



Comparison of annual flood characteristics in four watersheds in relation to the wetland surface areas (Southern Quebec, Canada)

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Abstract This study compares the characteristics (magnitude, duration, frequency and timing) of annual flood (floods) in southern Quebec in relation to the wetland surface areas in four different watersheds, grouped into two pairs over the 1930–2019 period. The four watersheds are: the two watersheds of the Matane (1% wetland surface area) and Rimouski (3% wetland surface area) rivers located on the south shore and characterized by temperate maritime climate on the one hand, and the watersheds of the Matawin (9% wetland surface area) and Petite-Nation (15% wetland surface area) on the north shore and characterized by temperate continental climate on the other. The study revealed that the magnitude (specific discharges) of annual flood flows is on average about four times greater in the Matane River watershed than in the Petite-Nation River watershed. However, the duration of these flood flows is on average about six times shorter in the first (Matane river) than in the second (Petite Nation river) watershed. Despite the small sample size analyzed, the correlation analysis revealed that out of 13 physiographic and climatic variables, wetland surface area is the variable that best correlates with the magnitude (negative

correlation) and duration (positive correlation) of flows. Therefore, wetlands significantly reduce the intensity of annual floods but significantly increase their duration due to the “surface water storage” they exert on surface runoff. No significant differences in the frequency and timing of annual flood peaks were observed among the four watersheds.

Keywords Annual flood · Magnitude · Frequency · Duration · Timing · Surface water storage · Wetlands · Southern Quebec

Introduction

It is increasingly demonstrated that one of the major impacts of current global warming is the increase in the intensity and frequency of floods in many parts of the world (Berghuijs et al. 2017; Tabari 2020). Thus, according to Tellman et al. (2021), the total number of populations exposed to flooding increased from 58 to 86 million between 2000 and 2015, an increase of 48%. Located in the temperate region, considered one of the most sensitive regions to this amplification of floods (Berghuijs et al. 2017), the province of Quebec (Canada) faced several severe floods that had significant socio-economic costs. However, these floods did not uniformly affect all watersheds. Some watersheds have thus proven to be more sensitive than others to these extreme hydrological events.

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Several factors can be invoked to explain this difference in sensitivity to floods and inundations observed between catchment areas (St-Hilaire et al. 2015): the physiographic characteristics of the catchment areas, land use and land covers, the degree of urbanization of the catchment areas, etc. Regarding land use, Lavigne et al. (2004) demonstrated that the decrease in forest area (clearcutting) in the Famine River watershed caused a significant increase in the magnitude of floods varying between 28% for spring flood peaks, generated mainly by the melting snow, and 101% for summer–autumn floods generated by rains. As for the impacts induced by agriculture, the results are rather divergent. Muma et al. (2011) observed few significant changes in the magnitude of spring and summer–autumn floods, whereas Assani et al. (2016) observed a significant increase of this magnitude in the watershed of the L'Assomption River, which is more agricultural than that of the adjacent Matawin River.

The development of agriculture in Quebec has led to a very significant decrease in wetlands in watersheds (Ruiz 2019). However, it has been shown that wetlands attenuate to varying degrees the intensity of floods and inundations in watersheds. Nevertheless, this “sponge effect” role varies spatially and temporally because it depends on many intrinsic factors (area, topography, antecedent humidity conditions, water level, soil characteristics, type of plants and vegetation that colonize them, etc.) than extrinsic (location in the watershed, seasonality, degree of connectivity with river channels, etc.). There is already a relatively abundant literature on these different factors (e.g., Acreman and Holden 2013; Ahlén et al. 2020; Ameli and Creed 2019; Bullock and Acreman 2003; Gulbin et al. 2019; Jones et al. 2018; Lane et al. 2018; Martinez-Martinez et al. 2015; Quin and Destouni 2018; Rajib et al. 2020; Vanderhoof et al. 2016; 2017; Wu et al. 2020).

In Quebec, the impacts of wetlands on the floods are still very little studied. Fossey et al. (2015); Fossey and Rousseau (2016a, b) analyzed the influence of the location of wetlands on the magnitude of floods, particularly in two highly agricultural watersheds of the Yamaska and Bécancour rivers in the context of climate change using a hydrological model (PHYSITEL/HYDROTEL). They demonstrated that the flows of these two rivers were influenced both by geographically isolated wetlands (non-floodplains

wetlands) and those located in the floodplains (riparian wetlands). Still using hydrological modelling, Blanchette et al. (2019) analyzed the impacts of the decrease in wetland area (15%) observed in the St. Charles River watershed between 1978 and 2014 on the magnitude of floods in particular. This decrease would have caused a slight attenuation in the magnitude of all recurrence flood flows varying between two and one hundred years.

The analysis of these three studies already carried out in Quebec on the hydrological impacts on the magnitude of floods makes it possible to identify the following important facts:

- These three studies analyzed the impacts of wetlands on the temporal variability of the magnitude of flood flows in the context of climate change or land use change. Consequently, they did not address the issue of the impacts of these wetlands on the spatial variability of this magnitude. They cannot therefore directly explain the influence of the difference in surface areas of wetlands between two given watersheds to explain their different sensitivity or vulnerability to floods.
- The three studies were limited to the analysis of the impacts of wetlands on the magnitude of floods only. Other fundamental characteristics of these floods (duration, frequency, timing and variability) have not been analysed. Yet these characteristics each play multiple roles in the functioning of aquatic ecosystems as clearly demonstrated by the “natural flow” paradigm (Poff et al. 1997). From management and flood control perspective, it is important to determine the impacts of wetlands on each of these fundamental flow characteristics.
- In Quebec, in all watersheds, wetlands coexist with other bodies of water and depressions likely to store surface runoff. It is therefore important to take into account the interaction between these different components of the landscape to better explain their impacts on the characteristics of floods. In other words, in reality, we cannot separate the effects induced exclusively by wetlands from those induced by the other components because of this coexistence and this interaction. Consequently, the study of the spatial variability of the impacts of wetlands including other components of the landscape (lakes and depressions)

on floods is naturally necessary, as has already been demonstrated by several studies (Quin and Destouni 2017; Rajib et al. 2020; Yu et al. 2019). In the same vein, the analysis of the hydrological impacts induced by a type of wetland does not seem to be justified due to the coexistence and interaction of several types of wetlands in the same watershed in Quebec.

