Variability of Mean Annual Flows in Southern Quebec (Canada)

Ali Arkamose Assani

Department of Environmental Sciences and the 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; ali.assani@uqtr.ca

Abstract: Snow is the main source of streamflow in temperate regions characterized by very cold and snowy winters. Due to global warming, these regions are experiencing a significant decrease in snowfall. The main objective of this study is to analyze the impacts of snowfall on the spatio-temporal variability of mean annual flows (MAFs) of 17 rivers, grouped into three hydroclimatic regions, from 1930 to 2019 in southern Quebec. In terms of spatial variability, snowfall is the variable most correlated with MAFs (positive correlation), followed by drainage density (positive correlation) and wetland surface areas (negative correlation). Due to the influence of these three factors, MAF values are generally higher in the most agricultural watersheds of the southeastern hydroclimatic region on the south shore than in the less agricultural watersheds of the southwestern hydroclimatic region on the north shore of the St. Lawrence River. As for temporal variability, the four statistical tests applied to the hydrological series detect no significant downward trend in MAFs, despite having reduced snowfall. Instead, they suggest an evolution toward an increase in mean annual flows, as a result of increased rainfall due to the increase in temperature. This evolution is more pronounced on the north shore than on the south shore, likely due to the presence of wetlands and others water bodies, whose runoff water storage capacity does not change over time to be able to store the surplus of the quantity of water brought by the increase in rain.

Keywords: mean annual flows; snowfall; wetland surface areas; temperature; rainfall; southern Quebec

1. Introduction

In cold temperate regions characterized by very cold and snowy winters, one of the major impacts of global warming is a significant decrease in snowfall. This decrease has already been observed in many parts of the world [1–5]. From a hydrological perspective, snow is the main source of streamflow and aquifer recharge in these regions. The consequences of this decrease in snow cover have mainly been analyzed in relation to the temporal variability of extreme flows (floods and low flows). For example, Blöschl et al. [6] clearly demonstrated that the decrease in snow cover resulted in a significant decrease in the magnitude of spring freshets caused by snowmelt in eastern Europe. Similar impacts have been observed in other regions [7] and predicted by all climate models (e.g., [8]).

However, none of these studies analyzed the impacts of this decrease in the magnitude of floods on mean annual flows. In general, while studies exist in the scientific literature on extreme flows, very few have focused on the impacts of climate change on mean annual flows (e.g., [9–11]). However, in the current context of global warming, mean annual flows can be used to detect the impacts of changes in temperature and precipitation regimes on river flows as a result of this warming [12,13]. In this context, their analysis is fully justified along with that of extreme flows.

Quebec, which has a cold temperate climate, has experienced a significant decrease in snow cover since the middle of the last century due to global warming (e.g., [14–16]). Several Canada-wide studies have focused on the impacts of global warming on extreme flows (e.g., [17–21]); there have also been studies on this topic conducted exclusively in Quebec [22–27].
Nevertheless, very few studies have focused on temporal variability in general and the impacts of global warming in particular on mean annual flows in Canada [28,29]. Others have analyzed this temporal variability to determine the climatic indices that influence it (e.g., [30–34]). Furthermore, there have been no studies on the influence of snowfall on the spatio-temporal variability of these flows. Moreover, on the methodological level, none of these studies analyzed the effects of persistence, either in the short (STP) or the long term (LTP), on the stationarity of these average annual flows.

In light of these considerations, this study aims to fill these gaps by pursuing the following objectives:

1. Identify the physio-climatic factors and the factors related to land use and land cover that influence the spatial variability of mean annual flows in southern Quebec.
2. Analyze the temporal variability of mean annual flows to determine the influence of short-term persistence (STP) and long-term persistence (LTP) effects on their stationarity in the current context of global warming. This objective aims to test the hypothesis that the significant decrease in snow cover led to the decrease in mean annual flows in southern Quebec. This is the primary objective of this study.
3. Determine whether the factors influencing spatial variability can amplify or mitigate the effects of global warming on the temporal variability of these flows.
4. Determine the influence of spring flows resulting primarily from snowmelt on the spatio-temporal variability of mean annual flows in the various hydroclimatic regions of southern Quebec.

This study is part of the research program aimed at determining the impacts of climate change on the spatio-temporal variability of flows at different time scales in relation to land cover and land use in southern Quebec.

2. Methods

2.1. Description of the Watersheds

This study is based on an analysis of mean annual flows measured continuously from 1930 to 2019 in 17 watersheds (Figure 1 and Table 1). These flows were minimally disturbed by human activity. These watersheds were grouped into three homogeneous hydroclimatic regions [22] on both shores of the St. Lawrence River in southern Quebec. The first hydroclimatic region (southwest hydroclimatic region) is located on the north shore, and the rivers in its watersheds cut through the Canadian Shield, which mainly consists of metamorphic and igneous rocks covered by glaciofluvial deposits. The climate is continental temperate. The forest consists mainly of sugar maple trees (sugar maple-yellow birch forest and basswood-sugar maple forest). The second hydroclimatic region (southeastern hydroclimatic region) is located on the south shore, south of 47° N. The rivers of this region drain the geological formations of the Appalachians and the St. Lawrence Lowlands, which consist mainly of sedimentary rocks covered in sediment of different origins (glacial, lacustrine, marine, etc.). Forest formations consist of sugar maple trees (sugar maple-hickory stands, basswood-sugar maple forests, and sugar maple-yellow birch forests). The climate is mixed temperate with maritime and continental features. North of this parallel on the same shore is the third hydroclimatic region (east hydroclimatic region), which has watersheds contained in the same two geological formations. However, the sugar maple forest is gradually replaced by the fir forest (balsam fir–white birch stands and balsam fir–yellow birch stands). The climate is becoming increasingly maritime at higher latitudes.
Climate data were obtained from the Environment and Climate Change Canada website (https://climat.meteo.gc.ca/climate_normals/index_f.html, accessed on 18 June 2021). These are the mean temperatures and precipitation from the annual and seasonal climate normals for 1971 to 2000 and for 1981 to 2010. Daily flow data were taken from the website of Quebec’s Ministère d’Environnement et de la Lutte contre les changements climatiques (https://www.cehq.gouv.qc.ca/index_en.asp, accessed on 20 February 2020). Finally, physiographic data and data related to types of land use and land cover were drawn from the Université du Québec à Trois-Rivières GEOLAB laboratory [26,35]. These data were described by [24]. It is important to mention that measurements of the daily flows of the Du Nord, Eaton, Matawin and Blanche rivers began in 1931, 1932, 1933 and 1934, respectively. For the Matawin River, these data were described by [24].

