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Water Level Temporal Variability of Lake Mégantic during the Period 1920–2020 and Its Impacts on the Frequency of Heavy Flooding of the Chaudière River (Quebec, Canada)

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Abstract: The objective of this study is to analyze the temporal variability in water levels of Lake Mégantic (27.4 km^2) during the period 1920–2020 in relation to anthropogenic and natural factors on the one hand, and its impact on the intensity and frequency of heavy flooding (recurring floods $\geq$ 10 years) of the Chaudière River of which it is the source, on the other hand. The application of four different Mann–Kendall tests showed a significant decrease in lake water levels during this period. The Lombard test revealed two breaks in the average daily maximum and average water levels, but only one break in the average daily minimum water levels. The first shift, which was smoothed, occurred between 1957 and 1963. It was caused by the demolition in 1956 of the first dam built in 1893 and the significant storage of water in the dams built upstream of the lake between 1956 and 1975. The second shift, which was rather abrupt, occurred between 1990 and 1993. It was caused by the voluntary and controlled lowering of the lake's water levels in 1993 to increase the surface area of the beaches for recreational purposes. However, despite this influence of anthropogenic factors on this drop in water levels, they are negatively correlated with the global warming climate index. It is therefore a covariation, due to anthropogenic factors whose impacts are exerted at different spatial scales, without a physical causal link. However, the winter daily minimum water levels, whose temporal variability has not been influenced by anthropogenic activities, are positively correlated with the NAO and AO indices, but negatively with PDO. Finally, since the transformation of Lake Mégantic into a reservoir following the construction of the Mégantic dam in 1893 and 1973 to control heavy flooding in the Chaudière River, all recurrent floods $\geq$ 10 years have completely disappeared in the section of this river located downstream of Lake Mégantic. However, the disappearance of these floods and the drop in water levels of Lake Mégantic have not significantly impacted the stationarity in the flow series of the Chaudière River since 1920.

Keywords: water levels; flows; precipitation; reservoir; climatic indices; stationarity; correlation; Lake Mégantic; Chaudière River

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1. Introduction

Lakes of natural and anthropogenic origin are among the most widespread aquatic ecosystems on the continents. They significantly influence hydrological, biogeochemical, and ecological processes. They have provided many services to humans for millennia. Hydrologically, lakes contribute significantly to the storage of runoff water, coming from rain and/or melting snow and glaciers. They thus constitute one of the largest reservoirs of surface fresh water on the continents. If we consider lakes with a surface area < 10 ha, the total volume of water stored has been estimated at 181,900 km^3 [1]. At the watershed scale, this storage influences the water cycle to varying degrees through the processes of evapotranspiration, flow (floods and low flows), and infiltration (low flow) [2]. Like other water bodies, in the current context of global warming, lakes are subject to the effects of rising temperatures. Global warming can significantly impact fluctuations in their water levels. These impacts can be amplified or attenuated by anthropogenic activities (dams, agriculture, urbanization, deforestation, etc.). In this regard, numerous studies have been devoted to the analysis of natural and/or anthropogenic factors which influence the temporal variability in these water levels in several regions of the world (e.g., [3–12]). These studies have highlighted the great sensitivity of lakes to climate change and various anthropogenic activities. All these studies have demonstrated that these natural and anthropogenic impacts on water levels can vary from one lake to another even in the same climatic context. However, most of this work has been devoted to large lakes. There is little work on small lakes (<50 km^2), and even less on small river lakes (e.g., [13]). Unlike large lakes, the water levels of these small lakes, particularly those river lakes, are greatly affected by changes in the flow of their tributaries. Furthermore, even for these small lakes, most studies are much more interested in limnological and hydrobiological aspects than in hydro-climatological aspects.

Like other cold temperate regions of the world which have been subject to several successions of glacial and interglacial periods, the province of Quebec is one of the regions in the world which has the greatest number of lakes. In fact, in Canada, Quebec is the province with the largest number of lakes inherited from these periods. There are more than 500,000 lakes of different sizes (https://www.aventuresnouvellefrance.com/blog/lacs-rivieres-du-quebec/, accessed on 15 March 2024). These lakes have developed in all sectors of the watersheds due to the geological diversity of the province. They are much more numerous on the north shore of the Canadian Shield due to the impermeability of the rocks than on the south shore. This is mainly made up of sedimentary rocks. Many of them serve as the sources of many rivers in the province.

However, despite their spatial expansion in the landscape of the province and their certain contribution to the water cycle, on a strictly hydrological level, there are very few studies that have looked at the temporal variability in their water levels in the context of current global warming (e.g., [14]). These studies focused on the impacts of fluctuations in lake water levels on physicochemical characteristics as well as aquatic fauna and/or flora. The hydroclimatic aspects of these water level fluctuations have never been analyzed in relation to anthropogenic activities. The same is true of the numerous dam lakes and reservoirs. Paradoxically, there is a relatively abundant literature on the temporal variability in river flows. As part of these studies, extensive research on the variability in river flows during the period 1930 to 2020 was undertaken to determine the natural and anthropogenic factors that influence their spatiotemporal variability. These studies considered all temporal scales (e.g., [15–20]).

However, on a hydrological level, these flows are influenced by lakes, most of which serve as the source of numerous rivers in Quebec, as we have just highlighted. In addition, in many of these rivers, many lakes were also formed downstream of those located at the sources. Thus, they influence the fluctuations in the river flows downstream. Furthermore, many of these lakes have been transformed into reservoirs following the construction of numerous dams intended for different services (production of hydroelectric energy, flood control, navigation, recreational activities, resorts, etc.).

In light of these considerations, the main objective of this study is to fill this gap by analyzing the temporal variability in water levels in Lake Mégantic over a relatively long period (1920–2020) in relation to natural and anthropogenic factors (deforestation, agriculture and dam construction, etc.). Therefore, this is a purely hydroclimatic study. Remember that this aspect has never been analyzed in previous work on lake water levels in Quebec. This objective is based on the following hypothesis: the variability in water levels in Lake Mégantic results from the interaction of climatic and anthropogenic factors, like many river lakes in southern Quebec. Indeed, Lake Mégantic is very representative of natural river lakes, which have been transformed into reservoirs by the construction of dams at their outlets. The secondary objective of this study is to analyze the impact of Lake Mégantic as a reservoir on the control of heavy flooding of the Chaudière River of which it is the source. The hypothesis underlying this objective is to demonstrate that the lake has contributed to significantly reducing the frequency and intensity of heavy floods (recurrence floods $\geq$ 10 years), thus impacting the long-term trend in the flows of the Chaudière River. This is one of the rivers in Quebec that has faced serious recurring flooding since the 18th century (e.g., [21,22]).

2. Materials and Methods

2.1. Choice and Description of the Study Site

The choice of Lake Mégantic is justified by several factors: the existence of water level data measured over a relatively long period (more than 100 years), relatively strong anthropization of the watershed (construction of numerous dams in the watershed, deforestation, sharp increase in recreational and vacation activities, transformation of the lake into a reservoir to control flooding downstream, etc.), existence of climatic data, and the existence of data on the flows of the Chaudière River measured over a more or less long period, including Lake Mégantic.

Entirely circumscribed in the Appalachians, an ancient, folded mountain range composed mainly of sedimentary rocks, the watershed of Lake Mégantic covers a total area of approximately 781 km^2. From a hydroclimatic point of view, the Lake Mégantic watershed is in the southeast hydroclimatic region (south of 47° N), characterized by a mixed temperate continental and oceanic climate (e.g., [15]). Agriculture is less developed there, with the watershed being essentially forested (>80%). The total surface area of Lake Mégantic is 27.4 km^2 with a maximum depth of 75 m. Originally, Lake Mégantic was a natural lake which was transformed into a reservoir by the construction of dams at its downstream end. In 1893, the first dam was erected on the Chaudière River 3 km downstream from the lake. With a height of 6 m, this dam caused a rise in the water level of the lake by 1.37 m. It was demolished in 1956 and replaced by a small embankment in 1966 at the outlet of the lake. This containment was definitively replaced by the current Mégantic dam (height: 33 m, total retention capacity: 95,600,000 m^3), the construction of which began in 1968 and was completed in 1973 [23] (Figures 1 and 2). Alongside these works, numerous dams of different sizes were also erected, particularly during the period 1956 and 1975 upstream of the lake. These reservoirs stored significant volumes of water, as shown in Figure 3. In fact, the volumes of water stored in the different reservoirs were multiplied by 27 between 1955 and 1975 upstream of the lake. They went from 4,154,850 m^3 in 1955 to 113,547,649 m^3 in 1975.

