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LISTE DES ABRÉVIATIONS, SIGLES ET ACRONYMES

UQTR	Université du Québec à Trois-Rivières
NOAA	National Oceanic and Atmospheric Administration
ONA	Oscillation nord-atlantique
OAM	Oscillation atlantique multi-décennale
OA	Oscillation arctique
OAU	Oscillation australe
OPD	Oscillation pacifique décennale
ENSO	El Nino et Oscillation australe
SON	Septembre-Octobre-Novembre
JFM	Janvier-Février-Mars
SOND	Septembre-Octobre-Novembre-Décembre
DJFM	Décembre-Janvier-Février-Mars
CCA	Analyse canonique de corrélation

CHAPITRE I

INTRODUCTION

1.1 Mise en contexte

1.1.1 Les changements climatiques

La hausse des températures est une des nombreuses conséquences aux changements climatiques qui sévissent à travers le monde entier depuis la décennie 1970. Ces changements du climat apportent avec eux de nombreuses et diverses conséquences telle l'amplification des phénomènes hydrologiques extrêmes, comme les sécheresses et les inondations (p. ex., Cloke *et al.*, 2010; Gosling *et al.*, 2011; Kundzewicz *et al.*, 2010). Ainsi, de nombreux travaux sont de plus en plus consacrés à l'analyse de la variabilité interannuelle de ces phénomènes extrêmes dans de nombreux pays (p. ex., Bhutiyani *et al.*, 2008; Burn et Hag Elnur, 2002; Burn *et al.*, 2008; Carson, 2007; Cunderlik et Ouarda, 2009; Dettinger, 2011; Douglas *et al.*, 2000; Fanta *et al.*, 2001; Hannaford et Marsh, 2008; Jiang *et al.*, 2005; Kundzewicz *et al.*, 2005, Lindeström et Bergström, 2004; Masih *et al.*, 2011; Petrow et Merz, 2009; Pinter *et al.*, 2006; Robson, 2002; St.George, 2007; Svensson *et al.*, 2005; Villarini et Smith, 2010; Villarini *et al.*, 2009, 2010, 2011a, 2011b, 2011c; Zimmer et Merz, 2009).

Pour illustrer l'ampleur de ces phénomènes, prenons l'exemple de la République tchèque où, en 2002, on a mesuré le débit le plus élevé de la Vltava (longue rivière située à Prague) depuis les 175 dernières années. Même situation à Dresde en Allemagne, la même année, où les eaux de l'Elbe ont atteint 940 cm, alors que la « barre » des 800 cm n'avait jamais été dépassée entre 1880 et 2001, ce qui en dit long sur l'ampleur de cette catastrophe hydrologique (Kundzewicz *et al.*, 2008). Ces phénomènes se déroulent également à l'échelle locale, affectant le climat du Québec. Rappelons ici les inondations de Saint-Jean-sur-le-Richelieu en 2011 qui causèrent de

nombreux dégâts et blessés. Bien que le Québec soit choyé de posséder quatre saisons, celles-ci ont également des impacts sur les débits des rivières et leurs régimes hydrologiques. Lorsque le printemps arrive, la quantité de neige présente au sol fond parfois très rapidement, causant des crues printanières de haute intensité. Celles-ci, tout comme les crues estivo-automnales, sont bien documentées au Québec, à l'instar des crues hivernales. Les études réalisées abordent en majorité l'impact de la hausse des températures sur ces deux types de crues (Assani *et al.*, 2010, 2011, Mazouz *et al.*, 2012). Trois principales conclusions ont été tirées de ces études.

