

Article

Impacts of Agricultural Areas on Spatio-Temporal Variability of Daily Minimum Extreme Flows during the Transitional Seasons (Spring and Fall) in Southern Quebec

Ali Arkamose Assani ^{1,*} , Ayoub Zeroual ² , Alexandre Roy ^{1,3} and Christophe Kinnard ¹ 

¹ Department of Environmental Sciences and Research Centre for Watershed-Aquatic Ecosystem Interactions (RIVE, UQTR), University of Quebec at Trois-Rivières, 3351 Boulevard des Forges, Trois-Rivières, QC G9A 5H7, Canada; Alexandre.Roy@uqtr.ca (A.R.); Christophe.Kinnard@uqtr.ca (C.K.)

² Higher National School of Hydraulics, Blida 09000, Algeria; zeroualayoub34@yahoo.fr

³ Centre d'Applications et de Recherches en Télédétection (CARTEL), Université de Sherbrooke, Sherbrooke, QC J1K 2R1, Canada

* Correspondence: Ali.Assani@uqtr.ca

Abstract: Several statistical methods were used to analyze the spatio-temporal variability of daily minimum extreme flows (DMEF) in 17 watersheds—divided into three homogenous hydroclimatic regions of southern Quebec—during the transitional seasons (spring and fall), during the 1930–2019 period. Regarding spatial variability, there was a clear difference between the south and north shores of the St. Lawrence River, south of 47° N. DMEF were lower in the more agricultural watersheds on the south shore during transitional seasons compared to those on the north shore. A correlation analysis showed that this difference in flows was mainly due to more agricultural areas ((larger area (>20%) on the south than on the north shore (<5%)). An analysis of the long-term trend of these flows showed that the DMEF of south-shore rivers have increased significantly since the 1960s, during the fall (October to December), due to an increase in rainfall and a reduction in cultivated land, which increased the infiltration in the region. Although there was little difference between the two shores in the spring (April to June), we observed a decrease in minimum extreme flows in half (50%) of the south-shore rivers located north of 47° N.

Keywords: minimum extreme flows; spring; fall; agriculture; hydrology; watersheds; infiltration; long-term trend; statistical analysis



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1. Introduction

In cold temperate regions, the impacts of global warming on minimum river flows are relatively complex. This complexity results from the different impacts of warming on the two types of river flow feeding regimes: snowmelt and rainfall. Many studies have already shown a significant decrease in snowfall in many regions, in the current context of global warming [1–5]. As for rainfall, the impacts of warming generally result in increased rainfall in winter (increase in temperature) and in summer (increase in evapotranspiration) [6–8]. Despite numerous studies on the temporal variability of minimum flows in the context of global warming [9–26], few have focused on analyzing the impacts of these changes in seasonal precipitation regimes on minimum flows. Furthermore, the impacts of global warming on minimum flows can be amplified or mitigated by land use, particularly agriculture, as observed in a number of watersheds in certain agricultural regions of the USA [13,27].

Like other cold temperate regions, the climate in Quebec regions consists primarily of two seasons: winter (cold and snowy) and summer (hot and/or rainy), and these longer seasons are bisected by two transitional seasons, spring and fall. Spring marks the transition from cold (winter) to hot (summer), while fall marks the opposite transition from hot (summer) to cold (winter). From a hydrological perspective, the sequence of the

seasons strongly influences river flow regimes during the two transitional seasons. Spring flows are primarily influenced by snowmelt from the winter, while fall flows are primarily influenced by rainfall. As such, the factors affecting spatio-temporal flow variability during these two transitional seasons are not necessarily the same, and are not affected by global warming in the same way.

Studies in Quebec on the impacts of global warming on temperature and precipitation have shown that, in winter, these impacts mean rising temperatures and decreasing snowfall [28–30]. In summer, these impacts also mean a rise in the temperature, combined with increasing rainfall [31,32]. The hydrological impact of these changes in temperature and precipitation regimes were studied in winter and summer only [33–36]. Research conducted during the spring and fall has so far focused on the temporal variability of floods [37–39]. However, unlike the two previous seasons, these two transitional seasons are characterized by periods of high and low flows, in Quebec. In spring, low flows occur before or after snowmelt, and, in fall, after a period without rain. It is important to stress that these periods of low flow do not necessarily correspond to periods of hydrological drought. However, despite the existence of these periods of low flows, there are still no studies dedicated specifically to daily minimum extreme flows during the transitional seasons (spring and fall), despite their vital role in the function and evolution of aquatic ecosystems and human activity [40,41]. In Quebec, for example, certain indices (standards) for calculating the instream flows, to protect aquatic habitats, take these minimum flows into account in spring and in fall [42]. From a seasonal perspective, almost all previous research conducted in cold temperate regions analyzed minimum daily flows in winter and/or summer exclusively. There are no studies on minimum flows in the transitional seasons (spring and fall), and none that analyze the factors affecting these flows from a spatial perspective. Given these considerations, our study focused on the following three objectives:

1. Identify factors that influence spatial variability in daily minimum extreme flows in southern Quebec in spring (April to June) and fall (October to December). This objective is based on the hypothesis that, due to the differences in the mechanisms and processes affecting daily minimum extreme flows in the spring and fall, the factors affecting spatial variability also differ during these seasons in Quebec. It is important to remember that minimum extreme flows in spring are mainly associated with recession (surface runoff), whereas in fall they are generally associated with the direct recharge of bedrock aquifers during low-water events.
2. Compare the temporal variability, or long-term trend (stationarity of hydrological series), of daily minimum extreme flows in spring and fall. This objective is based on the hypothesis that daily minimum extreme flows decrease in spring, due to a decrease in snowfall in winter and early snowmelt, and in fall, due to increased evapotranspiration caused by higher temperatures in summer and early fall.
3. Finally, the 2010s is considered the wettest decade on record in North America. Given that this moisture caused several catastrophic floods in Quebec over the course of the decade, its impact on the evolution of daily minimum extreme flows during these seasons should be analyzed. We will test the hypothesis of whether this moisture caused a significant increase in daily minimum extreme flows in the spring and fall, in addition to flooding.