The Chaudière River has its source in Lake Mégantic and covers a distance of 185 km before flowing into the St. Lawrence River, of which it is one of the main tributaries on the south shore (Figure 1). Its watershed covers an area of 6685 km^2. With its tributaries, it cuts into two geological formations: the Appalachians (90% of the watershed area) and the Saint-Laurent lowlands (10%). The Saint-Laurent lowlands, with a relatively flat topography, are also mainly made up of rocks and sedimentary deposits [22] (Figure 1).

2.2. Data Sources and Constitution of Hydroclimatic Series

The data on the daily water levels of Lake Mégantic and those on the characteristics of the dams built in the watershed were taken from the website of the Water Expertise Center of the Ministry of the Environment and the Fight against Climate Change, Wildlife and Parks of the province of Quebec (https://www.cehq.gouv.qc.ca/hydrometrie/, consulted on 20 February 2021). These data cover the period 1920 to 2020. However, there are no data for the years 1964, 1965, and part of the year 1966. These missing data only represent less than 5% of all data during the period of 100 years. In addition, the analysis of climatic data and pristine river flows revealed that these three years did not contain extreme hydroclimatic events likely to significantly impact the averages of the lake water level series. Finally, all the statistical tests used cope perfectly with missing data. Thus, these did not affect their results. In addition to the water levels, we also extracted the data of the daily flows of the Chaudière River measured downstream of Lake Mégantic on the one hand,

and those of the flows of the Famine River (696 km^2), one of its pristine main tributaries, on the other hand. For the Chaudière River, we retained the flows which are measured at two stations located downstream near the Mégantic dam: S1 (1170 km^2), from 1915 to 1983, and S2 (781 km^2) since 1977 (Figure 1). The flows of the Famine River have been measured since 1964 (Figure 1). Regarding the climatic data, the temperature and daily precipitation data measured at the Saint-Ludger station (45°45′ N, 70°41′ W, 335 m) were extracted from the website of the same ministry. Finally, as for the climate index data, they were extracted from the National Oceanic and Atmospheric Administration (NOAA) website (https://psl.noaa.gov/data/climateindices/list/, accessed on 20 May 2022). We extracted monthly data from six climate indices whose influence on the variability in flows, temperatures, and precipitation has already been demonstrated in southern Quebec (e.g., [24–26]). These are the following climate indices: AMO (Atlantic Multidecadal Oscillation), AO (Arctic Oscillation), NAO (North Atlantic Oscillation), Niño3.4, PDO (Pacific Decadal Oscillation), and the Global Mean Land/Ocean Temperature Index (GMLOT).

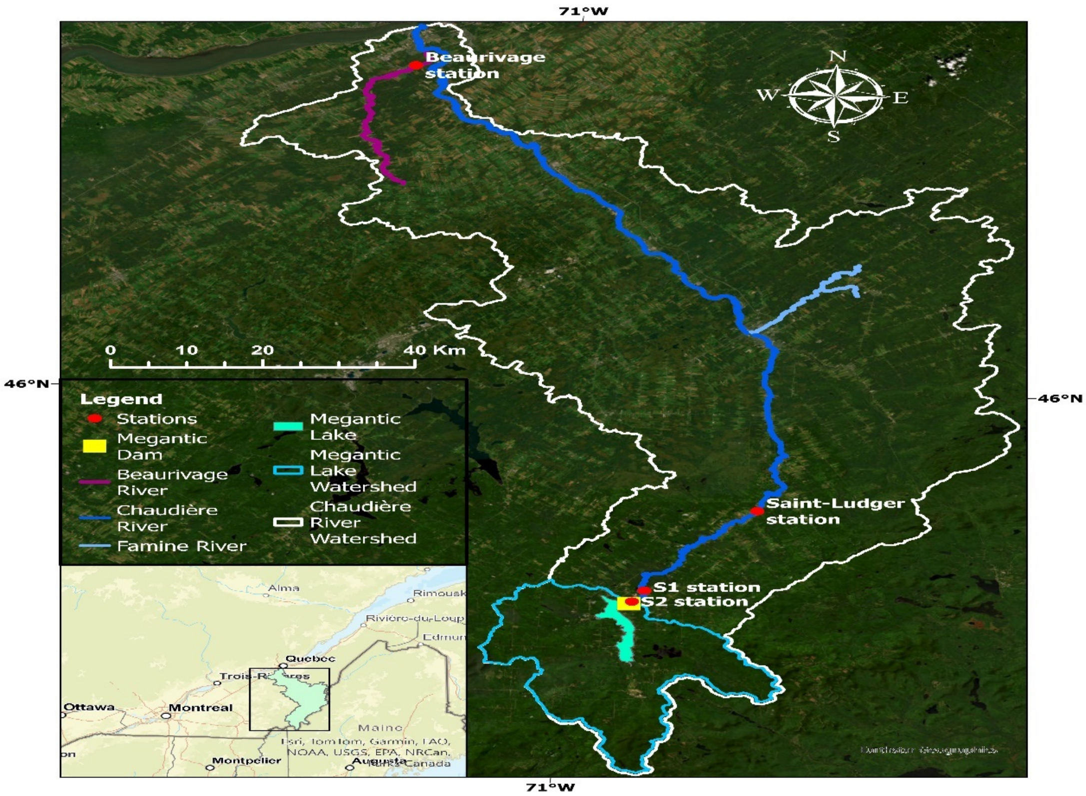

Figure 1. Lake Mégantic and the Chaudière River watersheds. Saint-Ludger station is a climatic station. The other stations are hydrometric stations.

For the water levels of Lake Mégantic and the flows of the Chaudière and Famine Rivers, the following hydrological series were created: five series of average water levels and flow rates (average daily values on annual and seasonal scales), maximum (the highest daily values measured on annual and seasonal scales) and minimum (the lowest values measured on annual and seasonal scales) annual and seasonal daily values (winter: from January to March; spring: from April to June; summer: from July to September, and autumn: October to December). For the temperature and precipitation data, the following four climatic series were created on an annual scale: the annual daily mean temperatures, the total annual quantities of rainfall, snowfall, and total precipitation (snow and rain). Finally, regarding the climatic indices, for each index, we created five annual and seasonal series such as those of water levels and flows.

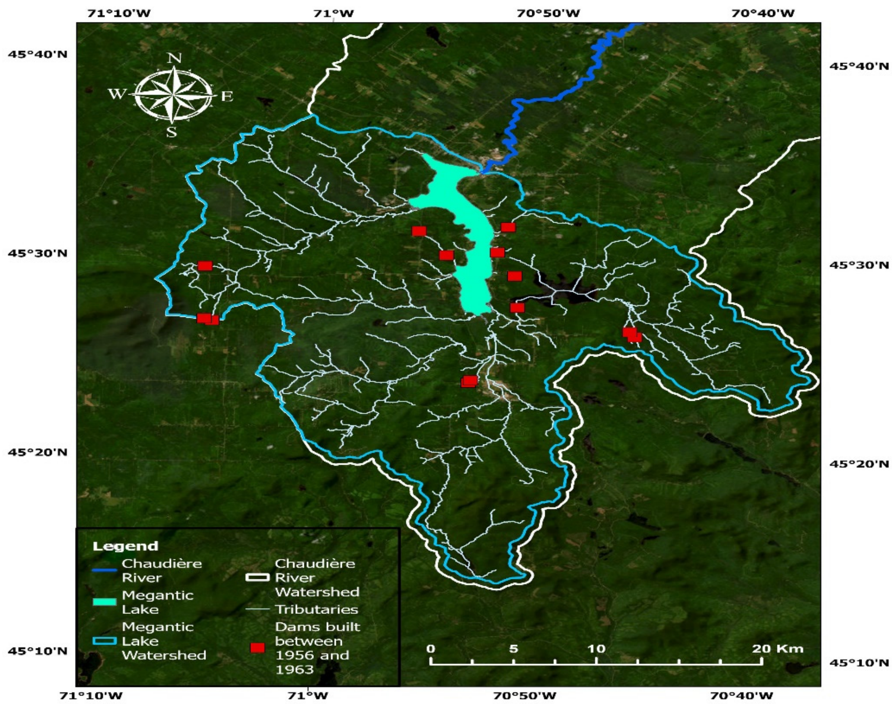

Figure 2. Lake Mégantic watershed.