- En ce qui concerne la régionalisation hydrologique, ces auteurs ont identifié trois régions hydrologiques pour les crues printanières générées principalement par la fonte de neiges : deux régions en rive sud et une région en rive nord. Quant aux crues estivo-automnales générées exclusivement par la pluie, on a délimité quatre régions hydrologiques : trois en rive sud et une seule en rive nord qui est identique à celle des crues printanières.
- Quant à la variabilité interannuelle des débits de crues dans les différentes régions hydrologiques, Assani *et al.* (2010) ont observé une hausse significative de la magnitude des crues printanières en rive nord alors qu'aucun changement n'a été observé dans les deux régions hydrologiques de la rive sud. Cette même hausse affecte aussi la magnitude des débits de crues estivo-automnales en rive nord. En rive sud, contrairement aux crues printanières, la magnitude des crues estivo-automnales augmente significativement dans le temps, au sud du 47°N.
- Enfin, en ce qui concerne la relation entre les indices climatiques et les débits de crues, en rive nord, les débits de crues saisonnières sont significativement corrélés à l'oscillation atlantique multi-décennale (OAM) au printemps et à l'oscillation arctique (OA) en été et en automne. En rive sud au nord du 47°N, ils sont corrélés à l'oscillation australe (OAU) durant les deux saisons alors qu'au sud de ce parallèle, ils sont significativement corrélés à l'oscillation arctique au printemps.

Le présent document vise donc à étudier le phénomène de la variabilité spatio-temporelle des débits maximums journaliers en hiver, permettant ainsi de documenter les crues hivernales et leurs impacts.

1.2 La problématique – Revue de littérature

Les phénomènes hydroclimatiques extrêmes tels qu'énumérés plus haut, affectent non seulement l'économie des régions touchées, mais également le mode de vie des populations y demeurant.

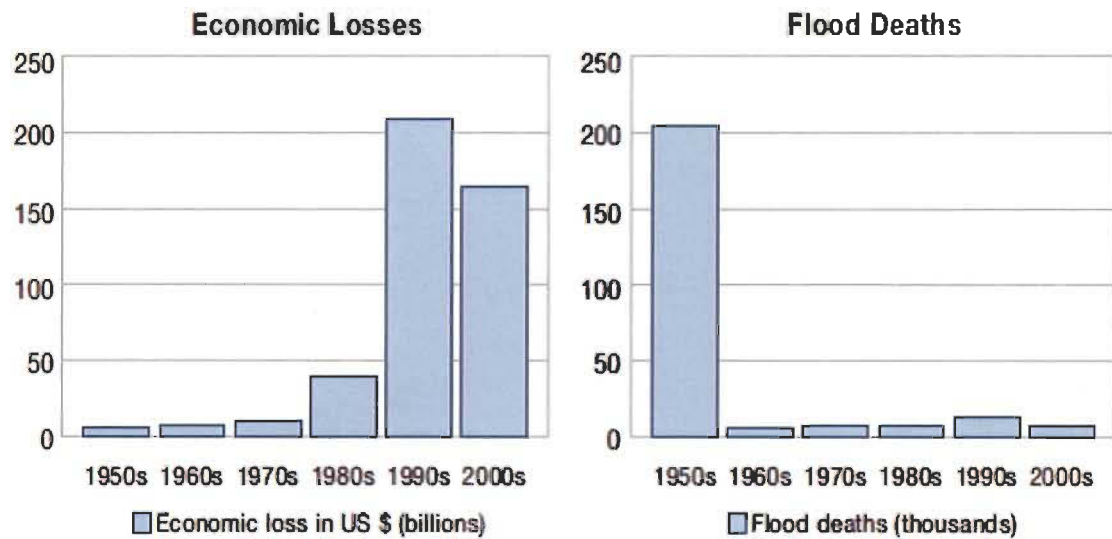


Figure 1.1 Pertes économiques et mortalités (tirée de Jha *et al.*, 2012).

Comme l'illustre la figure 1.1, les pertes financières causées par les inondations ont augmenté de manière exponentielle durant les deux dernières décennies. Cependant, le nombre de morts qui leur sont associés a significativement diminué depuis 1950. Il s'ensuit que les inondations constituent de plus en plus un fléau dans l'économie mondiale et ses impacts seraient amplifiés dans le temps en raison du réchauffement climatique. Les phénomènes extrêmes comme les inondations sont de plus en plus fréquents et d'intensité élevée, ce qui justifie, en partie l'exponentiation des coûts.

