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Extreme Hydrological Drought in Southern Quebec (Canada): Natural and Anthropogenic Factors Interactions on its Spatio-Temporal Variability

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Abstract

Despite the relatively humid character of their climate, many cold temperate regions face increasingly extreme hydrological droughts that turn rivers from steady to intermittent. The spatio-temporal variability of these droughts depends on the interaction of natural and anthropogenic factors. The objective of this study is to determine these factors in southern Quebec (Canada). The annual daily minimum flows (1-day) of 17 rivers, grouped into three homogeneous hydroclimatic regions, were analyzed during the period 1930-2019. With regard to spatial variability, the comparison of the flow averages by means of ANOVA and Kruskal-Wallis tests revealed that the flows of rivers of the north shore (southwestern hydroclimatic region) are on average twice as higher than those of the southern shore (Southeastern and Eastern hydroclimatic regions). Linear correlation analysis revealed that these flows are negatively correlated with agricultural areas and snowfall but positively with wetlands areas and watershed mean slopes. As for temporal variability, the southeastern region river flows, the most agricultural, have increased significantly over time due to the significant decrease in agricultural areas and the increase in the amount of rainfall. In the eastern hydroclimatic region, flows have generally decreased due to the significant decrease in the autumn snowfall. Finally, in the southwestern hydroclimatic region, the less agricultural, overall, no significant change in flows occurred, probably due to the low amount of fall snowfall, the decrease in which was offset by the increase in rainfall. This study reveals that the eastern hydroclimatic region is the most vulnerable to the decrease in the amount of snow, which is the main source of low flows in Quebec. Finally, few significant correlations were observed between climatic indices and flows.

Keywords: Annual daily minimum extreme flows; Agriculture; Wetlands; Snowfall; Long-term trend; Climatic indices; Southern Quebec

Introduction

Climate change is increasingly reflected in the amplification of extreme hydrological events in particular. Thus, in 2022, most countries in Western Europe in particular have just been confronted with one of the worst episodes of hydrological drought rarely recorded on the continent [1]. This extreme drought has thus transformed the hydrological regimes of many streams and rivers. Despite the reputedly humid climatic character of Western Europe, many rivers have however seen their permanent hydrological regimes transformed into intermittent hydrological regimes due to the total drying up of their flows, even for some large rivers of the continent. This change in hydrological regime is also affecting many streams in many regions of the world, which are considered naturally humid. The North American continent is no exception to this trend (https://www.carbonbrief.org/climate-change-made-2022s-northern-hemisphere-droughts-at-least-20-times-more-likely/; https://www.bbc.com/news/62751110). This trend towards the occurrence of increasingly intense, long-lasting and frequent drought episodes will increase in the future decades, as predicted by numerous climate and hydrological models [2,3]. However, the extent of these changes from one watershed to another in the same hydroclimatic region will depend on the physiographic characteristics of the watersheds, the soil cover and human activities (agriculture, urbanization, dams and reservoirs, etc.) (e.g., [4-7]). It goes without saying that this amplification of drought will affect to varying degrees the functioning and ecological integrity of river ecosystems and all human activities that depend directly or indirectly on low flows.

In Quebec, the hydrological regimes of all streams larger than 100km^2 are characterized by a permanent flow throughout the year due to the humid nature of the region. However, due to the significant drop in the amount of snow (e.g., [8,9]), which is the main source of aquifer recharge that influences low flows (e.g., [10]), the risk of transformation of this permanent regime into an intermittent regime is becoming increasingly high.

Several studies have already been devoted to the analysis of minimum flows in Quebec. But all these studies were mainly limited to the analysis of these flows at seasonal scales [11-17]. As for the annual scale, a few pan-Canadian studies have already analyzed the spatial and temporal variability of minimum flows [18-22]. However, these studies only analyzed the flows of a few rivers in Quebec. These rivers do not make it possible to highlight the regional hydroclimatic differences that exist in Quebec on the one hand and the impacts of the physiographic characteristics of the watersheds as well as those of the land use and cover on this spatio-temporal variability of low flows. Moreover, none of these studies analyzed the impacts of the significant reduction in the amount of snow on the spatio-temporal variability of low flows across the province of Quebec. However, Assani et al. [23]) analyzed the natural factors of the spatial variability of annual daily minimum flows measured in many watersheds in Quebec. But this study did not include all natural factors or any anthropogenic factors. Finally, Assani et al. [24] analyzed the impacts of dam management methods on annual daily minimum flows.

To deepen these pan-Canadian studies and complete those already devoted to seasonal low flows in Quebec, our article aims to analyze the interactions between natural factors (climate, physiographic characteristics of watersheds, wetlands, forests) and anthropogenic factors (agriculture, urbanization, deforestation, afforestation) on the temporal variability of annual low flow (annual daily minimum flows). It is part of a research program that aims to determine the main natural and anthropogenic factors that influence the spatial and temporal variability of river flows in southern Quebec at annual, seasonal and daily scales. The originality of this study program lies in its global approach, which consists in analyzing the interaction of these different natural and anthropogenic factors on the spatio-temporal variability of flows, whereas almost all previous studies were limited to analyzing their influence separately respectively. Thus, it makes it possible to determine the factors that influence both the spatial and temporal variability of flows in the context of current global warming. The purpose of this research program is to subsequently integrate these factors into climate and hydrological models for a better prediction of flows in the future according to the different scenarios of greenhouse gas emissions.

Methodology

Selection and description of the watersheds

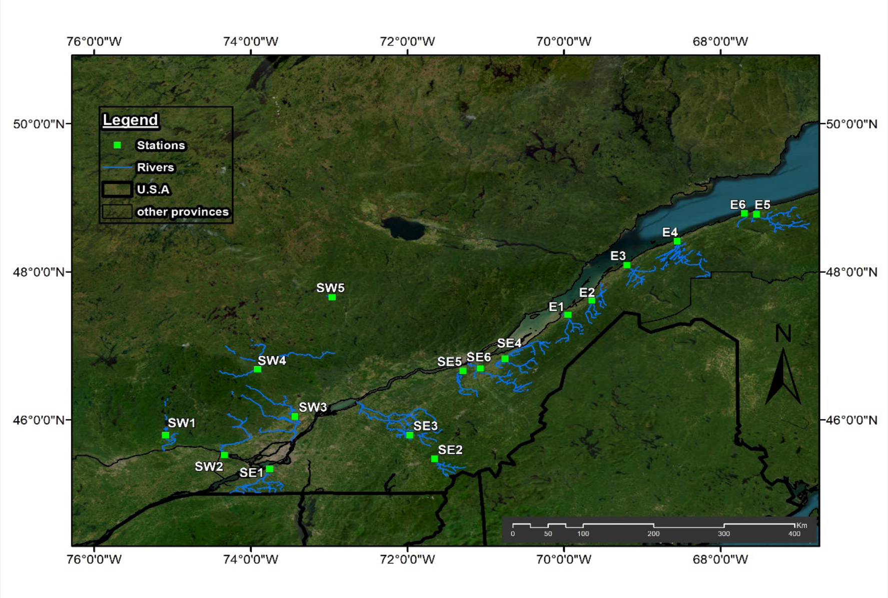

Figure 1: Locations of the rivers studied. SW = Southwestern Hydroclimatic Region, SE = Southeastern Hydroclimatic Region, E = Eastern Hydroclimatic Region.