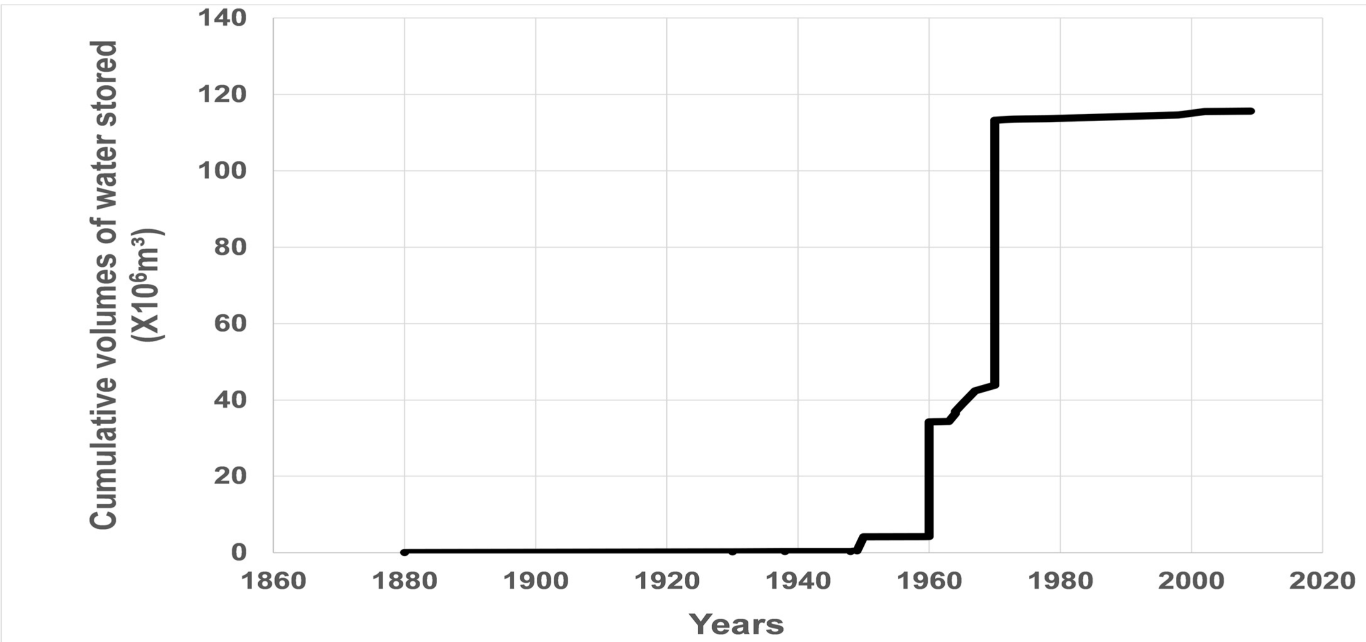

Figure 3. Interannual variability in cumulative volumes of water stored upstream of Lake Mégantic.

2.3. Statistical Data Analysis

The main objective of this study is to analyze the stationarity (change in the mean) in the Lake Mégantic water levels and its impacts on the stationarity in the flows of the Chaudière River. To achieve this objective, in the first step, we analyzed the temporal variability in water levels, flows, temperatures, and precipitations. Five statistical tests were applied. The first test was that of Mann–Kendall (MMK) [27]. But as this test does not make it possible to eliminate the effects of persistence in the short and long term, we applied three other tests to eliminate the impacts of these two effects on the stationarity of the hydroclimatic series. The first two tests applied make it possible to eliminate the effects of the short-term persistence by data pre-whitening (TPCW) (e.g., [28]) and the correction of the variances of statistical series (MMKH) (e.g., [29]). The last test made it possible to eliminate long-term persistence (LTP) effects (e.g., [30]). All these tests have already been described extensively in the scientific literature.

In the second stage, we analyzed the relationship between climate indices and the water levels of Lake Mégantic at annual and seasonal scales using simple and multivariate correlation methods. It turned out that multivariate methods based on canonical correlation, redundancy analysis, and the Bayesian method did not lead to any conclusive results at the annual and seasonal scales. Consequently, only the results obtained by the simple linear correlation method were retained.

In the third step, we applied the Lombard test (e.g., [31,32]) to detect the shifts in the averages of the hydroclimatic series. The choice of this test is justified by the fact that it makes it possible to determine abrupt or gradual (smoothed) shifts in averages, unlike other commonly used tests. It is a more general test than other commonly used tests which can only detect abrupt shifts.

Finally, at the last stage, to demonstrate the impacts of Lake Mégantic being transformed into a reservoir from 1893 to 1956 and since 1973, on the intensities and frequencies of flooding of the Chaudière River, we compared the magnitude and frequency in the flows of heavy flooding (recurring floods $\geq$ 10 years) downstream of the Mégantic dam and in the Famine River, which is one of its main pristine tributaries. This comparison made it possible to verify the contribution of Lake Mégantic to flood control in the Chaudière River. Remember that the method used to estimate recurrence flows $\geq$ 10 years is that developed by [33] for Quebec. This is a regionalized method based on the law of GEVs (Generalized Extreme Values). It has already been exposed in several works (e.g., [20,33]). The advantage of this method lies in the fact that it makes it possible to estimate the flood flows of different return periods of all the rivers of Quebec even in the absence of flow measurements. It is therefore recommended by the provincial Ministry of the Environment, the Fight against Climate Change, Wildlife and Parks for estimating the flows of different recurrences across the entire province, which justifies its use in this work.

3. Results

3.1. Analysis of the Temporal Variability in Water Levels in Lake Mégantic during the Period 1920–2020

The results of the Lombard tests and four Mann–Kendall tests applied to daily maximum, minimum, and average water levels on annual and seasonal scales are presented in Table 1. The temporal variability in these water levels during the 1920–2020 period is presented in Figure 4 (daily maximum water levels) and Figure 5 (daily minimum water levels). Regarding the four Mann–Kendall tests, their results are consistent. They reveal a significant drop in annual and seasonal daily maximum daily and mean water levels (negative Z values). As for annual and seasonal daily minimum water levels, this decrease is observed only in spring and autumn, the two flood seasons. As for the Lombard test, the shifts in the averages in the daily maximum and average water level series occurred between 1957 and 1963. However, in autumn, this break occurred in 1945–1946 for daily minimum water levels and between 1937 and 2011 for daily average water levels. This last shift is much more gradual (smoothed) than the other shifts.

To detect other breaks in the averages, the water level series before and after these main breaks (1957–1963) were analyzed using the Lombard test. The results are presented in Table 2. It is clear from this table that the annual and seasonal daily maximum and average water level series were affected by a second shift in the means occurring during the period 1990–1993. This second shift was, therefore, more abrupt than the first. This second shift was even detected on the series of daily average water levels in autumn. As for the annual and seasonal daily minimum water level series, apart from the summer season, no new shift in the averages was detected. It is important to note that the period 1920–1956 (before the occurrence of the first break in averages) is not affected by any shift in water level averages (Table 2).