Figure 1. Location of stations. SE = Southeastern Hydroclimatic Region; E = Eastern Hydroclimatic Region; SW = Southwestern Hydroclimatic Region.

Table 1. Rivers analyzed.

| Rivers        | Code | Drainage Area (Km²) | Latitude (N) | Longitude (W) |
|---------------|------|---------------------|--------------|---------------|
| **Southeastern Hydroclimatic Region (South Shore)** |      |                     |              |               |
| Chateaugay    | SE1  | 2492                | 45°19'49"   | 73°45'44"     |
| Eaton         | SE2  | 646                 | 45°28'05"   | 71°39'18"     |
| Nicolet SW    | SE3  | 562                 | 45°47'30"   | 71°58'05"     |
| Etchemin      | SE4  | 1152                | 46°39'25"   | 71°39'18"     |
| Beaurivage    | SE5  | 708                 | 46°39'25"   | 71°17'20"     |
| Du Sud        | SE6  | 821                 | 46°49'22"   | 70°45'22"     |
| **Eastern Hydroclimatic Region (South Shore)** |      |                     |              |               |
| Ouelle        | E1   | 796                 | 47°22'52"   | 67°57'14"     |
| Du Loup       | E2   | 1042                | 47°36'43"   | 69°38'41"     |
| Trois-Pistoles| E3   | 930                 | 48°05'21"   | 69°11'43"     |
| Rimouski      | E4   | 1615                | 48°24'46"   | 68°33'18"     |
| Matane        | E5   | 1665                | 48°46'25"   | 67°32'25"     |
| Blanche       | E6   | 223                 | 48°47'20"   | 67°41'51"     |
| **Southwestern Hydroclimatic Region (North Shore)** |      |                     |              |               |
| Petite Nation | SW1  | 1331                | 45°47'27"   | 75°05'22"     |
| Du Nord       | SW2  | 1163                | 45°31'08"   | 74°20'11"     |
| L’Assomption  | SW3  | 1286                | 46°02'45"   | 73°26'19"     |
| Matawin       | SW4  | 1387                | 46°40'50"   | 73°55'00"     |
| Vermillon     | SW5  | 2662                | 47°39'20"   | 72°57'44"     |
flows of the Du Nord, Eaton, Matawin and Blanche rivers began in 1931, 1932, 1933 and 1934, respectively. For the Matawin River, data from 1940, 1941 and 1943 were incomplete. This is also the case for 1940 on the Matane River.

2.2. Statistical Data Analysis
2.2.1. Analysis of Spatial Variability of Data

This analysis consisted of three main steps:

In the first step, annual means for annual flows (means calculated over the 365 days of each year) for each river from 1930 to 2019 were calculated using daily flows. These means were calculated in two ways: from October to September and from January to December. The approaches led to similar results. These means were then compared using parametric (ANOVA) and non-parametric (Kruskal–Wallis) tests. It is important to note that at this stage, flows measured in m$^3$/s were converted into specific flows expressed in L/s/km$^2$ to eliminate the influence of watershed size on the results.

In the second step, these means were correlated with physiographic and climatic variables and types of land use and land cover in watersheds. Linear correlation (parametric) and Spearman rank (non-parametric) methods were applied. As both methods led to the same results, only those obtained from the first method are presented.

In the third step, mean annual flows were compared to mean seasonal spring flows. Note that in Quebec, due to its cold temperate climate, mean annual flows are strongly influenced by snowmelt in the spring. Snowmelt is the main source of streamflow [36] and aquifer recharge [37,38]. For this comparison, two ratios were calculated: the ratio of mean annual flows (MAFs) to spring mean daily flows (SMDFS) and the ratio of mean annual flows to spring maximum daily flows (SMAXDFS). These two ratios, expressed as percentages, were labelled as R-Mean and R-Max, respectively. They measure the contribution of the spring daily mean flows and the annual daily maximum flows generated mainly by snowmelt in Quebec on the mean annual runoff (MAF). If the values of these two ratios are high, the contribution of spring flows to annual runoff is relatively high. Thus, the annual flow tends to concentrate during the spring season when the snow melts. This thus becomes the main source of this annual flow. To complete this comparison, the correlation between mean annual flows and the two spring flow series measured from April to June was calculated. The purpose of this correlation calculation was to identify the type of spring flows that could potentially be used to estimate mean annual flows based only on those measured in spring.

2.2.2. Analysis of the Temporal Variability of the Data

To analyze the long-term trend for mean annual flows, five different statistical trend analysis tests were carried out.

First, the trend-free prewhitening (TFPWMK) method was applied to eliminate autocorrelation effects on the long-term trend. It was described in detail by [39]. The second test, the modified Mann-Kendall test (MMKH), was applied to eliminate all autocorrelations; however, it was completed by correcting the variance of the hydrological series [40]. The third test, long-term persistence (LTP), eliminated the effects of long-term persistence (Hurst effect [41], while the first two tests only eliminated the effects of short-term persistence (STP). The purpose of the fourth test was to detect the dates of the shift by means of the hydrological series ([42]. The rationale for selecting this test is that it can detect abrupt or gradual breaks in means, unlike all other statistical tests used in hydrology. These four tests are widely described in the scientific literature and are commonly used to analyze the long-term trend and breaks by means of the hydrological series (e.g., [43–46]). Note that other tests based on Bayesian statistics (e.g., [19,21]) lead to the same results as the most widely used tests described previously. The fifth and final test was applied to verify the spatial autocorrelation of flows. It has been described in detail by [19,47]. This test (no spatial autocorrelation) confirmed the results of the previous four tests; the results of the fifth test will therefore not be presented here.
3. Results

3.1. Spatial Variability of Mean Annual Flows

The mean annual flow values are presented in Figure 2. They vary spatially in southern Quebec even if the differences between the watersheds are not very important. They ranged from 14 L/s/km² (Châteauguay River) to 25.5 L/s/km² (Blanche River). Generally speaking, in the two hydroclimatic regions in the southwest and east, these values were generally less than 20 L/s/km², except for a few rivers. However, they exceeded this threshold in the southeastern hydroclimatic region—the most agricultural region in Quebec. The application of ANOVA and Kruskal–Wallis tests revealed that the means of the flows of 17 rivers are globally significantly different at the 5% threshold.