The 17 rivers under study were selected based on the existence of flow data measurements spanning an 85-year period (1930–2019) and the limited impact of human activities on these flow measurements (Figure 1 & Table 1). These rivers belong to three predefined hydroclimatic regions in southern Quebec [12]: the southwestern region, located on the north shore and characterized by a continental temperate climate; the southeastern region, located on the south shore south of 47°N and characterized by a mixed temperate climate; and the eastern region, located on the south shore north of this parallel and characterized by a maritime (oceanic) temperate climate.

Table 1: Some characteristics of watershed analyzed.

Rivers	Code	ID	Drainage Area (Km^2)	Latitude (°N)	Longitude (°W)
Southwestern Hydroclimatic Region					
Petite Nation	SW1	40406	1331	45°47’27”	75°05’22”
Du Nord	SW2	40110	1163	45°31’08”	74°20’11”
L’Assomption	SW3	52219	1286	46°02’45”	73°26’19”
Matawin	SW4	50119	1387	46°40’50”	73°55’00’
Vermillon	SW5	50142	2662	47°39’20”	72°57’44”
Southeastern Hydroclimatic Region					
Châteaugay	SE1	30905	2492	45°19’49”	73°45’44”
Eaton	SE2	30234	646	45°28’05”	71°39’18”
Nicolet SW	SE3	30101	562	45°47’30”	71°58’05”
Beaurivage	SE4	23401	1152	46°39’25”	71°39’18”
Etchemin	SE5	23303	708	46°39’25”	71°17’20”
Du Sud	SE6	23106	821	46°49’22”	70°45’22”
Southeastern Hydroclimatic Region					
Ouelle	E1	22704	796	47°22’52”	67°57’14”
Du Loup	E2	22513	1042	47°36’43”	69°38’41”
Trois-Pistoles	E3	22301	930	48°05’21”	69°11’43”
Rimouski	E4	22003	1615	48°24’46”	68°33’18”
Matane	E5	21601	1655	48°46’25”	67°32’25”
Blanche	E6	21702	223	48°47’20”	67°41’51”

On the south shore, the rivers drain the Appalachians (an ancient fold mountain chain) and the St. Lawrence Lowlands, which has a relatively flat topography (Figure 1 & Table 1). These two geological formations consist mainly of sedimentary rocks. The rivers on the north shore flow primarily on the Canadian Shield, which consists mainly of metamorphic rocks. It is therefore less permeable than the two geological formations of the south shore. There is no data on the characteristics of aquifers that supply low flows throughout Quebec [25]. Therefore, information on the interaction between these aquifers and low flows is only available for a few of the watersheds analyzed in this study (e.g., [26-32]).

Data sources analyzed

Data on the physiographic characteristics of watersheds and land use patterns were provided by the Glaciolab laboratory at the Université du Québec à Trois-Rivières. The methods used to gather and analyze this data have already been described in detail, namely by [13]. The data comprised: average or mean slope (°), drainage density (km/km^2), agricultural area (%), forest area (%), and urbanized area (%). Wetland area (%) data were taken from [33]. These areas also include those of other types of water bodies such as lakes. Daily flow data for these 17 rivers were taken from the website of the Ministère d’Environnement et de Lutte contre les changements climatiques du Québec’s Centre d’expertise hydrique du Québec (https://www.cehq.gouv.qc.ca/index_en.asp, accessed on 2020-02-20). Annual and seasonal precipitations (rainfall and snowfall) and temperature normals data were taken from the Environment Canada website (https://climat.meteo.gc.ca/climate_normals/index_f.html, accessed on 2021-06-18). These consist of averages for 1941-1970, 1971-2000 and 1981-2010.

As for the climate indices data, they were extracted from the NOAA (National Oceanic and Atmospheric Administration) website (https://psl.noaa.gov/data/climateindices/list/., accessed on 2020-02-23). We selected 7 climatic indices whose influence on the temporal variability of minimum flows has already been demonstrated in Canada and Quebec (e.g., [12,18]). These seven climate indices used are as follows: Atlantic multi-decadal Oscillation (AMO), Arctic Oscillation (AO), Global Mean Land/Ocean Temperature (GMLOT), North Atlantic Oscillation (NAO), Oceanic Niño Index (Nino3.4), Oceanic Niño Index (ONI) and Pacific Decadal Oscillation (PDO). For each climatic index, three series were created: an annual series (average of 12 monthly values), a winter semi-annual series (average of six-monthly values from January to June) and a summer semi-annual series (average of six monthly values from July to December). These series were calculated over the period 1950-2019.

Statistical data analysis

Statistical analysis of spatial variability

The first step consisted of establishing the hydrological series of flows for each river. Each series comprised the lowest daily flow values measured annually from 1930-2019. These were the annual daily minimum flow series (1-day). Flow rates (expressed in m^3/s) were converted into specific flow rates (expressed in $l/s/km^2$), after which the mean and standard deviation of each series were calculated. This unit conversion eliminated the influence of watershed size on flow means, which allowed them to be compared regardless of the difference in watershed size. The choice of analyzing the annual daily minimum flows measured on a single day (Q1) rather than the average of the annual daily minimums flows calculated over 7 consecutive days (Q7), used in almost all previous work published on Quebec, is justified by the fact that the first flows (Q1) make it easy to differentiate between temporary flow regimes (zero values of Q1) and permanent flow regimes (non-zero values of Q1) insofar as this temporary character of the discharge may last less than 7 days.

In the second step, the means of these specific flow rates were compared using parametric (analysis of variance, ANOVA) and non-parametric (Kruskal-Wallis) tests. In the last step, the annual daily minimum specific flows were correlated to physiographic and climatic variables using linear and Spearman's rank correlation methods. These two methods lead to the same results. It is important to note that the relationship between minimum flows and the factors that spatially influence them spatially is not necessarily linear. However, the fact that the study is exclusively based on annual averages calculated over a very long period (>85 years) justifies the use of this linear method which seems the most appropriate.

Statistical analysis of the temporal variability of the data

This analysis was also applied in three stages. At the first stage, three types of tests were applied to analyze the temporal variability or stationarity of the hydrological series. The first, the original Mann-Kendall (MK) test, was applied to detect the long-term trend of hydrological series [34]. However, this test did not eliminate the short- (STP, autocorrelation) or long-term persistence effects (LTP) on the stationarity of the hydroclimatic series. To eliminate the effects of short-term persistence (autocorrelation), four modified Mann-Kendall tests were applied: prewhitening method (MMK) (e.g., [35]), trend-free prewhitening method (TFPW) [36], modified Mann-Kendall test 1 (MMKY) [37], and modified Mann-Kendall test 2 (MMKH) [38]. The first two tests were based on prewhitening data; the other two were intended to correct the variance in the presence of autocorrelation. The second type of test eliminated the effects of long-term persistence (LTP), otherwise referred to as the Hurst effect [39], on the long-term trend.