Table 1. Results of the analysis of the interannual variability of water levels in Lake Mégantic using the Lombard test and various Mann–Kendall tests during the period 1920–2020.

Scale	MMK		TPCW		MMKH		LTP		Lombard Test	
	Z	*p*-Values	Z	*p*-Values	Z	*p*-Values	Z	*p*-Values	S_n	T1–T2
					Year					
Maximum	**−8.909 ***	0.000	**−9.135 ***	0.000	**−9.817 ***	0.000	**−4.917 ***	0.000	**0.671 ***	1957–1963
Minimum	−1.232	0.218	−1.181	0.238	−1.144	0.253	−0.758	0.449	0.025	-
Mean	**−8.545 ***	0.000	**−9.970 ***	0.000	**−6.404 ***	0.000	**−2.096 ***	0.036	**0.624 ***	1959–1963
					Winter					
Maximum	**−5.418 ***	0.000	**−5.454 ***	0.000	**−8.285 ***	0.000	**−2.691 ***	0.007	**0.292 ***	1959–1960
Minimum	**−3.302 ***	0.001	**−3.650 ***	0.000	**−3.218 ***	0.001	−1.602	0.109	**0.106 ***	1959–1960
Mean	**−4.880 ***	0.000	**−5.382 ***	0.000	**−5.606 ***	0.000	**−2.446 ***	0.014	**0.205 ***	1959–1960
					Spring					
Maximum	**−8.584 ***	0.000	**−8.742 ***	0.000	**−9.103 ***	0.000	**−5.233 ***	0.000	**0.648 ***	1957–1963
Minimum	**−4.839 ***	0.000	**−4.553 ***	0.000	**−5.698 ***	0.000	**−3.695 ***	0.000	**0.200 ***	1962–1963
Mean	**−9.972 ***	0.000	**−11.341 ***	0.000	**−4.093 ***	0.000	**−2.708 ***	0.007	**0.755 ***	1960–1963
					Summer					
Maximum	**−8.244 ***	0.000	**−8.926 ***	0.000	**−5.117 ***	0.000	**−2.615 ***	0.009	**0.572 ***	1960–1963
Minimum	−0.983	0.326	−0.921	0.000	−1.190	0.234	−0.591	0.554	0.005	-
Mean	**−6.312 ***	0.000	**−6.685 ***	0.000	**−6.629 ***	0.000	**−2.524 ***	0.012	**0.380 ***	1961–1962
					Fall					
Maximum	**−6.235 ***	0.000	**−6.280 ***	0.000	**−6.877 ***	0.000	**−4.238 ***	0.000	**0.339 ***	1962–1963
Minimum	**−3.797 ***	0.000	**−3.186 ***	0.000	**−4.150 ***	0.000	**−2.254 ***	0.024	**0.134 ***	1945–1946
Mean	**−6.379 ***	0.000	**−6.163 ***	0.000	**−5.816 ***	0.000	**−3.802 ***	0.000	**0.354 ***	1937–1911

* = Z and S_n values statistically significant at the 5% threshold. T1 = year of the start of the shift in the mean and T2, year of the end of the shift in the mean. Blue: negative trend.

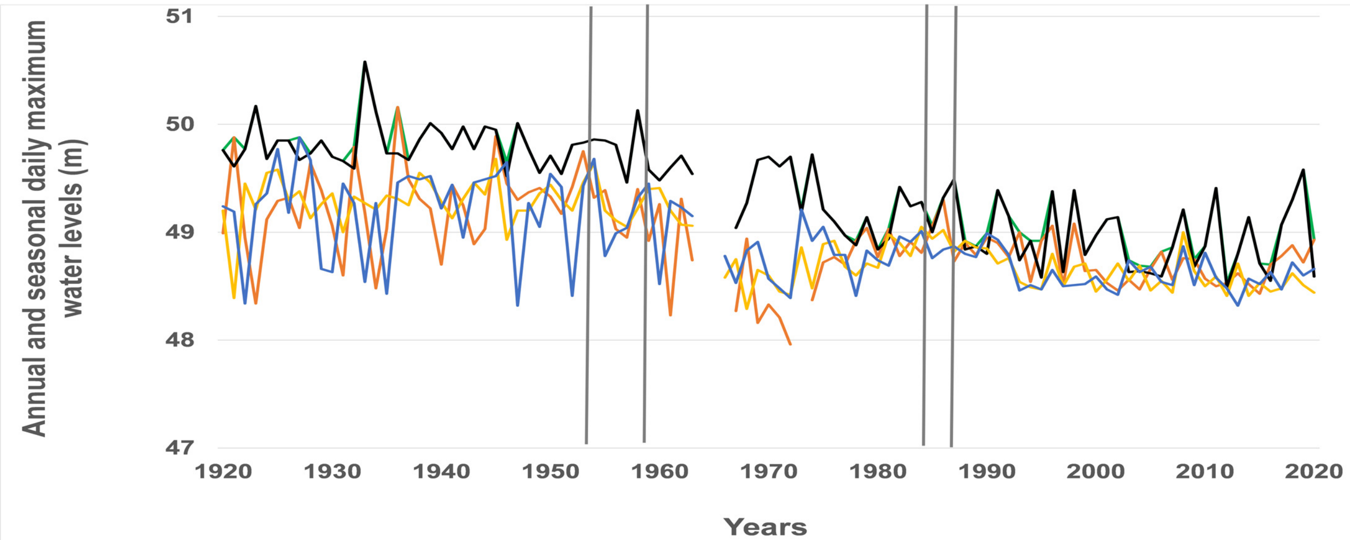

Figure 4. Interannual variability in annual and seasonal daily maximum water levels of Lake Mégantic during the period 1920–2020. Year: green curve; winter: red curve; spring: black curve; summer: yellow curve; autumn: blue curve. The vertical bars demarcate the two major periods of shifts in the averages (1957–1963 and 1990–1993).

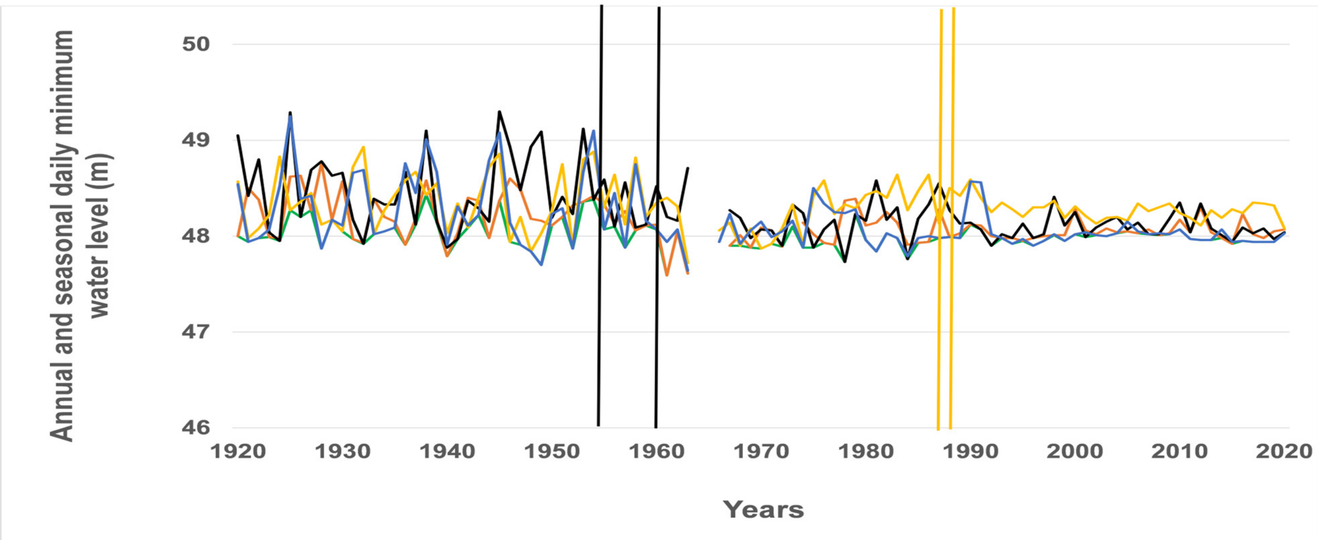

Figure 5. Interannual variability in annual and seasonal daily minimum water levels of Lake Mégantic during the period 1920–2020. Year: green curve; winter: red curve; spring: black curve; summer: yellow curve; autumn: blue curve. The vertical bars demarcate the two major periods of shifts in the averages (1957–1963 and 1990–1993).

