

UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

**VARIABILITÉ TEMPORELLE DES NIVEAUX D'EAU DU
LAC MÉGANTIC PENDANT LA PÉRIODE 1920-2020**

**MÉMOIRE PRÉSENTÉ COMME EXIGENCE PARTIELLE DE LA
MAÎTRISE EN SCIENCES DE L'ENVIRONNEMENT**

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Avril 2025

Université du Québec à Trois-Rivières

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PENDANT LA PÉRIODE DE 1920 À 2020**

PAR

SAMUEL GOULET

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REMERCIEMENTS

Je tiens à remercier mon directeur de maîtrise M. Ali A. Assani, professeur au département des sciences de l'environnement de l'Université du Québec à Trois-Rivières, de m'avoir offert ce projet de recherche et de m'avoir permis, par le fait même, d'enrichir mes connaissances académiques et d'avoir favorisé mon développement dans de multiples compétences en hydroclimatologie. Je remercie également mon codirecteur, M. Alexandre Roy, professeur au département des sciences de l'environnement à l'Université du Québec à Trois-Rivières, pour les outils, l'encadrement, les conseils ainsi que son implication dans mon travail de recherche. Je remercie aussi messieurs Christophe Kinnard et Stéphane Campeau, tous deux professeurs au département des sciences de l'environnement à l'Université du Québec à Trois-Rivières, d'avoir accepté d'intégrer mon comité d'orientation et d'évaluation pour ce travail. Je remercie également les membres du laboratoire du ReMoTE-Nord de m'avoir permis de partager leur espace de travail et pour leurs conseils tout au long de mon parcours aux cycles supérieurs. Pour terminer, je remercie l'aide financière aux études (AFE) et le CRSNG pour le financement de ce projet.

RÉSUMÉ

Pour mettre en valeur ses richesses naturelles, le Québec a construit de nombreux barrages et réservoirs. Ceux-ci ont créé ainsi de nombreux lacs de retenue de différentes tailles qui servent parfois des sources à de nombreux cours d'eau. Malgré la présence de ces nombreux plans d'eau dans la province, ceux-ci n'ont jamais fait l'objet d'études hydroclimatiques afin de pouvoir déterminer, entre autres, les impacts des changements climatiques sur la variabilité temporelle de leurs niveaux d'eau en relation avec celle des débits de rivières situées en amont et en aval. C'est dans le but de compenser cette lacune que la variabilité temporelle des niveaux d'eau d'un lac de retenue, soit le lac Mégantic, a été analysée dans le cadre de ce travail de recherche. Cette étude était dotée de trois objectifs. Le premier était de caractériser la tendance des niveaux d'eau maximums, minimums et moyens saisonniers et annuels entre 1920 et 2020 du lac Mégantic. Le second objectif était de déterminer le(s) type(s) de facteur(s) climatique(s) et/ou anthropique(s) qui a/ont influencé les variations à long terme des niveaux d'eau. Le troisième objectif était de déterminer si les fortes crues de la rivière Chaudière ont été influencées par la variabilité temporelle des niveaux d'eau du lac Mégantic entre 1920 et 2020. L'analyse de la variabilité à long terme des niveaux d'eau a été effectuée par l'entremise de 4 tests statistiques de tendances et d'un test de rupture des moyennes de Lombard. Les résultats de ces tests de tendance ont démontré que les niveaux d'eau du lac Mégantic ont significativement diminué dans le temps entre 1920 et 2020. Le test de Lombard a mis en évidence deux ruptures des moyennes des niveaux d'eau journaliers maximums et moyens saisonniers et annuels, mais seulement une rupture des moyennes des niveaux d'eau journaliers minimums. La première rupture, ayant touché les niveaux d'eau journaliers et moyens, fut progressive et a eu lieu entre 1957 et 1963. Elle a été causée par la démolition, en 1956, du premier barrage construit en 1893 et le stockage significatif d'eau dans les barrages construits en amont du lac entre 1956 et 1975. La deuxième rupture touchant les mêmes types de niveaux d'eau que la précédente, fut cette fois plutôt abrupte et a eu lieu entre 1990 et 1993. Elle a été causée par l'abaissement volontaire et contrôlé du niveau d'eau du lac en 1993 pour augmenter la superficie des plages à des fins récréatives. Concernant les niveaux d'eau minimums, aucune rupture n'a été détectée à l'échelle annuelle, mais une rupture a été détectée en hiver, au printemps et en automne entre 1957 et 1963. La rupture survenue entre 1990 et 1993 a été détectée seulement en été. Enfin, depuis la transformation du lac Mégantic en réservoir à la suite de la construction du barrage Mégantic en 1893 et 1973 pour contrôler les inondations importantes de la rivière Chaudière, toutes les inondations de récurrence ≥ 10 ans ont complètement disparu dans la section de cette rivière située en aval du lac Mégantic. Toutefois, la disparition de ces inondations et la baisse des niveaux d'eau du lac Mégantic n'ont pas significativement impacté la stationnarité des séries de débit de la rivière Chaudière depuis 1920. Malgré l'influence de ces facteurs anthropiques sur la tendance à long terme des niveaux d'eau, ceux-ci sont corrélés négativement à l'indice climatique de réchauffement global. Cependant, cette corrélation ne peut être interprétée comme une relation de causalité. En effet, elle doit plutôt être interprétée comme une covariation due à des facteurs anthropiques qui s'exercent à des échelles spatiales différentes : les niveaux d'eau sont influencés localement par les barrages alors que le réchauffement climatique est influencé planétairement par les émissions de gaz à effet de serre.

