation in peak flow and runoff volume between historical and increased rainfall to account for climate change is presented in Figure 5.

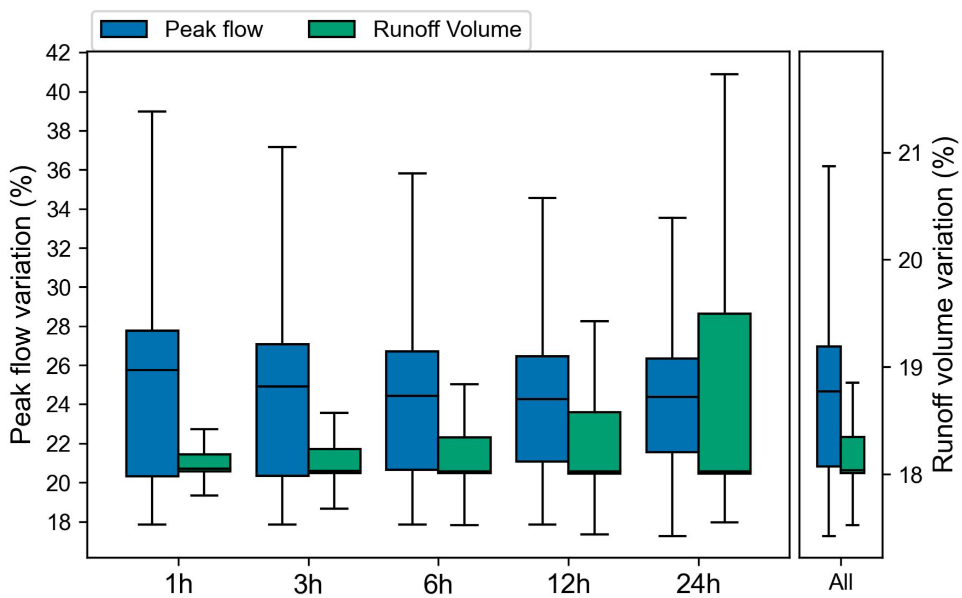

Figure 5 Variations in peak flow and runoff volume between rainfall events taking climate change into account, and those not taking them into account for each duration.

The median variation in computed peak flow across all durations is 24.4%. This value varies between 24.3% (12-hour duration) and 25.8% (1-hour duration). Regardless of the duration, the variation exceeds the 18% rainfall scaling factor. The Kruskal-Wallis test detects significant differences in means variations of computed peak flow across durations.

The median variation in computed runoff volume shows slight variability, ranging from 18.0% (12-hour duration) to 18.1% (1-hour duration). Across all stations, this variation is 18%, which is the same as the rainfall scaling factor. The interquartile range varies between 0.16% and 1.49% as the rainfall duration increases. The Kruskal-Wallis test also indicates significant differences between the means of variations for each rainfall duration due to the increasing data dispersion with rainfall duration.

3.2 Analysis of the influence of artificial watershed characteristics

As part of the sensitivity analysis, an ANOVA was conducted to examine various artificial watershed input characteristics. These characteristics encompassed the area, shape, slope, impermeability, surface roughness for both impervious and pervious areas, as well as soil types. The ANOVA results for computed peak flow and runoff volume are presented in Figures 6 and 7, respectively.