Table 2. Results of the analysis of the interannual variability in water levels in Lake Mégantic using the Lombard test before and after the main shift in the average (1957–1963).

Water Levels	Before Mean Shift Period (1920–1956)		After Mean Shift Period (1964–2020)	
	Sn	T1–T2	S_n	T1–T2
		Year		
Maximum	0.010	-	**0.0403 ***	1991–1993
Minimum	0.000	-	0.339	-
Mean	0.000	-	**0.258 ****	1991–1993
		Winter		
Maximum	0.010	-	**0.116 ****	1991–1993
Minimum	0.001	-	0.002	-
Mean	0.000	-	**0.258 ****	1991–1993
		Spring		
Maximum	0.001	-	**0.0395 ***	1990–1993
Minimum	0.001	-	0.0152	-
Mean	0.005	-	**0.208 ****	1990–1993
		Summer		
Maximum	0.001	-	**0.197 ****	1991–1992
Minimum	0.001	-	**0.120 ****	1991–1992
Mean	0.001	-	**0.223 ****	1991–1993
		Fall		
Maximum	0.001	-	**0.115 ****	1991–1992
Minimum	0.001	-	0.018	-
Mean	0.001	-	**0.163 ****	1991–1992

** = S_n values statistically significant at the 5% threshold; * = Sn values statistically significant at the 10% threshold T1 = year of the start of the break in the mean and T2, year of the end of the break in the mean. Blue: decrease in means after the shift.

It follows that the annual and seasonal daily maximum and average water levels are affected by two shifts in the averages while the annual and seasonal daily minimum water levels are affected by a single shift. The first shift affected the daily minimum flows in spring and autumn while the second affected the daily minimum flows in summer and on an annual scale. Only the daily minimum flows in winter were not affected by any break in the average.

3.2. Analysis of the Temporal Variability in the Flows of the Famine River as Well as the Temperatures and Precipitation Measured at the Saint-Ludger Climatic Station

The temporal variability in water levels in Lake Mégantic was compared to that of the flows of the Famine River, a pristine tributary of the Chaudière River which flows downstream of the lake. Remember that the measurements of these flows cover the period 1964–2020, the period synchronous with those of the lake water levels measured after the first break in the averages (1957–1963). This period corresponds to the phase of continuous decrease in lake water levels. The results of the application of the Lombard and Mann–Kendall tests (the latter were applied only to the flow of the Famine River) are presented in Table 3. Unlike the temporal variability in the lake water levels, neither the flow rates of the Famine River (positive Z values), temperatures, nor precipitation show any decrease. In fact, for the Famine River, maximum daily flows increased significantly over time in autumn only. The increase in the average of these flows, which was abrupt, occurred in 2002–2003. As for daily minimum flows, they have increased significantly on an annual scale and in winter. These breaks in the averages occurred at the same time as that of the maximum flows in winter but earlier (1992–1993) than that which occurred on an annual scale. As for temperatures and precipitation, they have increased significantly over time (Figure 6), except for the total annual snowfall, which tends to decrease over time. This significant increase in averages occurred in 1996–1997 for annual average daily temperatures and in 1971–1972 for total annual rainfall.

Table 3. Results of the analysis of the interannual variability in the flows of the Famine River using the Lombard test and various Mann–Kendall tests during the period 1964–2020.

	MK		**TPCW**		**MMKH**		**Lombard Test**	
	Z	***p*-Values**	**Z**	**Sn**	**T1–T2**	***p*-Values**	**S_n**	**T1–T2**
				Famine River				
				Year				
Maximum	1.138	0.255	1.118	0.264	1.138	0.255	0.0168	-
Minimum	**2.665 ****	0.008	**2.207 ****	0.027	**2.269 ****	0.023	**0.0678 ****	2002–2003
Mean	0.389	0.697	0.203	0.839	0.432	0.666	0.0029	-
				Winter				
Maximum	1.150	0.344	0.855	0.392	1.194	0.232	0.008	-
Minimum	**2.657 ****	0.014	**2.396 ****	0.017	**2.657 ****	0.008	**0.072 ****	1992–1993
Mean	1.180	0.070	1.378	0.168	1.810	0.070	0.025	-
				Spring				
Maximum	0.557	0.573	0.261	0.794	0.587	0.558	0.0071	-
Minimum	0.933	0.351	0.697	0.486	0.999	0.318	0.0093	-
Mean	−0.572	0.567	−0.900	0.368	−0.576	0.567	0.0055	-
				Summer				
Maximum	−1.033	0.3016	0.943	0.346	−1.033	0.010	0.0101	-
Minimum	**1.798 ***	0.072	1.301	0.193	**1.729 ***	0.084	0.0283	-
Mean	−1.395	0.163	−1.466	0.143	−1.310	0.190	0.028	-

Table 3. *Cont.*

	MK		TPCW		MMKH		Lombard Test	
	Z	*p*-Values	Z	Sn	T1–T2	*p*-Values	S_n	T1–T2
				Fall				
Maximum	**2.059 ***	0.039	**1.673 ***	0.094	**1.803 ***	0.071	**0.054 ****	2002–2003
Minimum	−0.624	0.533	−0.640	0.522	−0.773	0.440	0.003	-
Mean	1.503	0.133	1.356	0.175	1.503	0.173	0.025	-
Saint-Ludger station (Annual daily mean temperature and annual total precipitations)								
Temperature							**0.1744 ****	1996–1997
Rainfall							**0.0634 ****	1971–1972
Snowfall							0.0063	-

** = Z and S_n values statistically significant at the 5% threshold; * = Z and S_n values statistically significant at the 10% level; T1 = year of the start of the shift in the average and T2, year of the end of the shift in the average. Red: increase in means after shift.

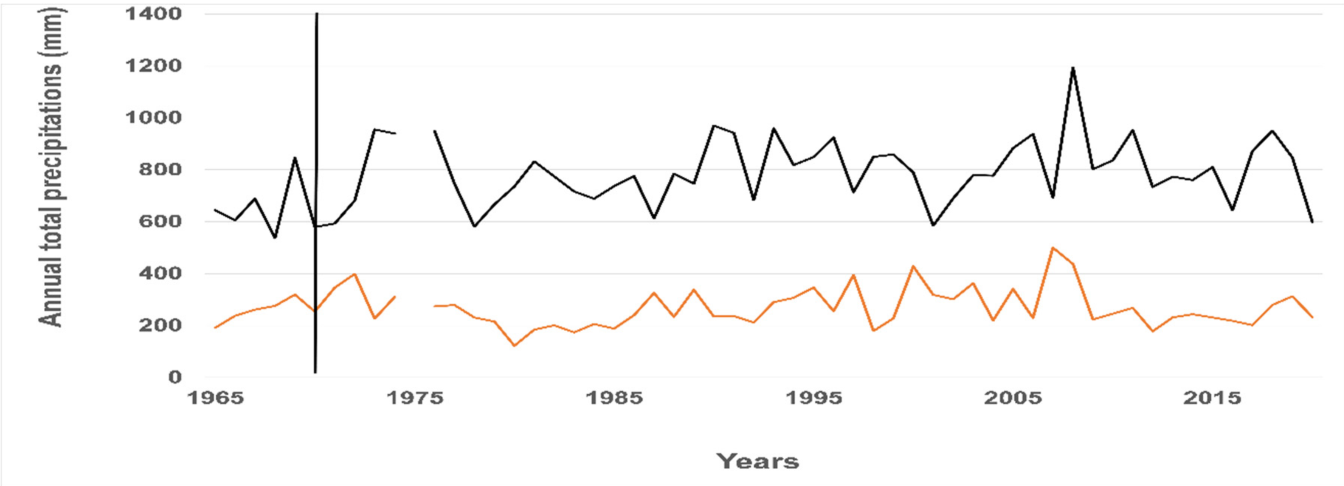

Figure 6. Interannual variability of the annual total rainfall (black curve) and snowfall (red curve) at the Saint-Ludger station during the period 1950–2020. The vertical bar indicates the end year of shift (T2) in the average.