Mots clefs : niveaux d'eau, débits, précipitations, réservoir, indices climatiques, stationnarité, corrélation, lac Mégantic, rivière Chaudière

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CHAPITRE I

INTRODUCTION

I.1 Mise en contexte

Le réchauffement climatique a pour impact de modifier le cycle de l'eau à l'échelle mondiale (Palmer et al., 2009). L'étude d'Arnell et Gosling (2013) a révélé que la majorité des modèles climatiques projettent une diminution significative des débits annuels sur un peu plus de 14% de la surface totale du globe et une augmentation significative des débits annuels sur près de 25% de sa surface totale. L'Europe centrale, le bassin méditerranéen, le Mashriq, l'Amérique centrale et le Brésil sont les régions les plus susceptibles de connaître une diminution de leur débit tandis que celles les plus propices à connaître une augmentation sont les hautes latitudes de l'Europe de l'Est, la Sibérie et le Canada.

La variabilité temporelle des débits des cours d'eau au Canada a fait l'objet de plusieurs études au cours des dernières années. Un élément mis en évidence par plusieurs des études est que le réchauffement climatique amplifie non seulement le débit des rivières du pays, mais aussi qu'il modifie la période d'occurrence des crues et des étiages (Schnorbus et al., 2012; Burn et al., 2010; Huziy et al., 2013). La modification de la période d'occurrence des crues et des étiages est en partie due à la diminution de la quantité de neige et l'augmentation de la quantité de pluie que le Canada a connue au cours des dernières décennies (Il Jeong et Sushama, 2018; Notaro et al., 2014). Dans la région des Grands Lacs, plusieurs études ont révélé que les précipitations, les températures et les débits ont augmenté au cours des dernières décennies (McBean et Motiee, 2008; d'Orgeville et al., 2014; Bartolai et al., 2014). Cette augmentation a eu notamment pour effet d'accroître les débits des rivières Saint Clair, Niagara et du fleuve Saint-Laurent, tel qu'il a été démontré dans l'étude de McBean et Motiee (2008). Les lacs de retenues, qui sont influencés par les apports naturels des rivières et la gestion des barrages et réservoirs, sont tout aussi sensibles aux changements des régimes de précipitations.

I.2 Problématique

La variabilité temporelle des débits des rivières au Québec méridional est bien documentée (Assani, 2022; Assani, 2023; Assani, 2024 ; Assani, 2024a; Guerfi et al., 2015). Cependant, il existe peu d'études sur la variabilité temporelle des niveaux d'eau des lacs de retenues au sud du Québec. Ce manque de connaissance en la matière est problématique puisque les barrages de retenue au Québec sont en augmentation (Astrade, 1998). Les risques sur la dynamique de l'écoulement de l'eau dans les bassins versants touchés par la construction de ce type d'ouvrages peuvent provoquer des conséquences inconnues (Dupont, 2005; Assani et al., 2006).

De plus, comme les barrages de retenue sont pourvus, pour la plupart, d'un mode de gestion dans le but de répondre à un objectif, cela implique l'apparition de fluctuations de niveaux d'eau qui n'auraient pas lieu en conditions naturelles. Ces fluctuations de niveaux d'eau des lacs peuvent induire des problématiques environnementales telles que l'accélération du processus d'eutrophisation et accroître la vulnérabilité de la biodiversité lacustre (Bakker et Hilts, 2016; Li et al., 2018; Gownaris et al., 2018). Ces deux enjeux environnementaux peuvent ensuite mener vers d'autres conséquences. Parmi ces conséquences, il y a celle de l'insalubrité de l'eau, la diminution de l'abondance de certaines espèces de poissons et l'augmentation des risques d'érosions des berges (Qin et al., 2013; Moyle et Leidy, 1992; Hofmann et al., 2008). Ces risques sont tous des raisons justifiant l'importance d'accroître nos connaissances en matière de variabilité temporelle de niveaux d'eau des lacs de retenue.

Le lac Mégantic, situé dans la région hydroclimatique du Sud-Est, est un lac de retenue dont son barrage à son exutoire, nommé le « *Barrage Mégantic* », est le plus gros barrage du bassin versant du lac Mégantic. Le barrage Mégantic est le barrage le plus important du BVLM puisqu'il est située à l'exutoire du lac Mégantic. À sa construction en 1893, il eut pour effet de relever le niveau du lac afin de faciliter la drave de billots de bois issue des activités de coupes forestières (Loewen et al. 2005 ; Mercie. 2020). Entre 1921 et le début des années 1960, le barrage agissait comme régulateur des niveaux d'eau du lac. Cependant, d'importantes variations saisonnières survenaient inter annuellement. Entre

1967 et 1973, le barrage fut reconstruit étant donné qu'il présentait des signes de dégradations. Pendant la reconstruction du barrage, le niveau d'eau était beaucoup plus bas qu'auparavant avec une courbe de variation toujours aussi saccadé qu'avant. Une fois la reconstruction terminée, le niveau d'eau était maintenu à une hauteur de 394,72 mètres au-dessus du niveau de la mer ce qui équivalait à une hausse de 50 centimètres par rapport au niveau d'eau durant la reconstruction. En 1993, à la suite de la demande de plusieurs riverains du lac, le niveau d'eau fut abaissé de 30 centimètres afin de libérer davantage de plages et de favoriser les activités récréotouristiques (Provencher et al 1998).

Il importe de mentionner que les fluctuations journalières des niveaux d'eau du lac Mégantic résultent de l'ensemble des opérations quotidiennes de stockages (fermetures complètes ou partielles des vannes d'évacuation des eaux) et des déstockages (ouvertures totales ou partielles des vannes d'évacuation des eaux) des eaux. Les opérations de stockages entraînent une hausse des niveaux d'eau du lac et, inversement, celles de déstockages provoquent une baisse de ses niveaux d'eau. L'ensemble de toutes ces opérations définissent le mode de gestion d'un lac de barrage.

La gestion des eaux retenues par le barrage Mégantic est effectuée quotidiennement par un gardien contractuel demeurant à proximité du barrage ou par le personnel technique de la Direction des barrages publiques (Ministère du développement durable, de l'environnement et de la lutte contre les changements climatiques, 2016).