In the second stage, tests were applied to determine the years of the shift in means of the hydrological series. Three tests were used: the original Pettitt test [40], the modified Pettitt test [41], and the Lombard test [42,43]. The first two tests detected abrupt breaks in means, whereas the final test detected both abrupt and progressive breaks. The last two tests eliminate the effects of autocorrelation on these breaks in the means. Several authors have described these statistical tests analyzing the long-term trend in detail (e.g., [43,44]). To avoid needlessly weighing down the text with formulas, no further mathematical descriptions are provided here as they are covered extensively in the studies cited.

Finally, in the third step, the annual daily minimum flows were correlated with the annual and semi-annual means series of the 7 climatic indices using linear correlation analysis and multivariate analysis (canonical correlation and redundancy analysis). However, these multivariate analyzes did not lead to conclusive results.

Results

Spatial variability of flows

In Quebec, annual daily minimum flows (1-day) can occur in cold season (winter), when precipitation falls mainly in the form of snow, and in warm season (summer-fall) when the amount of rain does not compensate for the loss of water by evapotranspiration. We therefore calculated the frequency of occurrence of minimum flows during the two seasons. Figure 2 shows that flows occur more frequently in summer than in winter (< 40%) in the three hydroclimatic regions, with the exception of the Matane River (SS11). On the other hand, for the Châteaugay River (SS1), all flows occurred exclusively in summer.

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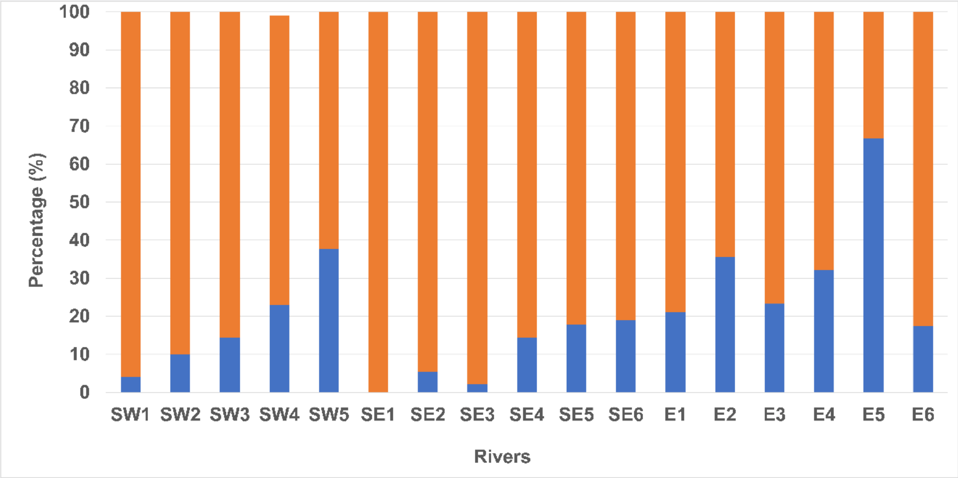

Figure 2: Seasonal frequency of annual daily minimum flows. Red bars: summer; blue bars: winter.

The means of annual daily minimum specific flow of the rivers analyzed are presented in Figure 3. The average values calculated during the period 1930-2019 vary between 1.26 l/s/km^2 (Trois-Pistoles River, E1) to 7.01l/s/km^2 (Du Nord River, SW1). Specific flow values were higher in the southwest hydroclimatic region (SW1 to SW5) on the north shore than those of the two other regions (SE1 to SE6 and E1 to E6), located on the south shore. When comparing these values for the rivers south of 47°N, flows were on average two times higher on the north shore than on the south shore. For example, flow means of the Vermillon River (2,662km^2), located on the north shore (3.7 l/s/km^2), were approximately three times greater (1.4 l/s/km^2) than those of the Châteauguay River (2,492km^2), despite the fact that the Drainage area of the first river is significantly larger than that of the second river. The application of the ANOVA and Kruskal-Wallis tests confirmed this difference, at the 5% threshold, in the average flows between the rivers on the two shores.

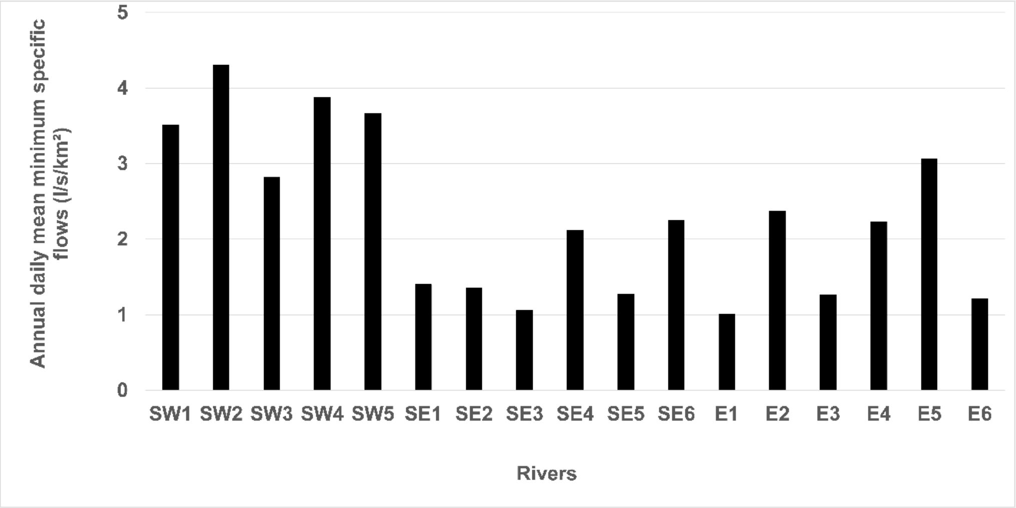

Figure 3: Comparison of mean values of annual daily minimum specific flows (l/s/km^2) from 1930–2019.

Correlation coefficient values calculated between the flows and the physiographic and climatic variables are shown in Table 2. This table shows that annual daily minimum specific flows were significantly correlated, at 5% threshold, with four variables whose average values in the three hydroclimatic regions are shown in Figure 4. They were positively correlated with mean slopes of watersheds and wetlands surface area but negatively correlated with agricultural surface area. As for climate variables, the annual daily minimum specific flows were negatively correlated with snowfall during the fall season.

