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Impact of Wetland Surface Area on Seasonal Daily Extreme Flow Characteristics during the Summer-Fall Season in Southern Quebec (Canada)

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Abstract

The objective of this paper is to determine the impact of wetlands on the characteristics (magnitude, frequency, duration, timing and variability flow) of daily maximum and minimum extreme flows in summer-fall season (July to November) over the 1945-2019 period in Petite Nation watershed. Three relatively close watersheds [Matawin River (1,390km^2), Petite Nation River (1,330km^2) and L'Assomption River (1,340km^2)], which are differentiated mainly by the types of land use (wetland and agricultural areas), were studied. In the Petite Nation River watershed, which has the largest wetland surface area (15%), the frequency of flood occurrence significantly decreased, resulting in a decrease in the magnitude and duration of seasonally daily maximum flows and their early occurrence during the season. In contrast, the interannual rate change flow in the timing and duration of these flows is greater than that observed in the other two watersheds. The "sponge effect" of wetlands on daily maximum flows was not observed on daily minimum flows, whose magnitude is not significantly different from those of the Matawin River (reference watershed). In contrast, in the Petite Nation watershed, minimum flows last longer and occur on average later in the season than in the other two watersheds.

Keywords: Wetlands; Deforestation; Agriculture; Urbanization; Magnitude; Frequency; Duration; Rate change flow; Timing; Flood; Low flow; Rainy season; Southern Quebec

Introduction

Wetlands are essential components of landscapes. They significantly influence the hydrological cycle in watersheds. This influence has already been the subject of a relatively abundant literature. Many aspects of this influence have thus been analysed: the hydrological functioning of wetlands (e.g., [1-3]), their interactions (connectivity) and their impacts with other water bodies (e.g., [4-11]), river channels (e.g., [12-16]) and groundwater (e.g., [17-19]). Some studies have analyzed the impacts of global warming on this hydrological functioning and on these interactions and impacts on other water bodies and rivers (e.g., [20-22]).

There is an abundant literature on the impacts of wetlands on the spatio-temporal variability of river flows (see [23-25]). It appears from all these studies that the impacts of wetlands on river flows are not uniform but varied between watersheds depending on the type and physiographic characteristics. For example, some wetlands reduce flood magnitude while others amplify it. The same applies to low flows. In addition, most of these studies are limited to the analysis of the impacts on the magnitude of the flows, the impacts on the four other fundamental characteristics (timing, duration, frequency and variability) are rarely analysed despite their influence on the functioning and integrity of river ecosystems [26].

Sculpted by the succession of different glacial and interglacial periods, the landscapes of southern Quebec are dotted with many wetlands of different types and sizes. However, despite their widespread presence in watersheds, there are still very few studies on their impacts on river flows. Most of the studies already published have mainly focused on the hydrological functioning and the connectivity of some wetlands located at the headwater basins with river channels and groundwater (e.g., [27-35]), sometimes in the context of global warming [36-39].

However, Blanchette et al. [40] analyzed the impacts of the decrease in the area of wetlands, among other things, on the flood and low flow rates of the Saint-Charles River in southern Quebec during the period 1978 to 2014. However, this watershed, which was very agricultural, became much urbanized during this study period. Even using a hydrological model, it seems difficult to isolate with certainty the hydrological impacts induced by the reduction in the surface area of wetlands from those induced by changes in the surface area of other types of land use such as agriculture (decrease significant increase in area) and urbanization (significant increase in area). In addition, a recent study has just shown that in southern Quebec, the spatio-temporal variability of flows, in particular low flows, in agricultural watersheds is much more influenced by the reduction in agricultural areas than by that of wetlands [41]. It therefore becomes important to reconsider the conclusions of this study because of the possible interaction of other types of land use on the temporal evolution of the flows of this river. Finally, this study analyzed the impacts of changes in the area of wetlands on the temporal variability of the magnitude flows only. Consequently, it does not make it possible to determine the impacts of these wetlands on the spatial variability of the other characteristics flows. These aspects have not yet been analyzed in southern Quebec. It is therefore important to fill this gap in order to better determine the impacts of wetlands on river flows in southern Quebec.

Due to the absence of any study relating to the impacts of wetlands on spatial variability on the five fundamental characteristics of flows in southern Quebec on the one hand, and the diverse hydrological impacts they can generate, on the other, this study aims to analyze the impacts of wetlands on daily maximum and minimum extreme flows in southern Quebec. To fill this gap, this study has the following four objectives:

a) Quantify the impacts of wetlands on the five basic characteristics (magnitude, duration, frequency, timing and variability) of daily maximum and minimum flows, defined according to the concept of natural flow regime [26]. It is important to note that no study has ever fully analyzed the impacts of wetlands on these five flow characteristics in a watershed.

b) Determine which flow type (maximum or minimum) and characteristics are most affected by wetlands in Southern Quebec.

c) Determine how wetlands impact the relationships between river flows and climate variables (temperature and precipitation). Verifying these relationships is important because they can be used to estimate flows in ungauged watersheds based on similar climatic conditions and certain physiographic watershed characteristics. Differences in wetland surface area between a gauged watershed and an ungauged watershed are not yet taken into account when estimating flows from ungauged watersheds using flows measured in gauged watersheds in Southern Quebec.

d) The last objective is to compare the hydrological impacts of wetlands to the impacts of agriculture and deforestation on the characteristics of daily maximum and minimum flows in southern Quebec.

With regard to this last objective, it is important to remember that several studies have already analyzed the impacts of deforestation and agriculture on the spatial variability of flow characteristics in southern Quebec [41-47]. All these studies demonstrated that both types of land use have a much greater impact on minimum flows than daily maximum flows, resulting in a significant decrease in the magnitude of these minimum flows. The other characteristics (frequency, duration, timing and variability) were not impacted. Nevertheless, Muma et al. [44] found that, due to the diversity of factors that generate fall rainfall, the magnitude of daily maximum flows for agricultural watersheds were characterized by greater interannual variability. Assani et al. [42] observed an increase in the magnitude of daily maximum flows in an agricultural watershed compared to the increase measured in an adjacent non-agricultural watershed. This study is therefore part of this work aimed at determining the hydrological impacts associated with the different types of land use and land cover in southern Quebec.

It is important to emphasize that this study does not compare the temporal (interannual) variability of flows according to the areas of wetlands whose areas remain constant throughout the study period (1945-2019) in the watersheds. Consequently, the study is not part of the issue of climate change on the impacts of wetlands on the temporal variability of flows. Consequently, it is exclusively devoted to the analysis of the spatial variability of the characteristics of the flows in the three catchment areas.

Methods

Description of the watersheds

Three watersheds were selected because of their spatial proximity, their very similar physiographic characteristics and, above all, their different land uses (Figure 1 & Table 1). They are the L'Assomption, Matawin and Petite Nation river watersheds. Two thirds of the L'Assomption River watershed surface area is located on the Canadian Shield and one third on the St. Lawrence Lowlands. The watersheds of the other two rivers are completely contained on the Canadian Shield, consisting of metamorphic (mainly gneiss) and mafic rocks, which are almost impermeable. In many places they are covered by loose, quaternary coarse river/glaciomarine deposits (sand, gravel, lime, etc.). This lithological diversity gives the channels a morphology characterized by an almost regular alternation of large, winding sections with very low gradients (low water velocity) in loose deposits and narrow,

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straight and steep sections (high water velocity) often punctuated by outcrops of Canadian Shield rocks in the form of rapids and waterfalls. In the St. Lawrence River Lowland, the L'Assomption River carves a winding channel with a very low gradient in an almost flat topography, consisting mostly of clayey, hence barely permeable loose glaciomarine sediment.

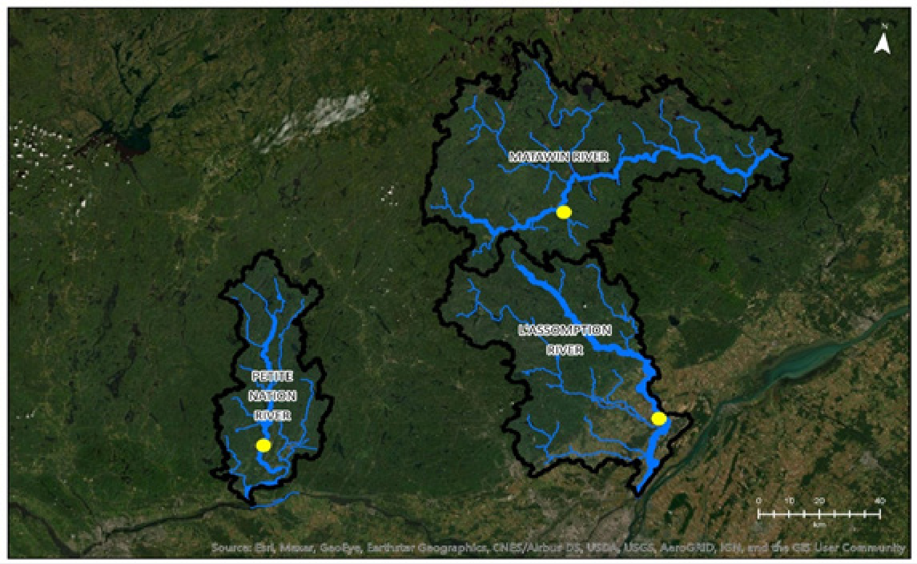

Figure 1: Location of watersheds and station.