➤ En conditions d'étiages

Le niveau d'eau du lac Mégantic est maintenu à l'élévation de 394,42 mètres $\pm$ 30 centimètres. À la demande du ministère des forêts, de la faune et des parcs, un abaissement du plan d'eau jusqu'à l'élévation de 394 mètres est réalisé du 15 octobre au 15 novembre afin de faciliter la fraie du Touladi. Après la crue printanière, les débits excédentaires sont évacués progressivement jusqu'au 15 novembre. En période estivale, un débit minimal écologique de 2.5 m³/s est assuré dans la rivière Chaudière.

➤ En conditions de crues

En condition de crue, la gestion vise à minimiser les inondations en aval tout en respectant la cote maximale d'exploitation de 395,69 mètres au lac Mégantic. Au début du mois de mars, les vannes sont ouvertes progressivement afin de vidanger le lac jusqu'à l'élévation de 394 mètres et ce, dans le but d'emmagasiner une partie de la crue printanière. Lorsque la crue s'amorce, les vannes sont complètement ouvertes afin d'évacuer des débits comparables aux apports d'eau et de ralentir l'augmentation du niveau du lac. Lorsque les vannes sont ouvertes, l'écoulement à la sortie du lac n'est plus contrôlé par le barrage mais par la capacité hydraulique de la rivière et le pont de la rue Frontenac, situé tout juste en aval du barrage. Le niveau du lac se stabilise alors lorsque les débits entrants sont équivalents aux débits sortants. Une fois les crues terminées, l'élévation du lac retourne à 394,42 mètres $\pm$ 30 centimètres (Direction principale des barrages publics. 2016).

Le mode de gestion du barrage Mégantic a changé à plusieurs reprises au cours du dernier siècle (Maisonnette et al., 1997; Provencher et al., 1998 ; Loewen et Simard, N.D). Ces changements de mode de gestion ont créé plusieurs enjeux locaux depuis la conception du barrage. Le premier type d'enjeu est d'ordre social. En effet, en 1973, certains riverains se sont plaints du rehaussement du niveau d'eau par la nouvelle construction du barrage Mégantic. Il y eut alors des controverses et des débats scientifiques dans le but d'obtenir un éclaircissement judiciaire sur les limites réelles des propriétés (Loewen et al., 2005). Le deuxième enjeu était en lien avec la biodiversité du lac. Certains pêcheurs étaient préoccupés par l'hypothèse que le mode de gestion du lac pouvait nuire à la fraie du *Salvelinus namaycush* (Touladi), du lac Mégantic. Une décision ministérielle a alors été prise pour que chaque automne, le niveau d'eau du lac soit progressivement abaissé pour favoriser la fraie du Touladi à l'automne. Le troisième enjeu était d'ordre récréatif. Au début des années 1990, plusieurs riverains souhaitaient diminuer les niveaux d'eau du lac afin de libérer davantage de plages pour favoriser les activités récréotouristiques. À la suite de l'approbation de cette diminution par le ministère du Loisir, de la Chasse et de la Pêche, un quatrième enjeu, d'ordre d'intégrité écologique, a été soulevé. Cet enjeu était en lien avec la pérennité du milieu humide qui borde l'amont du lac Mégantic. Plusieurs riverains

croyaient que la prospérité du milieu humide était à risque à cause de la diminution des niveaux d'eau du lac (Maisonneuve et al., 1997; Provencher et al., 1998; Biron et al., 2020).

Les exemples d'enjeux mentionnés ci-dessus touchent tous le milieu lacustre du lac Mégantic. Cependant, l'aval du lac peut également être impacté par le mode de gestion d'un barrage de retenue. Dans le cas du lac Mégantic, il est la source principale de la rivière Chaudière qui est l'une des rivières du Québec les plus vulnérables aux inondations (Mercier, 2020). Il est donc possible que le mode de gestion du barrage ait un lien avec les inondations qui sont survenues au cours du dernier siècle dans la rivière Chaudière (Maisonneuve et al., 1997; Provencher et al., 1998). Les municipalités les plus souvent inondées sont celles de Beauceville, Saint-Joseph et Scott, qui sont situés à une distance entre 60 et 85 kilomètres en aval du lac Mégantic (Biron et al., 2020). Ces inondations engendrent des coûts de réparation élevés et peuvent brimer le bien-être des résidents qu'elles touchent. Par exemple, les inondations survenues lors du printemps 2019 ont forcé le gouvernement provincial à verser 96 millions de dollars dans la région administrative de la Chaudière-Appalaches, qui est la région dans laquelle la rivière Chaudière occupe la plus grande superficie. À Sainte-Marie, plus de 212 maisons avaient été détruites par les inondations survenues au printemps 2019 et 69 millions de dollars avaient été versés par le gouvernement à la municipalité pour réparer les dégâts. Lors de cette même inondation,

67 maisons ont dû être détruites à Scott et 21 pour la municipalité de Saint-Joseph (figure 1.1) (Media, 2020).