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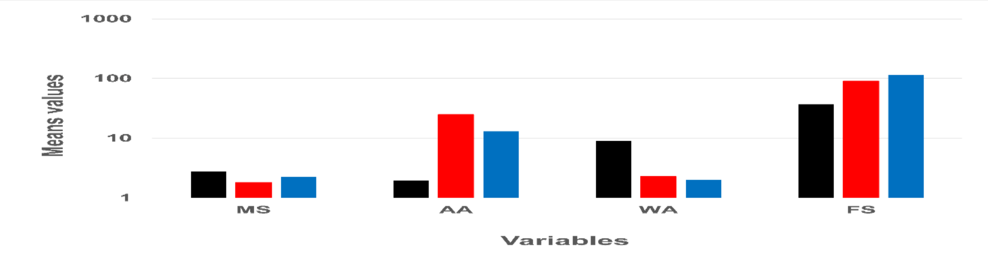

Figure 4: Comparison of the mean values of the four variables significantly correlated with the flows. MS = Watersheds mean slopes (°); AA = Agricultural area (%), WA= wetlands areas (%); FS = Fall snowfall (cm). Black bars= Southwestern Hydroclimatic Region; red bars: Southeastern Hydroclimatic Region; blue bars: Eastern Hydroclimatic Region.

Temporal variability of annual daily minimum flows

Long-term trend flows analysis

Results of the various tests applied to analyze the long-term trend in the flow series are presented in Table 3 and the interannual variability of river flows in the three hydroclimatic regions are presented in Figure 5-7. They show that the temporal variability of annual daily minimum flows was not consistent across Quebec despite the overall decline in snowfall. In the southwestern hydroclimatic region on the north shore (SW1 to SW5), the five tests detected a significant trend in only one of the rivers (Rivière du Nord, SW1). This trend was negative, which means that flows decreased over time in this river. In general, the negative values of Z of the different tests suggest an overall downward trend in minimum flows in this hydroclimatic region. In the southeastern hydroclimatic region (SE1 to SE6) on the south shore, all test results were consistent. These tests showed a significant long-term trend for all the rivers in this region, except the Eaton River (SE2), for which the LTP test did not detect a significant trend. Rivers in this region have therefore seen an increase in flows over time.

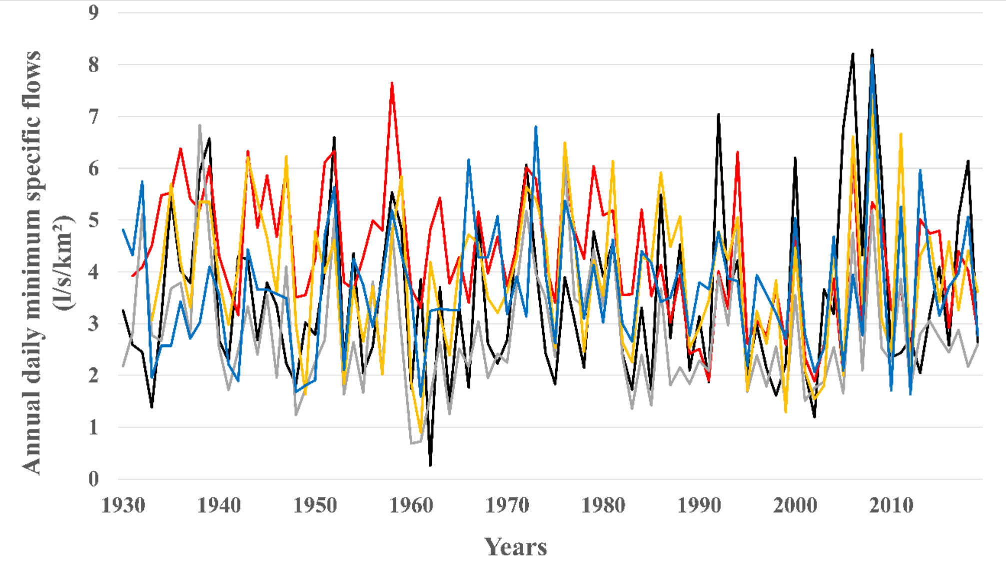

Figure 5: Interannual variability of annual daily minimum specific flows (l/s/km²) in the Southwestern hydroclimatic region from 1930 to 2019. Petite Nation River: black curve; Du Nord River: Red curve; L'Assomption River: grey curve; Matawin River: yellow curve; Vermillon River: blue curve.

In the eastern hydroclimatic region (E1 to E6) on the south shore, the results of the different tests reveal a long-term trend characterized by a significant decrease in flows for more than half of the rivers analyzed (4 out of 6). Only the flows of the Matane River (E5) have increased significantly (positive trend) over time. It follows that despite the general decrease in the snowfall in

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Quebec, the long-term trend in the variability of the annual daily minimum flows is not uniform. These flows increase over time in the southeastern hydroclimatic region, the most agricultural of the three hydroclimatic regions (see Figure 4) but decrease overall in that of the eastern which is moderately agricultural. No significant change in flows is observed in the southwestern region, the least agricultural of the three.

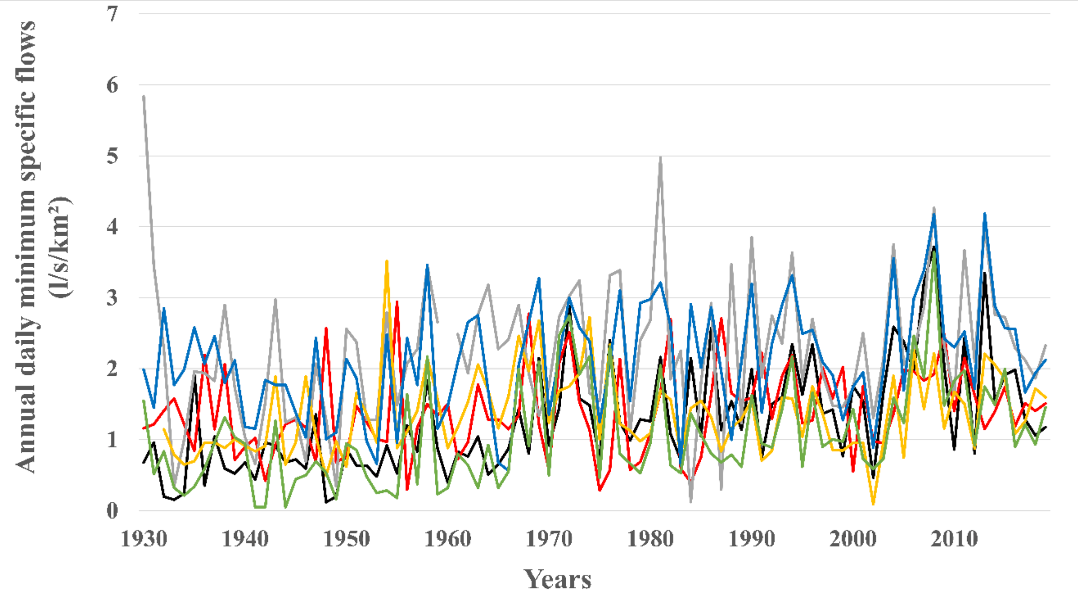

Figure 6: Interannual variability of annual daily minimum specific flows (l/s/km²) in the Southeastern hydroclimatic region from 1930 to 2019. Châteaugay River: orange curve; Eaton River: yellow curve; Nicolet River: black curve; Etchemin River: green curve; Beaurivage River: blue curve; Du Sud River: grey curve.