Table 1: Comparison of the physiographic characteristics of the watersheds of the L'Assomption, the Petite-Nation and Matawin rivers.

Variables	L'Assomption	Petite Nation	Matawin
Physiographic Variables			
Drainage area (km^2)	1340	1330	1390
Mean slope (m/km)	3.75	2.50	2.56
Drainage density (km/km^2)	0.49	0.43	0.46
Forests surface area (%)	68	83	90
Wetlands surface area (%)	3.7	15	9
Agricultural surface area (%)	17.7	0.6	0
Urbanized surface area (%)	5.7	0	0

The L'Assomption River springs from Lake L'Assomption in Mont Tremblant National Park and drains into a 4,200km^2 watershed before flowing into the St. Lawrence River. The Matawin River, whose watershed is adjacent to that of the L'Assomption, originates in Matawin Lake and flows into the Saint-Maurice River after draining into a 5,775km^2 area. The Petite Nation River, a tributary of the Ottawa River, springs from Lac des Plages and drains into a 2,250km^2 watershed. On the Canadian Shield, the watersheds of these three rivers are mainly covered by maple trees. The climate is continental temperate, characterized by cold, snowy winters and warm summers.

The three watersheds have different land uses. In the L'Assomption River watershed, forest coverage is less than 70%, and agriculture, practiced exclusively in the St. Lawrence Lowlands, occupies more than 15% of the total watershed surface area. Wetlands (lakes, marshes, swamps, bogs, alluvial plains, etc.) account for less than 5% of the watershed surface area due mainly to the development of agriculture, which led to the drying and drainage of many wetlands. It is the only one of the three watersheds with an urbanization rate over 5%. It is important to note that the agricultural and urbanized area is more extensive downstream from the flow rate gauging station (Joliette station). The Matawin River watershed is almost entirely forested. Agriculture is not practised there, and human settlement is very limited. Wetlands account for nearly 9% of the watershed surface area. The main forest economic activity is tree harvesting. In the Petite Nation River watershed, the surface area covered by forests is less than in the Matawin River watershed, while its wetland coverage is larger. The physiographic data presented in the table 1 was obtained from Glaciolab of the University of

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Quebec at Trois-Rivières. These data are already been described in detail by [39] in particular. Of these three watersheds, the Matawin River watershed is the least affected by human activity. It thus constitutes the natural reference watershed. In addition, the percentage of wetland surface area is highly representative of Canadian Shield river watersheds, which have an average wetland surface area of approximately 10%.

It is important to emphasize that the three watersheds selected represent the spatial distribution of the wetlands area in the watersheds of Southern Quebec. In fact, the watershed of the L'Assomption River is representative of the agricultural and urbanized watersheds whose wetland area has significantly decreased due to drainage works. The Matawin River watershed represents the typical watersheds of the Canadian Shield little affected by drainage works. Finally, the watershed of the Petite Nation river represents the watersheds with the largest area of wetlands. In three watersheds, these wetlands are made up of different types: bogs, peatlands, swamps, bogs, lacs, fens, alluvial plains. But it was not possible to determine the exact area of each of these different types in each watershed. But lakes, peatlands and alluvial plains occupy more area than others types. In any event, even if the surface area data for these different types of wetlands were available, it would be scientifically impossible to determine the influence of each type of wetland on flow rates at the scale of watershed larger than 1000km^2.

Constitution of hydro-climatic statistical series

Constitution of climatic series

To analyze the potential influence of temperature and precipitation on the spatio-temporal variability of flow characteristics in the three watersheds, the characteristics of these two climate variables were compared. Precipitation in the Matawin (reference watershed) and Petite Nation watersheds has been measured daily since 1950. However, for the Petite Nation watershed, daily measurements were discontinued in 2013. Daily measurements for the L'Assomption River watershed only cover the period from 1950 to 1972 and were therefore excluded from this analysis. However, L'Assomption watershed measurements were compared to the adjacent Matawin River watershed measurements for 1950-1972. The comparison revealed a strong relationship (strong correlation) between temperature and precipitation in the two watersheds due to their geographical proximity. The climatic data come from Environment Canada website (https://climat.meteo.gc.ca/index f.html, accessed 2021-02-05). These Climatic data are measured at the Nominingue station in the Petite Nation river watershed and at Saint-Michel-Des-Saints in the Matawin river watershed.

The following pluviometric statistical series were compiled based on daily rainfall data measured in the Matawin and Petite Nation watersheds:

a) The statistical series of total daily rainfall (TR) measurements from June to November each year from 1950 to 2013. June rainfall was included as it influences soil moisture and runoff in July. May rainfall, however, has very little influence on soil moisture in July, as it falls on soil that is often covered by snow or even partially frozen. As a result, May rainfall does not significantly contribute to the infiltration and runoff process in July.

b) The statistical series of daily maximum rainfall (DMAXR) measured each year from July to November (1950-2013). The rainfall during this period can affect the magnitude, duration, timing and variability flow of daily maximum and minimum flows.

c) The statistical series of total number of rainy days (TNRD). The number of rainy days influences the infiltration and runoff processes, but that influence depends on the intensity of rainfall. The number of rainy days was therefore taken into account, and the following three statistical series were created: a series that includes low-, medium- and high-intensity rainfall (RD > 0mm), a series that accounts for medium- and high-intensity rainfall (RD ≥ 10mm), and lastly, a series that accounts for high-intensity rainfall only (RD ≥ 20mm).

It is important to keep in mind that temperature influences the extent of evapotranspiration, and this climate variable affects runoff and infiltration processes in watersheds. As a result, daily maximum temperatures were examined to analyze the extent of evapotranspiration. Unlike rainfall, daily temperatures have only been measured in a quasi-regular manner since 1970 in both watersheds. The following statistical series were therefore created for 1970-2013:

a) The statistical series of daily mean maximum temperatures (DMMAXT) measured from 1970-2013, as well as the highest values (DMAXT) of daily maximum temperatures measured each year from June to November.

b) The series of total number of days of daily maximum temperatures reaching or exceeding 15°C (TDTMax ≥ 15°C), 20°C (TDTMax ≥ 20°C) and 25°C (TDTMax ≥ 25°C). These three statistical series make it possible to assess the extent of evapotranspiration in the three watersheds.

Constitution of hydrological series

In Quebec, the influence of land use on flows is particularly evident in warm seasons, when precipitation falls exclusively as rain, thereby immediately triggering runoff and infiltration (e.g., [19,32]). To analyze this influence, we considered the period from July to November. During this period, the rivers are fed mainly by rainwater. The months of April, May and June were excluded because during these three months, river flows are, to varying degrees, influenced by the freshet generated mainly by snowmelt, although this melting may be accelerated by rain in some years. Flow data were extracted from the website (https://www.cehq.gouv.qc.ca/, accessed on 2020-02-2020) of the water expertise centre of Quebec's ministry of the environment and the fight against climate change.

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The study is based on daily flow data measurements taken between 1945 and 2019, i.e., 75 years of continuous daily flow measurements, available for the three watersheds selected. For each series of seasonal daily flows (from July to November), we started by creating the daily maximum and minimum extreme flow series. The daily maximum extreme flow series consisted of the highest (maximum) flows measured each season (from July to November) during the 1945–2019 period. Similarly, the daily minimum extreme flow series comprised the lowest (minimum) flows measured each season over the same period. In each of two series, the following four basic characteristics were defined according to the concept of natural flow regime [38,40]: magnitude, timing, duration and variability. In regard to the magnitude of daily maximum extreme flows, the mean (MMean) of the series, the highest value (MMAX) and the lowest value (MMIN) were calculated. The magnitude of flows was expressed in $l/s/km^2$ to compare the three watersheds because of the difference in the size of their watersheds even though this difference is very small. In regard to the timing of daily maximum extreme flows, the series comprised the occurrence days (Julian days) of daily maximum extreme flows for each season (July to November) over the 1945-2019 period. The mean date of occurrence (TMEAN), the latest date of occurrence (TMAX) and the earliest date of occurrence (TMIN) were also calculated for this series. The maximum daily extreme flow duration series was defined as the number of days during which flow measurements reached or exceeded the lowest value (MMIN) of the daily maximum extreme flow series. As with the other two series, for the daily maximum extreme flow duration series, the mean (DMean), the highest value of the duration series (DMAX) and the lowest value in the duration series (DMIN) were calculated. The same approach was applied to construct the daily minimum extreme flow series characteristics by calculating the following nine variables: for magnitude (mmean, mmax and mmin), for timing (tmean, tmax and tmin) and for duration (dmean, dmax and dmin). To determine the minimum extreme flow duration in each season, all flows below the mmax value (the highest value in the minimum flow duration series over the 1945–2019 period) were counted. These variables are summarized in Table 2.