2. Materials and Methods

2.1. Description of the Watersheds and Data Sources

To test these three hypotheses, we analyzed the daily minimum extreme flows in 17 watersheds in spring and fall from 1930 to 2019. Human activity has very little impact on flow measurements. The 17 watersheds were divided into three hydroclimatic regions, defined in southern Quebec [33,37]: two on the south shore of the St. Lawrence River, and only one on the north shore (Figure 1 and Table 1). The eastern hydroclimatic region, located on the south shore, north of 47° N, is characterized by a cold temperate maritime

climate, whereas the climate of the southeastern hydroclimatic region, just south-east of this parallel, is mixed temperate (part continental and part maritime). The north shore hydroclimatic region is characterized by a cold temperate continental climate. The rivers on the south shore run through the Appalachians and the St. Lawrence Lowlands, becoming more scarce heading northward. These two geological formations consist mainly of sedimentary rocks. The rivers on the north shore flow almost entirely on the Canadian Shield, which consists mainly of metamorphic rocks.

In hydrogeological terms, on the north shore of the St. Lawrence River, on the Canadian Shield, aquifers are located in cracks and faults in the bedrock, as well as in superficial deposits originating mainly from glaciers and rivers. On the south shore, they are found in crystalline, metamorphic, and sedimentary rock, as well as in lacustrine, glacial, marine, and river deposits covering these deep rocks. It is important to note that no studies have been done on the hydrogeological characteristics of these aquifers for southern Quebec as a whole. Existing studies only examined a few watersheds on both shores.

Physiographic variables were summarized per basin; they include mean watershed slope, drainage density, and land cover and use. Land cover and use (forest, wetland, agricultural and urban relative areas) variables were obtained 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.

Table 1. Rivers analyzed.

Rivers	Code	Drainage Area (Km ²)	Latitude (N)	Longitude (W)	Agricultural Area (%)
Southeastern Hydroclimatic Region (South Shore)					
Chateaugay	SE1	2492	45°19'49"	73°45'44"	41.9
Eaton	SE2	646	45°28'05"	71°39'18"	10.7
Nicolet SW	SE3	562	45°47'30"	71°58'05"	26.3
Etchemin	SE4	1152	46°39'25"	71°39'18"	25.5
Beaurivage	SE5	708	46°39'25"	71°17'20"	34.7
Du Sud	SE6	821	46°49'22"	70°45'22"	10.4
Eastern Hydroclimatic Region (South Shore)					
Ouelle	E1	796	47°22'52"	67°57'14"	2.8
Du Loup	E2	1042	47°36'43"	69°38'41"	10.2
Trois-Pistoles	E3	930	48°05'21"	69°11'43"	16.5
Rimouski	E4	1615	48°24'46"	68°33'18"	8.8
Matane	E5	1665	48°46'25"	67°32'25"	8.9
Blanche	E6	223	48°47'20"	67°41'51"	30.2
Southernwest Hydroclimatic Region (North Shore)					
Petite Nation	SW1	1331	45°47'27"	75°05'22"	0.7
Du Nord	SW2	1163	45°31'08"	74°20'11"	0.4
L'Assomption	SW3	1286	46°02'45"	73°26'19"	8.6
Matawin	SW4	1387	46°40'50"	73°55'00"	0
Vermillon	SW5	2662	47°39'20"	72°57'44"	0

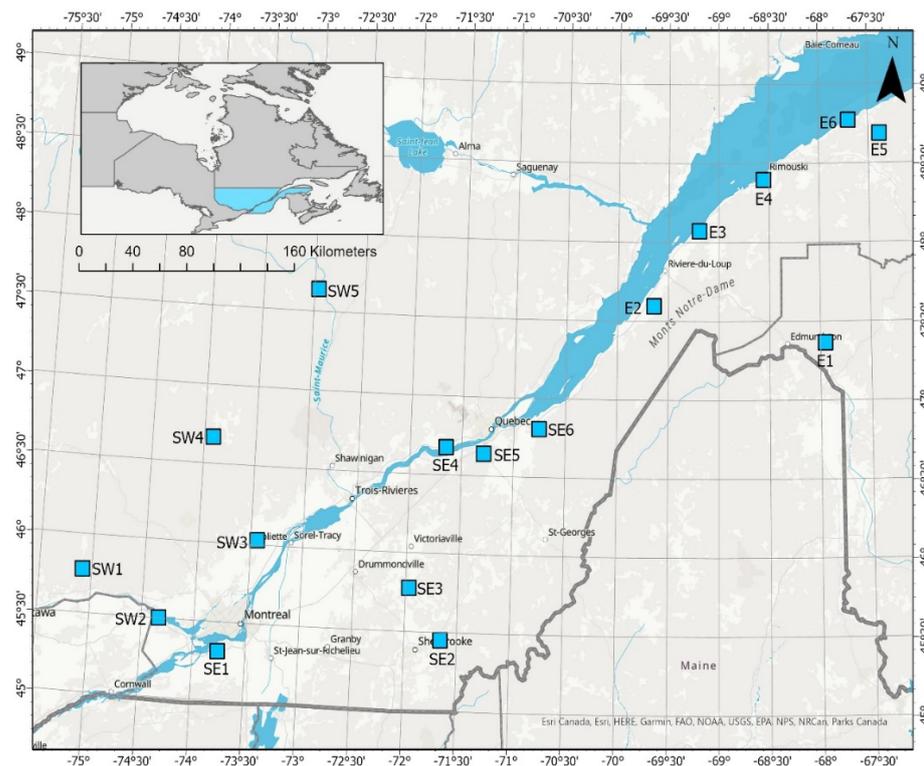


Figure 1. Location of river stations. SW = Southwestern hydroclimatic Region; SE = Southeastern Hydroclimatic Region; E = Eastern Hydroclimatic Region; the circles represent major towns.