In light of these facts, our study pursues the following objectives:

- (i) Analyze the impacts of wetlands on the spatial variability of the flow characteristics of the annual flood.
- (ii) Determine the flood characteristics that are significantly affected by wetlands. In their synthesis, Acreman and Holden (2013) had raised this issue. But it has never been analyzed in the scientific literature. It is therefore important to analyze it.
- (iii) Determine if the affected characteristics amplify or mitigate the environmental impacts of flooding.
- (iv) Demonstrate that the impacts of wetlands on annual flood flow characteristics is independent from climatic conditions in southern Quebec.

It is important to note that this analysis will not be based on hydrological models, which will be addressed at a later stage. Modelling the hydrological impacts of wetlands on the all five annual flood flows characteristics are much more complex. In addition, hydrological modeling is appropriate for analyzing the impacts of wetlands on the temporal variability of flows and not on their spatial variability. Thus, all the studies based on this hydrological modeling focus exclusively on the temporal variability of flows, particularly in the context of climate change or changes in the surface areas of wetlands associated with anthropogenic activities.

Methods

Selection of the watersheds studied and their description

To study the influence of wetlands on spring flood characteristics, two pairs of watersheds were selected, based on the following criteria:

- The selected watersheds must have very similar physiographic characteristics and be representative of the climatic conditions of Southern Quebec.
- They must be differentiated mainly by their wetland surface areas (swamps, marshes, bogs, lakes, etc.). The other watersheds were excluded because they could not have shown the influence of wetlands on annual floods. By selecting these watersheds, we were able to define the three objectives outlined in the introduction.
- Finally, flow data measurements must be available over a relatively long period, i.e. greater than 85 years, so as permit the comparison of watershed reactions in wet and dry periods.

Based on these three criteria, two pairs (four) of watersheds were selected: the watersheds of the Matane and Rimouski rivers on the one hand, and those of the Petite-Nation and Matawin rivers. Their physiographic and climatic characteristics are shown in Table 1 and their locations in Fig. 1.

The Matane and Rimouski river watersheds are almost entirely contained within the Appalachians on the south (right) bank of the St. Lawrence River, into which they both flow directly. From the geological perspective, this formation is an ancient fold mountain chain made up of sedimentary rocks (shale, sandstone, limestone, conglomerates, etc.). It is connected to the St. Lawrence River by a piedmont (plateau) and lowlands (flat topography) area of the St. Lawrence, gradually narrowing to the east (absent in the Matane watershed). These different topographic units are covered by deposits of various origins (including marine, glacial, river, glaciomarine, fluvio-glacial deposits) consisting of elements of different granulometric sizes (stones, gravel, sand, silt and clay). According to Buffin-Bélanger et al. (2016), these deposits would be more permeable in the Matane River watershed than those of other surrounding watersheds. In terms

Table 1 Comparison of the physiographic and climatic characteristics of the Matane, Rimouski, Matawin and Petite river watersheds

Variables	Code	The Appalachians rivers		The Canadian Shield rivers	
		Matane	Rimouski	Petite Nation	Matawin
Physiographic variables					
Drainage area (km ²)	PV1	1655	1610	1330	1390
Mean slope (m/km)	PV2	3.86	2.47	1.24	1.25
Drainage density (km/km ²)	PV3	0.47	0.54	0.43	0.46
Forests surface area (%)	PV4	90.9	89.9	83.1	90
Wetlands surface area (%)	PV5	1	3	15	9
Agricultural surface area (%)	PV6	8.9	8.8	0.6	0
Urbanized surface area (%)	PV7	0	0	0	0
Climatic variables					
Annual total precipitation(mm)	CV8	1203.6	960	1084.4	877.7
Annual total rainfall (mm)	CV9	766.4	686.5	833.1	720.1
Annual total snowfall (cm)	CV10	437.2	273.5	251.3	157.6
Winter–Spring total precipitation (mm)	CV11	557.7	432.7	480.2	414.4
Winter–Spring total rainfall (mm)	CV12	283.7	250	326.1	286
Winter–Spring total snowfall (cm)	CV13	274	182.7	154.1	128.4
Annual daily mean temperature (°C)	CV14	2.7	3.9	3	2.7
Monthly May daily mean maximum temperature (°C)	CV15	15.1	14.6	17.5	17.1