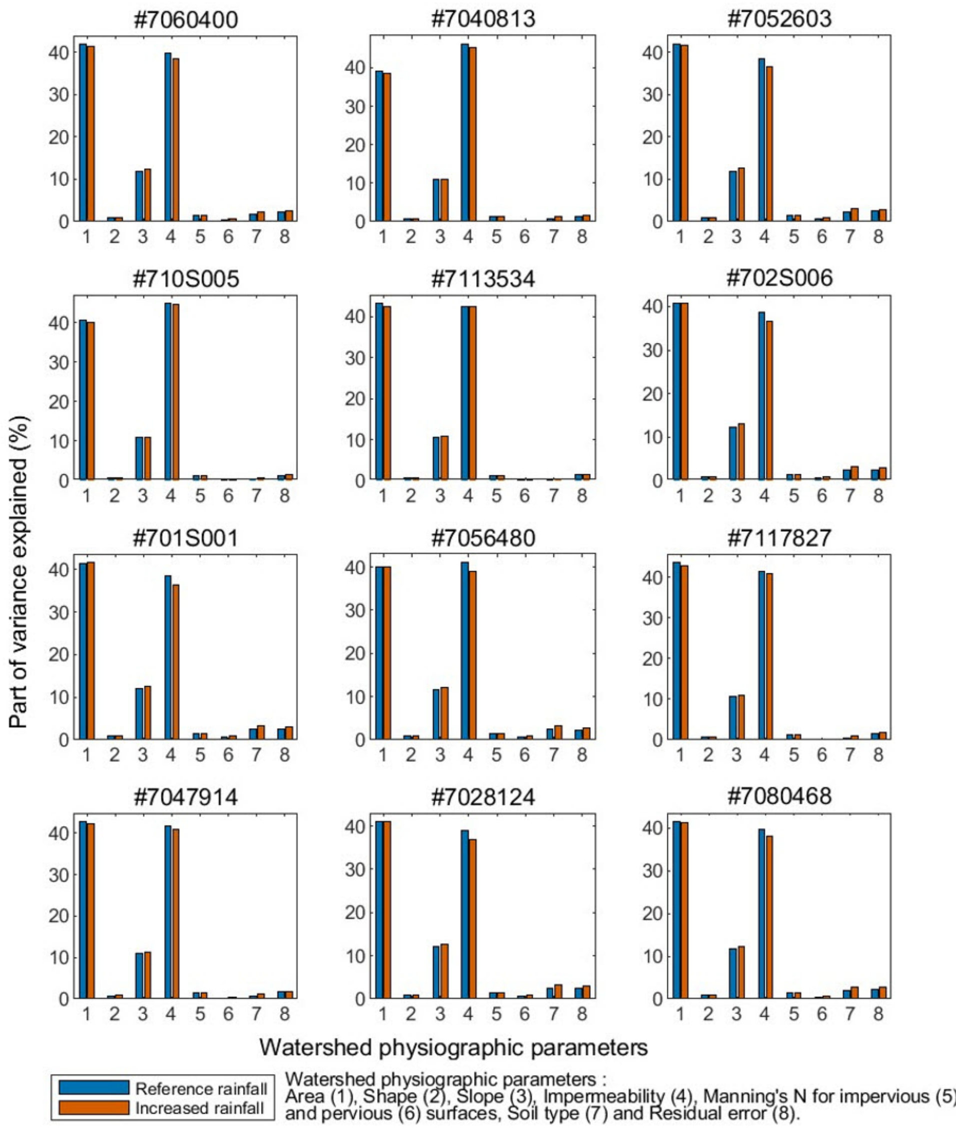

Figure 6 Results of the ANOVA evaluating the sensitivity of peak flow, with (blue) and without (orange) rainfall increase due to climate change, in relation to artificial watershed characteristics across different meteorological stations (identified with their station number on each subplot).