As for watershed morphology, two key variables were measured: the mean slope of the watershed, and drainage density. These two variables were calculated using 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). These two variables significantly influence the runoff and infiltration processes that impact minimum flows. Mean slope values of the watersheds analyzed varied between 0.46 and 3.85 m/km on the south shore, and 2.2 and 3.75 m/km on the north shore. Drainage density values varied between 0.33 and 0.53 km/km² on the south shore, and 0.37 and 0.49 km/km² on the north shore. Other morphological variables, such as drainage length, were strongly correlated with the surface area and/or mean slope of the watersheds.

With respect to land use, the proportion of agricultural area was greater than 10% on the south shore south of 47° N, and below 10% on the north shore (Table 1). However, the proportion of wetland surface area was less than 5% on the south shore, but greater than 8% on the north shore (except for the watershed of the L'Assomption River, which was the most agricultural). Overall, the south shore had a smaller forest area than the north shore. There was a significant difference between the two shores, south of 47° N. Finally, in all of the watersheds analyzed, the amount of urbanized surface area was less than 1%, with the exception of the watersheds of the Châteauguay River (43%), on the south shore, and L'Assomption River (5%), on the north shore. There was little water extraction from aquifers for irrigation or industry, even in the highly agricultural watersheds on the south shore.

Flow data were taken from the website of the Ministry of Environment and the Fight against Climate Change's Water expertise Centre of Quebec (https://www.cehq.gouv.qc.ca/index_en.asp, accessed on 20 February 2020). Data on physiographic variables were also kindly provided to us by the Centre. They include mean watershed slope and drainage density, as well as percentages of forest, wetland, agricultural and urbanized areas. Climate data was taken from the Environment Canada website (https://climat.meteo.gc.ca/climate_normals/index_f.html, accessed on 18 June 2021). These are the climatic norms,

measured at a station in each watershed during the period of 1971–2000. These climatic norms were compared to those of 1941–1970 and 1981–2010, when values were available. In the case of a difference between the three, we calculated their means. The climatic variables analyzed were seasonal precipitation and temperature.

For each of the 17 rivers under study, we created two seasonal hydrological series: spring (April to June) and fall (October to December) daily minimum extreme flows. This involved measuring the lowest flow values of one (1) day per season, each year between 1930 and 2019. We calculated the arithmetic mean (Mean) for each hydrological series and determined the maximum (Max) and minimum (Min) values.

2.2. Statistical Analysis of the Hydrological Series

To analyze the spatial variability of daily minimum extreme flows, we compared the arithmetic means of the hydrological series using parametric and non-parametric tests (ANOVA and Kruskal–Wallis respectively). The arithmetic means, as well as maximum and minimum flow values, were then correlated with the watersheds' physiographic and climatic factors. To ensure that watershed size would have no influence on the results, we converted these three flow variables into specific flows (L/s/km²).

We used two types of tests to analyze the temporal variability of daily minimum extreme flows. The first was to analyze the long-term trend in the hydrological series using six different statistical tests based on the Mann–Kendall (MK) test. The purpose of some of these tests was to eliminate the effects of short-term persistence (STP) by removing the influence of autocorrelation (MMK-PW and TFPW), or correcting the variance introduced by autocorrelation (MMKY and MMKH). Other tests were designed to eliminate the effects of long-term persistence (LTP). Only one test (MMK-LTP) was used for this purpose. To avoid weighing down the text with formulas, all tests have been summarized in Table 2 and supplemented with references containing detailed descriptions. For more information on their mathematical descriptions and application in hydroclimatology, we direct readers to this section.

Table 2. Summary of Mann–Kendall tests applied to the hydrological series under analysis.

Name of the Test	Acronym	Purpose of the Test	References
Elimination of STP (Short Term Persistence) Effects			
Original Mann–Kendall	MK	Detect the long-term trend (does not take STP or LTP into account).	[43]
Prewhitening method	MMK-PW	Eliminate the influence of autocorrelation by prewhitening data.	[44]
Trend Free Prewhitening Method	TFPW	Eliminate autocorrelation by prewhitening data.	[45]
Modified Mann–Kendall Test1	MMKY	Eliminate autocorrelation by variance correction.	[46]
Modified Mann–Kendall Test2	MMKH	Eliminate autocorrelation by variance correction.	[47]
Elimination of LTP (Long Term persistence) Effects			
Long Term Persistence MK	LTP	Eliminate LTP effects.	[48]

In the final stage of the statistical analysis, we conducted three more tests to detect shifts in the mean of the hydrological series: the Pettitt (PT) test, the modified Pettitt test (TPM), and the Lombard test (LT). While the first two tests exclusively detect abrupt shifts, the final test can detect both abrupt and gradual (smooth) shifts. Unlike the original Pettitt

(PT) test [49], the modified Pettitt test (TPM) and the Lombard test eliminate the influence of autocorrelation on the detection of shift in mean [50–52].

3. Results

3.1. Comparison of Spatial Variability of Daily Minimum Extreme Flows in Spring and Fall

Spring and fall daily minimum extreme flow values are presented in Table 3 and Figure 2. In spring, average flow values were higher on the north shore than on the south shore. The difference between the two shores was most significant south of 47° N, between the rivers of the southwestern hydroclimatic region (>7 L/s/km²) and those of the southeastern hydroclimatic region (<6 L/s/km²). The same applies to minimum values. This difference between the flow values of the two hydroclimatic regions of the two shores was also observed in the fall, even for maximum values.

Table 3. Comparison of seasonal minimum extreme daily flows (L/s/km²) in spring and fall between 1930 and 2019.