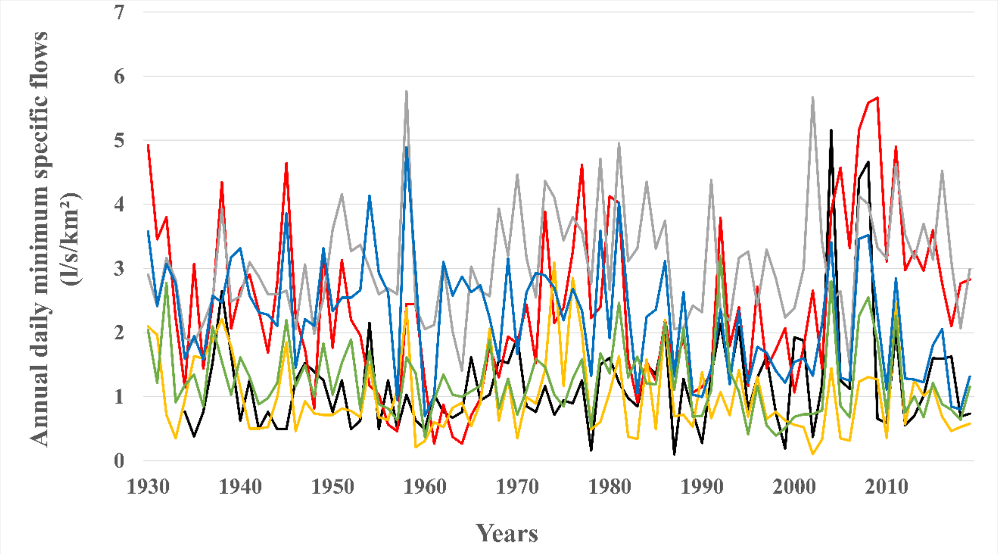

Figure 7: Interannual variability of annual daily minimum specific flows (l/s/km²) in the Eastern hydroclimatic region from 1930 to 2019. Ouelle River: orange curve; Du Loup River: red curve; Trois-Pistoles River: green curve; Rimouski River: blue curve; Matane River: grey curve; Blanche River: black curve.

The application of the three tests which detect the shifts in the means of the hydrological series has highlighted two major periods of these shifts (Table 4). The first period of these breaks occurred before the 1970s. After these shifts, the average of annual

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daily minimum flows increased significantly over time (see Table 3), with the exception of the shift that occurred in the Châteaugay River watershed (SE1) in the southeastern hydroclimatic region on the shore south. As for the second period of breaks, these occurred after 1970. After these shifts, the average flows decreased significantly.

Table 2: Correlation coefficients calculated between physiographic variables and magnitude (L/s/km²) of annual daily minimum extreme flows from 1930–2019.

Factors	Correlation Coefficients
Physiographic Variables	
Drainage Density (km/km^2)	-0.186
Mean Slope (°)	0.571**
Forests Area (%)	0.438
Agricultural Area (%)	-0.689**
Wetlands Area (%)	0.664**
Climatic Variables	
Annual total rainfall (mm)	0.071
Annual total snowfall (cm)	-0.431
Annual total precipitations (mm)	-0.253
Winter-Spring total rainfall (mm)	0.284
Winter-Spring total snowfall (cm)	-0.325
Winter-Spring total precipitations (mm)	-0.045
Summer-Fall total rainfall (mm)	-0.102
Fall total snowfall (cm)	-0.514**
Summer-Fall total precipitations (mm)	-0.359
Annual daily mean maximum temperature (°C)	0.174
Winter-spring daily mean maximum temperature (°)	0.267
Summer-fall daily mean maximum temperature (°C)	0.101

** = statistically significant value at the 5% threshold.

Table 3: Results of the various Mann-Kendall tests applied to the annual daily minimum extreme flow series from 1930-2019.

Rivers	MK		MMK-PW		TFPW		MMKH		LTP	
	Z	p-value	Z	p-value	Z	p-value	Z	p-value	Z	p-value
Southwestern Hydroclimatic Region										
Petite Nation	0.202	0.84	0.131	0.896	-0.167	0.868	0.474	0.635	0.149	0.882
Du Nord	-3.845**	0	-3.218**	0.001	-4.011**	0	-3.845**	0	-2.459**	0.014
L'Assomption	-0.958	0.338	-0.953	0.34	-1.053	0.293	-0.938	0.348	-0.63	0.532
Matawin	-0.854	0.393	-1.015	0.31	-0.947	0.343	-0.934	0.348	-0.781	0.439
Vermillon	0.634	0.526	0.989	0.323	0.918	0.359	0.679	0.497	0.68	0.497
Southeastern Hydroclimatic Region										
Chateaugay	2.586**	0.01	2.442**	0.015	2.491**	0.013	2.586**	0.01	2.515**	0.012
Eaton	2.142**	0.025	2.031**	0.042	2.346**	0.019	1.977**	0.048	1.276	0.202
Nicolet SW	4.625**	0	3.526**	0	4.915**	0	4.625**	0	3.188**	0.001
Etchemin	2.510**	0.012	2.215**	0.027	2.718**	0.007	2.510**	0.012	1.889*	0.059
Beaurivage	6.285**	0	3.831**	0	6.177**	0	6.285**	0	6.092**	0
Du Sud	2.161**	0.031	2.357**	0.018	2.562**	0.01	2.161**	0.036	1.958**	0.05

Eastern Hydroclimatic Region										
Ouelle	-1.792*	0.073	-1.449	0.147	-1.690*	0.091	-2.249*	0.025	-1.209	0.229
Du Loup	1.534	0.125	-1.676*	0.094	-2.562*	0.007	0.75	0.453	0.397	0.691
Trois-Pistoles	-2.109**	0.035	-1.889*	0.059	-1.910*	0.056	-2.047**	0.041	-1.612	0.108
Rimouski	-3.761**	0	-3.044**	0.002	-3.562**	0	-3.761**	0	-3.444**	0
Matane	2.248**	0.025	1.953*	0.051	2.250**	0.024	2.248**	0.025	1.329	0.184
Blanche	1.554	0.108	1.146	0.252	1.454	0.146	1.473	0.103	1.328	0.106

** = statistically significant Z value at the 5% threshold; * = statistically significant Z value at the 10%.

Table 4: Results of the Pettitt and Lombard tests applied to the annual daily minimum extreme flow series from 1930-2019.