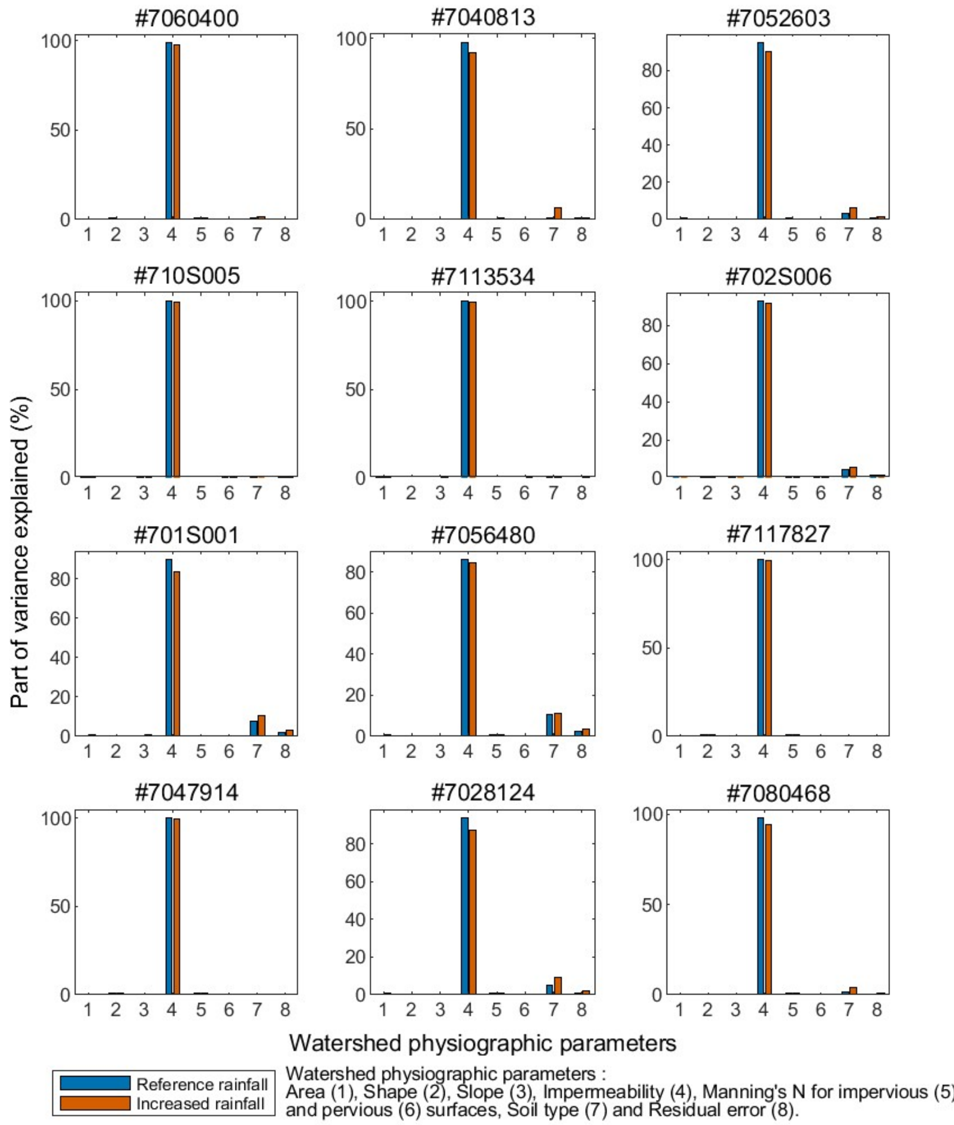

Figure 7 Results of the ANOVA evaluating the sensitivity of runoff volume, with (blue) and without (orange) rainfall increase due to climate change, in relation to artificial watershed characteristics across different meteorological stations (identified with their station number on each subplot).

Notably, across all meteorological stations, the two most influential characteristics regarding peak flow are artificial watershed area and impermeability. They account for an average of 41.8% and 39.7% of the total variance, respectively. However, their influence tends to slightly diminish in response to increased rainfall as a result of climate change, settling at an average of 41.3% and 38.3%, respectively.

The slope, identified as the third most important characteristic, contributes on average to 11.8% of the peak flow variance when rainfall is not increased to account for climate change, and 12.4% when it is increased.

As for the other characteristics, they collectively explain an average of 4.5% of the total variance for the historical rainfall, and 5.4% for the increased rainfall. Finally, there remains 2.2% and 2.5% of unexplained variance, representing residual error, i.e., signifying the variance not explained by the studied characteristics with and without considering increased rainfall, but related to higher-order interactions that were not considered here.

A Kruskal-Wallis test showed that there were significant differences between the mean results attributed to the area, impermeability, and slope characteristics compared to the results obtained with the other characteristics, whether considering the impact of climate change or not, as shown below.