Table 2: Definition of the variables of the characteristics of daily maximum and minimum extreme flows during the summer-fall season (July to November) over the 1945–2019 period.

Variables	Definition
Magnitude ($l/s/km^2$)	
MMEAN (mmean)	Mean of the daily maximum (minimum) flow series, 1945–2019
MMAX (mmax)	The highest value in the daily maximum (minimum) flow series, 1945-2019
MMIN (mmin)	The lowest value in the daily maximum (minimum) flow series, 1945-2019
Timing (Julian Days)	
TMEAN (tmean)	Mean of the dates of occurrence of daily maximum (minimum) flows, 1945–2019
TMAX (tmax)	The last date of occurrence of the daily maximum (minimum) flows in the season, 1945-2019
TMIN (tmin)	The earliest date of occurrence of the daily maximum (minimum) flows in the season, 1945-2019
Duration (Days)	
DMEAN (dmean)	Mean of the total number of days during which daily maximum (minimum) flows were measured ≥ MMIN (≤ mmax) during the rainy season, 1945-2019
DMAX (mmax)	Highest total number of days (maximum duration) during which daily maximum (minimum) flows were measured ≥ MMIN (≤ mmax)
DMIN (mmin)	Lowest total number of days (minimum duration) during which daily maximum (minimum) flows were measured ≥ MMIN (≤ mmax)
Flood Frequency (Years)	
FMEAN	Annual mean of the total number of floods observed each season (July to November), 1945-2019
FMAX	Highest total number of floods in a season (July to November), 1945-2019
FMIN	Lowest total number of floods in a season (July to November), 1945-2019
F (%)	Total number of years in which the highest daily maximum flow was generated by a flood occurring between July and November
NF (%)	Total number of years in which the highest daily maximum flow was not generated by a flood occurring between July and November
NYNF	Number of years without a flood occurring between July and November, 1945-2019

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For interannual variability in flow characteristics, the coefficient of variation (ratio of the standard deviation to the mean presented as a percentage) of magnitude series (VMag for maximum flows and vmag for minimum flows), timing (VTM for maximum flows and vtm for minimum flows) and duration (VDR for maximum flows and vdr for minimum flows) were calculated. In addition to these four flow characteristics, the frequency or number of floods occurring from July to November during the 1945-2019 period was also calculated. This count was made from daily flows (hydrographs of daily flows). It is important to note that a flood is defined as an increase in flows caused by rain (see Figure 5, for example). For this frequency series, the mean (FMean), the highest (FMAX) and the lowest (FMIN) values of the series were also calculated. It is important to note that not all daily maximum flows are associated with floods because these did not occur every year in all watersheds. The daily maximum extreme flows generated by floods between July and November (F) were distinguished from those generated by freshets between May and June (NF). These two variables further highlight the influence of land use on flood and low flows occurrences in the three watersheds.

Statistical analysis of hydro-climatic data

This statistical analysis was completed in three steps. In the first step, a spatial variability analysis was conducted by comparing the means of climate and hydrological variables for the three watersheds using parametric (ANOVA) and non-parametric (Kruskal-Wallis) tests. Frequencies and durations were compared based on the data, using the classic Chi-square test. Coefficient of variation values were not subjected to statistical testing.

In the second step, the temporal variability of climate variables was compared using correlation coefficients. The objective of this analysis was to determine the degree of synchrony between climate variables measured in the Matawin and Petite Nation watersheds. In the last step, climate variables were correlated with hydrological variables to determine whether wetland surface area can influence this correlation.

Results

Comparison of climate variables in the Matawin and Petite-Nation watersheds

The spatio-temporal variability of flows in these two watersheds is primarily influenced by climate factors because of their influence on infiltration and runoff processes. To demonstrate the influence of wetlands on flow characteristic differences in the three watersheds analyzed, it was important to rule out climate variables as the cause of this difference. The values of these variables were compared between the Matawin and Petite Nation watersheds. For the reasons given above, climate data from the L'Assomption River watershed were not included in this comparison.

Rainfall and temperature variables measured in summer-fall season are shown in Table 3. The mean of all rainfall variables analyzed was consistently higher in the Matawin River watershed than in the Petite Nation River watershed. In fact, the means of total rainfall and total number of rainy days were almost twice as high in the Petite Nation River watershed as in the Matawin River watershed. In contrast, coefficient of variation values for all these variables were higher in the Matawin River watershed than in the Petite Nation River watershed. However, no significant difference was observed between the two watersheds in terms of the maximum rainfall measured from 1950-2013. Unlike rainfall variables, no statistically significant differences in temperature variables were observed between the two watersheds. The temperature regime is therefore similar.

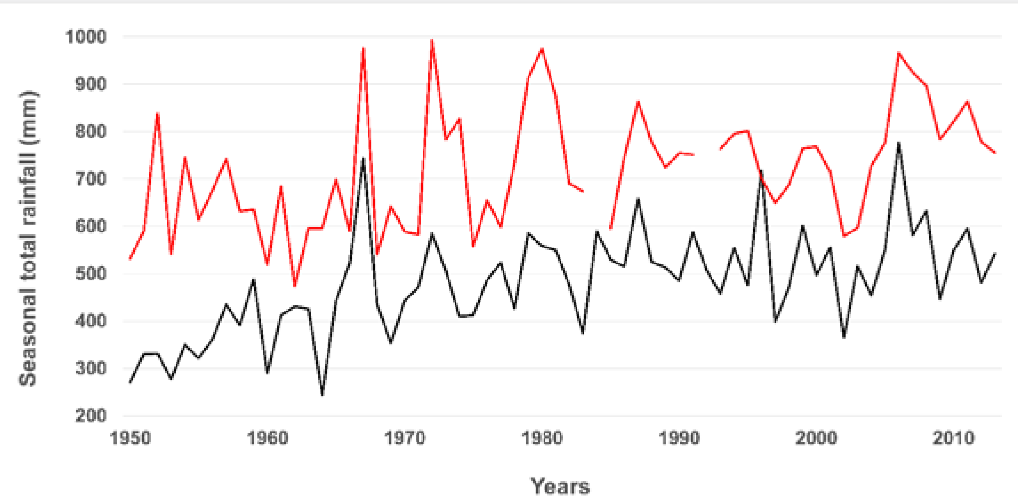

Figure 2: Comparison of summer-fall rainfall totals in the Matawin River (black curve) and Petite-Nation River (red curve) watersheds from 1950-2013.

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In terms of temporal variability, correlation coefficient values (Table 3) showed that the temporal variability of all rainfall variables was almost synchronous in both watersheds, as the correlation coefficient values were statistically significant and relatively high (> 0.500), with the exception of maximum rainfall values, which were relatively low (< 0.500). Figure 2 illustrates this synchrony for seasonal total rainfall. The synchrony in temporal variability was observed for maximum temperatures and for the number of days with temperatures reaching or exceeding 25°C, that is, for the hottest days of the season (Figure 3). No synchrony was observed for the total number of days with a daily temperature reaching or exceeding 15°C. Lastly, Figure 2 & 3 clearly show that temperature and rainfall (quantity and number of days) increased significantly over time in both watersheds.

Table 3: Comparison of rainfall (mm) and daily maximum temperature (°C) characteristics in the Matawin River (Saint-Michel-Des-Saints station) and Petite-Nation River (Nominingue station) watersheds from 1950-2013.