Rivers	Pettitt Test			Modified Pettitt Test			Lombard Test	
	K	p-value	T	K	p-value	T	Sn	T1-T2
Southwestern Hydroclimatic Region								
Petite Nation	357	0.709	-	347	0.751	-	0.001	-
Du Nord	1095**	0	1981	950**	0.001	1981	0.161**	1980-81
L'Assomption	449	0.388	-	466	0.342	-	0.01	-
Matawin	353	0.651	-	360	0.622	-	0.009	-
Vermillon	426	0.457	-	459	0.36	-	0.007	-
Southeastern Hydroclimatic Region								
Chateaugay	874**	0.004	1985	862**	0.005	1985	0.085**	1984-85
Eaton	780**	0.01	1960	689**	0.032	1960	0.038*	1959-60
Nicolet SW	1240**	0	1966	908**	0.002	1965	0.217**	1965-66
Etchemin	847**	0.006	1967	741**	0.023	1966	0.082**	1965-67
Beaurivage	1536**	0	1968	987**	0.001	1968	0.369**	1964-68
Du Sud	621*	0.087	1956	591	0.117	-	0.046**	1952-53
Eastern Hydroclimatic Region								
Ouelle	470	0.331	-	462	0.352	-	0.027	-
Du Loup	864**	0.005	2003	563	0.152	-	0.043**	2002-03
Trois-Pistoles	669*	0.052	1988	671*	0.052	1988	0.049**	1992-94
Rimouski	1044**	0	1982	954	0.001	1981	0.152**	1985-86
Matane	794**	0.012	1967	664*	0.055	1967	0.051*	1966-67
Blanche	436	0.221	-	379	0.524	-	0.102	-

** = statistically significant Z value at the 5% threshold; * = Statistically significant value at the 10% threshold. T = year of the break in mean; T1 = year of start of the break in the mean; T2 = year of end of the break in mean.

Correlation between climatic indices and flows

The values of the correlation coefficients calculated between the annual climatic indices and the annual daily minimum flows are presented in Table 5. It is important to indicate that these values of the correlation coefficients are comparable to those calculated with the two other half-yearly cold season (winter) and warm season (summer) series. Table 5 reveals that in the three hydroclimatic regions, no climatic index is significantly correlated with the flows of all the rivers. Consequently, across Quebec, there is no spatial consistency in the relationship between the climatic indices and the annual daily minimum flows. Nevertheless, the GMLOT index is positively correlated with the flows of four rivers (three in the southeastern hydroclimatic region and only one in the eastern hydroclimatic region) but negatively with the flows of two rivers (one in the southwestern hydroclimatic region and the other in the eastern one).

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Discussion

Spatial variability of annual daily minimum flows

A comparison of mean values revealed a clear difference in flows between the north and south shores of the St. Lawrence River. Annual daily minimum flows were on average twice as high on the north shore than on the south shore. The correlation analysis (Table 2) showed that four factors were significantly correlated with these flows to explain this spatial variability: agricultural area (negative correlation), wetland areas (positive correlation), mean slopes of watersheds (positive correlation), and the fall snowfall (negative correlation).

Table 5: Correlation coefficients calculated between the daily minimum annual flows and the climatic indices.

Rivers	AMO	AO	GMLOT	NAO	NINO	ONI	PDO
Southwestern Hydroclimatological Region North Shore							
Petite Nation	0.037	0.132	0.128	0,160	0.084	0.048	0.044
Du Nord	-0.14	-0.174	-0.352**	-0.049	-0.026	0.082	0.144
L'Assomption	-0.280**	0.089	-0.096	0.107	0.019	0.01	-0.054
Matawin	-0.259**	0.079	-0.056	0.113	-0.069	-0.085	0
Vermillon	-0.129	-0.03	-0.078	0.039	0.07	-0.07	-0.063
Southeastern Hydroclimatological Region South Shore							
Châteaugay	0.071	0.07	0.179	-0.075	0.279	0.226	-0.022
Eaton	-0.171	0.005	-0.163	0.001	-0.082	-0.04	-0.053
Nicolet SW	-0.136	0.19	0.221*	0.08	-0.05	-0.156	-0.094
Etchemin	-0.138	0.19	0.221*	0.08	-0.05	-0.156	-0.094
Beaurivage	-0.055	0.240*	0.371**	0.232*	0.079	-0.062	0.147
Du Sud	-0.125	0.272**	0.102	0.118	-0.004	-0.037	-0.066
Eastern Hydroclimatological Region South Shore							
Ouelle	-0.375**	0.106	-0.176	0.131	-0.127	-0.113	-0.019
Du Loup	0.193	0.1	-0.079	0.131	0.041	0.035	0.059
Trois-Pistoles	0.129	0.081	0.473**	-0.025	0.058	-0.082	0.071
Rimouski	-0.191	-0.141	-0.405**	-0.108	-0.165	-0.059	-0.197
Matane	-0.071	-0.091	0.076	-0.134	0.021	0	0.054
Blanche	0.035	0.145	0.187	0.061	0.008	-0.073	0.051

** = statistically significant value at the 5% threshold; * = statistically significant value at the 5% threshold.

The agricultural area on the south shore was larger than that of the north shore. In fact, Figure 4 clearly shows that the average agricultural area of the watersheds on this shore is respectively 25% south of 47°N (southeastern hydroclimatic region) and 13% south of this parallel (eastern hydroclimatic region). On the other hand, on the north shore (Southwestern hydroclimatic region), this average is reduced to only 2%. A number of studies conducted in Quebec watersheds have shown that agricultural practices cause a significant decrease in minimum flows from less water infiltration due to soil sealing (e.g., [46-48]). There is therefore a significant reduction in low flows supplied by aquifers, whose recharge depends primarily on infiltration.

Wetlands are known to have a "sponge effect" by storing and absorbing runoff water, thus supplying aquifers that support low flows (e.g. [49-51]). Overall, wetlands and others water bodies (small lakes) occupy an average of 9% of the areas of the watersheds on the north shore but only 2% on average on the south shore (Figure 4) due to the intensive drainage carried out as part of the modernization of agricultural practices in Quebec since 1950 [52]. In Quebec, Blanchette et al. [53] have clearly demonstrated that the reduction in wetland areas in the Saint-Charles River watershed between 1978 and 2014 led to a significant drop in minimum flows. In two other watersheds (Bécancour and Yamaska rivers), Fossey and Rousseau [54,55] demonstrated that the hydrological impacts induced by these wetlands are not influenced by their location in the watersheds. Thus, even geographically isolated wetlands far from river channels induced the same types of hydrological impacts as those induced by riparian wetlands. Finally, Assani [56] showed that wetlands reduce the rate of recession of low flow in summer and fall in north shore. But at the scale of a watershed, the impacts of all water bodies (wetlands, lakes and other depressions) are much lower on low flows than on flood flows. Thus, agriculture has much more impact on the spatial variability of low flows than water bodies in southern Quebec [13].