![Figure 2. Comparison of mean annual flows in the three hydroclimatic regions from 1930 to 2019.](image)

The correlation analysis between mean annual flow values and physiographic variables showed that flows were positively correlated with drainage density but negatively correlated with the surface areas of wetlands in watersheds (Table 2). For climate variables, flows were only positively correlated with snowfall. The highest correlation was observed between flows and snowfall in the winter/spring season.

| Variables                        | MAF      | R-Means  | R-Max   |
|----------------------------------|----------|----------|---------|
| **Physiographic variables**      |          |          |         |
| Drainage Density (km/km²)        | 0.576 *  | −0.408   | 0.2411  |
| Mean Slope (m/km)               | 0.375    | −0.380   | 0.1307  |
| Forets Area (%)                 | 0.227    | −0.523 * | −0.008  |
| Agricultural Area (%)           | 0.175    | 0.343    | 0.2003  |
| Wetlands (%)                    | −0.5225 *| 0.1117   |         |
| **Climatic variables**          |          |          |         |
| Annual total rainfall (mm)      | 0.067    | 0.490 *  | −0.1211 |
| Annual total snowfall (cm)      | 0.570 *  | −0.477   | 0.0932  |
| Annual total precipitations (mm)| 0.304    | −0.008   | 0.132   |
### Table 2. Cont.

| Variables                        | MAF     | R-Means | R-Max   |
|----------------------------------|---------|---------|---------|
| Winter-Spring total rainfall (mm)| −0.077  | 0.496 * | −0.0764 |
| Winter-Spring total snowfall (cm)| 0.607 * | −0.593  | 0.1624  |
| Winter-Spring total precipitations (mm)| 0.495 * | −0.168  | 0.1039  |
| Summer-Fall total rainfall (mm)  | 0.167   | 0.413   | 0.2095  |
| Fall total snowfall (cm)         | 0.5369 *| −0.3237 | 0.0912  |
| Summer-Fall total precipitations (mm)| 0.395  | 0.096   | 0.2026  |
| Annual daily mean maximum temperature (°C)| −0.362 | 0.805 * | −0.1342 |
| Winter daily mean maximum temperature (°C)| −0.445 | 0.785 * | −0.3093 |
| Winter-spring daily mean maximum temperature (°C)| −0.425 | 0.881 * | −0.1493 |
| Summer daily mean temperature (°C)| −0.282 | 0.731 * | −0.0099 |
| Summer-fall daily mean maximum temperature (°C)| −0.303 | 0.783 * | −0.0719 |

R-Means = MAF/SDMF; R-MAX = MAF/SDMAXF; MAF = Mean Annual Specific Flows; SDMF = Spring Daily Mean Specific Flows; SDMAXF = Spring Daily Maximum Specific Flows. * = statistically significant value at the 5% level. N.B. Wetlands also include other bodies of water such as small lakes.

### 3.2. Temporal Variability of Mean Annual Flows in Quebec

The results of the four statistical tests are presented in Table 3. The three Mann-Kendall tests produced similar results and were supported by the Lombard test. Two aspects must be highlighted: the signs of the Z-score values of the tests and their significance. For the southwest hydroclimatic region on the north shore, all Z-scores were positive. This reflected an evolution toward an increase in mean annual flows in this region (Figure 3). Nevertheless, this trend was statistically significant for only three rivers (Figure 2). The same evolution was also observed for almost all rivers in the southeast hydroclimatic region with Z-scores that were also positive. However, only the Z-score for the Châteauguay River was significant at the 5% threshold (Figure 2); the Nicolet Sud-Ouest River and the Beaurivage River were only significant at the 10% threshold. Moreover, the LTP test did not detect any significant trends for the two last rivers, even at this threshold. In this hydroclimatic region, only the Rivière Du Sud had a negative Z-score. A negative Z-score was observed for over half of the rivers in the east hydroclimatic region. This result suggests an evolution toward a decrease in mean annual flows in this hydroclimatic region, in contrast to the other two hydroclimatic regions. Moreover, no trends were statistically significant, even at the 10% threshold. The Lombard test detected breaks in means for three rivers in the southwestern hydroclimatic region and for only one river (Châteaugay river) in the southeastern hydroclimatic region. Apart from the Matawin River, breaks in means of mean annual flows occurred during the second half of the 1960s in both hydroclimatic regions.

![Figure 3. An example of interannual variability of mean annual flows from 1930 to 2019. Red curve: Du Nord River; black curve: Châteauguay River.](image-url)
Table 3. Results of the various Mann-Kendall tests applied to the mean annual flows series from 1930 to 2019.

| TFPW | MMKH | LTP-MMK | Lombard Test |
|------|------|---------|--------------|
| Z    | p-Value | Z    | p-Value | Z    | p-Value | Sn | T1/T2 |
| **Petite Nation** | 5.348 ** | 0.000 | 5.707 ** | 0.000 | 3.380 ** | 0.001 | 0.293 ** | 1964/71 |
| **Du Nord** | 2.793 ** | 0.005 | 2.846 ** | 0.004 | 3.104 ** | 0.002 | 0.0788 ** | 1968/69 |
| L’Assomption | 1.464 | 0.143 | 1.422 | 0.155 | 1.390 | 0.165 | 0.0161 | - |
| Matawin | 2.226 * | 0.026 | 6.224 ** | 0.000 | 3.661 ** | 0.000 | 0.0785 * | 1942/43 |
| Vermillon | 0.939 | 0.348 | 0.732 | 0.464 | 0.711 | 0.477 | 0.0031 | - |