Rainfall (1950-2013)										
	Total Rainfall		Daily Maximum Rainfall		Total Number of Rainy Days > 0mm		Total Number of Rainy Days ≥ 10mm		Total Number of Rainy Days ≥ 20mm	
	Matawin	Petite Nation	Matawin	Petite Nation	Matawin	Petite Nation	Matawin	Petite Nation	Matawin	Petite Nation
Mean	**481.3* (110.28)**	**712* (140.29)**	43.2 (17.51)	48.3 (15.53)	**76* (15.32)**	**109* (17.49)**	**15* (4.37)**	**24* (4.58)**	**5* (2.46)**	**8* (2.67)**
Max	776.8	993.7	118	103.6	99	153	30	53	11	16
Min	244.1	209.1	17.5	24.1	43	67	6	13	0	2
CV (%)	22.9	19.7	40.6	32.1	20.3	16.0	28.5	19.3	50.2	33.4
CC	0.6567**		0.3632		0.6476**		0.5988		0.6476*	
Temperature (1970-2013)										
	Daily Mean Maximum Temperature		Daily Maximum Temperature		Total Number of Days with T≥ 15°C		Total Number of Days with T≥ 20°C		Total Number of Days with T≥ 25°C	
	Matawin	Petite Nation	Matawin	Petite Nation	Matawin	Petite Nation	Matawin	Petite Nation	Matawin	Petite Nation
Mean	16.8 (0.80)	16.8 (0.88)	31.7(1.78)	31.4 (1.95)	117 (6.60)	116 (9.19)	85 (8.23)	84 (9.74)	37 (11.2)	35 (10.08)
Max	36.7	36.7	36.7	36.7	130	137	99	103	66	54
Min	15	14.8	28.5	28.0	104		65	57	17	
CV (%)	4.8	5.2	5.6	6.2	5.7	7.9	9.7	11.6	30.4	28.6
CC	0.4103**		0.6706**		0.1988		0.3239		0.6244**	

( ) = standard deviation; CC = Correlation Coefficient. * = Mean values that are significantly different at the 5% threshold are shown in bold red. ** = Statistically significant correlation coefficients at the 5% level.

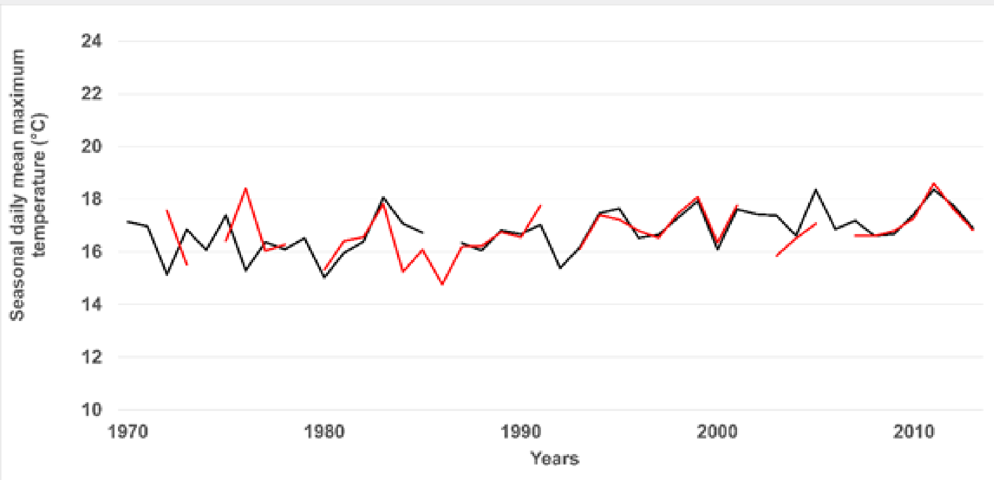

Figure 3: Comparison of mean summer-fall daily maximum temperature in the Matawin River (black curve) and Petite-Nation River (red curve) watersheds from 1970-2013.

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Comparison of frequency and characteristics of daily maximum extreme flows in the summer-fall season.

The frequency of floods and the characteristics of daily maximum extreme flows are shown in Table 4 & Figure 4. This table indicates that the number of floods per year during the summer-fall season (July to November) is on average at least half as much in the Petite Nation River watershed, characterized by a larger wetland surface area, than in the other two watersheds. As a result, in some years there was no floods in this watershed during the rainy season, although they occurred at least once in the other two watersheds. This was the case, for example, in 2002 (Figure 5). There were nine years without any floods during the 1945–2019 period. The mean frequency of floods occurrence per year is not significantly different in the Matawin and L'Assomption river watersheds despite the difference in their land uses.

Table 4: Comparison of flood frequency (number of flood per season) and seasonal daily maximum flow characteristics between the watersheds of the Matawin River and the Petite-Nation River during the summer-fall season (1945-2019).

	Matawin River	Petite Nation River	L'Assomption River
Flood Frequency (Number of Flood per Season)			
FMean	5.2 (2.6)*	1.6 (1.12)*	4.7 (1.6)
FMax	16	4	9
FMin	1	0	2
NYNF	0	9	0
F (%)	90.7	68.9	98.7
NF (%)	9.3	31.1	1.3
Magnitude (l/s/km^2)			
MMean	38.2 (19.10)*	21.9 (11.15)*	48.5 (30.07)*
MMax	113.7	53.6	130.6
MMin	8.8	7.14	10.7
Timing (Julian Days)			
TMean	266 (22.1)*	249 (67.3)*	280 (55.55)*
TMax	335	335	335
TMin	183	183	183
Duration (Days)			
DMean	87 (34.6)*	48.3 (34.93)*	55 (32.85)*
DMax	149	157	135
DMin	3	1	1
Variability (Rate Change Flow): CV (%)			
MMAG	49.9	50.8	62
MFR	50.3	67.7	34
MTM	22.1	27	19.8
MDR	50.3	67.7	59.8

( ) = standard deviation; * = means are significantly different at the 5% threshold. TMax = latest occurrence date; TMIN = earliest occurrence date. NYNF = Number of years with no floods occurrence from July to November. F = percentage of daily maximum extreme flows associated with a floods (floods peak) occurring from July to November. NF = percentage of maximum flows not associated with a flood that occurred between July and November.

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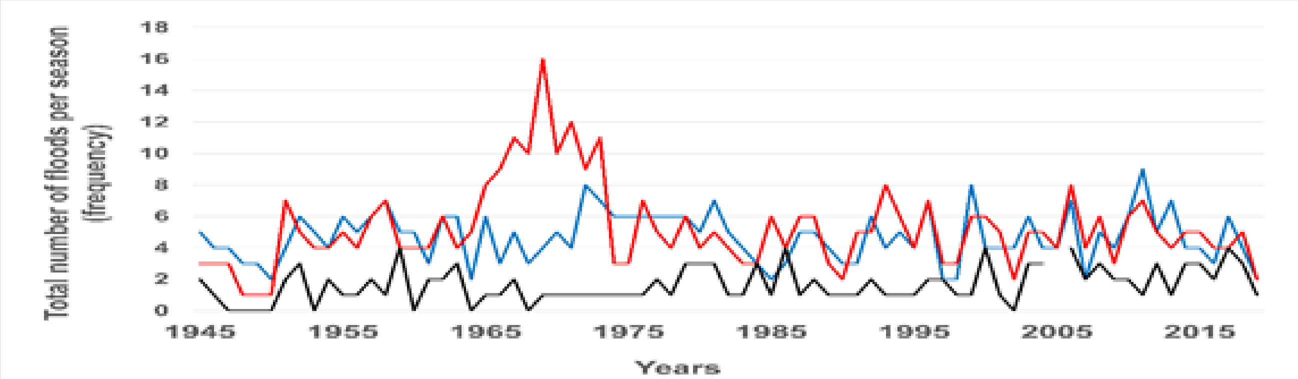

Figure 4: Comparison of the total number of floods (floods frequency) per season during the summer-fall season (1945-2019). L'Assomption River: blue curve; Matawin River: red curve; Petite Nation River: Black curve.

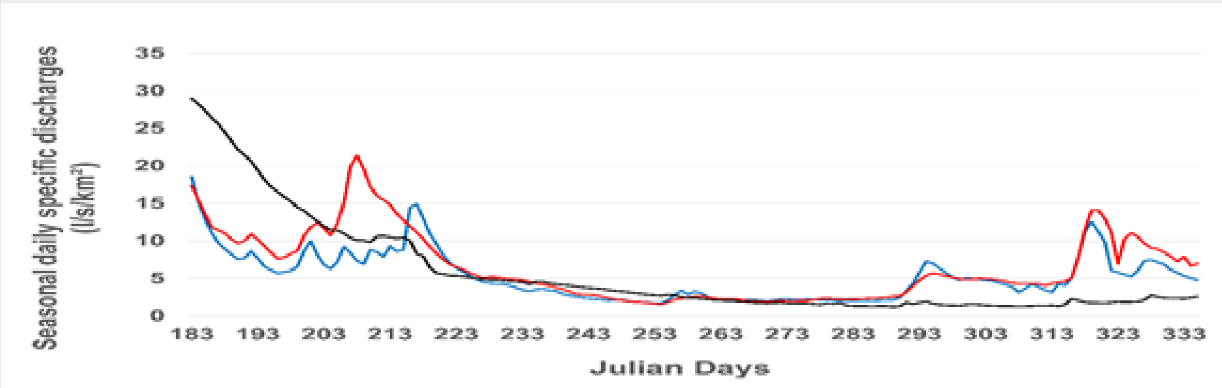

Figure 5: Comparison of the rate change flow of daily specific flows (L/s/km²) in summer-fall 2002 in the watersheds of the L'Assomption River (blue curve); Matawin River (red curve); Petite Nation River (Black curve). This figure shows the absence of the occurrence of floods in 2002 in the Petite Nation Rive watershed. L'Assomption River: blue curve; Matawin River: red curve; Petite Nation River: Black curve.