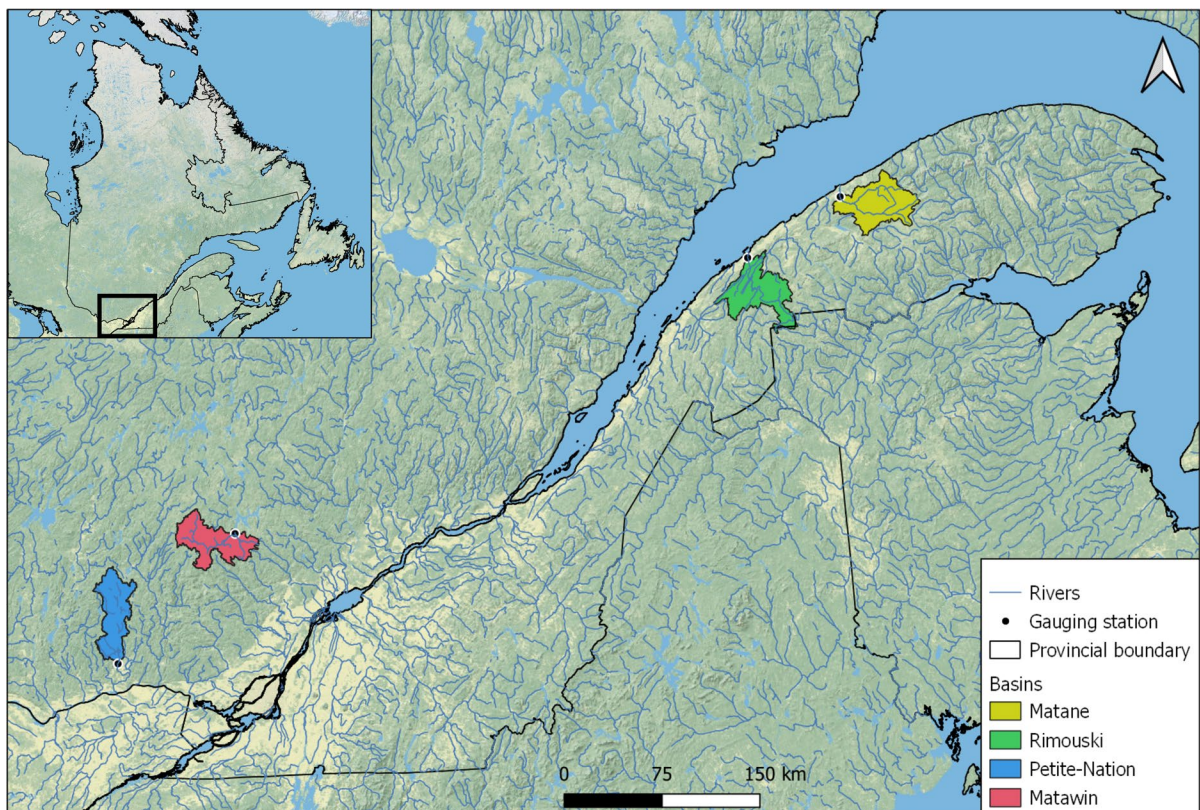


Fig. 1 Locations of the four watersheds in the study

of vegetation, the natural forest in the two watersheds is comprised of white and yellow birch trees. The climate is maritime, characterized by cool summers and less severe winters. It becomes more continental the farther you get from the St. Lawrence. The Matawin and Petite-Nation river watersheds are entirely located on the Canadian Shield on the north (left) bank of the St. Lawrence River. The Canadian Shield is a geological formation consisting mainly of metamorphic rocks (gneiss). There are also mafic and sedimentary rocks. When these rocks are not exposed on the surface, they are covered by loose fluvio-glaciomarine deposits (gravel, sand, till, etc.). The morphology of the channels of the Matawin and Petite-Nation rivers is characterized by an almost regular succession of large, winding sections with low gradients in loose deposits and steep, narrow, almost linear sections of rocky or pebble outcrops. In both watersheds, the forest consists mainly of sugar maple trees (*Acer saccharum*) (sugar maple-yellow birch and basswood-sugar maple). The climate is continental temperate, characterized by warm summers and cold winters. The Petite-Nation River flows from north to south, into the Ottawa River, the main tributary of the St. Lawrence River. In contrast, the Matawin River flows from west to east, into the Saint-Maurice River, as its main tributary. The Mont Tremblant massif separates their watersheds (Fig. 1).

Data sources

Daily flow data were also extracted from the website of the Centre d'expertise hydrique du Québec (<https://www.cehq.gouv.qc.ca/>, accessed on 2020-02-20). Climate data were obtained from climate stations located in the four watersheds. These stations are all managed by Environment and Climate Change Canada (https://climat.meteo.gc.ca/climate_normals/index_f.html, accessed on 2020-08-15). These data are the monthly climate normals calculated over the period 1971–2000. The climatic data of the watersheds are presented in Table 1.

Physiographic variables, presented in Table 1, were first calculated from 1/20,000 topographic maps and aerial photographs taken during the 1970 and 1980s. The areas of agriculture, forests and wetlands as well as those of other bodies of water were calculated using an electronic planimeter (Belzile et al. 1997). For wetlands and small water bodies,

which are difficult to map, their areas were calculated on aerial photographs taken at a scale of 1/15,000 enlarged to a scale of 1/6000 after their georeferencing and orthorectification. These data were then compared with those recently measured in the same watersheds by the Glaciolab laboratory of the University of Quebec at Trois-Rivières. For measurements of the mean slope of the watershed, and drainage density, the laboratory used the 400 m resolution Canadian Digital Elevation Model (CDEM), and the drainage network produced by the Ministry of Energy and Natural Resources of Quebec (MERN). As for agricultural, forest and wetland areas, they were calculated from the 1.1 km resolution Canada land-cover database, derived from an advanced very high resolution radiometer (AVHRR) sensor operating on board the United States National Oceanic and Atmospheric Administration (NOAA) satellites. The classification was based on approximately 45 cloud free summer images, spanning the period 1988–1991 (Assani et al. 2021). However, with regard to wetlands, the laboratory was only interested in the areas of large bodies of water such as lakes. For the other physiographic factors, their values calculated by these two databases were comparable in the four watersheds analyzed. In addition to these two sources, with regard to wetlands and other bodies of water, reference was also made to the cartographic data published by the organization “Canards Illimités (Unlimited Ducks)” (<https://www.donneesquebec.ca/recherche/dataset/milieux-humides-du-quebec>, viewed 15–20 September, 2020) as well as the field measurement data carried out by the organizations of the watersheds of the rivers analyzed. However, despite the use of these different sources, it was not possible to determine the area occupied by each type (small lakes, marshes, floodplains, swamps, wooded or non-wooded bogs, other depressions) of wetlands and other bodies water in each watershed. Nor was it possible to separate the areas of isolated wetlands and water bodies from those of wetlands and water bodies riparian or floodplains. It follows that the term wetlands used in its broadest sense in the context of this study as it includes all the different types of wetlands, small lakes and other depressions that can store surface runoff (see Rajib et al. 2020). This broad definition is justified by the fact that all these landscape components coexist in a watershed and interact on the water cycle (infiltration, runoff and evapotranspiration processes) in Quebec. Therefore,

their hydrological impacts should not be analyzed separately but together.