3.3. Relationship between Water Levels and Climate Indices

The results of the correlation analysis between the water levels of Lake Mégantic and the climatic indices are presented in Table 4. These results clearly demonstrate that the maximum and average daily water levels are negatively correlated with the climatic index of global warming (GMLOT) on annual and seasonal scales. However, for daily average water levels, they are not correlated with this index only in winter, during which they become significantly correlated with the NAO climate index. As for daily minimum water levels, they are significantly correlated with the global warming climate index only in spring and autumn, the two flood seasons during which these water levels decreased significantly over time, as shown above (see Table 1). In addition to this index, these minimum water levels are also positively correlated with the AMO, on an annual scale and in spring, as well as with the NAO and AO indices in winter. During this last season, they become negatively correlated with the PDO. No significant correlation was observed between the global warming climate index and the flows of the Famine River as well as the temperatures and precipitation measured at the Saint-Ludger station (the results are not presented here).

Table 4. Coefficients of correlation calculated between the water levels of Lake Mégantic and climate indices during the period 1950–2020.

	AMO	AO	GMLOT	NAO	NINO	ONI	PDO
				Year			
Maximum (year)	−0.095	**−0.284** **	**−0.611** **	−0.150	−0.195	0.001	**−0.351** **
Minimum (year)	**0.284** **	0.045	−0.008	−0.042	−0.041	−0.018	−0.108
Mean (year)	0.053	−0.140	**−0.597** **	−0.082	−0.189	0.015	−0.204 *
				Winter			
Maximum (fall)	0.109	−0.010	**−0.220** *	0.185	0.039	0.132	0.002
Minimum (fall)	0.039	**0.202** *	−0.039	**0.341** **	0.087	0.123	**−0.205** *
Mean (fall)	−0.012	0.123	−0.193	**0.294** **	0.021	0.088	0.034
				Spring			
Maximum (spring)	−0.104	−0.121	**−0.610** **	0.035	−0.152	0.021	**−0.399** **
Minimum (spring)	**0.323** **	**−0.237** **	**−0.251** **	−0.171	−0.013	0.094	−0.059
Mean (spring)	0.060	**−0.214** *	**−0.733** **	0.011	**−0.202** *	0.025	**−0.346** **
				Summer			
Maximum (spring)	0.090	−0.199	**−0.582** **	0.054	**−0.269** **	−0.100	**−0.229** *
Minimum (spring)	0.119	0.183	−0.037	−0.025	0.011	0.033	0.191
Mean (summer)	0.001	0.108	**−0.435** **	0.016	−0.173	−0.019	0.025
				Fall			
Maximum (summer)	−0.131	0.020	**−0.548** **	−0.037	−0.200	−0.016	−0.094
Minimum (summer)	−0.033	0.049	**−0.355** **	−0.008	−0.199	−0.095	−0.071
Mean (fall)	−0.109	0.020	**−0.530** **	−0.009	**−0.212** *	−0.041	−0.049

** = statistically significant value at the 5% threshold; * = statistically significant value at the 10% threshold. (fall) = climatic indices of the fall season significantly correlated with water levels. Red = positive correlation; Blue: negative correlation.

3.4. Analysis of the Impacts of Lake Mégantic on the Long-Term Flow Trend and Flooding of the Chaudière River

Having become a sort of reservoir following the construction of dams in 1893 and 1973, Lake Mégantic's role is, among other things, to control the flooding of the Chaudière River of which it is the source (outlet). To determine the impacts of the Mégantic dam on the temporal variability in the flows of the Chaudière River, we analyzed the flows of this river measured at two stations (S1 and S2) located downstream of the dam during the period 1915 to 2020 using the Lombard and Mann–Kendall tests. In Table 5 only the results of the first test are presented. It is only at station 1 (S1) that we detected a break in the averages during the period 1915 to 1983 on the series of daily maximum flow on an annual scale, in winter and sp3ing on the one hand, and on the series of average daily spring flows, on the other hand. Concerning the maximum daily flows, the shifts in the means occurred in 1931–1932 in spring and in 1970–1971 in winter. As for the daily average spring flows, the break in the average occurred in 1952–1953. The various Mann–Kendall tests, the results of which are not presented in this table, demonstrated that after these breaks in averages, the maximum and average flow rates significantly increased over time at this station on the Chaudière River, unlike the water levels of Lake Mégantic, which have decreased over time. In addition, the dates (years) of shifts in the mean flows of the Chaudière River are not synchronous with those of the water levels of Lake Mégantic. This is the case with the flow measured at station S2 during the period from 1977 to 2020. These flows are not affected by any break in the averages. It follows that the drop in water levels of Lake Mégantic did not impact the stationarity in the flow series of the Chaudière River since the quantity of water released downstream is regulated by the Mégantic dam. In addition, the voluntary lowering of lake water levels carried out in 1993 was controlled to minimize its impact on the flows of the Chaudière River.

Table 5. Results of the analysis of the interannual variability of the flows of the Chaudière River downstream of Lac Mégantic using the Lombard test.

Daily Flows	S1 (1170 km^2): 1920–1983 Sn	T1–T2	S2 (781 km^2): 1979–2020 Sn	T1–T2
		Year		
Maximum	**0.0647 ***	1931-1932	0.0045	-
Minimum	0.0136	-	0.0172	-
Mean	0.0238	-	0.0138	-
		Winter		
Maximum	**0.0453 ***	1970-1972	0.0110	-
Minimum	0.0053	-	0.009	-
Mean	0.0353	-	0.0037	-
		Spring		
Maximum	**0.0557 ***	1931-1932	0.0180	-
Minimum	0.0261	-	0.0027	-
Mean	**0.0476 ***	1952-1953	0.0052	-
		Summer		
Maximum	0.0172	-	0.0019	-
Minimum	0.0039	-	0.0080	-
Mean	0.0070	-	0.0093	-
		Fall		
Maximum	0.0183	-	0.0197	-
Minimum	0.0045	-	0.0041	-
Mean	0.0078	-	0.0117	-

* = Sn values statistically significant at the 5% threshold. T1 = year of the start of the break in the mean and T2, year of the end of the break in the mean.

Furthermore, to analyze the impacts of the Mégantic dam on the intensity and frequency of flooding in the Chaudière River, we compared the intensity and frequency of recurrent floods ≥ 10 years measured at station S2, downstream of the Mégantic dam, and in the Famine River during the period of joint measurements of the flow of two rivers from 1980 to 2020. The results presented in Table 6 and Figure 7 clearly demonstrate that no recurrence flow ≥ 10 years has been measured downstream of Lake Mégantic during this period. On the other hand, during the same period, recurrence flows ≥ 100 years were even measured in the Famine River. The return period of its highest daily flow even exceeded 500 years. This figure also reveals that the difference in annual daily maximum flows between the two rivers has become increasingly greater since the 2000 decade. This reflects an increase in flood intensities in the Chaudière River watershed under natural conditions. Finally, it is important to point out that no recurrent flood ≥ 10 years was also observed at station S1 during the period 1920 to 1980 (the results are not presented here). We can therefore conclude that the heavy flooding has disappeared in the section of the Chaudière River located just downstream of the Mégantic dam. However, it is important to keep in mind that further downstream from the dam, these heavy floods frequently occur due to the very frequent formation of ice jams and the resulting break-ups ([19,20]) on the one hand, and the contributions of its pristine tributaries such as the Famine River, on the other hand.