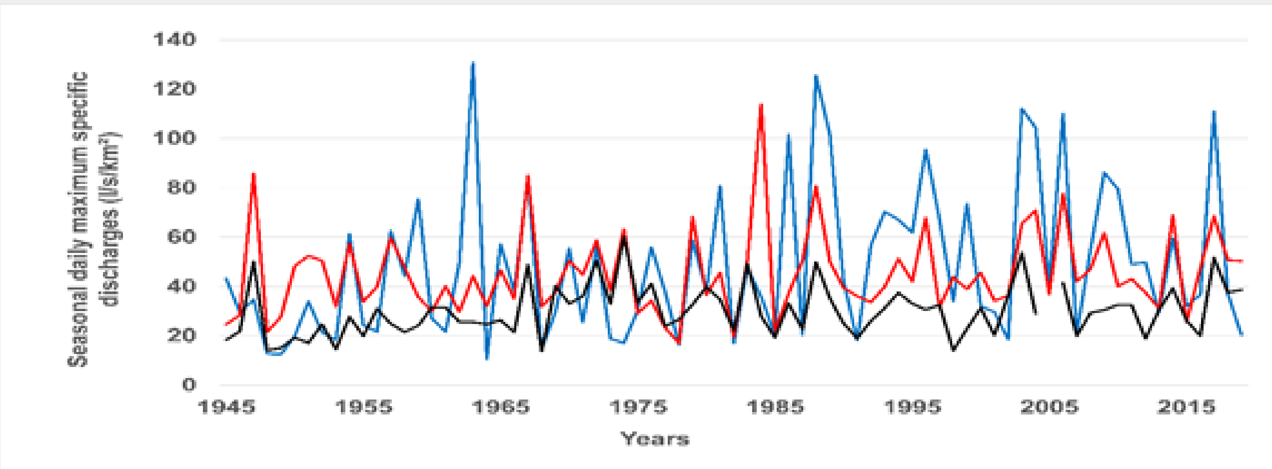

Figure 6: Comparison of the interannual variability of seasonal daily maximum flows during the rainy season (1945–2019).

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Nevertheless, the highest annual frequency of floods was observed in the Matawin River forest watershed. There were 16 floods in the 1969 season. As a result, only one third of daily maximum extreme flows are associated with floods in the Petite Nation River watershed, whereas in the other two watersheds, the proportion was at least 90% (almost all maximum flows).

The significant decrease in flood frequency is reflected in the significant decrease in the magnitude of daily maximum extreme flows in the Petite Nation River watershed. On average, this magnitude is about half that observed in the other two watersheds (Figure 6). The highest mean magnitude is observed in the agricultural and urbanized L'Assomption River watershed.

The same applies to the maximum and minimum values of these flows. This decrease in floods frequency is also responsible for the decrease in the mean duration of daily maximum extreme flows in the Petite Nation River watershed (Figure 7). The duration of these flows is on average almost half as long as in the Matawin River watershed. However, the duration of these flows was longer in the second watershed than in the first. In the agricultural and urbanized L'Assomption River watershed, the mean duration of maximum flows is shorter than that observed in the Matawin forest watershed.

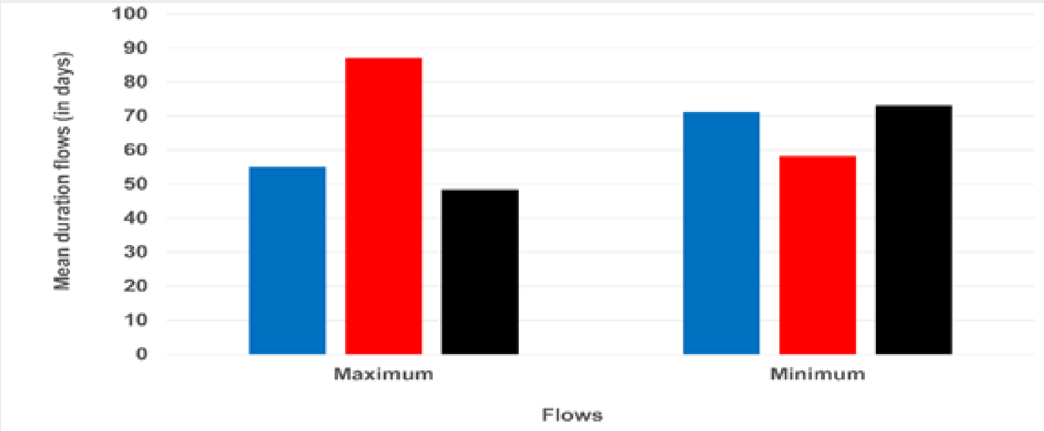

Figure 7: Comparison of the mean duration in days of seasonal daily maximum and minimum flows during the rainy season (1945-2019). L'Assomption River: blue bar; Matawin River: red bar; Petite Nation River: Black bar.

Comparison of the characteristics of daily minimum extreme flows in the summer-fall season.

The characteristics of these daily extreme minimum flows are presented in Table 5. No statistically significant difference was observed between the mean magnitudes of these flows measured in the Matawin and Petite Nation watersheds. However, this mean magnitude is significantly higher than that in the L'Assomption River agricultural watershed (Figure 8). The highest and lowest magnitudes were observed in the Petite Nation watershed. The mean duration of these minimum flows is significantly longer in the Petite Nation River watershed than in the Matawin River watershed (Figure 7). However, it is not significantly different from that calculated for the L'Assomption River watershed.

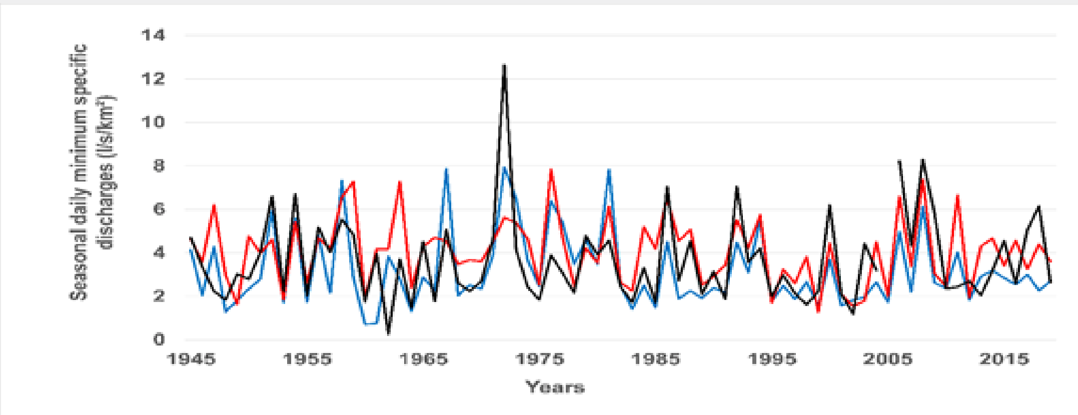

Figure 8: Comparison of the interannual variability of seasonal daily minimum flows during the rainy season (1945-2019). L'Assomption River: blue curve; Matawin River: red curve; Petite Nation River: Black curve.

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Table 5: Comparison of seasonal daily minimum extreme flow variables between the Matawin River, the Petite-Nation and the L'Assomption River watersheds (1945-2019).