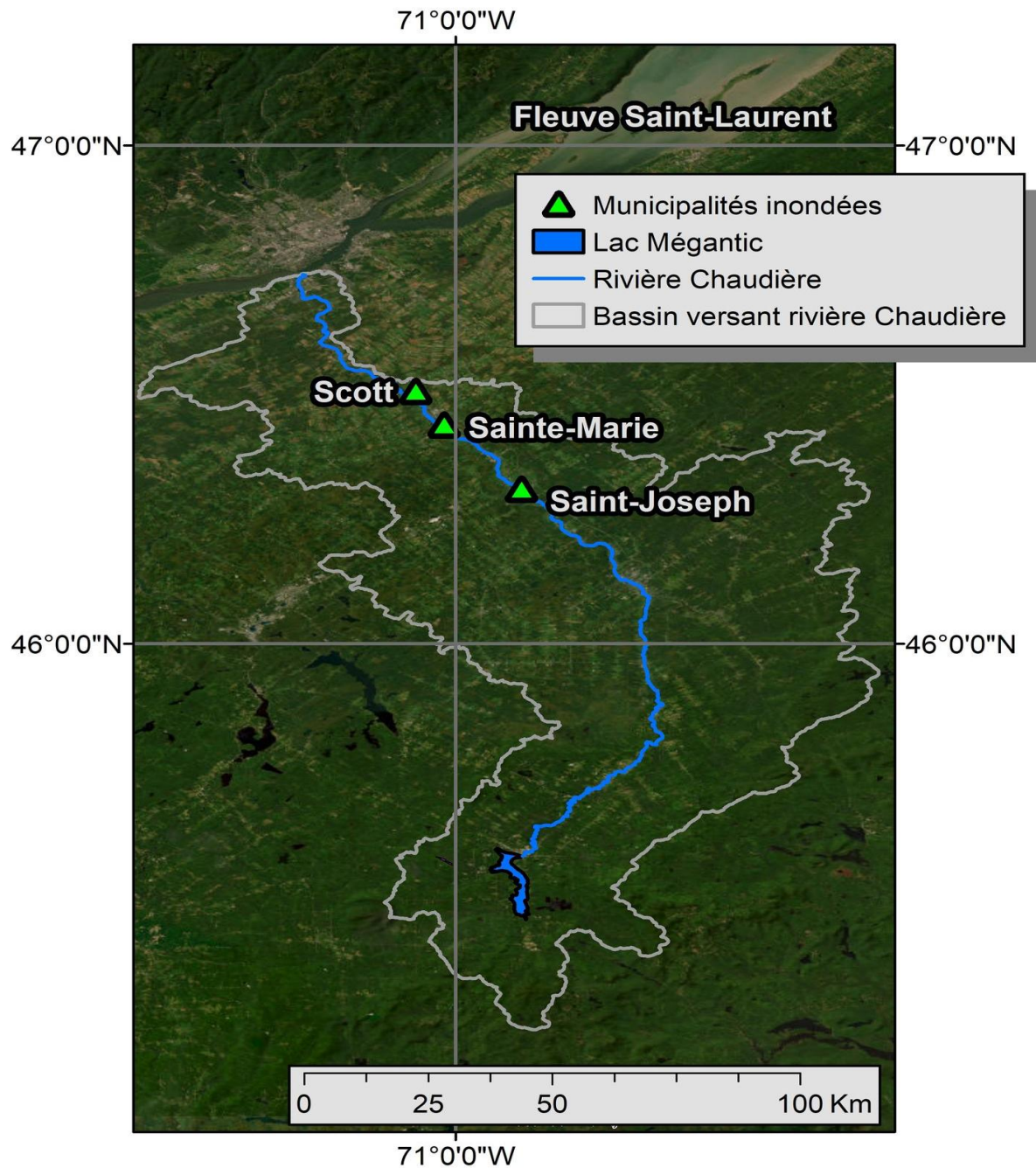


Figure I.1. Bassin versant de la rivière Chaudière et municipalités de Scott, Sainte-Marie et Saint-Joseph inondées en 2019

I.3 Objectifs et hypothèses de la recherche

Le projet vise à analyser les interactions entre les facteurs anthropiques et naturels sur la variabilité temporelle des niveaux d'eau des lacs de retenue au Québec dans le but de combler les lacunes de connaissances actuelles dans ce domaine dans le contexte actuel de réchauffement global. Dans cette optique, l'étude se focalise sur la variabilité temporelle des niveaux d'eau du lac Mégantic pendant la période de 1920 à 2020. Cette analyse permettra également d'identifier les principaux facteurs influençant cette variabilité, afin de mieux comprendre les dynamiques des variations des niveaux d'eau en amont de la rivière Chaudière, qui, il convient de le souligner, est une réputée pour ses inondations récurrentes à travers le temps (Biron et al., 2020; COBARIC. 2022).. L'étude est également réalisée dans le but de fournir aux acteurs responsables de la gestion de l'écoulement des eaux de la rivière Chaudière un outil de référence pour les décisions relatives à cette gestion. Pour atteindre l'objectif principal de cette étude, trois objectifs spécifiques ont été définis :

1. Analyser la variabilité temporelle des niveaux d'eau maximums, minimums et moyens saisonniers et annuels entre 1920 et 2020. En se basant sur les témoignages rapportés par des riverains du lac à l'organisme de bassin versant de la rivière Chaudière (COBARIC), nous posons l'hypothèse que les niveaux d'eau du lac ont significativement diminué depuis les 30 dernières.

2. Déterminer quel(s) type(s) de facteur(s) climatique(s) et/ou anthropique(s) entre la diminution des précipitations neigeuses, l'augmentation des précipitations liquides, les indices climatiques, la diminution de l'agriculture, la diminution de la déforestation et toutes les activités liées aux barrages de retenue ont provoqué les variations de niveaux d'eau détectées entre 1920 et 2020. Nous posons l'hypothèse que les changements dans la variabilité temporelle des niveaux d'eau du lac sont provoqués principalement par le barrage à l'exutoire du lac, soit le barrage Mégantic, puisqu'il a été documenté que son mode de gestion a changé à plusieurs reprises et qu'il fut déconstruit et reconstruit entre 1920 et 2020.

3. Déterminer si les crues de la rivière Chaudière ont été influencées par la variabilité temporelle des niveaux d'eau du lac Mégantic entre 1920 et 2020. Nous posons l'hypothèse que les crues de la rivière Chaudière ont été influencées par la variabilité temporelle des niveaux d'eau du lac Mégantic entre 1920 et 2020 puisque le lac constitue la source principale de la rivière.

Le chapitre suivant présente les résultats de la recherche sous le format d'article scientifique. L'article en question a été publié dans la revue Hydrologie le 23 août 2024.

CHAPITRE II

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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N.B. Cet article a été publié dans la revue Hydrology du mois de septembre 2024. La référence complète de l'article :

Citation: Goulet, S.; Assani, A.A.; Roy, A. 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). *Hydrology*, **2024**, 11, 130. <https://doi.org/10.3390/hydrology11090130>

II.1. Abstract. The objective of this study is to analyze the temporal variability in water levels of Lake Mégantic (27.4 km²) 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 ≥ 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 ≥ 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

II.2. 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 $181,900 \text{ km}^3$ [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 ($< 50 \text{ km}^2$), 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 ≥ 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]).