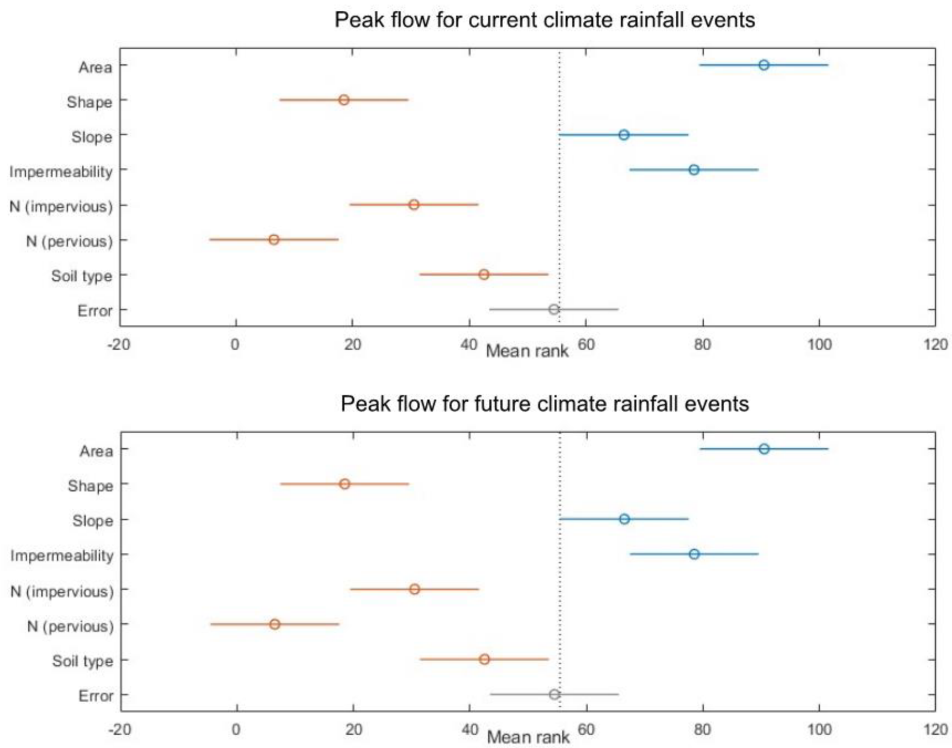

Figure 8 Results of the Kruskal-Wallis test on peak flow for current and future climate rainfall events.

The hydrographs of an average watershed, with and without considering climate change, during a rainfall event with the IDF curves of Montreal, a frequency of 10 years and a duration of 6 hours, are illustrated in Figure 9. In turn, the characteristics of area, impermeability, and slope were varied between the minimum, average, and maximum values identified in Table 2.