	Matawin River	Petite Nation River	L'assomption River
Magnitude (l/s/km^2)			
mmean	4.1 (1.29)*	3.7 (2.17)	2.9 (1.58)*
mmax	7.8	12.6	7.3
mmin	1.8	0.26	0.66
Timing (Julian Days)			
tmean	248 (26.15)*	269 (34.95)*	247 (30.00)
tmax	313	331	319
tmin	185	189	185
Duration (Days)			
dmean	58 (35)*	73 (42)*	71(39)*
dmax	133	153	153
dmin	1	5	1
Vmag	38.6	58.4	53.9
Vtm	10.5	13	54.9
Vdr	60.8	57.6	12.2

As for timing, minimum flows occur later on average in the Petite Nation River watershed than in the other two watersheds, where they are not significantly different. Interannual variability in the magnitude of minimum extreme flows is higher in the first watershed than in the other two. There is a large difference in coefficient of variation (CV) values between the Matawin and Petite Nation river watersheds. The interannual variability in the timing of these flows is higher in the L'Assomption River agricultural watershed than in the other two, more forested, watersheds. The opposite is true for the interannual variability of minimum flow durations.

Comparison of the relationship between climate and hydrological variables in the three watersheds

Comparison of the relationship between climate variables and characteristics of maximum daily extreme flows in the three watersheds.

Table 6: Comparison of the values of the correlation coefficients between the characteristics of the maximum daily flows and the rainfall variables in summer-fall season in three watersheds (1950-2013).

Charactertics of Flows	Total Rainfall	Daily Maximum Rainfall	Total Rainy Days (>0mm)	Total Rainy Days (>10mm)	Total Rainy Days (>20mm)
Matawin River Watershed (Saint-Michel- Des-Saints)					
Frequency	0.227	0.088	0.115	**0.302**	0.162
Magnitude	**0.555**	**0.460**	**0.317**	**0.448**	**0.452**
Duration	**0.442**	**0.313**	0.127	**0.508**	**0.486**
Timing	**0.342**	0.088	**0.266**	**0.252**	0.225
L'Assomption River Watershed					
Frequency	**0.288**	0.094	0.042	**0.425**	**0.372**
Magnitude	**0.386**	**0.264**	0.238	**0.370**	**0.406**
Duration	**0.483**	**0.257**	0.175	**0.575**	**0.562**
Timing	-0.012	-0.116	-0.063	0.054	-0.064
Petite Nation River Watershed (Nominingue Station)					
Frequency	**0.339**	0.242	0.175	**0.333**	0.187
Magnitude	0.059	-0.000	**0.335**	0.057	0.070
Duration	**0.542**	**0.279**	**0.301**	**0.501**	**0.561**
Timing	0.001	-0.055	0.191	0.215	-0.123

The values of the correlation coefficients statistically significant at the 5% level appear in bold red (positive correlation).

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The correlation coefficient values calculated between climate and hydrological variables in the three watersheds are presented in Table 6 & 7 for maximum flows and in Table 8 & 9 for minimum flows. In terms of precipitation, Table 6 shows that in the Matawin River watershed (reference watershed), flood frequency was only significantly correlated with the total number of days with medium- and high-intensity rainfall (TNRD ≥ 10mm). This correlation was positive. The magnitude of these flows was positively correlated with the five rainfall variables (amount of rain and number of rainy days). The same was true for duration. However, duration was not significantly correlated with maximum seasonal rainfall. Lastly, the timing of maximum flows was not significantly correlated with the maximum rainfall and the number of days of high-intensity rain (TNRD ≥ 20mm). In the L'Assomption River watershed, the most agricultural watershed, flood frequency was significantly correlated with total rainfall and the number of days of high-intensity rainfall (TNRD ≥ 20mm). The magnitude of flows was not significantly correlated with the total number of rainy days (TNRD ≥ 0mm). This agricultural watershed differed mainly due to the lack of any significant correlation between the timing of maximum flows and the five rainfall variables. The Petite Nation River watershed, which has the largest wetland surface area, differed primarily from the other two watersheds because of the lack of any correlation between the magnitude of maximum flows and total rainfall. Like the Matawin River watershed, this flow characteristic correlated only to the total number of rainy days (TNRD ≥ 10mm) in the Petite Nation River watershed.

Table 7: Comparison of correlation coefficient values for daily maximum flow characteristics and summer-fall temperature variables in the three watersheds (1970-2013).

Charactertics of Flows	Mean	Tmax	Total Days with T ≥ 15°C	Total Days with T ≥ 20°C	Total Days with T ≥ 25°C
Matawin River Watershed (Saint-Michel- Des-Saints station)					
Frequency	-0.135	-0.278	-0.090	-0.143	-0.151
Magnitude	-0.088	-0.173	-0.028	0.074	-0.066
Duration	**-0.401**	**-0.426**	-0.243	-0.241	**-0.457**
Timing	0.191	0.177	0.127	-0.002	0.383
L'Assomption River Watershed					
Frequency	-0.119	-0.034	-0.216	-0.075	-0.061
Magnitude	-0.032	0.069	-0.093	0.082	0.127
Duration	**-0.337**	-0.133	-0.262	-0.219	-0.217
Timing	0.217	-0.113	**0.371**	**0.341**	0.109
Petite Nation River Watershed (Nominingue Station)					
Frequency	-0.152	**-0.439**	**-0.522**	**-0.421**	**-0.441**
Magnitude	0.034	0.199	-0.025	0.004	0.030
Duration	-0.097	-0.196	-0.105	-0.070	-0.113
Timing	-0.028	0.173	-0.108	0.003	0.291

The values of the correlation coefficients statistically significant at the 5% level appear in bold red (positive correlation) and bold blue (negative correlation).

Table 8: Comparison of correlation coefficient values for daily maximum flow characteristics and summer-fall rainfall variables in the three watersheds (1950-2013).

Charactertics of Flows	Total Rainfall	Daily Maximum Rainfall	Total Rainy Days (>0mm)	Total Rainy Days (>10mm)	Total Rainy Days (>20mm)
Matawin River Watershed (Saint-Michel- Des-Saints)					
Magnitude	**0.256**	**0.262**	0.026	**0.392**	**0.291**
Duration	**-0.423**	**-0.330**	-0.127	**-0.507**	**-0.468**
Timing	**-0.100**	0.025	-0.055	-0.254	-0.208
L'Assomption River Watershed					
Magnitude	**0.284**	**0.268**	0.087	**0.401**	**0.399**
Duration	**-0.360**	**-0.303**	-0.011	**-0.484**	**-0.522**
Timing	0.047	0.115	0.038	-0.106	-0.086
Petite Nation River Watershed (Nominingue Station)					
Magnitude	**0.397**	**0.262**	0.163	**0.442**	**0.522**
Duration	**0.410**	0.240	**0.278**	**0.492**	**0.521**
Timing	0.008	0.003	-0.174	-0.212	-0.056

The values of the correlation coefficients statistically significant at the 5% level appear in bold red (positive correlation) and bold blue (negative correlation).

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Table 9: Comparison of correlation coefficient values for daily maximum flow characteristics and summer-fall rainfall variables in the three watersheds (1950-2013).

Characteristics of Flows	TMeanmax	Tmax	Total Days with T ≥ 15°C	Total Days with T ≥ 20°C	Total Days with T ≥ 25°C
Matawin River Watershed (Saint-Michel- Des-Saints)					
Magnitude	**-0.463***	**-0.399***	-0.225	-0.253	**-0.553***
Duration	**0.460***	**0.465***	0.259	0.244	**0.525***
Timing	0.244	0.036	**0.341**	0.289	-0.040
L'Assomption River Watershed					
Magnitude	**-0.519***	-0.292	**-0.314***	**-0.308***	**-0.551***
Duration	**0.424***	**0.344***	0.278	0.228	**0.373***
Timing	0.270	0.095	0.257	**0.351***	0.039
Petite Nation River Watershed (Nominingue Station)					
Magnitude	-0,176	**-0.317***	0.010	-0.186	-0.294
Duration	-0.269	-0.247	-0.301	**-0.342***	-0.268
Timing	0.183	-0.180	0.278	0.141	-0.110

The values of the correlation coefficients statistically significant at the 5% level appear in bold red (positive correlation) and bold blue (negative correlation).

Unlike rainfall variables, there was very little difference in the relationship between temperature variables and daily maximum extreme flows in the three watersheds (Table 8). However, unlike the other two watersheds, flood frequency in the Petite Nation River watershed was negatively correlated with the maximum temperature and the number of days with temperatures reaching or exceeding 15°C. Furthermore, the duration of daily maximum flows was not significantly correlated with any temperature variables, whereas it was negatively correlated with the means of daily maximum temperatures in the other two watersheds. In the Matawin River watershed, this flow characteristic was also negatively correlated with the maximum temperature and total number of hot days (TDTMax ≥ 25°C). Finally, in the L'Assomption River watershed, the timing of daily maximum flows was positively correlated with the total number of days with temperatures reaching or exceeding 15° and 20°C.

Comparison of the relationships between climate variables and daily minimum extreme flow characteristics in the three watersheds.