II.3. Data and methods

II.3.1. 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 km². 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 km² 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 m³), 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 m³ in 1955 to 113,547,649 m³ in 1975.

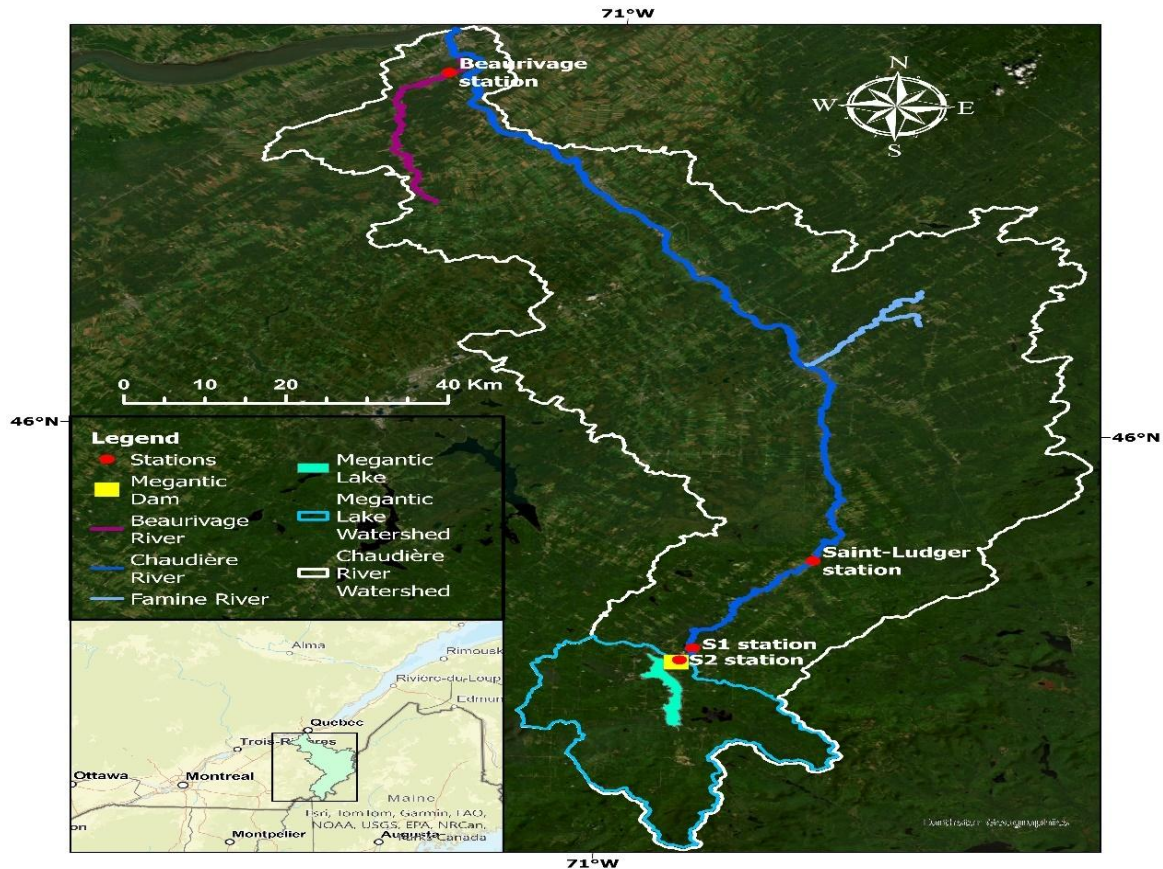


Figure II.1. Lake Mégantic and the Chaudière River watersheds. Saint-Ludger station is a climatic station. The other stations are hydrometric stations.