Rivers	Spring			Fall		
	Max	Mean	Min	Max	Mean	Min
Southeastern Hydroclimatic Region						
Chateaugay	9.2	3.3 (1.61)	0.56	9.3	2.6 (1.74)	0.28
Eaton	7.0	3.1 (1.30)	0.88	8.1	3.2 (1.62)	0.78
Nicolet SW	10.8	2.8 (1.95)	0.25	8.3	3.4 (1.98)	0.53
Etchemin	14.1	3.6 (2.67)	0.88	18.1	4.5 (2.30)	1.00
Beaurivage	47.3	3.6 (4.98)	0.56	9.5	3.3 (1.94)	0.16
Du Sud	13.5	5.5 (2.52)	0.30	13.0	4.6 (2.08)	0.12
Eastern Hydroclimatic Region						
Ouelle	16.1	3.9 (2.38)	0.54	7.3	2.9 (1.74)	0.35
Du Loup	13.1	5.8 (2.42)	0.71	11.7	4.3 (2.43)	0.27
Trois-Pistoles	11.4	4.1 (2.14)	1.4	3.2	1.3 (0.59)	0.37
Rimouski	25.4	6.3 (3.95)	1.7	15.9	4.7 (2.76)	0.70
Matane	21.4	8.0 (4.22)	1.73	15.9	4.7 (2.77)	0.70
Blanche	21.1	5.2 (3.43)	2.0	18.3	4.1 (3.75)	0.38
Southernwest Hydroclimatic Region						
Petite Nation	24.3	9.8 (4.01)	3.6	20.9	4.8 (3.26)	1.2
Du Nord	16.5	8.1 (2.79)	3.9	15.2	7.0 (2.56)	2.7
L'Assomption	14.3	7.9 (2.83)	2.5	12.9	5.4 (2.80)	0.72
Matawin	27.2	8.9 (4.33)	2.7	14.2	6.6 (2.45)	2.0
Vermillon	15.6	7.6 (3.09)	2.2	14.4	6.5 (2.64)	1.7

(1.61) = standard deviation.

Based on the analysis of correlation coefficients, calculated between these values and the physiographic and climatic variables, the mean and minimum values of the daily minimum extreme flows were significantly better correlated with main slope (positive correlation) and agricultural areas (negative correlation) during the two seasons (Table 4). There were also positively correlated with wetland areas, in spring only. In fall, this factor was correlated only with the minimum value of flows. Forest areas were positively correlated with the mean value of flows in spring. Maximum values were not significantly correlated with any physiographic factor during the two seasons. Finally, no climatic factor was significantly correlated with daily minimum extreme flows during the two seasons.

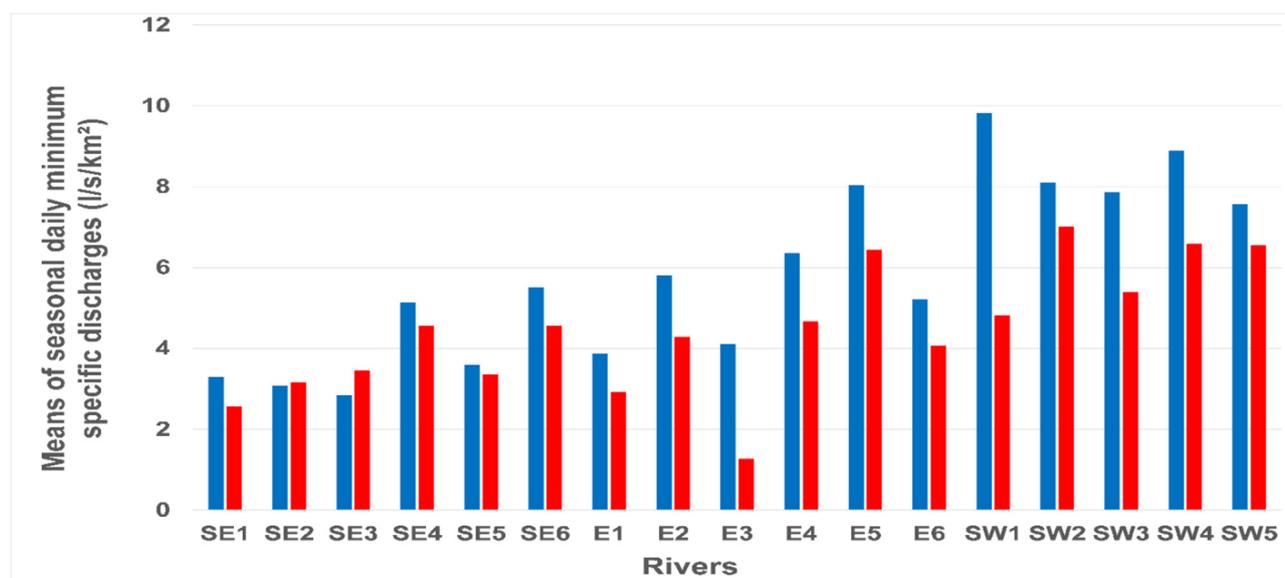


Figure 2. Comparison of average daily minimum extreme flow values in spring (blue bars) and fall (red bars) between 1930 and 2019.

Table 4. Correlation coefficients calculated between physio-climatic variables and magnitude (L/s/km²) of daily minimum extreme flows in spring and fall between 1930 and 2019.

Variables	Spring			Fall		
	Max	Mean	Min	Max	Mean	Min
Physiographic Variables						
Drainage density (km/km ²)	0.472	−0.119	−0.147	−0.014	−0.127	−0.216
Mean slope (m/km)	−0.030	0.671 **	0.550 **	0.469	0.669 **	0.549 **
Forests surface area (%)	0.002	0.484 **	0.388	0.150	0.463	0.381
Agricultural surface area (%)	0.081	−0.687 **	−0.648 **	−0.231	−0.580 **	−0.572 **
Wetlands surface area (%)	0.266	0.666 **	0.789 **	0.447	0.426	0.528 **
Climatic Variables						
Seasonal (spring/fall) total rainfall (mm)	−0.082	0.161	−0.082	0.094	−0.146	−0.088
Seasonal (spring/fall) total snowfall (cm)	0.253	−0.271	−0.407	−0.052	−0.399	−0.370
Seasonal (spring/fall) total precipitation (mm)	0.015	0.071	0.138	0.007	−0.399	−0.351
Winter-spring/ summer-fall total rainfall (mm)	−0.098	0.099	0.254	0.109	−0.087	−0.160
Winter-spring/summer-fall snowfall (cm)	0.058	−0.139	−0.282	−0.052	−0.399	−0.369
Winter-spring/summer-fall total precipitation (mm)	0.001	−0.018	−0.039	0.052	−0.284	−0.321
Seasonal (Winter/Spring) daily mean maximum temperature (°C)	−0.400	0.122	0.274	−0.238	−0.118	−0.003
Winter-Spring/Summer-Fall daily mean maximum temperature (°C)	−0.423	0.056	0.252	−0.084	0.088	0.121