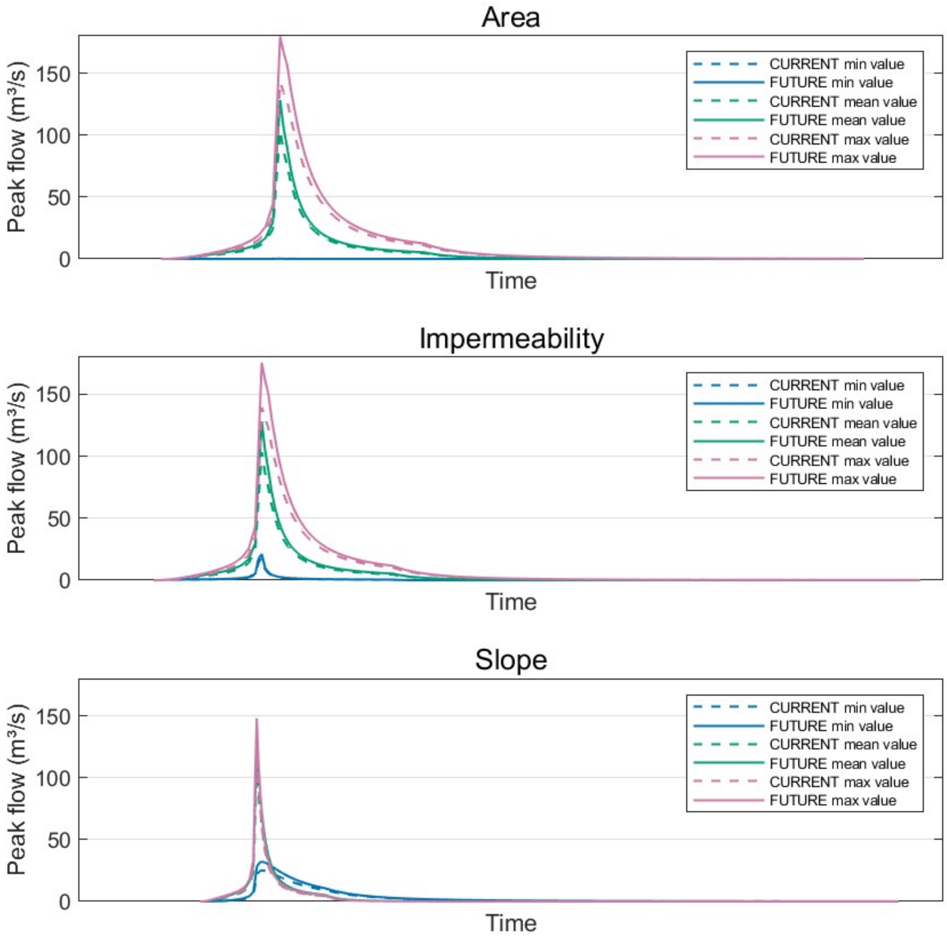

Figure 9 Hydrographs of the minimum, mean, and maximum values of artificial watershed characteristics with the greatest impact on peak flow, with and without increase to consider the influence of climate change for the Montreal station #702S006 with a 10-yr rainfall return period and 6h duration.

In all cases, the peak flow intensity varies considerably when the characteristics change. In the hydrographs, where the area and impermeability vary, the peak flows increase as the characteristics' values are increased. In the case of hydrographs where the slope varies, the shape of the hydrograph is also altered, showing a shorter time-to-peak and earlier recession curve as the slope is increased.

Regarding runoff volume, impermeability stands out, accounting for an average of 98.7% of the variance in historical rainfall and 97.6% for rainfall increased to accommodate the impact of climate change. In contrast, the combined explanation from other characteristics averages only 1.1% for historical rainfalls and 2.2% for future climate rainfalls, with residual errors at a mere 0.1% and 0.2%, respectively.

4. DISCUSSION

The analysis of rainfall parameters and artificial watershed characteristics has highlighted the relationships that exist between them and peak flow and runoff volume in a SWMM model. The present discussion aims to better understand the nature of those relationships.

4.1 Relationship between projected increase in rainfall and peak flow

Upon analyzing rainfall parameters, it becomes evident that the variation in peak flow in response to climate change surpasses the 18% rainfall increase factor. The median variation is 24.7%, with an interquartile range between 20.8% and 27.0% of peak flow. This greater variation in peak flow compared to the increase factor is explained by analyzing the rainfall-runoff transformation process of the hydrological model.

The artificial watershed receives rainfall, part of which is infiltrated, while the rest runs off to the outlet. Although rainfall is increased to account for climate change, the soil's infiltration capacity remains the same in the current or future climate. As a result, the flow increases by a larger fraction of the rainfall. This increase in rainfall consequently leads to a greater accumulation of water at the same time at the outlet. However, it is important to note that the relationship between the variation in peak flow and the increase in rainfall is complex, varying with the intensity, duration, or frequency of the rainfall.

Peak flow varies primarily based on rainfall intensity. In this study, rainfall intensity is represented by the meteorological station, which varies according to the historical rainfall it has recorded in its region. The analysis of the results shows that stations south of the 51st parallel generate higher median peak flows than the northern ones. The study of the IDF curves for these stations confirms that they have higher intensities than those to the north.