Definition of annual flood characteristics and statistical data analysis

The annual flood or annual flood is the one that generates the highest maximum daily flow (annual maximum daily flow) during a year. In Quebec, it is generated by melting snow in the spring (from April to June). This melting may or may not be associated with liquid precipitation (rain). According to the concept of natural flows regime (Poff et al. 1997), river flows can be defined by five basic characteristics: magnitude, frequency, duration, timing, and variability (flow rate change). In terms of magnitude, first, for each river, we developed the series of annual daily maximum flows composed of the daily maximum flows measured annually from 1930 to 2019. Then, this series was used to estimate the flows for the following recurrence intervals: 2 (Q2), 5 (Q5), 10 (Q10), 20 (Q20), 50 (Q50) and 100 (Q100) years. This estimate was made using the regional distribution calculated by Anctil et al. (1998). These authors subdivided the territory of Quebec into three homogeneous hydrological regions, i.e. homogeneous regions that group all rivers with similar flow characteristics (coefficients of variation, asymmetry and kurtosis) according to the discordance test developed by Hosking and Wallis (1993). In each homogeneous hydrological region, the authors worked out a regional Generalized Extreme Value (GEV) distribution whose three parameters (α , β and ξ) were used to estimate the flows for different recurrence intervals on both gauged and ungauged rivers. This regional distribution is recommended by Quebec's Ministère d'Environnement et de la Lutte contre les changements Climatiques to estimate flood flows in the province. Consequently, it was applied to this work. The values of these three parameters of the GEV distribution in each of the three homogeneous hydrological regions of Quebec and the different stages of estimating flow rates for different recurrences are described in detail in the article by Anctil et al. (1998). The Matane and Rimouski rivers belong to homogeneous hydrological region I, while the Matawin and Petite-Nation rivers belong to homogeneous hydrological region II.

After estimating the flow rates associated with different return periods (from Q2 to Q100 years), their frequency (number of years a given recurrence rate was measured) was calculated over the 1930–2019 period. Regarding the duration (in days) of a given recurrence flow, the number of days that this flow was reached or exceeded in a given year over the same 90-year period (1930–2019) was determined. The timing of the annual daily maximum flow corresponds to the Julian day of the occurrence of that flow. If that flow occurs over several days, the Julian day of the first occurrence was used. This study did not compare the characteristic of variability (rate change flow) because it was already included in the estimate of the magnitude of different recurrence flows.

The means of these characteristics were compared with the Kruskal-Wallis non-parametric test. Finally, although the sample sizes were very small (only four watersheds), these four characteristics were correlated with five physiographic and seven climatic variables to determine whether wetland surface area is the main factor in spatial variability for flood characteristics in the four watersheds analyzed.

Results

The comparison of the average magnitude, expressed in specific flows ($l/s/km^2$), of different annual flood flows calculated and estimated in both watershed pairs is reported in Table 2. Figure 2 compares the interannual variability of annual daily maximum flows measured in the two watershed pairs over the 1930–2019 period. This table shows that for the two Appalachian watersheds, the magnitude of all flows of different recurrences in the Matane River, whose wetlands have a smaller surface area, is systematically higher than in the Rimouski River, despite the fact that the surface areas of the two watersheds are almost equal. The same behaviour is also observed in both Canadian Shield watersheds. The magnitude of the different flows of the annual flood of the Matawin River is higher than that of the Petite-Nation River, which has a larger wetland surface area, despite the similarities in the other physiographic characteristics of their watersheds, in particular average gradient and drainage density. A comparison of the two Canadian Shield rivers with the two Appalachian rivers shows

Table 2 Comparison of the magnitude ($l/s/km^2$) of annual floods as a function of the flows of different recurrences (intervals in years) in the four watersheds over the 1930–2019 period

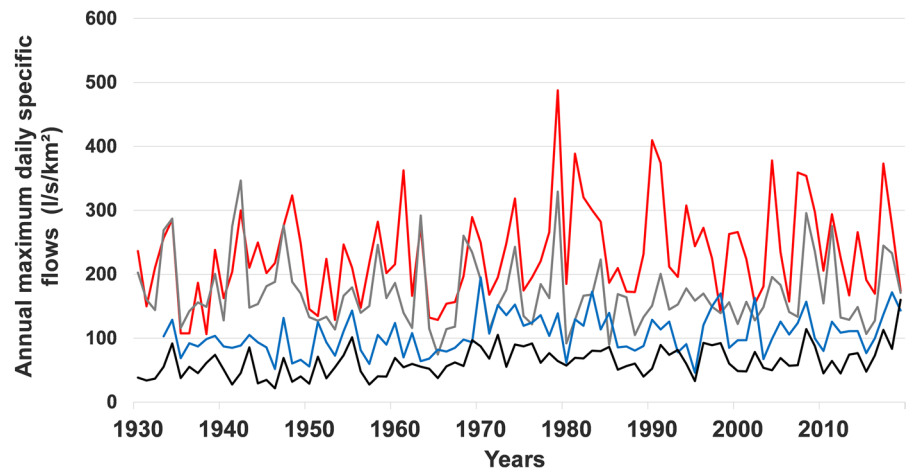
Rivers	Qm	Q2	Q5	Q10	Q20	Q50	Q100	Qmax
Appalachians rivers								
Matane	231.7* (75.04)	217.8	292	340.6	386.9	444.9	488.9	487.6
Rimouski	171* (55.56)	160.8	215.5	251.4	285.7	328.4	361.2	346.6
Canadian Shield Rivers								
Matawin	105.7* (30.82)	102.5	132.1	150.1	165.9	186	202.2	195
Petite Nation	63.3* (23.48)	61.4	79.2	89.9	99.4	111.4	123.5	160.2

Qm = annual mean daily maximum flow. The magnitude values of the flows of different recurrences were estimated using regional Generalized Extreme Value (GEV) distribution (Anctil et al. 1998)

() Standard deviation

*Significantly different means at the 5% level

Fig. 2 Comparison of the interannual variability in the magnitude of the specific flows of annual daily maximums over the 1930–2019 period. Matane River: red curve; Rimouski River: Grey curve; Matawin River: blue curve; Petite Nation River: black curve



that the magnitude of annual flood flows is higher in the Appalachians than on the Canadian Shield. The surface area of the wetlands in the Canadian Shield river watersheds is larger than that of those in the Appalachian river watersheds. The disparity in magnitude of the different flood timings is smaller between the two Appalachian rivers than between the Canadian Shield rivers. In this region, we noted a smaller difference between maximum flows (Qmax) measured in the two river watersheds (Table 3). In fact, in the Matawin River watershed, the recurrence of this peak flow is less than 100 years, whereas that measured in the Petite-Nation River watershed exceeded this threshold.