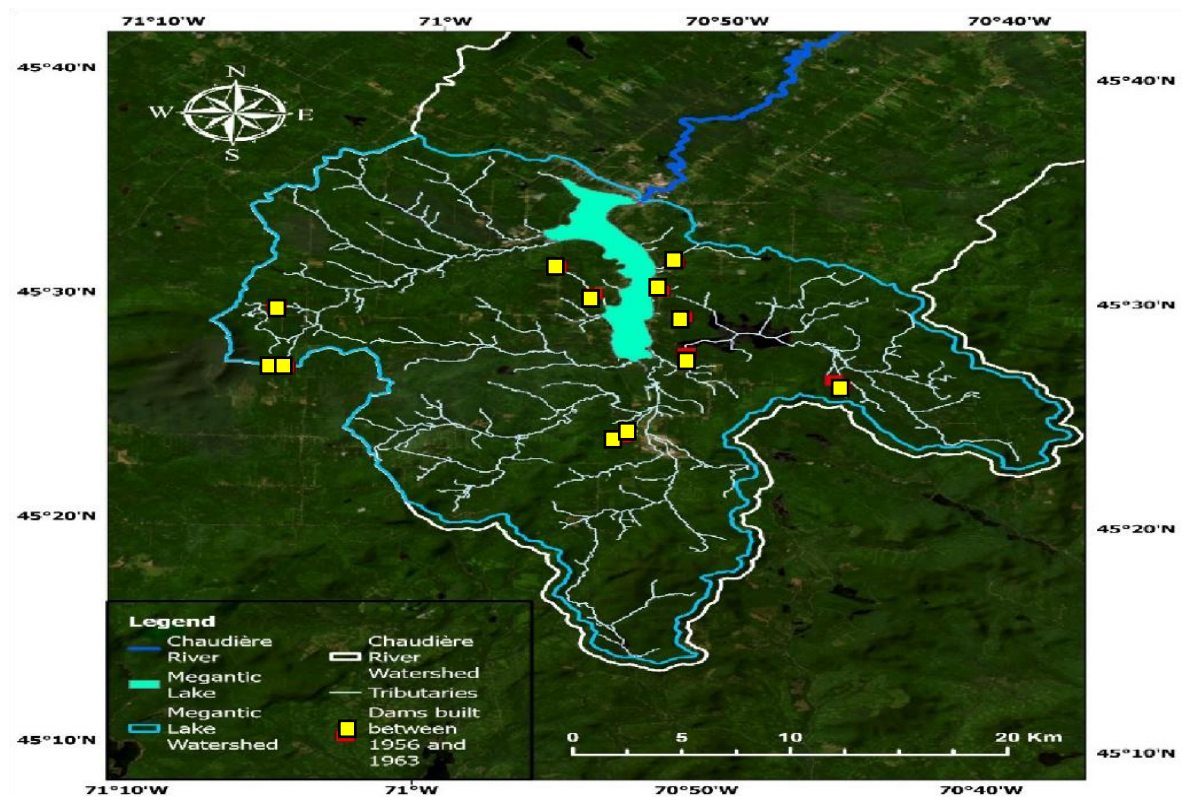


Figure II.2. Lake Mégantic watershed.

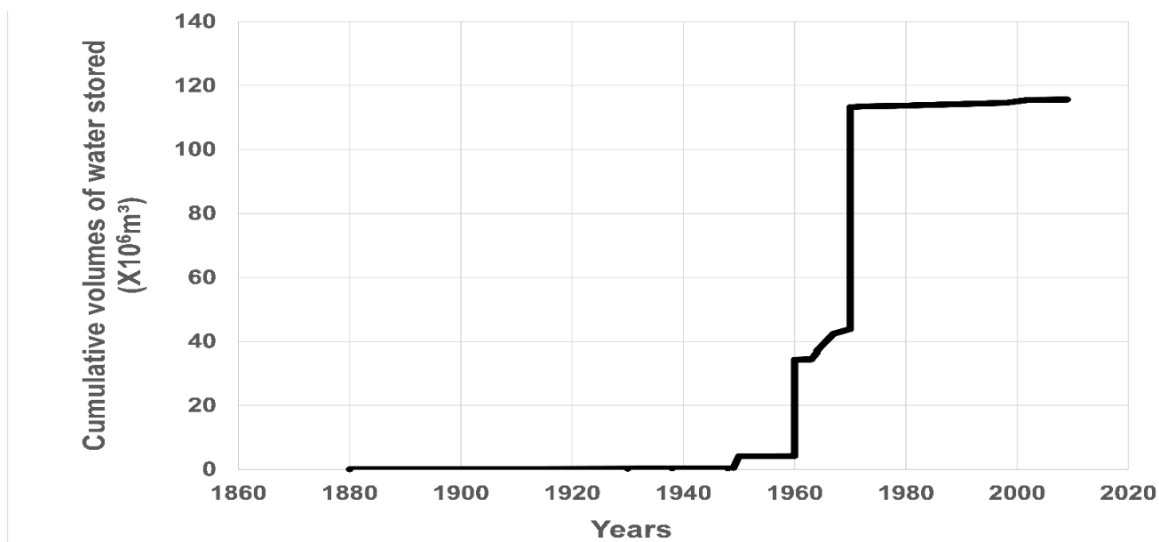


Figure II.3. Interannual variability in cumulative volumes of water stored upstream of Lake Mégantic.

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 km². 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).

II.3.2. 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 km²), 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 km²), from 1915 to 1983, and S2 (781 km²) 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).

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.

II.3.3. 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 ≥ 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 ≥ 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

II.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 II.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	
	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*	1937-2011

* = 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.

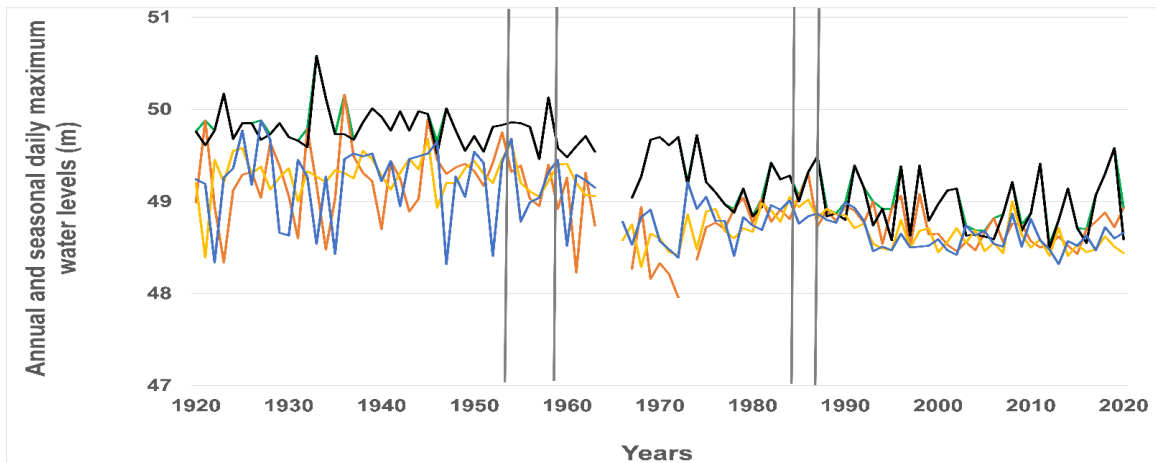


Figure II.4. Interannual variability in annual and seasonal daily maximum water levels of Lake Mégantic during the period 1920–2020. Year: green curve; winter: red curve; spring: black curve; summer: yellow curve; autumn: blue curve. The vertical bars demarcate the two major periods of shifts in the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