**Southeastern Hydroclimatic Region**

| Chateaugay | 3.838 ** | 0.000 | 4.377 ** | 0.000 | 3.421 ** | 0.001 | 0.1385 ** | 1968/69 |
| Eaton | 0.572 | 0.567 | 0.551 | 0.582 | 0.373 | 0.709 | 0.0032 | - |
| Nicolet SW | 1.747 | 0.081 * | 1.748 | 0.080 * | 1.262 | 0.207 | 0.036 | - |
| Etchemin | 1.129 | 0.259 | 0.834 | 0.404 | 0.573 | 0.567 | 0.0138 | - |
| Beaurivage | 1.818 | 0.069 * | 1.840 | 0.066 * | 0.965 | 0.335 | 0.0265 | - |
| Du Sud | -0.372 | 0.710 | -0.439 | 0.661 | -0.341 | 0.737 | 0.0017 | - |

**Eastern Hydroclimatic Region**

| Ouelle | -0.345 | 0.730 | -0.732 | 0.464 | -0.268 | 0.792 | 0.0033 | - |
| Du Loup | -0.790 | 0.429 | -0.997 | 0.319 | -0.793 | 0.431 | 0.0102 | - |
| Trois-Pistoles | 1.045 | 0.296 | 0.885 | 0.376 | 0.668 | 0.504 | 0.0079 | - |
| Rimouski | -0.110 | 0.913 | -0.244 | 0.807 | -0.261 | 0.800 | 0.0019 | - |
| Matane | 0.090 | 0.928 | -0.040 | 0.968 | -0.085 | 0.937 | 0.0021 | - |
| Blanche | 1.742 | 0.081 | 0.680 | 0.496 | 0.312 | 0.755 | 0.0108 | - |

** = Statistically significant value at the 5% level; * = Statistically significant value at the 10% level. T1 = year of start mean shift; T2 = year of end mean shift.

3.3. Relationship between Mean Annual Flows and Spring Flows

Note that in cold temperate regions characterized by very snowy winters, the annual runoff depended heavily on the melting of snow accumulated during the cold season. However, many factors were at play. To determine the spatial variability of this influence, the relationship between mean annual flows and spring flows was analyzed. Two variables were considered for these types of flows: spring mean daily flows (SMDFs) and spring maximum daily flows (SMAxDFs). The latter variable frequently corresponds with the magnitude of the annual freshet usually generated by snowmelt.

The correlation coefficients calculated between the mean annual flows and the two spring flow variables are presented in Table 3. For spring mean daily flows, correlation values were relatively lower in the southeast hydroclimatic region—the region that is the most agricultural—than in the other two hydroclimatic regions. In fact, the value was less than 0.700. This threshold was exceeded in the southwest hydroclimatic region on the north shore. For the last hydroclimatic region in the east, the correlation coefficient values varied much more than those in the other two hydroclimatic regions. They ranged from 0.65 (Riviè\'re des Trois Pistoles) to 0.97 (Blanche River). For the second variable, the same trend was observed. Correlation values were lower in the southeast hydroclimatic region than in the other two regions. It is important to note that correlation coefficient values were much lower than those calculated with spring mean flows. Thus, mean annual flows were very weakly correlated with spring maximum daily flows in southern Quebec.

To compare mean annual flows with spring flows, ratios between the mean annual flows and the two spring flow variables were calculated. These ratios are presented in Table 4. For spring mean flows, the ratios varied between 39.3% (Blanche River) and 65.7% (Ch\’a\'teauguay River). Table 4 clearly demonstrates that the values of these ratios were generally greater than 50% in the southeast hydroclimatic region, 50% on average in the southwest hydroclimatic region on the north shore, and less than 45% in the east hydroclimatic region. As for spring maximum daily flows, all ratios were less than 15%,
except for those of the Vermillon River (19%) on the north shore and the Etchemin River (27%) on the south shore. No spatial disparity was observed in relation to these ratios.

Table 4. Mean values of ratios (%) calculated between mean annual flows and spring mean and maximum daily flows from 1930 to 2019.

| Rivers          | R-Mean | R-Max | Correlation Coefficients |
|-----------------|--------|-------|--------------------------|
|                 | MAF-SDMF | MAF-SDMAXF |
| **Southwestern Hydroclimatic Region** | | |
| Petite Nation   | 50.3    | 12    | 0.795                    | 0.659 |
| Du Nord         | 50.7    | 10.3  | 0.746                    | 0.499 |
| L’Assomption    | 47.1    | 12.1  | 0.752                    | 0.459 |
| Matawin         | 50.2    | 9.3   | 0.741                    | 0.431 |
| Vermillon       | 50.9    | 19.4  | 0.779                    | 0.630 |
| **Southeastern Hydroclimatic Region** | | |
| Chateaugay      | 65.7    | 9.3   | 0.608                    | 0.416 |
| Eaton           | 61.1    | 9.7   | 0.477                    | 0.229 |
| Nicolet SW      | 62.7    | 12.3  | 0.481                    | 0.231 |
| Etchemin        | 50.8    | 27    | 0.593                    | 0.346 |
| Beaurivage      | 50.3    | 12.3  | 0.636                    | 0.247 |
| Du Sud          | 48.0    | 13.9  | 0.618                    | 0.324 |
| **Eastern Hydroclimatic Region** | | |
| Ouelle          | 42.9    | 9.4   | 0.752                    | 0.380 |
| Du Loup         | 44.6    | 10.9  | 0.708                    | 0.502 |
| Trois-Pistoles  | 40.9    | 11.9  | 0.648                    | 0.440 |
| Rimouski        | 41.1    | 14.2  | 0.710                    | 0.449 |
| Matane          | 42      | 11.2  | 0.636                    | 0.377 |
| Blanche         | 39.3    | 18.2  | 0.958                    | 0.865 |

R-Mean = MAF/SDMF; R-Max = MAF/SDMAXF; MAF = Mean Annual Specific Flows; SDMF = Spring Daily Mean Specific Flows; SDMAXF = Spring Daily Maximum Specific Flows. All the correlation coefficients are statistically significant at the 5% level.