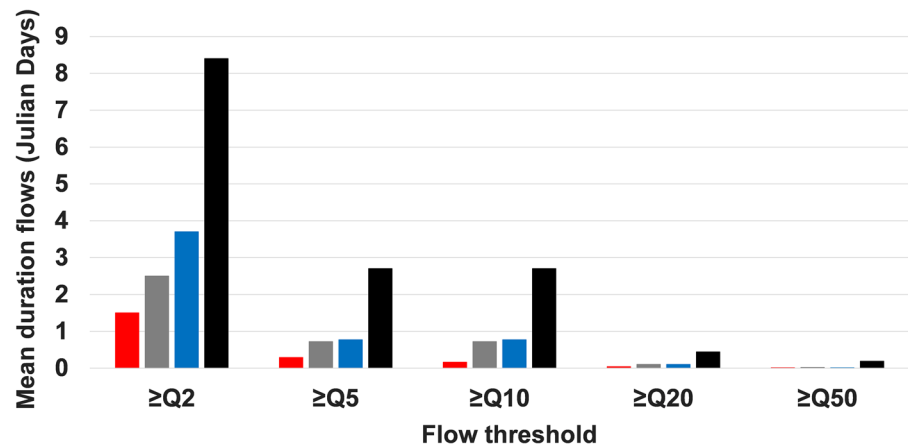
As for the durations of heavy floods, there is a very big difference between the annual flood flows in the watersheds (Table 3 and Fig. 3) in the two regions. In the Appalachians, the duration of different recurrence flows is longer in the Rimouski River watershed than in the Matane River watershed, which has the smaller wetland surface area. The same is true of the two rivers of the Canadian Shield: the duration of different recurrence flows is longer in the Petite-Nation River watershed than in the Matawin River watershed. The difference in durations between the latter two rivers is greater than that observed between the first two rivers. In addition, unlike the Appalachian rivers, this

Table 3 Comparison of total and average annual flood durations (in days) based on the flows of different recurrences (intervals) in the four watersheds over the 1930–2019 period

Rivers	≥ Q2		≥ Q5		≥ Q10		≥ Q20		≥ Q50	
	Total	Mean	Total	Mean	Total	Mean	Total	Mean	Total	Mean
Appalachians Rivers										
Matane	138	1.5*	26	0.29*	14	0.16*	4	0.04*	1	0.01
Rimouski	226	2.5*	65	0.72*	23	0.26*	9	0.10*	2	0.02
Canadian Shield Rivers										
Matawin	324	3.7*	67	0.77*	27	0.31*	9	0.10*	1	0.01*
Petite Nation	754	8.4*	246	2.7*	84	0.93*	40	0.44*	17	0.19*

*Significantly different averages at the 5% level

Fig. 3 Comparison of means of the durations of annual daily maximum flows (days) for different recurrence years (return-intervals) over the 1930–2019 period. Matane River: red bar; Rimouski River: Grey bar; Matawin River: blue bar; Petite Nation River: black bar



difference in flow duration increases with the increase in the flow recurrence threshold.

Comparing the timing of annual daily maximum flows showed no statistically significant differences between the two Canadian Shield watersheds (Table 4). As a result, annual flood peaks occur almost synchronously in both watersheds. Nevertheless, it should be noted that only once in 90 years has the annual daily maximum flow been recorded as occurring in the fall in the Petite-Nation River watershed; this occurrence has never been observed in the other watershed (Matawin). All heavy floods are generated

by snowmelt in the spring in both watersheds. In contrast, in the Appalachians, flood peaks occur, on average, relatively early in the Rimouski watershed. There is an average interval of four days in the occurrence of annual flood peaks between the two watersheds. In both watersheds, the annual flood occurs in the spring when the snow melts. However, in the Matane River watershed, one annual flood occurred in the fall (1950). Finally, in terms of flood frequency, there was no significant difference between the four watersheds (the results are not presented here).

Table 4 Comparison of timing variables (Julian days) of annual daily maximum flows over the 1930–2019 period

Variables	The Appalachians Rivers		The Canadian Shield Rivers	
	Matane	Rimouski	Matawin	Petite Nation
Mean	128 (24.2)	124 (12.2)	120 (11.8)	121 (23.2)
Median	127	125	119	120
Tmax	334	174	144	318
Tmin	92	92	91	90

T_{\max} = the latest date of occurrence; T_{\min} = the earliest date of occurrence. () = standard deviation

The results of the correlation analysis between these four flow characteristics and 13 physiographic and climatic variables are presented in Tables 5 (magnitude) and 6 (duration, frequency and timing). Despite the small sample size (only four watersheds), these results support the previous analysis. In fact, the

magnitude of flood flows was strongly correlated with the surface area of wetlands (PV6) (Table 5). This correlation was negative. This magnitude was also correlated with agricultural surface area (PV5), but this correlation was significant only at the 10% threshold and was positive. As for flow duration, it was exclusively correlated significantly with wetlands surface area. This correlation was positive, but unlike magnitude, the correlation coefficient values decreased with the flow recurrence threshold so that this correlation was no longer statistically significant for recurrence rates ≥ 20 years. Frequency only had a negative correlation with forest surface area (PV4), but this correlation was significant only for recurrence rates ≥ 5 years. Finally, the flow occurrence period (timing) was positively correlated with snowfall (CV9 and CV12) (Table 6). Increased snowfall caused peak floods to occur later in the season due to the relatively long time required for all the snow to melt.