Table 6. Comparison of the frequencies (in years) of the flow rates of different return periods of the Chaudière (downstream of Lake Mégantic) and Famine rivers during the period 1980–2020.

Return Period (in Years)	Chaudière River (781 km^2) Downstream from Mégantic Dam		Famine River (696 km^2) Pristine River	
	Flows (m^3/s) *	Frequency (in Years)	Flows (m^3/s) *	Frequency (in Years)
Q10	241.9	0	223.2	13
Q25	276.4	0	255	10
Q50	299.6	0	276.4	7
Q100	320.9	0	296	3
Qmax	190.6	<Q10	500.2	>Q500

Qmax = the highest daily flow measured during the period 1980–2020; * = flow values estimated by the regionalized GEV law ([31]).

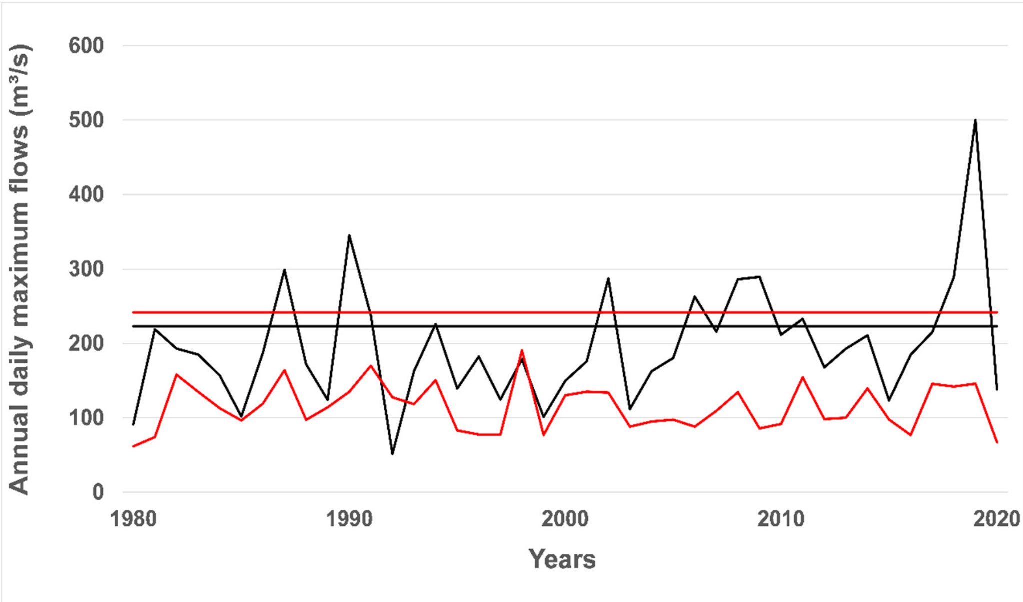

Figure 7. Interannual variability in annual maximum daily flows of the Chaudière River downstream of the Mégantic dam (red curve) and the Famine River (black curve) during the period 1980–2020. The horizontal lines indicate the values of recurrence flows $\geq$ 10 years estimated at the two stations (see Table 6).

4. Discussion

The application of four Mann–Kendall tests, which eliminate short- and long-term dependence effects, highlighted a significant decrease in the daily water levels of Lake Mégantic during the period 1920–2020. This lake also serves as the source of the Chaudière River. However, only winter daily minimum water levels did not significantly decrease during this period. The application of the Lombard test made it possible to detect two breaks in the averages of the daily maximum and average water levels but only one break in the averages of the daily minimum water levels. The first break, which was gradual, occurred between 1957 and 1963. As for the second break in the averages, which was relatively abrupt, it occurred between 1990 and 1993. For the daily minimum water levels, the break in the averages affected the minimum daily flows in spring and fall, two flood seasons, and the last break affected minimum water levels in summer.

The decrease in lake water levels and its two breaks in averages may result from the interaction of natural and anthropogenic factors. Regarding the natural factors, the analysis of annual precipitation (snow and rain) measured at the Saint-Ludger climatic station during the period 1964–2020 using the same statistical tests revealed a significant increase in the annual total rainfall. The application of the Lombard test revealed that the date (year) of the abrupt break in the average of this rainfall occurred between 1971 and 1972. This date is not synchronous with those of the breaks in the average water levels of Lake Mégantic. Furthermore, the analysis of the annual and seasonal daily flows of the Famine River, one of the main pristine tributaries of the Chaudière River, by means of these same statistical tests, demonstrated that these flows did not significantly decrease over time, unlike the water levels of Lake Mégantic during the period 1964–2020. On the contrary, we observed a significant increase in the annual and winter daily minimum flows on the one hand, and that of the autumn daily maximum flows of the Famine River, on the other hand. In addition to the Famine River, the analysis of the annual and seasonal daily flows of the Beaurivage River, the largest natural tributary of the Chaudière River, had also revealed no significant drop in flows during the period 1930–2020 (e.g., [15–20]). It appears from all these results that the significant decrease in water levels in Lake Mégantic cannot be explained by natural factors. As for anthropogenic factors, the Lake Mégantic watershed, like other watersheds in Quebec, has undergone a significant reduction in agricultural areas since 1950 ([34]). This decline resulted in a significant increase in annual and seasonal daily minimum flows ([19]). Consequently, even if the agricultural area is small in the Lake Mégantic watershed, its decrease cannot explain the decrease in lake water levels. The second factor of anthropogenic origin is the dismantling in 1956 of the first dam built in 1893. Remember that the construction of this dam caused a rise in the lake level of around 1.4 m. It follows that after the destruction of the dam, the water levels of the lake necessarily fell. This is the primary cause of this decrease in water levels. After the dismantling of this dam, there was a significant increase in the number of dams of different sizes built upstream of the lake during the period 1955–1975. These water reservoirs thus stored large volumes of water upstream of the lake (see Figure 2). This storage has certainly contributed to varying degrees to the drop in water levels in Lake Mégantic. It is the combination of the destruction of the dam in 1956 and the significant storage of water in the reservoirs built upstream of the lake after 1955 which would explain the smoothed (gradual) nature of the shift in the average water levels highlighted by the test of Lombard between 1957 and 1963. The erection of a small dam in 1966 at the request of residents did not significantly raise the water levels of the lake. However, the main objective of this small containment work was to raise the levels in summer for recreational purposes. This would explain the absence of any break in the daily minimum water levels in summer, an absence which was reflected on the annual scale because the annual daily minimum flows occur mainly in summer in the catchment basins of the Lake Mégantic and the Chaudière River. As for the second break in averages that occurred abruptly between 1990 and 1993, it is the result of the voluntary and controlled lowering of the water levels of Lake Mégantic carried out by the Ministry of the Environment and Wildlife of Quebec in 1993, in response to the demand from lakeside residents who wanted to increase the surface area of the beaches for recreational activities ([35]). This lowering was 30 cm. This increase in the beach area would also explain the significant decrease in minimum water levels that occurred exclusively in summer, unlike the daily minimum water levels of three other seasons. Summer is the season during which many recreational activities are practiced in Quebec. As for the absence of any significant change in daily minimum water levels in winter, this could be explained by the generalized increase in river flows observed on the south shore in winter due to the early melting of snow and increased rainfall in autumn, which feeds winter low water (e.g., [16,18,19]).