The only physiographic factor significantly correlated with annual daily minimum flows was the mean slope of watersheds. This correlation was positive when, in principle, it should be negative since the higher the mean slope of a watershed, the greater the impact of the runoff process compared to that of infiltration, all other physiographic characteristics being equal. This positive correlation observed in Quebec is simply explained by the fact that watersheds on the north shore have higher mean slopes (average: 3°) overall than those on the south shore (average: 2°) (see Figure 4), which are predominantly spread over geological formations (St. Lawrence Lowlands) with a relatively flat topography. This positive correlation between the watersheds means slopes and the flows cannot therefore be interpreted as a causal link between the two variables but as a simple covariation due to the agricultural areas and those of the wetlands spatial variability on the two shores.

Finally, the only climate variable that was significantly correlated with annual daily minimum flows was snowfall, specifically in the fall (it does not snow in all Quebec regions in summer). Note that fall is one of Quebec's main periods for recharging water tables. This recharging influences the magnitude of annual daily minimum flows in winter and summer—two seasons in which these flows occur. Consequently, the magnitude of these flows depends on the amount of water entering the tables in fall, thus determining the volume of water for the second recharging period during the spring snowmelt. Therefore, the greater the fall recharge, the greater the magnitude of winter or summer annual daily minimum flows. However, increased snowfall in fall reduces the aquifer recharge during this season due to ground frost (decrease infiltration), resulting in a decrease in the magnitude of annual daily minimum flows. This interaction between snowfall, the magnitude of the aquifer recharge in fall and the magnitude of winter or summer annual daily minimum flows explains the negative correlation between snowfall and the flows observed in Quebec. The watersheds on the north shore that see less snowfall in fall than those on the south shore are therefore characterized by higher annual daily minimum flows. Figure 4 clearly shows that the amount of snowfall in autumn is about three times less on average on the north shore (37 cm) than on the south shore (> 90cm).

Temporal variability of annual daily minimum flows

Despite the general decline in the amount of snow highlighted in Quebec [8,9], the main source of groundwater supply and river low flows, the analysis of the annual daily minimum flows (1-day) by means of five statistical tests for analyzing the long-term trend and two mean break detection tests demonstrated that the long-term trend of the temporal variability of these flows varies greatly from one hydroclimatic region to another. It follows that this drop in the snowfall did not cause a generalized decrease in annual low flows across all of Quebec, as might be expected. This heterogeneity in the temporal variability of flows results from the influence of other factors.

The rivers of the southeastern hydroclimatic region on the south shore south of 47°N, the most agricultural region of Quebec (Figure 4), are characterized by a significant increase in flows over time. This increase occurred before the 1980s. It may be the result of two main factors. The first factor is undoubtedly the increase in the rainfall observed during all seasons since the 1970s in Quebec (e.g., [57,58]), in particular, and in the northeastern region of the North American continent (e.g., [59-63]), in general. This increase has thus made it possible to compensate for the reduction in the quantity of snow which supplies the water tables and the low water levels. This factor alone is not enough to explain the increase in flows in this region because the increase in the amount of rainfall is observed throughout Quebec, as has already been pointed out. The second factor that can contribute significantly to the increase in these flows is the significant decrease in agricultural area since the modernization of agriculture initiated from 1950 [52]. Following this modernization, more than half of the agricultural areas, formerly reserved for crops, have been set aside and/or reforested. This change in land use has particularly affected this most agricultural hydroclimatic region of the province of Quebec. The significant decrease in agricultural areas in favor of uncropped land and reforested land has favored the infiltration of water over time, thus causing an increase in minimum flows in this hydroclimatic region. Finally, unlike the other rivers in this hydroclimatic region, the date of the decrease in the flows of the Châteaugay River (SE1) occurred at the beginning of the 1980s (1985) (see Table 4). This delay or discrepancy can be explained by the fact that more than 30% of the area of the watershed is urbanized while this urbanized area is less than 10% in the other watersheds. Thus, due to this relatively strong urbanization, water infiltration remains relatively low compared to other watersheds. In addition, the Châteaugay River watershed is subject to the pumping of groundwater for domestic and industrial needs [10]. These factors have thus delayed the increase in minimum flows over time.

In the eastern hydroclimatic region, also located on the south shore but north of 47°N, the rivers are, on the other hand, characterized globally by a significant decrease in flow over time, despite an increase in rainfall. This decrease in flows would result from that of the snowfall, in particular in autumn. Remember that it is this hydroclimatic region that receives on average the greatest amount of snow during this fall season compared to that received by the other two hydroclimatic regions (see Figure 4). Moreover, unlike the southeastern hydroclimatic region, the eastern hydroclimatic region has not experienced a very significant decrease in its agricultural area since 1950. Thus, the infiltration of water resulting from this decrease in agricultural areas is relatively less than that observed in the other climatic region to the south. Finally, the increase in the rainfall in this region is less significant than that observed in the other two hydroclimatic regions [64]. Consequently, this increase does not sufficiently compensate for the decrease in the snowfall, particularly in autumn. However, only the Matane River (E5) is characterized by a significant increase in minimum flows over time even though, paradoxically, the watershed receives on average the greatest amount of snow (>400cm) in autumn compared to the other watersheds analyzed in the three hydroclimatic regions. Unlike other rivers, the annual daily minimum flows of the Matane River occur more frequently in winter (>60%) than in summer (see Figure 2). Thus, winter low flows are much more influenced by fall rainfall (which have increased over time) than by the amount of fall snow that melts in spring, mainly influencing low flows in summer. Besides, this increase in flows can then be explained by the particular geological characteristics of this catchment area. These characteristics would result in a layer of relatively thick unconsolidated sedimentary deposits in which the groundwater is lodged [65], thus allowing greater infiltration of water.

Unlike the two hydroclimatic regions on the south shore, the temporal variability of annual daily minimum flows has not changed significantly over time on the north shore, despite the significant increase in rainfall, the significant decrease in snowfall and the presence of more large area of wetlands. Intuitively, the increase in the rainfall on the one hand, and the presence of larger wetland areas, on the other hand, should lead to an increase in minimum flows over time due to greater infiltration. This lack of change in minimum flows over time can be explained by the fact that these wetlands store more surface water than infiltrate it. Thus, the supply of groundwater by the infiltration process is limited despite the increase in the amount of rainfall. In this regard, Assani [56,64,66] had clearly demonstrated that these wetlands impact surface runoff more than infiltration. It follows that the analysis of the temporal variability of flood flows generated by snowmelt and/or rain in this region has shown a general increase in flows over time due to the increase in rainfall unlike the other two hydroclimatic regions. In addition, this southwestern hydroclimatic region receives on average the lowest amount of snow in the fall (< 40cm) than that measured in the other two hydroclimatic regions (see Figure 4). The decrease over time of this relatively small amount of snow thus has a slight impact on the minimum flows, unlike in the eastern hydroclimatic region. However, only the Du Nord River (SW2) is characterized by a significant decrease in minimum flows over time. This decrease could probably be explained by the specific geological characteristics of the watershed. But there is currently no in-depth data on these geological features to further support this hypothesis.