Table 5 Correlation coefficients calculated between physiographic and climatic variables and magnitude of floods with varying recurrence intervals from 1930 to 2019

Variables	Qm	Q2	Q5	Q10	Q20	Q50	Q100	Q_{\max}
Physiographic variables								
PV2	0.535	0.531	0.536	0.540	0.543	0.543	0.546	0.471
PV3	0.767	0.769	0.767	0.766	0.764	0.765	0.763	0.872
PV4	0.429	0.441	0.426	0.416	0.405	0.393	0.390	0.338
PV5	0.900*	0.895	0.902*	0.907*	0.911*	0.916*	0.917*	0.913*
PV6	-0.967**	-0.968**	-0.967**	-0.966**	-0.966**	-0.963**	-0.964**	-0.924*
Climatic variables								
CV8	-0.414	-0.417	-0.413	-0.411	-0.409	-0.400	-0.402	-0.289
CV9	0.799	0.795	0.801	0.804	0.807	0.814	0.813	0.878
CV10	0.466	0.460	0.467	0.471	0.474	0.483	-0.482	0.585
CV11	-0.633	-0.639	-0.638	-0.639	-0.639	-0.635	-0.636	-0.547
CV12	0.881	0.879	0.882	0.884	0.885	0.890	0.889	0.938*
CV13	0.561	0.558	0.561	0.563	0.564	0.571	0.570	0.662
CV14	0.078	0.068	0.080	0.088	0.096	0.103	0.106	0.067
CV15	-0.876	-0.872	-0.878	-0.881	-0.884	-0.887	-0.889	-0.859

*Significantly values at the 10% threshold are shown in the bold

** Significantly values at the 5% threshold are shown in the bold

Table 6 Correlation coefficients calculated between physio-climatic variables and three characteristics of annual flood flows from 1930 to 2019

Variables	Mean Duration					Frequency					Timing
	≥ Q2	≥ Q5	≥ Q10	≥ Q20	≥ Q50	≥ Q2	≥ Q5	≥ Q10	≥ Q20	≥ Q50	Mean
Physiographic variables											
PV2	-0.653	-0.584	-0.624	-0.590	-0.603	-0.016	-0.556	-0.055	0.187	-0.187	0.349
PV3	-0.503	-0.468	-0.438	-0.429	-0.309	0.809	-0.198	0.231	-0.864	-0.490	0.865
PV4	-0.648	-0.745	-0.715	-0.753	-0.760	0.753	-0.968**	-0.776	-0.613	-0.899	0.196
PV5	-0.732	-0.621	-0.639	-0.592	-0.509	0.365	-0.376	0.050	-0.283	-0.257	0.891
PV6	0.960**	0.908*	0.915*	0.891	0.834	-0.666	0.740	0.408	0.550	0.661	-0.821
Climatic variables											
CV8	0.737	0.750	0.776	0.774	0.833	-0.201	0.852	0.408	0.009	0.538	-0.087
CV9	-0.444	-0.348	-0.337	-0.301	-0.169	0.534	0.022	0.527	-0.576	-0.190	0.961**
CV10	-0.033	0.051	0.071	0.099	0.232	0.347	0.361	0.130	-0.467	0.083	0.742
CV11	0.829	0.794	0.823	0.802	0.820	-0.250	0.786	0.338	0.067	0.480	-0.381
CV12	-0.582	-0.498	-0.486	-0.455	-0.329	0.651	-0.188	0.360	-0.669	-0.348	0.986**
CV13	-0.172	-0.108	-0.081	-0.062	-0.072	0.528	0.195	-0.029	-0.636	-0.116	0.789
CV14	-0.100	-0.003	-0.052	-0.010	-0.035	-0.576	0.000	0.141	0.690	0.414	0.037
CV15	0.806	0.710	0.732	0.691	0.633	-0.342	0.522	0.063	0.223	0.333	0.791

*Significantly values at the 10% threshold are shown in the bold

** Significantly values at the 5% threshold are shown in the bold

Discussion

Justification for the watersheds sample selection

The comparison of four characteristics for annual flood (flood) flows resulting mainly from snowmelt in two pairs of watersheds revealed a difference in hydrological behaviour between these watersheds. This difference relates to the magnitude and duration of the annual maximum flow. In the Appalachians, the magnitude of annual flood flows was higher in the Matane River watershed than in the Rimouski River watershed. The reverse was true for flow duration, which was greater in the Rimouski River watershed than in the Matane River watershed. In the Canadian Shield, the same hydrological behaviour was also observed: flow magnitude for the Matawin River was greater than for the Petite Nation River, whereas the opposite was true for flow duration. It follows that the difference in the hydrological behaviour observed between two watersheds in each pair in the two different climatic regions (maritime in the Appalachian region and continental on the Canadian Shield) is completely independent of the climatic and geological conditions of the watersheds. This absence of the

influence of climatic and geological characteristics on this hydrological behavior makes it possible to determine the influence of others factors on the one hand, and justifies the choice of these two pairs of watersheds for the determination of this influence on the other hand.

The discussion will therefore focus on the analysis of influential factors likely to explain this difference in hydrological behaviour (difference in flow magnitude and duration) between two watersheds in the same pair and between the four watersheds of both pairs. Theoretically, the same factor should explain the difference across Quebec. The results obtained and conclusions drawn from this study can thus be generalized to all watersheds in southern Quebec. From this perspective, a simultaneous analysis of many watersheds was not justified. Such an analysis would not have allowed us to accurately identify the influence of wetlands on annual flood characteristics due to the interaction of many diverse physiographic characteristics if numerous other watersheds had been included in the analysis. To demonstrate the validity of our approach, which was based on an analysis of a reduced number of watersheds, a comparison will be conducted of each factor that could explain the difference in the same

hydrological behaviour observed between two watersheds in each pair and between the two pairs of watersheds analyzed. At the end of this comparison, we will demonstrate the influence wetlands have on the difference in hydrological behaviour observed between the four watersheds analyzed. It is also worth remembering that this approach, which is based on a comparison of two watersheds (paired method), is widely used in hydrology to isolate a specific factor's influence on the spatial variability of flows. It is widely used in forest hydrology to determine the influence of deforestation, particularly on the hydrological cycle of water (e.g., Andréassan 2004; Best et al. 2003; Brown et al. 2005; Cosandey et al. 2005).