Despite the influence of exclusively anthropogenic factors on the decrease in water levels of Lake Mégantic, the analysis of correlations between these water levels and six climatic indices nevertheless revealed a negative correlation between these water levels and the global warming climate index (GMLOT). This index measures the evolution of the temperature of the planet's oceans and continents. As we know, the average surface temperature of ocean waters and continents has continued to increase since 1970 due to the increase in the quantity of CO2 of anthropogenic origin in the atmosphere. The analysis of the annual daily average temperatures measured at the Saint-Ludger station revealed a significant increase in this temperature, with the break in the average occurring in 1996–1997. This shift is after those which affect the series of water levels of the lake. Considering this result, the negative correlation observed between the global warming climate index and the water levels of Lake Mégantic can be interpreted as a simple covariation without the slightest causal link. This covariation is therefore due to anthropogenic factors whose impacts are exerted at different spatial scales. In fact, global warming is caused by the increase in CO_2 due to anthropogenic activities (global scale), while the drop in water levels in Lake Mégantic is due to the management of dams (local scale). Theoretically, an increase in temperature would have caused a strong evaporation of water from Lake Mégantic, thus causing its water levels to decrease. However, this increase in temperature is associated with an increase in the amount of annual rainfall in the Lake Mégantic watershed, which should in principle cause the lake's water levels to rise. In fact, this increase in the amount of rain has caused an increase in river flows in winter and fall in Quebec (see, [16,17,20]). However, in winter, only the daily minimum water levels were not impacted by anthropogenic factors because they did not decrease significantly during the period 1920–2020. Thus, their temporal variability is not influenced by anthropogenic factors. It follows that these daily minimum water levels are influenced by NAO, AO, and PDO climate indices.

Furthermore, it is important to note that numerous studies have already been devoted to analyzing the relationship between lake water levels and climate indices in many regions of the world (see the synthesis by [3]). In the case of the Great Lakes of North America, statistically significant correlations were observed between their water levels and several climate indices (PDO, PNA, NAO, and SOI) at different temporal scales (McGregor, 2017). The influence of NAO on the temporal variability in daily minimum flows in winter, particularly in Quebec, has already been demonstrated by [23]. However, none of these studies have ever used the global warming climate index, even in other regions of the world. The positive correlation observed between NAO and winter minimum water levels suggest that during the positive phase of this climate index, polar air descends less frequently in Quebec in winter in favor of warmer tropical air. This results in less cold winters with a more frequent occurrence of precipitation in the form of rain. This implies a predominantly zonal rather than meridian circulation of the Arctic polar air mass above the North American continent.

The decrease in water levels in Lake Mégantic has not significantly impacted the long-term trend (stationarity) of daily flows of the Chaudière River, of which the lake is the source. Indeed, no break in the average annual and seasonal daily flows was observed after 1964. On the other hand, Lake Mégantic, which became a reservoir after the construction of dams in 1893 and 1973, caused the total disappearance of all floods from recurrence $\geq$ 10 years in the section of the Chaudière River located downstream of the lake. Remember that the watershed of the Chaudière River is one of the watersheds faced with heavy recurring flooding, as demonstrated by the analysis of the flow of the Famine River, one of the main tributaries of this river. The same is true of the Beaurivage River, the main tributary ([16])). It follows that the total disappearance of these floods and the reduction in water levels of Lake Mégantic have not significantly impacted the long-term trend in daily flows of the Chaudière River in the section located downstream of the Mégantic dam because this makes it possible to regulate the quantity of water released into the river. This regulation thus makes it possible to control flooding downstream of the dam.

The impacts of climate change on lake water levels have already been the subject of numerous studies (e.g., [11]). However, almost all these studies concern large lakes. By comparing the water levels of eight large lakes in North America and Eurasia during the period 1960 to 2008, these authors demonstrated that the response to climate change can vary from one large lake to another even across the same continent. The water levels of some large lakes have increased while they have decreased significantly for others. This trend was also observed by [4], who analyzed a sample of more than 200 lakes of very different surface areas, spread across different continents. Similarly, Tan and Liu [9] also observed the same trend in their study based on the analysis of water levels in 39 large lakes located in China, Mongolia, and Russia. As for small river lakes, the analysis of the interannual average water levels of a small river lake, Wigry Lake (27.1 km^2), in Poland during the period 1924–2020 revealed a succession of periods of rise and fall in these water levels around a stationary average over time [13]. It is important to emphasize that it is a small river lake which has not been transformed into a dam lake, as was the case with Lake Mégantic.

Finally, this study is limited to the analysis of the interannual variability in water levels in a single small, highly anthropized lake. Therefore, it would be interesting in the future to compare the results of this study to those of studies that will be undertaken on other less anthropized small lakes. Furthermore, due to a lack of data before 1950, it was not possible to reconstruct the evolution of changes in land cover and land use that occurred in the lake watershed during the entire period 1920–2020.

In Quebec, the effects of current global warming are reflected in an intensification and increase in the frequency of summer floods due to the increase in the rainfall. This excess water supply can exceed the storage capacity of the dams built upstream of Lake Mégantic. This may result in an increase in the water levels of this lake itself and thus reduce its capacity to regulate the flooding of the Chaudière River downstream in the future. It is this aspect that must be monitored in the coming decades, during which we expect a significant increase in the amount of summer rain in southern Quebec. Many regions of the world are increasingly facing the limitation of runoff storage capacity by dams and reservoirs due to the increased frequency and intensity of precipitation caused by global warming.

5. Conclusions

Quebec is one of the regions in the world that has many lakes. These water bodies serve as sources for many rivers and reservoirs to produce hydroelectric power, flood control, as well as many other services and recreational activities. However, unlike river flows, the temporal variability in the water levels of these numerous lakes in relation to natural and anthropogenic factors has not yet been the subject of in-depth studies.

This study focused on the analysis of the temporal variability in water levels in Lake Mégantic during the period 1920–2020. This lake is the source of the Chaudière River and serves as a reservoir to control its flooding downstream of the Mégantic dam. The application of the four Mann–Kendall tests demonstrated a significant decrease in the levels of Lake Mégantic during the period 1920–2020. As for the Lombard test, it detected two shifts in the average daily maximum and average water levels, but only one break in the average daily minimum water levels. The first shifts occurred between 1957 and 1963, and the second between 1990 and 1993. The first shift affected the daily minimum water levels in spring and fall while the second shift only affected the daily minimum water levels in summer. The two shifts are both of anthropogenic origin. The first break (drop in water levels), which is gradual (smoothed), would be caused by the demolition in 1956 of the first dam built in 1893 on the one hand, and the storage of a large volume of water in the numerous dams erected upstream of Lake Mégantic during the period 1955–1975, on the other hand. The second shift, which was abrupt, was caused by the voluntary and controlled lowering of the water levels of the lake to increase the surface area of the beaches following the request of residents to practice recreational activities. However, despite this anthropogenic influence, a negative correlation was observed between lake water levels and the global warming climate index. In this context, this correlation is interpreted as a simple covariation due to anthropogenic factors whose impacts are exerted at different spatial scales (planetary and local). This correlation therefore does not reflect a causal link between the two variables. However, the winter daily minimum water levels, whose temporal variability has not been influenced by anthropogenic activities, are positively correlated with the NAO and AO indices but negatively with PDO.

The Chaudière River is repeatedly confronted with heavy flooding. However, downstream of Lake Mégantic, all recurrent floods $\geq$ 10 years have completely disappeared since the commissioning of the first Mégantic dam in 1893, while these floods continue to occur frequently in the natural tributaries of the river. It follows that the Mégantic dam fully fulfills its role of controlling the heavy flooding of the Chaudière River. However, the disappearance of these floods and the decrease in the levels of Lake Mégantic have not significantly impacted the long-term trend (stationarity) of the flows of the Chaudière River due to the regulation of the quantity of water released into the river by the Mégantic dams.

This study clearly demonstrates that the variability in water levels in Lake Mégantic was influenced mainly by anthropogenic factors through the management of dams. These have in fact caused the water levels of the lake to decrease while the flows, particularly the daily minimum flows, of most rivers in the region have increased due to the increase in the amount of rainfall across all of Quebec on the one hand, and the very significant reduction in agricultural areas which favored water infiltration, on the other hand.

Finally, on the hydrological level, in the context of current climate changes, the Lake Mégantic watershed seems to constitute a very appropriate framework for monitoring the impacts of the increase in the intensity and frequency of summer rainfall on the capacity of the storage of dams and reservoirs, and their role in regulating floods and flooding downstream in southern Quebec.

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