To determine the factors that influenced the spatial variability of these ratios, correlation coefficients between these ratios and physio-climatic variables were calculated (Table 2). The ratios between mean annual flows and spring mean daily flows were negatively correlated with forest surface areas and winter-spring snowfall but positively correlated with rainfall and daily maximum temperatures. These variables were very strongly correlated with the ratios. As for the ratios between mean annual flows and spring maximum daily flows, no correlation coefficients were statistically significant at the 5% threshold.

4. Discussion
4.1. Analysis of Spatial Variability of Mean Annual Flows

The main objective of this study was to analyze the influence of snow cover on the spatio-temporal variability of mean annual flows in southern Quebec from 1930 to 2019. In terms of spatial variability, the correlation analysis between these flows and many physiographic and climatic variables revealed that snowfall was the variable most correlated with flows, followed in succession by watershed drainage density and wetland surface area.

The positive correlation observed between flows and snow cover is entirely normal because, due to the cold temperate climate in Quebec, annual runoff depends mainly on snowfall that melts in the spring. Thus, the more snowfall in a watershed, the higher the annual runoff. In Quebec, snowfall was generally higher on the south shore than on the north shore; thus, it was the same for mean annual flows. In addition to snowfall, the second factor influencing spatial variability of flows was watershed drainage density. The influence of this factor was reflected in the faster transfer of runoff to river channels,
resulting in increased flows. Since the modernization of agricultural practices, which began in 1950 [48] in Quebec, many canals have been dug to drain wetlands with surface areas that have decreased significantly (<5%). In addition, river channel adjustments (avulsions) were made in agricultural watersheds, most of which were located on the south shore, south of 47°N in particular. In this region, the most agricultural region of Quebec (agricultural surface areas exceeding 10%), mean annual flow values were the highest due to the increase in this substantial amount of drainage. However, it is important to note that mean annual flows were not significantly correlated with agricultural surface areas as would normally be expected due to soil sealing. This lack of correlation between the two variables could be explained in part by the fact that the modernization of agriculture led to a significant reduction in cultivated land and an increase in uncropped land and reforested areas. These land use changes have had the effect of promoting water infiltration at the expense of runoff. This resulted in a significant increase in minimum flows at the expense of maximum flows in agricultural watersheds (e.g., [21]). However, despite this increase in infiltration, runoff remained consistently higher in this region—the most agricultural in nature—than in the other two hydroclimatic regions.

In contrast, intensive drainage into agricultural watersheds on the south shore resulted in a significant decrease in wetlands and other water bodies (lakes) with surface areas that now occupy less than 4% of the watersheds, while they occupied more than 8% of the watersheds on the north shore. The presence of larger wetland and other water bodies surface areas on the north shore resulted in significantly less runoff during snowmelt because the water was stored in large quantities in these wetlands and water bodies (e.g., [49–56]). This explains the negative correlation observed between wetland surface areas and mean annual flows. Thus, mean annual flows were generally lower on the north shore than on the south shore, partly due to the presence of these wetlands and other water bodies.

Furthermore, snowfall in the winter/spring season was also significantly correlated with the ratios between mean annual flows and spring mean daily flows. This correlation is negative because these ratios were higher south of 47°N (>50%) than north of this parallel (<45%) on the south shore, whereas the winter-spring snowfall was higher north of this parallel than south of it. However, these ratios were correlated with the amount of rainfall during the same season because rainfall was greater south of this parallel than north of it. This spatial variability in rainfall was due to that of maximum daily temperatures. They were also higher south of 47°N than north of it on the south shore due to the influence of latitude. They were strongly correlated with flow ratios. Finally, the negative correlation between these ratios and forest surface areas can be explained by relatively smaller forest surface areas south of 47°N than north of it due to agriculture, which promoted surface runoff. From a hydrological perspective, these ratios indirectly reflected the contribution of spring flows generated by snowmelt to total annual runoff. The significant influence of these spring flows resulted in a low ratio between mean annual flows and spring mean daily flows. This was the case in the eastern hydroclimatic region, where the influence of spring flows on total annual runoff exceeded 60%, whereas in the southeastern hydroclimatic region located to the south, it was less than 50% due to the increasing influence of summer-fall rainfall to annual runoff in the region.

4.2. Analysis of Temporal Variability of Mean Annual Flows

It is important to remember that all previous studies have shown a significant decrease in the amount of snow in Quebec ([14–16], like many cold temperate regions. This decrease was confirmed within the framework of this study by analyzing the data available in a few watersheds (these results are not presented here). In these cold temperate regions where the annual runoff strongly depends on the amount of snow, it has been shown that the impacts of the decrease in this amount of snow have caused a significant drop in these flows, in particular the magnitude of the floods (see [6]).
However, analysis of the stationarity of the hydrological series using three statistical tests from 1930 to 2019 revealed that the interannual variability of mean annual flows during the period was characterized by an upward trend in flows (positive Z-scores) for 12 of the rivers analyzed (71%) but a downward trend (negative Z-scores) in only five of these rivers. An evolution toward an increase in mean annual flows was observed in the two hydroclimatic regions south of 47° N on both shores of the St. Lawrence River, while all rivers characterized by an evolution toward a decrease in mean annual flows were located north of this parallel on the south shore. Nevertheless, with regard to the statistical significance of the tests, there was a significant positive trend for only four rivers, three of which were located on the north shore and only one (Châteauguay River) of which was located on the south shore, south of 47° N. It is important to note that this river’s watershed was the most urbanized (urbanized area of >40%) of all the 17 watersheds analyzed. These trend analysis results clearly demonstrate that, despite the significant decrease in the amount of snow, the average annual flows do not decrease significantly over time in southern Quebec. On the contrary, they increase or remain constant over time. In contrast, Zhang et al. (2001) observed a near-widespread decrease in mean annual flows in southern Canada.