** = significant values over the 5% threshold.

3.2. Comparison of Temporal Variability (Long-Term Trend) of Daily Extreme Flows in Spring and Fall

The results of six trend analysis tests are presented in Table 5 (spring) and Table 6 (fall). Except for the MMKY test, the other five tests yielded consistent results in spring. In total, a statistically significant long-term trend in daily extreme minimum flows was only observed in six rivers (35% of the rivers under analysis): five on the south shore (three to the south and two to the north of 47° N) and only one (L'Assomption) on the north shore, in spring. This trend was also observed in fall. Once again, except for the MMKY, a significant long-term trend in daily minimum extreme flows was observed in eight series: seven on the south shore and only one on the north shore. Unlike in spring, the trend was observed in almost all rivers (four out of six) south of 47° N. While long-term trends tended to be negative (most Z values were negative) on both shores in spring, except for south-shore rivers located south of 47° N, they tended to become positive in fall, except for south-shore rivers located north of 47° N (Eastern hydroclimatic region). As such, daily minimum extreme flows tended to increase in the southeastern hydroclimatic region in both spring and fall.

Table 5. Results of the various Mann–Kendall tests applied to daily minimum flow series in spring between 1930 and 2019.

Rivers	MK		MMK-PW		TFPW		MMKY		MMKH		LTP	
	Z	p-Value	Z	p-Value	Z	p-Value	Z	p-Value	Z	p-Value	Z	p-Value
Southeastern Hydroclimatic Region												
Chateaugay	1.115	0.265	1.393	0.164	1.279	0.201	2.621 **	0.009	1.102	0.271	1.190	0.234
Eaton	−0.317	0.751	−0.594	0.553	−0.565	0.572	−0.966	0.334	−0.351	0.726	−0.441	0.667
Nicolet SW	2.266	0.023	1.488	0.116	1.386	0.666	2.884 **	0.004	1.708 **	0.088	1.700 *	0.089
Etchemin	1.460	0.144	1.488	0.137	1.669	0.095	2.791 **	0.005	1.364	0.172	1.110	0.267
Beaurivage	5.309	0.000	5.142	0.000	5.589	0.000	9.559 **	0.000	4.723 **	0.000	4.737 **	0.000
Du Sud	0.220	0.826	0.620	0.534	0.641	0.521	0.502	0.615	0.179	0.858	0.183	0.855
Eastern Hydroclimatic Region												
Ouelle	−4.392 **	0.000	−3.81 **	0.000	−4.4 **	0.000	−11.9 **	0.000	−4.15 **	0.000	−4.32 **	0.000
Du Loup	0.540	0.589	1.024	0.306	1.152	0.249	0.992	0.321	0.523	0.601	0.284	0.777
Trois-Pistoles	−2.18 **	0.029	−1.92 *	0.055	−2.0 **	0.048	−3.74 **	0.000	−2.31 **	0.021	−2.10 **	0.037
Rimouski	−1.056	0.291	−1.123	0.261	−1.194	0.232	−1.319	0.187	−1.050	0.294	−1.130	0.262
Matane	−2.27 **	0.023	−2.69 **	0.007	−2.7 **	0.006	−3.84 **	0.000	−2.46 **	0.014	−2.92 **	0.004
Blanche	−0.384	0.701	−0.049	0.961	−0.118	0.906	−0.596	0.551	−0.450	0.653	−0.219	0.830
Southwestern Hydroclimatic Region												
Petite Nation	1.063	0.288	1.414	0.157	1.265	0.206	2.401	0.016	1.063	0.288	1.257	0.209
Du Nord	−0.393	0.694	−0.458	0.647	−0.407	0.684	−0.876	0.381	−0.761	0.447	−0.612	0.548
L'Assomption	−1.506	0.132	−1.449	0.147	−1.286	0.198	−5.57 **	0.000	−1.726 *	0.084	−2.97 **	0.003
Matawin	−1.506	0.132	−0.157	0.876	−0.157	0.876	−0.231	0.817	−0.121	0.904	−0.091	0.931
Vermillon	0.821	0.417	1.258	0.208	1.045	0.296	3.513	0.000	0.920	0.358	1.062	0.288

** = significant values over the 5% threshold are shown in red/blue bold; * = significant values over the 10% threshold are shown in red/blue bold. Blue = negative trends; red = positive trends.

Table 6. Results of the various Mann–Kendall tests applied to daily minimum flow series in fall between 1930 and 2019.