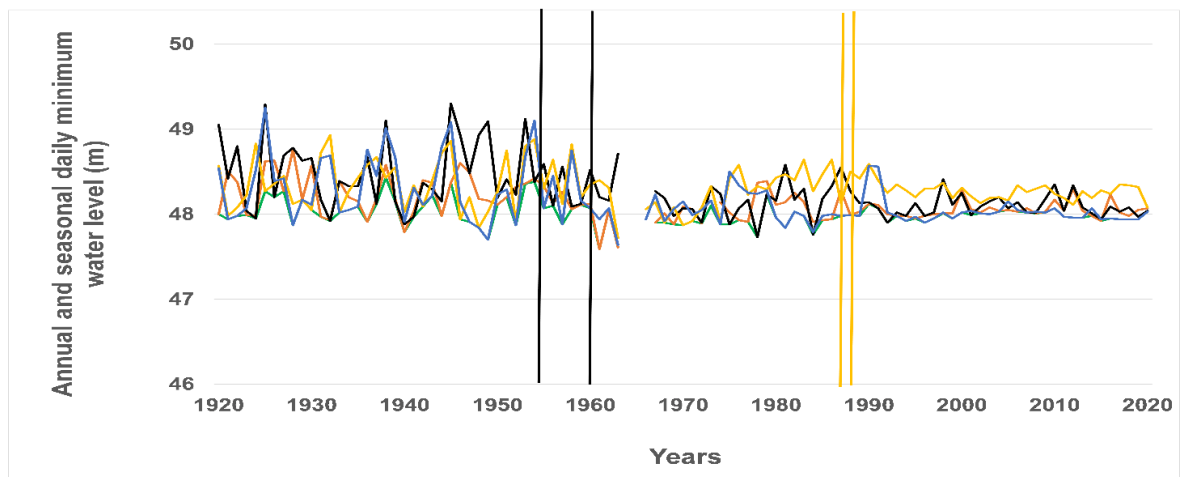


Figure II.5. Interannual variability in annual and seasonal daily minimum water levels of Lake Mégantic during the period 1920–2020. Year: green curve; winter: red curve; spring: black curve; summer: yellow curve; autumn: blue curve. The vertical bars demarcate the two major periods of shifts in the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

Table II.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)	
	S _n	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; * = S_n 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.

II.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.

II.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 II.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	S _n	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	-
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.

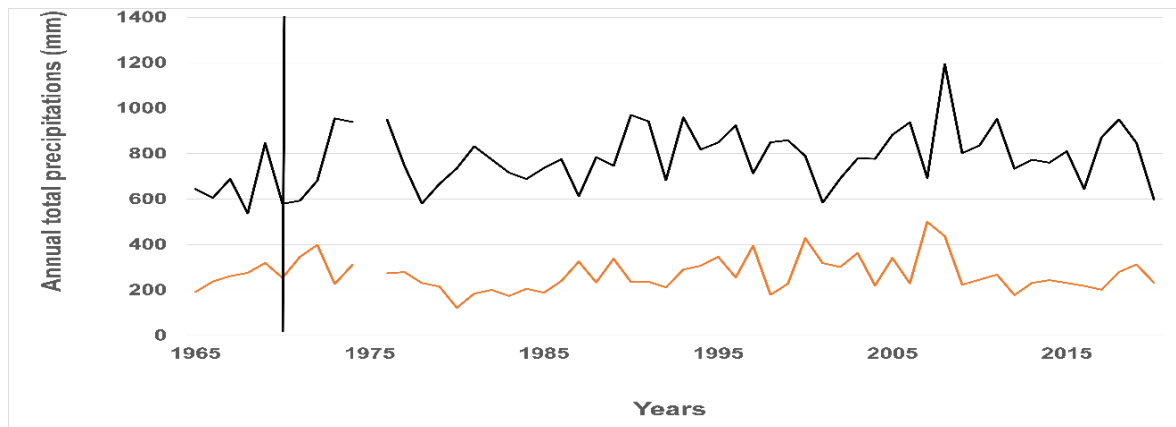


Figure II.6. Interannual variability of the annual total rainfall (black curve) and snowfall (red curve) at the Saint-Ludger station during the period 1950–2020. The vertical bar indicates the end year of shift (T2) in the average.

II.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 spring 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 II.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.

Table II.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 km²): 1920-1983		S2 (781 km²): 1979-2020	
	Sn	T1-T2	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 II.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]).

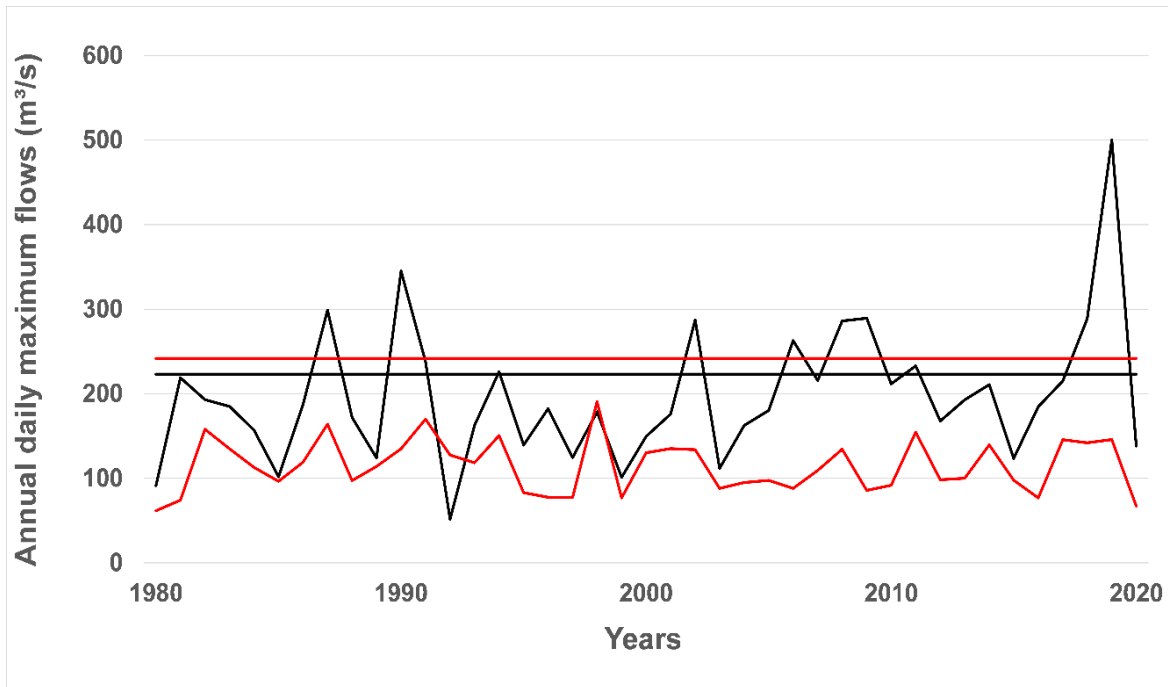


Figure II.7. Interannual variability in annual maximum daily flows of the Chaudière River downstream of the Mégantic dam (red curve) and the Famine River (black curve) during the period 1980–2020. The horizontal lines indicate the values of recurrence flows ≥ 10 years estimated at the two stations (Table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