Highlighting the influence of spatial variability on the magnitude and duration of annual floods in the four watersheds studied

A range of factors can explain this difference in the magnitude and duration of annual floods in the four watersheds studied. The first is the difference in precipitation. In the Appalachians, the amount of precipitation (rain and snow) was greater in the Matane River watershed than in the Rimouski River watershed, and this difference could logically explain why flow magnitude values were higher in the former watershed than in the latter. However, more precipitation in the Matane River watershed should theoretically also cause flood flows to be heavier than in the Rimouski River watershed given that the spring temperatures and forest area of both watersheds are nearly identical. Yet, despite these similarities—both of which influence the rate of snowmelt in spring—the annual flood lasted longer in the Rimouski River watershed, which had less snow and rain than the Matane River watershed. In the case of these two watersheds of the Canadian Shield, precipitation could clearly not be considered as a potential contributing factor in this hydrological behaviour. In fact, although precipitation (snow and rain) was higher in the Petite Nation River watershed, specific flows were higher in magnitude and shorter in duration in the Matawin River watershed. Ultimately, this factor was not significantly correlated to the magnitude or duration of flows.

The second factor that may explain the difference in hydrological behaviour between the watersheds of each pair of rivers in the two climatic regions

is their main slope, which could influence the runoff process during snowmelt. In the Appalachians, the main slope of the Matane River watershed was greater than that of the Rimouski River watershed. Consequently, increased surface runoff caused water to flow more quickly during snowmelt, which resulted in increased magnitude but shorter duration of flows in the first watershed. This factor could explain the difference in the hydrological behaviour of these two watersheds. However, while the rapid transfer of runoff from the watersheds to the channels depends on mean watershed slope, it also depends on drainage density, which was higher in the Rimouski River watershed than in the Matane River watershed. This difference should mean that runoff transferred more quickly from the watershed to the channel, offsetting the effects of the lower average slope of the Rimouski River watershed. The mean watershed slope must also be ruled out as a contributing factor because, in the Canadian Shield, the main slope and drainage density of both watersheds were almost the same, despite differences in hydrological behaviour. Ultimately, neither of these physiographic factors (mean slope and drainage density) was significantly correlated with either the magnitude or the duration of flood flows.

The third potential contributing factor is agriculture surface area. Unlike the previous two factors, agriculture surface area was significantly correlated with the magnitude of flow rates. However, it was not correlated with their duration. This factor must also be ruled out because the agriculture surface area of the watersheds of each pair were the same. In fact, there was no difference in agriculture surface area between the Matane and Rimouski river watersheds in the Appalachians and the Matawin and Petite Nation river watersheds in the Canadian Shield. In addition, the agricultural practices (no irrigation in particular) and the types of crops in the two watersheds are the same. Finally, the spring snowmelt that generates the annual floods (flood) occurs on agricultural land without cultivation or vegetation in the two watersheds because the plants begin to grow after this melting. The significant correlation observed with respect to magnitude could only be explained by the difference in agriculture surface area between the agricultural watersheds of the Appalachians and the non-agricultural watersheds of the Canadian Shield (difference between groups).

Forest cover must also be dismissed as a contributing factor as its decrease led to accelerated snowmelt in spring, which in turn reduced the duration of floods but increased their magnitude. This influence did not explain how the difference in hydrological behaviour affected flow duration, in particular. In fact, the Petite Nation River watershed, which had the smallest forest cover of the four watersheds studied, was characterized by very low magnitudes due to long flow durations. This hydrological behaviour is incompatible with smaller forest surface areas. This argument is based on the conclusion of the study of the impact of deforestation on the magnitude of flood flows in Quebec. Indeed, Lavigne et al. (2004) demonstrated that the decrease in forest cover following clearcutting in the Famine River watershed led to an increase in the magnitude of the annual flood flows generated by snowmelt.

The final factor that varied greatly between the watersheds was wetland surface area, which was fifteen times larger in the Petite Nation River watershed than in the Matane River watershed. No other physiographic or climate-related values between the two watersheds studied were as starkly different. This difference between the wetland surface area of these two watersheds resulted in substantial differences in the magnitude and duration of their annual floods. Specific flows of the flood were four times higher on average in the Matane River watershed than in the Petite Nation watershed, which has a smaller area than in the first watershed. Generally speaking, specific flows diminish as watershed size increases. As such, the flow of the Matane River watershed should be lower than that of the Petite Nation River watershed. However, the duration of the annual flood was six times shorter on average in the Matane River watershed than in the Petite Nation River watershed, even though flow durations should theoretically increase in larger watersheds.

There is already an abundant literature on the impacts of wetlands on the magnitude of floods in particular. Several almost exhaustive summaries of this work have already been published (see Bullock and Acreman 2003; Acreman and Holden 2013; Lane et al. 2018). These works had clearly demonstrated that the impact of wetlands on the magnitude of floods depends on many intrinsic (e.g., surface area, topography, antecedent wetness conditions, soil characteristics and management, presence or not vegetation,

plant properties, hydraulic conductance, etc.) and extrinsic factors (e.g., landscape location and configuration in the watershed, seasonality, precipitation, runoff pathway, connectivity with channel rivers, etc.) as already mentioned in the introduction. Regarding the location of wetlands relative to river channels, for example, in their review, Bullock and Acreman (2003) reported that with respect to the slope non-floodplain wetlands (NFWs), in 42% of inventoried studies, these caused a decrease in the magnitude of the flows while 44%, rather, caused an increase in this magnitude. Taking into account their location in the watershed, Acreman and Holden (2013) reported in their synthesis that “uplands rain-fed generally tend to be flood generating area while floodplains wetlands have a greater potential to reduce floods”. In Quebec, remember that Fossey and Rousseau (2016a, b), and Blanchette et al. (2018) demonstrated that both non-floodplain and floodplain (riparian) wetlands led to a reduction in the magnitude of floods generated by snowmelt and rain in the three watersheds analyzed.