The correlation coefficient values calculated between the characteristics of daily minimum extreme flows and rainfall variables are presented in Table 8. In all three watersheds, the magnitude of daily minimum flows was positively correlated with the same rainfall variables. Duration was also correlated to nearly the same variables. This correlation only remained positive in the Petite Nation River watershed; it was negative in the other two watersheds. Finally, the timing of flows was not significantly correlated with any rainfall variable in the three watersheds.

A similar trend was observed for temperature variables whose correlation coefficient values are recorded in Table 9. However, the opposite trend was observed in the sign of correlation, which was negative, between flow magnitude and the temperature variables. The same negative trend for the sign of correlation was also observed for duration. The correlation was positive in the Matawin and L'Assomption watersheds but negative for the Petite Nation watershed. Finally, unlike rainfall, the timing of minimum flows was significantly (positively) correlated with temperature in the Matawin and L'Assomption watersheds.

Discussion

The comparison of the characteristics of daily flows during the summer-fall season over the 1945-2019 period in three watersheds differentiated by the type of land use demonstrated a clear difference between the daily maximum and minimum extreme flow characteristics of the Petite Nation River and the flow characteristics of the other two rivers. In terms of maximum flows, the Petite Nation River's low flood frequency (occurrence) differentiates it from the other two rivers. Flood frequency was on average three times lower in the Petite Nation River watershed than in the other two watersheds. This significant decrease in flood frequency has resulted in a decrease in the magnitude and duration of maximum flows as well as in early occurrence. Furthermore, the interannual variability in the frequency, duration and timing of these maximum flows was greater in the Petite Nation River watershed than in the other two watersheds. As for the characteristics of daily minimum extreme flows, the Petite Nation River watershed was differentiated from the Matawin River watershed by longer duration, late occurrence and greater interannual variability of flow magnitude.

There are many factors that could explain the difference in the characteristics of daily maximum and minimum extreme flows observed in the Petite Nation River and the other two

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rivers analyzed. The influence of climate factors (rainfall and temperatures) will be examined first, followed by physiographic factors.

Analysis of the influence of climate factors on the spatial variability of the characteristics of daily maximum and minimum extreme flows

The first factor is undoubtedly the amount of rain and the number of rainy days. However, a comparison of these rainfall variables revealed that the amount of rain and number of rainy days were higher in the Petite Nation River watershed than in the Matawin River watershed. In fact, these rainfall variables were on average almost twice as high in the Petite Nation watershed as in the Matawin watershed. It follows that this very significant difference in rainfall should have resulted in higher flood frequency, higher maximum flow magnitude and duration, and lower interannual variability in the Petite Nation River watershed than in the Matawin River watershed. However, the opposite was true. Precipitation can therefore not explain the difference in the characteristics of maximum flows observed between the two watersheds. Furthermore, there was no difference in the temporal variability (long-term trend) of precipitation between the two watersheds. In fact, the amount of rainfall and number of rainy days increased significantly over time in both watersheds. In terms of daily minimum extreme flows, the difference in precipitation between the two watersheds should have resulted in greater flow magnitude in the Petite Nation River watershed than in the Matawin River watershed. However, the results clearly showed that there was no significant difference in the magnitude of daily minimum extreme flows between the two watersheds, despite a large difference in the amount of rainfall and the number of rainy days between the two watersheds.

The correlation analysis of daily maximum extreme flow characteristics and rainfall variables revealed little difference between the two watersheds. The flow characteristics were correlated to nearly the same rainfall variables, with the exception of timing, which was not correlated with any rainfall variable in the Petite Nation River watershed. As for daily minimum extreme flows, the main difference between the two watersheds was the correlation between flow duration and the rainfall variables. This duration was negatively correlated with rainfall variables in the Matawin River watershed but positively correlated in the Petite Nation River watershed. These results suggest that in the Matawin River watershed, rainfall largely contributes to runoff, resulting in a decrease in minimum flow duration but an increase in maximum flow duration. However, the opposite was true in the Petite Nation watershed. Figure 5 seems to support this interpretation, as the Petite Nation River was not extremely affected by rainfall, unlike the Matawin River, although the Matawin River is more forested than the Petite Nation River.

The second climate factor is temperature, which affects the evapotranspiration process. A comparison of temperature values in the two watersheds revealed no significant differences. Similarly, no significant difference in temporal temperature variability was observed between the two watersheds. It follows that the temperature regime is the same in both watersheds. This climate factor can therefore not explain the difference in the maximum and minimum flow characteristics observed between the two watersheds. Nevertheless, the correlation analysis of this climate factor and the flow characteristics revealed a difference between the two watersheds. The duration of maximum flows was negatively correlated with temperature (mean and maximum) and total number of hot days (TDTMax ≥ 25°C), whereas no correlation was found between these variables in the Petite Nation River watershed. These results suggest that evapotranspiration associated with high temperatures decreases the duration of floods in the Matawin River watershed, unlike in the Petite Nation River watershed. However, in the Petite Nation watershed, evapotranspiration affects flood frequency, unlike in the Matawin River watershed. The duration of daily minimum extreme flows was positively correlated with temperature in the Matawin River watershed but negatively correlated in the Petite Nation River watershed. To explain this difference in the sign of correlation for the two watersheds, it is necessary to compare the interaction between aquifers, which influence minimum flows, and river channels. This will be discussed later.

Based on this analysis, climate factors (rainfall and temperature) do not explain the difference between the daily maximum and minimum extreme flow characteristics observed in the Petite Nation River watershed and in the other two watersheds.

Analysis of the influence of physiographic factors land use on the spatial variability of the characteristics of daily maximum and minimum extreme flows in the three watersheds

The first two physiographic factors likely to explain the differences in flows observed between the watersheds of the Matawin and Petite Nation rivers are the porosity of the soils and the water table depth characteristics. In fact, greater soil porosity and lower water table depth (greater water absorption) by promoting strong infiltration can explain lower frequency and magnitude of floods in the Petite than in the Matawin watershed. However, these two factors must be excluded for the following reasons:

i. The granulometric characteristics of the sediments which constitute the soils of these watersheds are identical because these soils have developed on the same sedimentary deposits of marine, glacial and fluvial origin and the same types of rocks of metamorphic and magmatic origin.

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ii. The groundwater in the two watersheds is housed in these same deposits and in the fractures that run through the rocks, mainly of metamorphic origin (gneiss). These constitute the main substratum of two watersheds belonging to the geological province of Grenville.

iii. A difference in soil porosity and a low depth to the water table (far from the surface) in the Petite Nation River watershed should in principle result in a greater magnitude of low flows which are strongly influenced by the process of infiltration than runoff. However, the analysis data clearly demonstrated that there is no statistically significant difference between the magnitude of the low water flows measured in the two watersheds.

The third physiographic factor likely to explain the difference in flow characteristics between the two watersheds is the general topography. This controls the average slope of the watersheds which influences the infiltration and runoff processes. However, the physiographic data presented in Table 1 clearly demonstrates that there is no difference in the values of the mean slope and the drainage density between the two watersheds. This factor must therefore be excluded as well.

With regard to land use and land cover, the surface area of the Petite Nation River watershed's wetlands and forests, as well as its agricultural and urbanized areas, differentiated the Petite Nation River watershed from the other two watersheds. Forest surface areas are larger in the Matawin River watershed than in the Petite Nation watershed, which has larger forest surface areas than the L'Assomption River watershed. However, the L'Assomption River watershed has larger agricultural and urbanized surface areas than the other two watersheds, which have almost identical agricultural and urbanized surface areas. Lastly, the Petite Nation River watershed has the largest wetland surface area compared to the other two watersheds. We will now analyze how each of these types of land use influences the spatial variability of flow characteristics in the three watersheds.

The impacts of agriculture and deforestation on certain daily maximum extreme flow characteristics in summer and fall have already been studied in Quebec, as was noted in the introduction [41-42,44,46]. The major hydrological impact caused by agriculture and deforestation was a significant reduction in daily minimum extreme flows. The other characteristics of these flows have not been impacted. As for daily maximum extreme flows, Muma et al. [44] showed that agricultural watersheds are characterized by higher interannual variability (CV) than was observed in non-agricultural watersheds. The other characteristics of maximum flows were not impacted by agriculture and deforestation. In this study, a comparison of the values for daily maximum extreme flow characteristics revealed that the L'Assomption River agricultural watershed is characterized by a higher magnitude and a later flow occurrence than the other two watersheds. The interannual variability of the magnitude was also high. In contrast, the interannual variability in the flood frequency and timing was lower in the L'Assomption River watershed than in the other two watersheds, reflecting a certain regularity in flood occurrence in this watershed caused by significant runoff. As for the daily minimum extreme flow characteristics, the L'Assomption River watershed was differentiated from the other two watersheds only by a lower flow magnitude, thus confirming the observations of previous studies. The various impacts caused by agriculture and deforestation were mainly the result of soil sealing, which promotes runoff but reduces water infiltration. The increase in surface runoff causes an increase in the magnitude of maximum flows and high interannual variability, as well as low interannual variability in frequency and timing. Reduced water infiltration decreases the magnitude of daily minimum extreme flows generated by water tables. This decrease in infiltration also delays soil saturation, resulting in a later occurrence of maximum flood flows than in non-agricultural watersheds.