When rainfall intensity is low, it may entirely infiltrate without reaching the outlet. When it is more intense, the part of the rainfall not infiltrated corresponds to the peak of the rainfall. The more intense the rainfall, the larger the part not infiltrated, consequently increasing the generated runoff. Figure 10 illustrates this phenomenon.

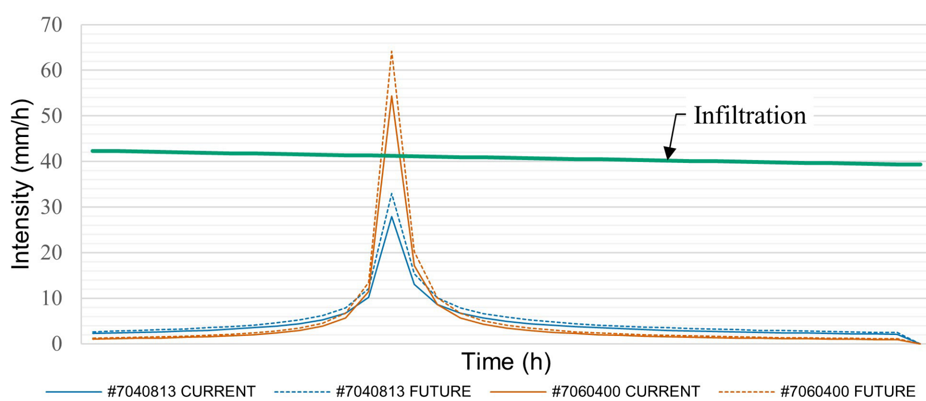

Figure 10 Rainfalls and infiltration in actual and future climate for stations #7040813 and #7060400, for a rainfall with a 2-yr frequency and a duration of 6h, and infiltration from soil class A.

Secondly, peak flow varies according to the frequency of rainfall. The higher the return period of the rainfall event (i.e., the rarer it is), the greater its intensity. It is in this manner that peak flow responds to increased rainfall. The results of the analysis indeed show that the median variation in peak flow increases with frequency.

Finally, peak flow varies according to the duration of rainfall. The shorter the duration of rainfall, the greater its intensity, and the same applies to peak flow. The median variation in peak flow thus decreases with an increase in the duration of rainfall.

It is thus possible to conclude that peak flow increases with the increase in rainfall. However, this increase is not direct, as an 18% increase in rainfall leads to a runoff increase exceeding this value. It also varies according to the return period and duration. Therefore, a higher peak flow can be expected for a station located in southern Quebec, with a long return period and a short duration. A literature review conducted by Martel et al. (2021) also demonstrated that long return period and/or short duration extreme rainfall will be the most impacted by climate change, which could lead to an even greater impact on peak flow in a future climate.

4.2 Relationship between projected increase in rainfall and runoff volume

Regarding the median variation in runoff volume, it remains relatively consistent across stations, frequency, and duration, corresponding approximately to the rainfall increase factor of 18.0%. The median variation is 18.0%, with an interquartile range between 18.0% and 18.3% of runoff volume, all stations combined. However, the dispersion of results varies according to the station, duration, and frequency.

The dispersion of data varies primarily according to the station. Stations south of the 51st parallel have a larger interquartile range than those north of it. An 18% increase in rainfall could therefore result in significantly higher volumes than this factor for regions where rainfall is more abundant, as shown in Figure 10.

Three processes contribute to generating the water volume at the outlet: rainfall, infiltration, and runoff. Rainfall will bring 18% more water into the system, but the other processes may not necessarily follow this increase. Stations with lower historical rainfall may infiltrate a greater proportion of rain before reaching their maximum infiltration capacity, unlike stations with historically intense rainfall. The portion of rainfall that is not infiltrated will add to the portion of rainfall contributing to the additional water volume at the outlet. The percentage increase in runoff volume can thus reach ratios higher than the increase factor.

The same principle applies according to the return periods. Shorter return periods are associated with less intense rainfall, while longer return periods correspond to more intense rainfall. Since the soil infiltration capacity remains constant regardless of the return period, more frequent rains can infiltrate a larger amount of water than less frequent events. This results in greater variability in runoff volume in the presence of longer return periods.