The absence of an overall decrease in these flows, despite a decrease in snowfall, can only be explained by the increase in rainfall observed on both shores of the St. Lawrence River. During the hot season (summer and fall), this increase in the amount of rainfall has been well documented throughout the northeastern part of North America [57,58], including Quebec [59,60]. This increase is also observed during the cold season (winter and spring) and its impacts translate into an almost general increase in the magnitude of winter floods and, to a lesser extent, that of spring floods. This increase in the amount of rainfall during the two seasons was confirmed by the analysis of data in a few stations as part of this study. It compensates for the deficit in the quantity of snow, thus making it possible to maintain or increase the annual flow. The increase in the amount of precipitation in the form of rain results from the almost general increase in temperature observed in Quebec and Canada as a whole.

In this context of increased rainfall following warming, the storage capacity of runoff water by wetlands and other water bodies does not change over time. Thus, the excess rainfall runs off, causing an upward trend in mean annual flows over time, which is more pronounced on the north shore (southwestern hydrologic region) than on the south shore [61]. On the latter, the significant decrease in agricultural areas since 1950 has reduced this upward trend in flows due to greater water infiltration, which easily absorbs excess rainfall.

This increase in water infiltration in the most agricultural watersheds on the south shore translates into a significant increase in minimum flows over time, unlike the watersheds on the north shore [24]. It follows that the presence of wetlands and other water bodies would tend to favor the increase in means annual flows over time, while the change in land use which results in a significant reduction in agricultural areas tends to attenuate this increase.

5. Conclusions

Like many cold temperate regions characterized by very snowy and cold winters, Quebec is experiencing a significant decrease in snowfall and an increase in winter temperatures due to global warming. The main objective of this study was to determine the impacts of these changes in temperature and precipitation regimes on the spatio-temporal variability of mean annual flows from 1930 to 2019.

With regard to spatial variability, the correlation analysis revealed that snowfall was the climate variable that was most positively correlated with mean annual flows. They were also positively correlated with watershed drainage density but negatively correlated with wetland/water bodies surface areas. As a result of these three factors, mean annual flows are generally higher in the most agricultural watersheds of the southeastern hydroclimatic
region on the south shore than in those less agricultural of the southwestern hydroclimatic
region on the north shore of the St. Lawrence River. On the north shore, the presence of
larger wetland and other water body surface areas supported runoff storage from snowmelt,
which limited its transfer to river channels. On the south shore, intensive drainage of these
wetlands into agricultural watersheds, since the modernization of agricultural practices
began in 1950, facilitated the rapid transfer of runoff to river channels.

As for temporal variability, the most significant finding of this study is the upward
trend in mean annual flows for most of the rivers analyzed despite the decrease in snowfall.
This upward trend is explained by the increase in temperature and rainfall, which com-
pensated for the decrease in snowfall. This increase in temperature and rainfall appears
to have had a greater impact on the rivers on the north shore than on those on the south
shore, likely due to the presence of wetlands, which are an important source of the moisture
needed to maintain rainfall intensities.

This study found that decreased snowfall did not lead to a widespread decrease in
mean annual flows in Quebec as expected due to the rise in temperatures and the resulting
increase in rainfall. However, no hydrologic and climate models have taken this increase
in temperatures and rainfall into account to predict the hydrological impact of decreased
snowfall in Quebec. In addition, in their predictions, these hydroclimatic models do not
take into account the amplification effects of wetlands and water bodies on the north shore
on the temporal variability of means annual flows on the one hand and the attenuation
effects exerted by the reduction in agricultural areas on this variability of flows on the south
shore on the other hand. This aspect must be taken into account to predict, with fewer
errors, the temporal variability of mean annual flows in future decades in southern Quebec.

**Funding:** This research was funded by the Natural Sciences and Engineering Research Council of
Canada (NSERC), grant number 261274/2019.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the author.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Danco, J.F.; DeAngelis, A.M.; Raney, B.K.; Broccoli, A.J. Effects of a Warming Climate on Daily Snowfall Events in the Northern
Hemisphere. *J. Clim.* 2016, 29, 6295–6318. [CrossRef]
2. Kapnick, S.B.; Delworth, T.L. Controls of Global Snow under a Changed Climate. *J. Clim.* 2013, 26, 5537–5562. [CrossRef]
3. Krasting, J.P.; Broccoli, A.; Dixon, K.; Lanzante, J. Future Changes in Northern Hemisphere Snowfall. *J. Clim.* 2013, 26, 7813–7828.
   [CrossRef]
4. O’Gorman, P.A. Contrasting responses of mean and extreme snowfall to climate change. *Nature* 2014, 512, 416–418. [CrossRef]
5. Janoski, T.P.; Broccoli, A.J.; Kapnick, S.B.; Johnson, N.C. Effects of Climate Change on Wind-Driven Heavy-Snowfall Events over
Eastern North America. *J. Clin.* 2018, 31, 9037–9054. [CrossRef]
6. Blöschl, G.; Hall, J.; Viglione, A.; Perdigão, R.A.P.; Parajka, J.; Merz, B.; Lun, D.; Arheimer, B.; Aronica, G.T.; Bilibashi, A.; et al.
   Changing climate both increases and decreases European river floods. *Nature* 2019, 573, 108–111. [CrossRef] [PubMed]
7. Aygün, O.; Kinnard, C.; Campeau, S.; Krogh, S.A. Shifting Hydrological Processes in a Canadian Agroforested Catchment due to
   a Warmer and Wetter Climate. *Water* 2020, 12, 7096–709-739. [CrossRef]
8. Boyer, C.; Chaumont, D.; Chartier, I.; Roy, A.G. Impact of climate change on the hydrology of St. Lawrence tributaries. *J. Hydrol.
   2010, 384, 65–83. [CrossRef]
9. Berghuijs, W.R.; Aalbers, E.E.; Larsen, J.; Trancoso, R.; Woods, R. Recent changes in extreme floods across multiple continents.
   *Environ. Res. Lett.* 2017, 12, 114035. [CrossRef]
10. Düll, P.; Schimied, H.M. How is the impact of climate change on river flow regimes related to the impact on mean annual runoff?
    A global-scale analysis. *Environ. Res. Lett.* 2012, 7, 014037. [CrossRef]
11. Lorenzo-Lacruz, J.; Vicente-Serrano, S.; Lopez-Moreno, I.; Morán-Tejeda, E.; Zabalza, J. Recent trends in Iberian streamflows
    (1945–2005). *J. Hydrol.* 2012, 414–415, 463–475. [CrossRef]
12. Jones, R.N.; Chiew, F.H.S.; Boughton, W.C.; Zhang, L. Estimating the sensitivity of mean annual runoff to climate change using
    selected hydrological models. *Adv. Water Resour.* 2006, 29, 1419–1429. [CrossRef]
13. McMahon, T.; Peel, M.C.; Pegram, G.G.S.; Smith, I.N. A Simple Methodology for Estimating Mean and Variability of Annual Runoff and Reservoir Yield under Present and Future Climates. J. Hydrometeorol. 2011, 12, 135–146. [CrossRef]