II.5. 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 (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 CO₂ 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 ≥ 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 km²), 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.

II.6. 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 ≥ 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.

Author Contributions: Conceptualization: A.A.A.; methodology: S.G. and A.A.A.; formal analysis: S.G., A.A.A., and A.R.; investigation: S.G., A.A.A., and A.R.; writing—original draft preparation: S.G., A.A.A., and A.R.; writing—review and editing, S.G. and A.A.A.; funding acquisition, A.A.A. All authors have read and agreed to the published version of the manuscript.

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

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

Acknowledgments: The authors would like to thank the Chaudière River watershed organization (COBARIC) for their valuable assistance in documenting the history of the watershed.

Conflicts of Interest: authors declare no conflicts of interest.

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CHAPITRE III

CONCLUSION GÉNÉRALE

III.1. Perspectives de l'étude

En raison de son réseau hydrographique dense, le Québec est une des régions du monde qui possède le plus grand nombre de lacs de retenues d'origine anthropique. On y dénombre plus de 4500 ouvrages (Astrade, 1998). Cependant, malgré ce nombre, la variabilité temporelle de leurs niveaux d'eau dans le contexte actuel des changements climatiques n'a jamais fait l'objet d'études spécifiques, à l'instar de débits de rivières qui les alimentent. Il serait donc intéressant d'envisager la conception de modèles prédictifs de variabilité temporelle de leurs niveaux d'eau. La conception de ces modèles permettrait de mieux prévenir les enjeux liés à la gestion de l'écoulement de l'eau dans les bassins versants, pouvant ainsi réduire les risques d'inondations tels que les municipalités de Scott, Sainte-Marie et Saint-Joseph ont dû faire face en 2019. Il serait également bénéfique d'effectuer une étude à une échelle globale dans laquelle la variabilité temporelle des niveaux d'eau de plusieurs lacs de retenues réparties dans les trois régions hydroclimatiques du Sud du Québec et avec des superficies de bassins versants différentes soit analysée. Ainsi, cela permettrait de faire ressortir des conclusions plus généralisables sur la variabilité temporelle des niveaux d'eau de lacs de retenues en fonction de différentes variables climatiques, des superficies de bassin versant et des modes de gestion des barrages et réservoirs.

En conclusion, la variabilité temporelle des niveaux d'eau de lacs de retenus est un phénomène dynamique et complexe qui dépend de plusieurs facteurs climatiques et anthropiques (Tan et Quang 2017; Zhang et al., 2022). Cette étude a permis de mettre en lumière la complexité des régimes hydriques du lac Mégantic en identifiant les tendances à long terme de ses niveaux d'eau. L'identification des causes des variations temporelles de ses niveaux d'eau et la détermination de leur influence sur les crues de la rivière Chaudière offrent une compréhension exhaustive de la dynamique hydroclimatique du

territoire qui permet, par le fait même, de répondre aux objectifs et aux hypothèses de ce mémoire.

III.2. Retombés et limites de l'étude

Cette étude permet d'éclaircir la contribution du lac Mégantic sur la problématique liée à la gestion des inondations de la rivière Chaudière. Elle permet également de mettre en lumière l'historique de variations des niveaux d'eau du lac Mégantic, permettant par le fait même aux riverains de mieux interpréter les variations de niveaux d'eau qu'ils ont observées dans le temps. Elle démontre également l'influence qu'un barrage de retenue peut avoir sur les débits de sa rivière, à son exutoire, permettant par le fait même de mieux évaluer les services et bienfaits que ce type d'ouvrages peut offrir.

Cependant, cette étude se limite seulement à l'analyse de la variabilité temporelle d'un seul lac de retenue. Or, au Québec, il en existe des milliers. Ce qui limite la généralisation de ses conclusions à tous les types de lacs de retenue d'eau au Québec. De plus, les études sur les impacts hydroclimatiques des barrages ont révélé que ces impacts sur les débits des rivières en aval varient selon les modes de gestion de barrages et réservoirs qui influencent en partie les niveaux d'eau des lacs de retenue. Ces modes de gestion sont caractérisés par les périodes (saisons) d'occurrence des débits minimums et maximums des rivières influencées par les barrages. Dans le cas du lac Mégantic, la rivière Chaudière est caractérisée par l'occurrence des débits minimums en été et des débits maximums au printemps, à l'instar des régimes hydrologiques des rivières naturelles dans cette région hydroclimatique.

Enfin, dans le contexte des changements climatiques du Québec caractérisé par la hausse de l'intensité et de la fréquence des fortes pluies génératrices des fortes inondations de plus en plus récurrentes, les lacs de retenue d'eau contribuent significativement à l'atténuation des impacts négatifs des inondations en aval. Ainsi, le lac Mégantic a contribué significativement à l'atténuation des intensités des inondations de la rivière, réduisant ainsi leurs coûts socio-économiques. Cependant, à long terme, cette capacité à atténuer ces inondations de la rivière Chaudière risque d'être compromise en raison de cette

hausse de l'intensité et de la fréquence des fortes précipitations qui se poursuivra dans un climat qui deviendra de plus en plus chaud.

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