Rivers	MK		MMK-PW		TFPW		MMKY		MMKH		LTP	
	Z	p-Value	Z	p-Value	Z	p-Value	Z	p-Value	Z	p-Value	Z	p-Value
Southeastern Hydroclimatic Region												
Chateaugay	1.362	0.173	0.173	3.399	3.694 **	0.000	8.468 **	0.000	3.831 **	0.000	2.947 **	0.003
Eaton	1.100	0.217	0.932	0.333	1.067	0.286	1.968 **	0.049	1.100	0.271	0.722	0.470
Nicolet SW	3.275 **	0.001	2.671 **	0.008	3.254 **	0.001	5.888 **	0.000	3.744**	0.000	2.085 **	0.037
Etchemin	2.754 **	0.006	2.112 **	0.035	2.676 **	0.007	4.545 **	0.000	1.992**	0.046	1.225	0.221
Beaurivage	3.820 **	0.000	2.662 **	0.008	3.600 **	0.000	6.502 **	0.000	3.574**	0.000	1.948 *	0.051
Du Sud	1.99 **	0.044	1.063	0.288	1.395	0.163	2.232 **	0.026	0.998	0.668	0.668	0.504
Eastern Hydroclimatic Region												
Ouelle	−0.472	0.637	−0.308	0.758	−0.359	0.719	−0.807	0.419	−0.454	0.650	−0.244	0.810
Du Loup	−0.991	0.322	−0.836	0.403	−0.799	0.424	−2.036 **	0.042	−0.991	0.318	−0.726	0.471
Trois-Pistoles	−2.141 **	0.032	−1.921 *	0.055	−1.957 *	0.050	−4.26 **	0.000	−2.14 **	0.032	−1.618	0.107
Rimouski	−0.493	0.622	−0.256	0.798	−0.314	0.754	−0.899	0.369	−0.505	0.614	−0.293	0.773
Matane	−2.265 **	0.024	−1.770 *	0.077	−2.05 **	0.040	−6.46 **	0.000	−2.27 **	0.024	−1.687 *	0.093
Blanche	0.752	0.452	0.537	0.591	0.583	0.560	1.504	0.133	0.752	0.452	0.498	0.620
Southwestern Hydroclimatic Region												
Petite Nation	1.362	0.173	1.503	0.133	1.532	0.125	2.995 **	0.003	1.046	0.163	1.531	0.126
Du Nord	0.872	0.383	0.968	0.333	0.792	0.428	2.881 **	0.004	1.156	0.248	1.860 *	0.063
L'Assomption	0.911	0.362	0.918	0.358	0.782	0.434	2.455 **	0.014	0.869	0.385	1.085	0.278
Matawin	0.358	0.720	0.247	0.805	0.194	0.847	1.022	0.307	0.444	0.657	0.496	0.620
Vermillon	0.092	0.927	0.256	0.798	0.249	0.804	0.200	0.841	0.079	0.930	0.094	0.925

** = significant values over the 5% threshold are shown in red/blue bold; * = significant values over the 10% threshold are shown in red/blue bold. Blue = negative trends; red = positive trends.

These long-term trends were partially confirmed by the three tests to detect shifts in means, the results of which were nearly consistent. In spring, these three tests detected breaks in the mean of flow of four rivers, three of which were located north of 47° N. However, the dates of these shifts were not synchronous, occurring in different decades (Table 7). In fall, breaks in mean were detected in seven rivers, five of which were located south of 47° N (Table 8). Surprisingly, these breaks in mean were nearly synchronous, and occurred during the 1960s (Figure 3) in these five rivers, which clearly indicates that their consistency is regional. In the two rivers north of this parallel, these shifts occurred later.

In the 1980s and 1990s, none of the three tests detected shifts in the mean of daily minimum flows on the north shore in either season, which suggests that there were also no shifts in the mean of daily minimum extreme flows in the rivers on the north shore in either season.

Rivers in the southeastern hydroclimatic region were further analyzed in the fall to determine if a shift in mean occurred subsequent to the break in the 1960s. The MK tests, and the tests to detect changes in shifts in mean, were repeated, and revealed no other statistically significant changes in either the long-term trend or the means of the hydrological series after the 1960s. Consequently, the moisture of the 2010s did not cause a significant increase in daily minimum extreme flows during the two transitional seasons in southern Quebec. However, Figure 3 shows that, even in the most agricultural south

shore watersheds south of 47° N, minimum flows decreased over the course of the decade, despite a substantial increase in flows in the 1960s.

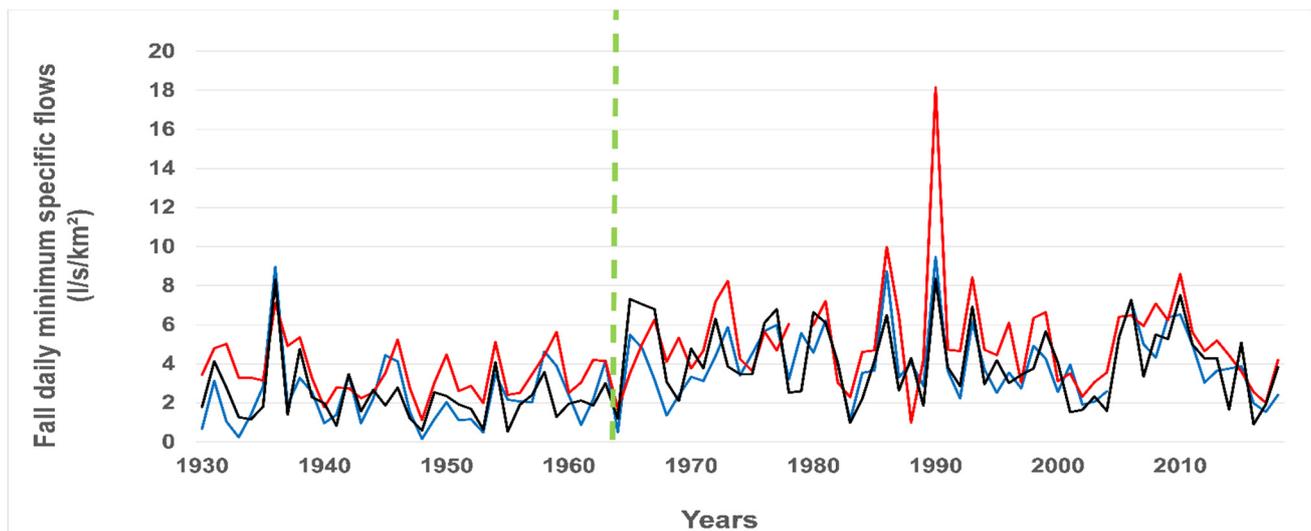


Figure 3. Example of the interannual variability in the daily minimum extreme flows in fall of three rivers in the southeast hydroclimatic region on the south shore. The dashed vertical green line indicates the year of shift in mean of the hydrological series. Beaurivage River (blue curve); Etchemin River (red curve); Nicolet SW River (black curve). The shift in mean of flows occurred almost the same year for all three rivers.