14. Brown, K.D. Analysis of snow cover variability and change in Quebec, 1948–2005. Hydrol. Processes. 2010, 24, 1929–1954. [CrossRef]

15. Guerfi, N.; Assani, A.A.; Mesfioui, M.; Kinnard, C. Comparison of the temporal variability of winter daily extreme temperatures and precipitations in southern Quebec (Canada) using the Lombard and copula methods. Int. J. Climatol. 2015, 35, 4237–4246. [CrossRef]

16. Yagouti, A.; Boulet, G.; Vincent, L.; Vescovi, L.; Mekis, E. Observed changes in daily temperature and precipitation indices for Southern Quebec, 1960–2005. Atmos. Ocean. 2008, 46, 243–256. [CrossRef]

17. Cunderlik, J.M.; Ouarda, T.B. Trends in the timing and magnitude of floods in Canada. J. Hydrol. 2009, 375, 471–480. [CrossRef]

18. Ehsanzadeh, E.; Adamowski, K. Trends in timing of low stream flows in Canada: Impact of autocorrelation and long-term persistence. Hydrol. Process. 2010, 24, 970–980. [CrossRef]

19. Khalili, M.N.; Ouarda, T.B.M.J.; Gachon, P.; Sushama, L. Temporal evolution of low-flow regimes in Canadian rivers. Water Resour. Res. 2008, 44, W08436. [CrossRef]

20. Khalili, M.; Ouarda, T.; Gachon, P. Identification of temporal trends in annual and seasonal low flows occurring in Canadian rivers: The effect of short- and long-term persistence. J. Hydrol. 2009, 369, 183–197. [CrossRef]

21. Zadeh, S.M.; Burn, D.H.; O’Brien, N. Detection of trends in flood magnitude and frequency in Canada. J. Hydrol. Reg. Stud. 2020, 28, 100673. [CrossRef]

22. Assani, A.; Charbon, S.; Matteau, M.; Mesfioui, M.; Quessy, J.-F. Temporal variability modes of floods for catchments in the St. Lawrence watershed. J. Hydrol. (2010). 2010, 385, 292–299. [CrossRef]

23. Assani, A.A.; Chalifour, A.; Légaré, G.; Manouane, C.-S.; Leroux, D. Temporal Regionalization of 7-Day Low Flows in the St. Lawrence Watershed in Quebec (Canada). Water Resour. Manag. 2011, 25, 3559–3574. [CrossRef]

24. Assani, A.A.; Zeroual, A.; Roy, A.; Kinnard, C. Impacts of Agricultural Areas on Spatio-Temporal Variability of Daily Minimum Extreme Flows during the Transitional Seasons (Spring and Fall) in Southern Quebec. Water 2021, 13, 3487. [CrossRef]

25. Beauchamp, M.; Assani, A.A.; Landry, R.; Massicotte, P. Temporal variability of the magnitude and timing of winter maximum daily flows in southern Quebec (Canada). J. Hydrol. 2015, 529, 410–417. [CrossRef]

26. Nalah, C.; Bezeouch, G.; Assani, A. Impacts of summer and winter conditions on summer river low flows in low elevation, snow-affected catchments. J. Hydrol. 2022, 605, 127393. [CrossRef]

27. Mazouz, R.; Assani, A.; Quessy, J.-F.; Légaré, G. Comparison of the interannual variability of spring heavy floods characteristics of tributaries of the St. Lawrence River in Quebec (Canada). Adv. Water Resour. 2012, 35, 110–120. [CrossRef]

28. Déry, S.J.; Stiegitz, M.; McKenna, E.C.; Wood, E. Characteristics and Trends of River Discharge into Hudson, James, and Ungava Bays, 1964–2000. J. Clim. 2005, 18, 2540–2557. [CrossRef]

29. Zhang, X.; Harvey, K.D.; Hogg, W.D.; Yuzyk, T.R. Trends in Canadian streamflow. Water Resour. Res. 2001, 37, 987–998. [CrossRef]

30. Adamowski, J.; Adamowski, K; Prokop, A. Quantifying the spatial temporal variability of annual streamflow and meteorological changes in eastern Ontario and southwestern Quebec using wavelet analysis and GIS. J. Hydrol. 2013, 439, 27–40. [CrossRef]

31. Negri, A.J.; Adler, R.F.; Xu, L.; Surratt, J. The Impact of Amazonian Deforestation on Dry Season Rainfall. J. Clim. 2004, 17, 1306–1319. [CrossRef]

32. Assani, A.A.; Landais, D.; Mesfioui, M.; Matteau, M. Relationship between the Atlantic Multidecadal Oscillation index and variability of mean annual flows for catchments in the St. Lawrence watershed (Quebec, Canada) during the past century. Hydrol. Res. 2010, 41, 115–125. [CrossRef]

33. Déry, S.J.; Wood, E.F. Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. Geophys. Res. Lett. 2004, 31, L18205. [CrossRef]

34. Déry, S.J.; Wood, E.F. Decreasing river in northern Canada. Geophys. Res. Lett. 2005, 32, L10 401. [CrossRef]

35. Belzile, L.; Bérubé, P.; Hoang, V.D.; Leclerc, M. Méthode Écodynamique de Détermination des débits Réservés pour la Protection des Habitats du Poisson dans les Rivières du Québec. In Rapport Présenté par l’INRS-Eau et le Groupe-Conseil Génivar Inc.; Au Ministère de l’Environnement et de la Faune et à Péches et Océans Canada: Québec, QC, Canada, 1997; 83p.