Regarding the duration, it is true that short-duration storms result in higher rainfall intensity. However, the longer the duration of rainfall, the longer the soil can infiltrate a large proportion of the rain, influencing the runoff volume at the outlet and leading to greater variability in longer-duration rainfall events.

4.3 Most important watershed characteristics for drainage infrastructure design

The results of the ANOVA show that the key watershed characteristics to consider in determining peak flow are impermeability, area, and, to a lesser extent, the slope of watersheds. The relative importance of area and impermeability tends to decrease slightly with climate change, making room for other characteristics such as slope or soil type.

These results align with the expected outcomes. The larger the area, the greater the runoff; the greater the impermeability, the less infiltration; and the steeper the slope, the faster the runoff will reach the outlet, thus influencing peak flow.

Regarding runoff volume, the most important watershed characteristic is impermeability, as it determines the percentage of rainfall that can or cannot infiltrate. Some regions in southern Quebec show an increased importance of soil types on runoff volume. As discussed earlier, infiltration plays a key role in the process of determining the runoff volume at the outlet of a watershed. The greater the intensity of the rain, as is the case in southern Quebec, the greater the variability in infiltration and runoff, influencing the importance of the watershed's soil type.

4.4 Limitations

This study has presented certain limitations that could be explored in future research. First, it is confined to rainfall data from twelve meteorological stations located in Quebec. Extending this analysis to include data from additional stations in Quebec, Canada, or even globally, could offer a more comprehensive perspective.

Concerning the creation of rainfall time series, only the temporal distribution of the Chicago storm was utilized. A future study could assess the impact of different temporal distributions on the results.

The experiment was limited to using the constant percentage increase method with an increase factor of 18%. To obtain a more precise depiction of the projected impact of climate change, it would be relevant to compare multiple methods associated with various climate change scenarios and evaluate their consequences.

It is important to note that the results should not be extrapolated beyond the study's limitations, the characteristics of the tested artificial watersheds are bounded by minimum and maximum values corresponding to small urban watersheds.

Additionally, the artificial watersheds studied did not have drainage infrastructure networks, elements that could significantly impact peak flow and runoff volume. This consideration should be factored into any interpretation or application of the results.

5. CONCLUSION AND RECOMMENDATIONS

The drainage infrastructure in Canada currently faces vulnerabilities, particularly in the context of challenges posed by climate change. These vulnerabilities have significant implications for the daily lives of citizens, necessitating substantial annual investments for the maintenance and improvement of these infrastructures.

This study introduces a new methodology for analyzing urban runoff in the context of climate change, addressing inherent challenges in hydrological modeling within real watersheds.

This project has provided a better overall understanding of watershed responses to increased rainfall due to climate change. However, the significant variability in results highlights the importance of case-by-case evaluations when analyzing the runoff of a particular watershed.

This project has also provided a more precise measurement of the relationship between rainfall and runoff. In the case of peak flow, it tends to exceed the increase in rainfall. Regarding volume, it corresponds to the rainfall increase factor. However, statistically significant variability has been observed in these results, especially for IDF curves in southern Quebec with high return periods and long durations.

The study has also underscored the importance of area, impermeability, and slope in determining peak flow, as well as impermeability and soil type in determining runoff volume. While modifying the area or slope of a watershed is rarely feasible, planning the development of urban watersheds could help to minimize impermeability and promote infiltration. This research has demonstrated that these measures could be implemented to reduce peak flow and runoff volume.

This project has established this new method for assessing a significant number of urban artificial watersheds in the context of climate change. Future studies could utilize this method to expand on the conclusions it can provide. It would be interesting to use this method to evaluate different climate change adaptation strategies using more realistic future rainfall extremes, such as rainfall scenarios derived from climate models. A subsequent study could also focus on a single, more complex watershed with an infrastructure network and assess the runoff from a range of rainfall scenarios.

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