Table 7. Results of the various Pettitt and Lombard tests applied to daily minimum flow series in spring between 1930 and 2019.

	Pettitt Test			Modified Pettitt Test			Lombard Test	
	K	p-Value	T	K	p-Value	T	S _n	T1–T2
Southeastern Hydroclimatic Region								
Chateaugay	545	0.178	-	580	0.129	-	0.017	-
Eaton	282	1.001	-	317	0.834	-	0.003	-
Nicolet SW	492	0.247	-	546	0.177	-	0.021	-
Etchemin	647	0.066	-	591	0.117	-	0.029	-
Beaurivage	1298 **	0.000	1968	1219 **	0.000	1968	0.258 **	1967–68
Du Sud	376	0.633	-	376	0.633	-	0.002	-
Eastern Hydroclimatic Region								
Ouelle	984 **	0.001	1986	889 **	0.003	1986	0.176 **	1930–99
Du Loup	530	0.203	-	536	0.193	-	0.006	-
Trois-Pistoles	593	0.114	-	606	0.101	-	0.0489 **	1951–52
Rimouski	363	0.684	-	341	0.776	-	0.010	-
Matane	765 **	0.017	1963	856 **	0.005	1963	0.061 **	1961–62
Blanche	389	0.488	-	297	0.879	-	0.003	-

Table 7. Cont.

	Pettitt Test			Modified Pettitt Test			Lombard Test	
	K	p-Value	T	K	p-Value	T	S _n	T1–T2
Southwestern Hydroclimatic Region								
Petite Nation	525	0.212	-	608	0.099	-	0.014	-
Du Nord	269	1.088	-	238	1.242	-	0.005	-
L'Assomption	378	0.625	-	415	0.492	-	0.018	-
Matawin	482	0.247	-	502	0.207	-	0.002	-
Vermillon	387	0.591	-	497	0.268	-	0.008	-

** = significant values at the 5% threshold are shown in red bold; T = year of the shift mean; T1–T2 = year before (T1) and after (T2) of shift mean; K = calculated values of Pettitt test; S_n = calculated values of Lombard test. Blue = drop in the means after the shift; Red bold = Rise in the means after the shift.

4. Discussion

Analysis of the spatial variability of minimum extreme flows in spring and fall revealed a clear difference between the rivers on the south shore of the St. Lawrence River (south of 47° N) and those on the north shore. The means of these flows tended to be greater on the north shore (>5 L/s/km²) than on the south shore (<5 L/s/km²). The correlation analysis between these flows and physiographic factors revealed that two main factors influence the spatial variability of flows: agricultural areas and mean slope, which, respectively, were negatively and positively correlated. In the spring, these flows are also influenced by wetland areas (positive correlation). The south shore watersheds, located south of 47° N, tend to have relatively large agricultural areas (>20%), but very small wetlands (<4%). Conversely, the watersheds on the north shore have larger wetlands (>8%) but very small agricultural areas (<5%). The impacts of land use on river flows are well documented in the scientific literature, even in Canada [53,54]. With respect to agriculture, previous research in Quebec has shown that agricultural land use reduces minimum flows due to soil sealing, which limits infiltration into aquifers, the main source of streamflow during low-water periods in winter, summer, and fall [55–58].

Table 8. Results of the two Pettitt and Lombard tests applied to the daily minimum flow series in fall between 1930 and 2019.

	Pettitt Test			Modified Pettitt Test			Lombard Test	
	K	p-Value	T	K	p-Value	T	S _n	T1–T2
Southeastern Hydroclimatic Region								
Chateaugay	1023 **	0.000	1964	930 **	0.001	1962	0.156 **	1961–62
Eaton	572	0.105	-	510	0.192	-	0.010	-
Nicolet SW	1137 **	0.000	1965	948 **	0.001	1964	0.107 **	1963–64
Etchemin	966 **	0.001	1965	784 **	0.009	1965	0.075 **	1964–65
Beaurivage	1114 **	0.000	1964	892 **	0.002	1964	0.121 **	1963–64
Du Sud	814 **	0.044	1970	752 **	0.011	1968	0.060 **	1966–68
Eastern Hydroclimatic Region								
Ouelle	431	0.397	-	373	0.596	-	0.003	-
Du Loup	456	0.327	-	430	0.400	-	0.013	-
Trois-Pistoles	656 *	0.080	1988	660 *	0.051	1988	0.049 **	1992–93
Rimouski	502	0.240	-	488	0.270	-	0.004	-
Matane	619 *	0.080	1976	556 *	0.148	-	0.055 **	1982–83
Blanche	308	0.800	-	302	0.829	-	0.004	-

Table 8. Cont.

	Pettitt Test			Modified Pettitt Test			Lombard Test	
	K	p-Value	T	K	p-Value	T	Sn	T1–T2
Southwestern Hydroclimatic Region								
Petite Nation	425	0.415	-	469	0.295	-	0.010	-
Du Nord	298	0.923	-	385	0.550	-	0.004	-
L'Assomption	442	0.386	-	526	0.195	-	0.009	-
Matawin	314	0.798	-	409	0.420	-	0.002	-
Vermillon	376	0.632	-	432	0.416	-	0.002	-

** (red/blue bold) = significant values over the 5% threshold; * (red bold/blue bold) = significant value over the 10% threshold. T = year of the shift in mean; T1–T2 = year before (T1) and after (T2) the shift in mean; K = calculated values of Pettitt test; Sn = calculated values of Lombard test. Blue = drop in the means after the shift; red = rise in the means after the shift.