36. Assani, A.A.; Tardif, S. Classification and characterization of natural hydrologic regimes in Quebec (Canada). Factors of spatial variability—An ecogeographical approach. J. Wat. Sci. 2005, 18, 247–266.

37. Levison, J.; Larocque, M.; Fournier, V.; Gagné, S.; Pellerin, S.; Ouellet, M. Dynamics of a headwater system and peatland under current conditions and with climate change. Hydrolog. Proc. 2014, 28, 4808–4822. [CrossRef]

38. Croteau, A.; Nastev, M.; Lefebvre, R. Groundwater recharge assessment in the Chateaugay River watershed. Can. Wat. Res. J. 2010, 35, 451–468. [CrossRef]

39. Yue, S.; Pilon, P.; Cavadias, G. Power of the Mann-Kendall and Spearman’s rho tests for detecting monotonic trends in hydrological series. J. Hydrol. 2002, 259, 254–271. [CrossRef]

40. Hamed, K.H.; Rao, A.R. A modified Mann-Kendall trend test for autocorrelated data. J. Hydrol. 1998, 204, 182–196. [CrossRef]

41. Hamed, K. Enhancing the effectiveness of prewhitening in trend analysis of hydrologic data. J. Hydrol. 2009, 368, 143–155. [CrossRef]

42. Lombard, F. Rank tests for changepoint problems. Biometrika 1987, 74, 615–624. [CrossRef]
43. Dinpashoh, Y.; Mirabbasi, R.; Jhajharia, D.; Abianeh, H.Z.; Mostafaeipour, A. Effect of short-term and long-term persistence on identification of temporal trends. J. Hydrol. Engineering ASCE 2014, 19, 617–625. [CrossRef]

44. Kumar, M.; Duffy, C.J. Detecting hydroclimatic change using spatio-temporal analysis of time series in Colorado River Basin. J. Hydrol. 2009, 374, 1–15. [CrossRef]

45. Koutsoyiannis, D.; Montanari, A. Statistical analysis of hydroclimatic time series: Uncertainty and insights. Water Resour. Res. 2007, 43, W05429. [CrossRef]

46. Quessy, J.-F.; Favre, A.-C.; Said, M.; Champagne, M. Statistical inference in Lombard’s smooth-change model. Environmetrics 2011, 22, 882–893. [CrossRef]

47. Douglas, E.; Vogel, R.; Kroll, C. Trends in floods and low flows in the United States: Impact of spatial correlation. J. Hydrol. 2000, 240, 90–105. [CrossRef]

48. Ruiz, J. Modernization agriculture and agricultural land cover in Quebec (1951–2011). Cah. Géographie Québec 2019, 63, 213–230. (In French) [CrossRef]

49. Blanchette, M.; Rousseau, A.N.; Foulon, É.; Savary, S.; Poulin, M. What would have been the impacts of wetlands on low flow support and high flow attenuation under steady state land cover conditions? J. Environ. Manag. 2019, 234, 448–457. [CrossRef]

50. Fossey, M.; Rousseau, A. Assessing the long-term hydrological services provided by wetlands under changing climate conditions: A case study approach of a Canadian watershed. J. Hydrol. 2016, 541, 1287–1302. [CrossRef]

51. Fossey, M.; Rousseau, A. Can isolated and riparian wetlands mitigate the impact of climate change on watershed hydrology? A case study approach. J. Environ. Manag. 2016, 184, 327–339. [CrossRef]

52. Rajib, A.; Golden, H.E.; Lane, C.R.; Wu, Q. Surface Depression and Wetland Water Storage Improves Major River Basin Hydrologic Predictions. Water Resour. Res. 2020, 56, e2019WR026561. [CrossRef] [PubMed]

53. Quin, A.; Destourni, G. Large-scale comparison of flow-variability dampening by lakes and wetlands in the landscape. Land. Degrad. Devol. 2018, 29, 3617–3627. [CrossRef]

54. Wu, Y.; Zhang, G.; Rousseau, A.N.; Xu, Y.J.; Foulon, E. On how wetlands can provide flood resilience in a large river basin: A case study in Nenjiang river basin, China. J. Hydrol. 2020, 587, 125012. [CrossRef]

55. Acreman, M.C.; Holden, J. How wetlands affect floods. Wetlands 2013, 33, 773–786. [CrossRef]

56. Lane, C.R.; Leibowitz, S.G.; Autrey, B.C.; LeDuc, S.D.; Alexander, L.C. Hydrological, Physical, and Chemical Functions and Connectivity of Non-Floodplain Wetlands to Downstream Waters: A Review. JAWRA J. Am. Water Resour. Assoc. 2018, 54, 346–371. [CrossRef] [PubMed]

57. Sadri, S.; Kam, J.; Sheffield, J. Nonstationarity of low flows and their timing in the eastern United States. Hydrol. Earth Syst. Sci. 2016, 20, 633–649. [CrossRef]

58. Small, D.; Islam, S.; Vogel, R.M. Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception? Geophys. Res. Lett. 2006, 33, L03403. [CrossRef]

59. Perreault, L.; Haché, M.; Slivitzky, M.; Bobée, B. Detection of changes in precipitation and runoff over eastern Canada and U.S. using a Bayesian approach. Stoch. Hydrol. Hydraul. 1999, 13, 201–216. [CrossRef]

60. Assani, A.A.; Lajoie, F.; Vadrnis, M.-E.; Beauchamp, G. Influence of the Arctic oscillation on the interannual variability of precipitation in the Saint-François river watershed (Quebec, Canada) as determined by canonical correlation analysis. J. Water Sci. 2008, 21, 21–33. (In French)

61. Assani, A.A. Spatio-temporal variability of daily maximum flows in fall season in southern Quebec (Canada). J. Flood Risk Manag. 2022, submitted.