Finally, the annual daily minimum flows are very little to the climatic index's contrary to the seasonal flows. These are positively correlated with NAO in the three hydroclimatic regions [12]. The low correlation observed between annual flows and climatic indices can be partly explained by the influence of land use and land cover as well as by changes in land use over time (reduction of agricultural area).

Conclusion

Annual daily minimum flows, which play a crucial role in the functioning of river ecosystems, result from the interaction of many factors that influence their spatial and temporal variability. The objective of this study was to identify the impacts of these different factors on this variability spatio-temporal based on the data available in the current context of global warming in southern Quebec.

In terms of spatial variability, annual daily minimum flows (1-day) are on average twice as high on the north shore as on the south shore. The correlation analysis between these flows and physio-climatic factors showed the statistically significant relationship of the following factors: mean slopes of watersheds (positive correlation) which are on average higher on the north shore than on the south shore, agricultural area (negative correlation) which are on average at least six times higher on the south shore than on the north shore, wetlands (positive correlation) which are on average four times lower on the north shore than on the south shore, and autumn snowfall which are on average at least three times higher on the south shore than on the north shore. Nevertheless, critical analysis of these four factors showed that agricultural area and autumn snowfall were likely to be the major factors causing this variability. Despite the sponge effect of wetlands, their influence seemed to be limited due to their relatively low connectivity with aquifers, which influence these flows.

In terms of the temporal variability of annual daily minimum flows, it is clear that its impact across the three hydroclimatic regions was not consistent, despite the significant decrease in snowfall throughout Quebec. Annual daily minimum flows increased significantly over time in the southeastern hydroclimatic region on the south shore south of 47°N. This increase in flows resulted from the major reduction in cultivated areas in favour of uncropped lands and afforestation, and an increase in rainfall. This change in agricultural practices facilitated water infiltration into aquifers, which is the primary factor affecting annual daily minimum flows. North of 47°N on the south shore, flows decreased overall due to decrease in the autumn snowfall with the highest amount of three hydroclimatic regions. On the north shore, there was no significant change in the mean of annual daily minimum flows since the increase in rainfall at the expense of snowfall impacted floods more than low flows, most likely due to the low connectivity between these wetlands and river channels. Be that as it may, it emerges from this study that across Quebec,

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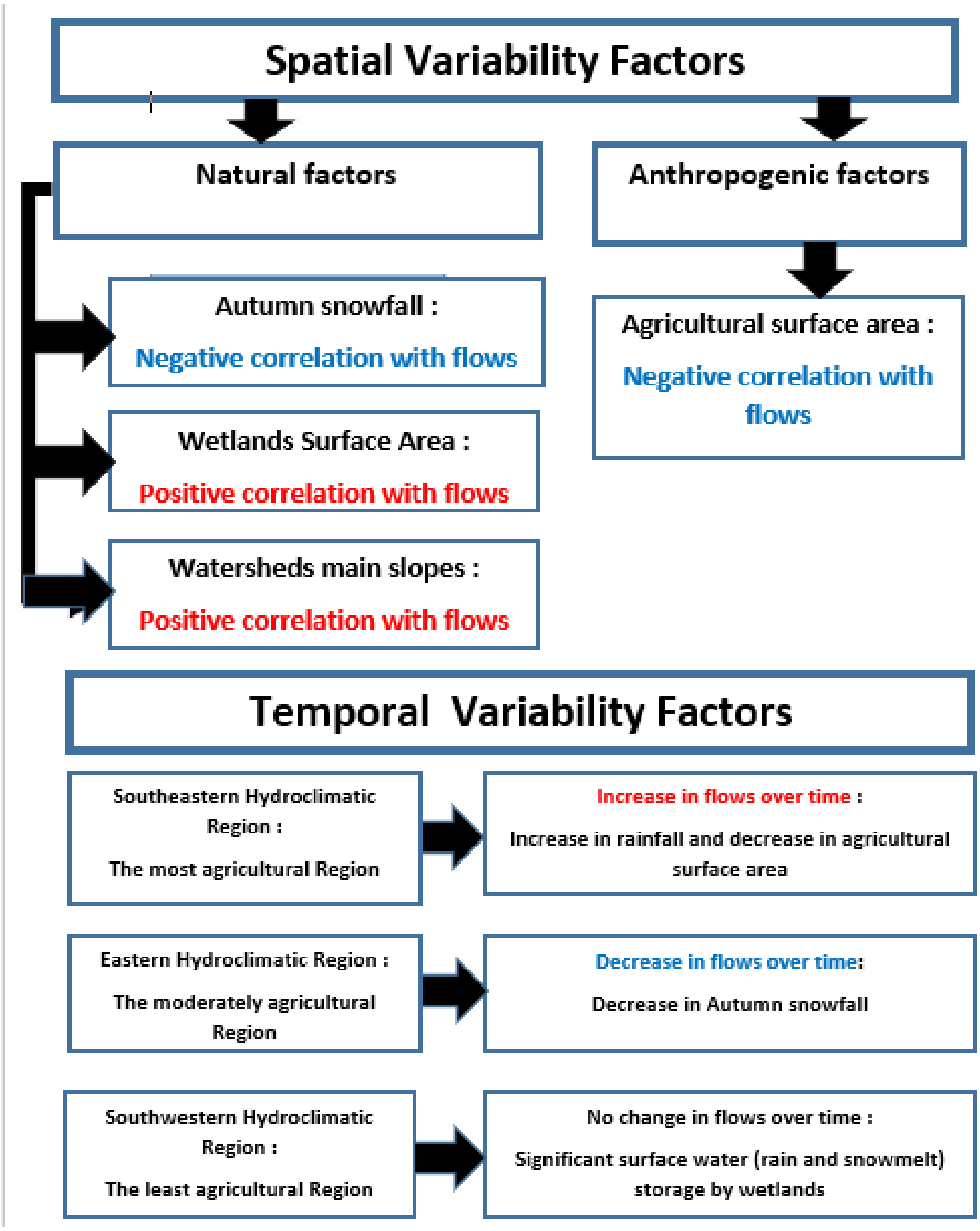
the increase in daily minimum flows occurred before 1970 due to the increase in rainfall and changes in land use when the decrease in theses flows occurred after this date due to the decrease in the snowfall.

The contribution of this study is to demonstrate that global warming will not have the same impacts on the spatio-temporal variability of annual daily minimum flows in Quebec. This variability is also strongly influenced by physiographic factors and types of land covert and use, factors that are not generally incorporated into climate models to predict the evolution of these flows in different climate change scenarios in Southern Quebec. Of all these factors, the reduction of agricultural areas in favor of uncropped land and reforested land has resulted in an increase in annual daily minimum flows over time. Consequently, this change in land use has supported the increase in these flows induced by the increase in rainfall in most agricultural regions of the southern shore. Finally, the hydroclimatic region on the south shore, characterized by a decrease in flow, appears to be the region most vulnerable to the decrease in autumn snowfall in autumn despite an increase in rainfall.

Graphical-Abstract



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