This soil sealing also accelerates spring recession in agricultural watersheds [51], which explains the low minimum extreme flows observed in spring and fall in the most agricultural watersheds on the south shore. As for the impacts of wetlands on these minimum extreme flows, there is still no research on the topic in Quebec, and very little internationally. In their summary on the hydrological impacts of wetlands, Bullock and Acreman [52] highlighted the complexity of the relationship between wetlands, aquifers, and minimum flows. This complexity led to divergent results: some studies showed that minimum flows decreased in wetlands, while others showed an increase. In Quebec, it is quite clear that wetlands cause an increase in extreme minimum flows in spring. In this season, minimum flows are mainly associated with recession caused by snowmelt. Thus, wetlands slow this recession, as minimum flows are maintained at higher values than those observed in agricultural watersheds on the south shore (the “sponge effect”), where discharge from snowmelt and/or rainwater is much faster. A recent study showed that spring freshets caused by snowmelt don't last as long in agricultural watersheds on the south shore than in those on the north shore, as runoff is more significant and faster in the first watersheds (Assani, 2021; unpublished work). In fall, minimum flows are mainly influenced by groundwater. In this season, precipitation mainly falls as rain. But, unlike freshets and rain-induced flood flows, the “sponge effect” of wetlands on the daily minimum extreme flows (July to November) acts tacitly, and results in a slower decrease in flows during low-flows events, probably due to the poor connectivity between these wetlands and aquifers [59]. This may partly explain the significant positive correlation observed between wetlands and the lowest value of the daily minimum extreme flows in fall.

In addition to agricultural areas and wetlands, there was a significant positive correlation between the mean slope and daily minimum extreme flows in both spring and fall. This correlation is explained by the fact that this physiographic factor, in the very agricultural south shore watersheds, is generally less steep than on the north shore, because a large share of the south shore watersheds' surface area lies in the St. Lawrence Lowlands, a geological formation with a relatively flat topography. By contrast, nearly all the north shore watersheds are located on the Canadian Shield, which has a relatively irregular topography (consisting of hills and valleys). Thus, this correlation between these two variables does not express a direct causal link, but a covariation due to agricultural areas of the watersheds.

Analysis of the temporal variability of daily minimum extreme flows also revealed a marked difference between south-shore and north-shore rivers south of 47° N, particularly in fall. In fact, at that time of year, south-shore rivers located south of this parallel tended to see a significant increase in daily minimum extreme flows, while no significant changes were observed in the north-shore rivers. This increase in flows happened in near-perfect synchronicity for most rivers during the 1960s. This increase can be explained by two factors:

1. The modernization of agricultural practices in southern Quebec since 1950, which led to a significant reduction of cultivated land. Cultivated land was left uncropped or reforested, the amount of which nearly tripled in area between 1950 and 1981 [60]. From a hydrological perspective, this type of land use change would promote the infiltration of water into the soil, increasing fall minimum extreme flows supplied primarily by groundwater. In addition to reduction in the cultivated area, the type of the crop has also changed. As a result, forage crop acreage was reduced by over half to make room for oats, corn, and soybeans, particularly between 1950 and 2011 [60]. This change in crop type could change the conditions for runoff and infiltration of snowmelt and rainwater to varying degrees. The increase in minimum flows resulting from changes in agricultural practices has been observed in many watersheds in agricultural regions of the United States [27].
2. Increased rainfall in summer and fall in the northeastern part of North America. Several studies have noted a significant increase in rainfall, particularly in fall, in the northeastern part of North America north of 44° N [13,17,22,25], and on the south shore of Quebec south of 47° N [61,62]. This increase occurred during the 1960s and early 1970s.

The reduction of cultivated land in favor of fallow land, in addition to the increase in precipitation, may therefore explain the increase in daily minimum extreme flows observed in fall in the southeastern hydroclimatic region (south of 47° N)—the most agricultural region in Quebec. This increase was also observed in rivers in the northeastern part of the United States [29,32].

The predominant fact to emerge from our analysis of temporal variability in spring was the tendency of daily minimum extreme flows to decrease on the south shore north of 47° N (Eastern hydroclimatic region), in contrast with the region just south of this parallel. This decrease may be linked to snowfall in winter [28,36], although this decrease in snow cover was more extensive on the north shore than on the south shore [36]. However, no significant changes in the means of flows were observed on the north shore. It follows that the decrease in amount of snow does not seem to affect the spring daily minimum extreme flows. The impacts of this decrease in the amount of snow would probably be mitigated by wetlands in the region. This hypothesis deserves to be explored.

5. Conclusions

Analysis of the spatial and temporal variability of daily minimum extreme flows during the transitional seasons (spring and fall) between 1930 and 2019 revealed a marked difference between rivers on the north and south shores of the St. Lawrence River south of 47° N. In terms of spatial variability, rivers on the south shore have lower daily minimum extreme flows than those on the north shore. This difference was mainly due to agricultural areas. South shore watersheds have a larger agricultural area than those on the north shore. Agriculture reduces water infiltration in fall and accelerates runoff in spring.

With respect to temporal variability, the same difference was observed between the north and south shores in fall. Daily minimum extreme flows have increased significantly in south-shore rivers since the 1960s. This increase is due to a reduction in cultivated land following the modernization of agricultural practices in Quebec since the 1960, as well as an increase in rainfall in the region since the 1970s. Decreased snowfall in Quebec does not yet appear to significantly affect the long-term trend of daily minimum extreme flows in spring, despite the observation of a downward trend north of 47° N on both the south and north shores. In fall, the overall increase in temperature in summer and early fall did not lead to a decrease in fall daily minimum extreme flows, as the increase in rainfall offsets the increase in evapotranspiration resulting from this summer–fall warming.

According to climate models, warmer temperatures in Quebec will result in a significant decrease in the amount of snow in spring, which will in turn reduce runoff and infiltration. This will result in a significant decrease in the magnitude of spring freshets and low-water levels. In fall, these climate models predict a significant increase in temperature

that will be accompanied by more intense rainfall. This scenario will result in a continuous increase in low-water flows. There will therefore be a continuous decrease in low-water flows in spring but a continuous increase in low-water flows in fall. It is this trend that will be followed in the future.

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