As for wetlands area, the Petite Nation River watershed is differentiated from the Matawin River watershed by its wetlands, which are approximately twice as extensive in the Petite Nation River watershed as in the Matawin River watershed. A comparative analysis of flow characteristics clearly highlighted differences in flow characteristics between these two watersheds. In terms of daily maximum extreme flows, as noted earlier, the Petite Nation River watershed differed from the Matawin River watershed in that it had a low flood frequency (on average three times lower), while the amount of rainfall and number of rainy days in the Petite Nation River watershed was on average twice as high as in the Matawin River watershed. In addition, no temperature difference was observed between the two watersheds. This suggests that this significant decrease in flood frequency in the Petite Nation River watershed could only be caused by the sponge effect of wetlands on surface runoff [see 23-25]. In fact, runoff water is stored in wetlands, preventing it from being transferred to river channels. Transfer occurs when wetlands become saturated with water. The extent of this transfer depends on several factors: the saturation level of the wetlands, wetland location, amount of rainfall, prior soil moisture levels, etc. In addition to these factors, transfer also depends on evaporation of the water stored in the wetlands. Evaporation reduces water levels in wetlands. This drop in water levels reduces rapid saturation during periods of rain and thus their ability to transfer water to river channels, which also contributes to decreased flood frequency. This finding is supported by a significant negative correlation between flood frequency and the total number of hot days (TDTMax ≥ 15°C) in particular. However, in the other two watersheds (Matawin and L'Assomption), there was no significant correlation between temperature and flood frequency.

It also resulted in a significant decrease in the duration of these maximum flows. Due to the absence of floods in some years in the Petite Nation watershed (see figure 5 for example), the highest maximum flows occur at the beginning of the season as they are generated by freshets from the previous spring season

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(May and June). Their timings are therefore earlier than in other watersheds. Alternating years without floods and years with floods results in greater interannual variability in the duration and timing of flow occurrences than observed in the Matawin River reference watershed. Paradoxically, this alternation does not affect the interannual variability in the magnitude of maximum flows because wetlands mitigate fluctuations in levels (flows) even during floods. Thus, the interannual variability in the magnitude of maximum flows is moderated. It should also be noted that unlike in the other two watersheds, the magnitude of maximum flows was not significantly correlated with the amount of rainfall due to the sponge effect of wetlands in the Petite Nation river watershed.

Many studies have already highlighted the impacts of wetlands on the decrease in the magnitude of flood flows (e.g., [12,13,21,25,49,50]). But the extent of this decrease depends on the amount of water stored by wetlands. This amount of stored water is influenced by many factors [24]: the sizes (width and depth) and the types of the wetlands, their location in the watershed, their distance from the stream channel, their degree of humidity before runoff, topography, etc. In Quebec, in their study on the impacts of the decrease in the area of wetlands in the Saint-Charles River watershed, Blanchette et al. [40] demonstrated that the decrease in this area of 15% between 1978 and 2014 caused a reduction the magnitude of flood flows varying between 7 and 16% depending on the return period of the flows analyzed. This decrease in magnitude was also observed in the watersheds of the Yamaska and Bécancour rivers [37]. In the case of the latter watershed, these authors observed that the two types of wetlands studied (isolated or non-floodplain and riparian or floodplain wetlands) induced the same hydrological impact characterized by a decrease in the magnitude of flood flows. It follows that in Quebec, the storage of runoff water is operated by wetlands that are more geographically isolated wetlands than those of the floodplains. Nevertheless, in the case of this last type of wetland, there would be a complex interaction between the flood flows and the fluctuation of the level of the water table in the alluvial plain which can attenuate or amplify the flood wave [30,51].

Regarding minimum extreme daily flows, the decrease in floods frequency does not affect their magnitude. However, it significantly increases their duration. Consequently, these flows occur later in the season compared to the timing observed in other two watersheds. Moreover, the interannual variability in their magnitude is affected, being higher in the Petite Nation River watershed than that observed in the Matawin River watershed. The low impact of wetlands on the magnitude of minimum extreme flows, unlike the characteristics of maximum extreme flows, suggests relatively low connectivity between these wetlands and the aquifers that feed the Petite Nation River channel during the low flow period than in the other two watersheds. It follows that unlike agriculture and deforestation, wetlands have a greater impact on the characteristics of maximum flow than on daily minimum extreme flow in Quebec. In the Canadian prairies and in several regions of the United States in particular, several studies have highlighted a connectivity between wetlands and groundwater (e.g., [17-19,52]. This connectivity allows wetlands to support low river flows. In Quebec, the same support to low flow by wetlands was observed by Fossey and Rousseau [37,38] as well as Blanchette et al. [40] in the three watersheds they studied. In the case of the Saint-Charles River watershed, in a scenario based on the comparison of the presence and absence of wetlands, the authors estimated an increase in low water flows varying between 2 and 20% depending on flow indicator. It is important to note that this connectivity in the three watersheds studied is simply explained by the presence of the St. Laurent Lowlands on which agriculture is practiced due to its more permeable substratum than that of the Canadian Shield, which is impracticable at farming. There is strong connectivity between wetlands and aquifers in the St. Laurent Lowlands, as several studies have already demonstrated [30,53,54]. Be that as it may, in the agricultural watersheds of southern Quebec, the spatio-temporal variability of minimum lows is strongly influenced by the agricultural area and not that of the wetlands. The example of the L'Assomption River watershed whose flows were analyzed as part in this study is the most eloquent example. This example corroborates the results already obtained in previous studies [41,42,44].

Conclusion

The effects of global warming are notably demonstrated by an increase in extreme hydrological events (flooding and very severe low flows). But these effects can be mitigated or amplified by watershed land use. In Quebec, no studies have yet been conducted on the impacts of wetlands on the characteristics of floods and low flows. To fill this gap, this study compared the spatio-temporal variability of flood and low flow characteristics as well as rainfall and temperature characteristics during the summer-fall season in three geographically close watersheds. These three watersheds are mainly differentiated by the surface area of the wetlands.

This study shows that the Petite Nation River watershed, which has the largest surface area of wetlands, is characterized by a very low flood frequency **(**the frequency of floods is on average two times lower in the watershed of Petite Nation river than in the two others watersheds**)**, despite the fact that the total amount of rainfall is approximately twice as high as in the other two watersheds (Matawin and L'Assomption). This significant decrease in frequency, caused by the sponge effect, has led to a significant decrease in the magnitude and duration of floods. The values of these two characteristics were almost two times lower than the values measured in the Matawin River watershed, which is considered a reference watershed. In addition, seasonal daily maximum flows occurred earlier (on average twenty days) than in the Petite Nation River watershed. Lastly, the interannual variability of flood frequency, magnitude and duration was greater than in the Petite Nation River watershed.

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With respect to daily minimum extreme flow characteristics, the Petite Nation River watershed was differentiated from the Matawin River watershed by the relatively longer duration (on average fifteen days) and later occurrence (on average twenty one days) of these flows. It follows that wetlands have a much greater impact on daily maximum flows than daily minimum flows, likely due to the relatively low connectivity between these wetlands and the aquifers in watersheds on the Canadian Shield. The sponge effect therefore only affects the flood flows, contrary to the impacts caused by agriculture and deforestation in southern Quebec.

Wetlands significantly reduce flood intensity but increase the duration of hydrological drought (low flow). This aspect must be taken into account when considering the issue of wetland restoration and conservation to combat the effects of global warming in Quebec. It is important to remember that all studies already published on the hydrology of wetlands in Southern Québec of concern only two types: peatlands and alluvial plains. Their hydrological impacts have always been analyzed separately.

The significant contributions of this study is to take into account all the hydrological impacts of the different wetlands types (lakes, marshes, peatlands, bogs, alluvial plains, etc.) on all the fundamental characteristics (magnitude, duration, timing, frequency and variability) on flows. From a hydrological perspective, this study makes a significant contribution through its detailed description of the mechanisms and processes by which wetlands influence all the characteristics of daily maximum flows and daily minimum extremes resulting from rainfall in Quebec.

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