Contrary to the magnitude of flood flows, there are practically no studies on the impacts of wetlands over their duration as can be seen from the above-mentioned synthesis works. Even in Quebec, the three works devoted to the impacts of the wetlands have been limited exclusively to their impacts on the magnitude of these floods. But, in his recent study, Assani (2022) demonstrated that wetlands cause a reduction in the duration of floods generated by rain, unlike that of floods generated by melting snow. The same is true for the frequency of floods. Wetlands significantly reduce the frequency of floods generated by rain, but they do not impact the frequency of those generated by melting snow. It follows that wetlands do not have the same impact on these two floods characteristics generated by snowmelt and rain in southern Quebec, contrary to their magnitude. However, the environmental and socio-economic impacts induced by floods also depend strongly on their duration and frequency. The longer these floods last and happen frequently, the greater and more devastating their impacts become.

Conceptually, this study is based on a relatively broad definition of wetlands including its different types (marshes, floodplains, swamps, bogs, etc.) as well as other types of water bodies (small lakes and depressions), likely to store runoff water on the surface. In Quebec, these different components of

the landscape coexist in all watersheds and interact on the water cycle as already mentioned. They thus contribute to influencing the spatial variability of the magnitude and duration of floods. Thus, unlike all the works devoted to the hydrological impacts induced exclusively by wetlands, this study did not focus on the impacts related to their intrinsic and extrinsic characteristics. We therefore limited ourselves to the analysis of the impacts of the area occupied by these different components of the landscape, given that the data did not make it possible to determine the area occupied by each of these components.

The analysis of the results shows that the impact of these different components of the landscape translates into a significant decrease in the magnitude of the annual daily maximum flows. This magnitude decreases with the increase in the area occupied by these components in a watershed as revealed by the significantly negative correlation observed between the two variables. It follows that, like certain wetlands, the collective effect of these various components of the landscape present in the watersheds translates into surface storage of runoff water from melting snow. It should be remembered that in Quebec, before the snow melts in the spring, all wetlands and bodies of water are completely frozen in winter. Before this winter freeze, all these components (wetlands and other bodies of water) are not completely filled with rainwater in the fall. Thus, when the snow melts in the spring, a large part of the runoff water is stored and then gradually released to the river channels. This explains the decrease in the magnitude of flood flows in parallel with the increase in the area of these components.

It is therefore not a process linked to the classic “sponge effect” which is exerted by wetlands alone, but a “surface water storage effect” process exerted by all components of the landscape that can store runoff water on the surface. This process has already been described by several authors (e.g., Holden and Burt 2003; Quin and Destouni 2017; Rains 2011; Rajib et al. 2020; Shook and Pomeroy 2011; Shook et al. 2013; Yu and Harbor 2019). In Quebec, Fosse et al. (2015) demonstrated that wetlands also contribute to the surface storage process of runoff water. The two processes or concepts are therefore hydrologically different. Because, the sponge effect involves surface and deep (underground) connectivity between wetlands and river channels, unlike the first

process which only involves surface connectivity. In this regard, Assani (2022) has just demonstrated that, despite the difference in wetland areas between the Matawin and Petite Nation rivers under study, there is no statistically significant difference between the magnitude of the low water flows measured in the two watersheds in summer and autumn while this difference was observed between the magnitude of flood flows generated exclusively by rain during these seasons. This result clearly demonstrates that the underground connectivity between the wetlands and the channels of two rivers is weaker than the surface connectivity, thus justifying the existence of two different concepts: the concepts of “surface water storage effect” and “sponge effect”. The latter implies above all an “absorption” or “imbibition” of runoff water and not a “surface storage or surface accumulation”.

Following this conceptual consideration, it can therefore be established that the “surface water storage” process causes an increase in the duration of floods generated by snowmelt because the different storage components, once saturated, establish surface connectivity that triggers the channeling of runoff water to river channels. This transfer appears to be relatively slow but sustained throughout the melting period. This explains an increase in the duration of floods reflected in a positive correlation between this hydrological characteristic and the area of the components of surface water storage. Thus, as part of this surface water storage process, the water levels in each component before snowmelt is a major factor in its connection with river channels in the transfer process. It is this storage process that explains the decrease in the duration and frequency of floods generated by rain in summer and autumn due to the high evapotranspiration of the water stored in these components (see Assani 2022). Finally, as has been pointed out, it is not known how the “sponge effect” impacts the duration of floods due to the lack of studies on this subject. The understanding of the impacts of the sponge effect exerted exclusively by wetlands in the strict sense on the characteristics of floods, and therefore on their dynamics, still seems poorly understood.

Conclusions

Sculpted by the succession of glacial and interglacial periods, the landscapes of the watersheds of southern

Quebec are dotted with numerous wetlands of different types (marshes, floodplains, swamps, bogs, etc.) and other bodies of water (lakes, depressions, etc.). These different components of the landscape interact on the processes of evapotranspiration, runoff and infiltration. But the impacts of their interaction on the spatial variability of flows in general, and annual floods generated mainly by snowmelt, in particular, have never been analyzed. To fill this gap, this study compared the spatial variability of the characteristics of the annual maximum flows (magnitude, duration, frequency, and timing), measured during the period 1930–2019, in two pairs of watersheds differing mainly by the surface area of these wetlands, thus defined in the broadest sense: the watersheds of the Matane and Rimouski rivers on the south shore, on the one hand, and those of the Matawin and Petite Nation rivers on the north shore, on the other. This comparison highlighted a negative correlation between the area of these components and the magnitude of the maximum annual flows on the one hand, but a positive correlation between this area and the duration of these flows. These correlations are explained by the surface storage of runoff water from snowmelt by these different components of the landscape, which slowly but steadily feed river flows for relatively long periods. This mechanism of “surface storage” of runoff water is slightly different from that of the “sponge effect” exerted exclusively by typical wetlands analyzed in the scientific literature.

The magnitude of socio-economic costs caused by floods depends on the magnitude, frequency and duration of their flows. This study shows that, in Quebec, wetlands reduce the magnitude of annual daily maximum flow. However, they significantly increase their duration. This increased duration can offset or mitigate the beneficial effects associated with a lower magnitude of floods. This aspect must be taken into account in the debate on the role of wetlands and others water bodies in reducing severe flooding in Quebec.

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Data availability The author may provide the data used in the manuscript upon request.

Declarations

Conflict of interest No conflicts of interest are declared.

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Consent for publication Not applicable.

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