À cela s'ajoutent les effets indirects à long terme comme les maladies, la nutrition réduite, les possibilités d'éducation et la perte de certains moyens de subsistance. Cependant, ces phénomènes sont également plus connus et étudiés, notamment dans les régions les plus propices à ceux-ci, ce qui permet de les prévenir davantage. Des plans de mesures d'urgence et d'évacuation permettent aujourd'hui de réduire les pertes humaines en prévoyant ces inondations et en avertissant les populations à temps.

D'après les simulations des modèles climatiques couplés aux modèles hydrologiques, les impacts du réchauffement climatique au Québec se traduiront principalement par une hausse de la température et des précipitations sous forme de pluies en hiver (Boyer *et al.*, 2010). Du point de vue hydrologique, ces changements climatiques provoqueront une hausse de la magnitude et de la fréquence des crues hivernales susceptibles d'accélérer l'érosion des berges des rivières, notamment en raison de la fonte des glaces et de leur dérive (Verhaar *et al.* 2010, 2011). Bien que la hausse de la température fût déjà observée au Québec depuis la décennie 1970 (Hudon, 2005) et que de nombreuses études démontrent l'impact de celle-ci sur la variabilité interannuelle des débits (Assani *et al.* 2010, Bhutiyani *et al.* 2008, Burn *et al.* 2004, Carson *et al.* 2007), il n'existe encore aucune étude sur les impacts des changements climatiques sur les débits hivernaux au Québec. Rappelons que ces derniers peuvent être générés principalement par la pluie qui peut provoquer ou non une fonte de neige lorsque celle-ci est présente au sol. Contrairement aux crues printanières et estivo-automnales, les crues hivernales sont générées par des processus complexes.

1.3 Objectifs et hypothèses d'étude

À la lumière de ces considérations, notre projet de recherche poursuit les objectifs suivants :

- Analyser la variabilité spatio-temporelle de la magnitude des débits maximums journaliers hivernaux au Québec méridional. Cet objectif repose sur l'hypothèse suivante : les débits maximums journaliers hivernaux ont

significativement diminué après 1970, en raison de la diminution de la quantité de neige, et ce malgré la hausse de la température et de la quantité de pluies.

- Analyser la variabilité spatio-temporelle de la période d'occurrence des débits maximums journaliers hivernaux au Québec méridional. Cet objectif repose sur l'hypothèse suivante : on s'attend à ce que les débits maximums journaliers hivernaux surviennent tôt dans la saison, après 1970, en raison de la hausse de la température.
- Analyser la relation entre les caractéristiques (magnitude et période d'occurrence) des débits maximums journaliers hivernaux et les indices climatiques au Québec méridional. Cet objectif repose sur l'hypothèse suivante : les deux caractéristiques des débits maximums journaliers hivernaux sont corrélées aux mêmes indices climatiques.

1.4 Méthodologie

1.4.1 Région de l'étude et sélection des données (rivières)

L'étude porte sur 17 rivières réparties sur la rive sud et nord du fleuve St-Laurent, au Québec. Seules les rivières dont les débits sont mesurés de manière continue depuis 1934 et étant peu affectés par les activités anthropiques (pas de barrages) ont été retenues. Les informations détaillées des rivières à l'étude sont présentées au tableau 1.1. Les données des débits journaliers ont été extraites du site Web d'Environnement Canada (http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm consulté en mars 2011).

Tableau 1.1
Rivières analysées

No	Rivière	Superficie (km ²)	Latitude (N)	Longitude (W)	Dma (m ³ /s)
Région Sud-Est					
SE1	Chateauguay	2500	45°17'	73°48'	26.0
SE2	Eaton	642	45°28'	71°39'	8.6
SE3	Etchemin	1130	46°38'	71°02'	28.5
SE4	Nicolet sw	544	45°47'	71°58'	8.4
SE5	Beaurivage	709	46°39'	71°17'	10.5
SE6	Du sud	826	46°49'	70°45'	14.7
Région Est					
E7	Ouelle	802	47°25'	69°56'	15.6
E8	Du loup	1050	47°49'	69°31'	15.4
E9	Trois-pistoles	932	48°05'	69°11'	13.4
E10	Rimouski	1610	48°24'	68°33'	26.5
E11	Matane	826	48°46'	67°32'	33.4
E12	Blanche	208	48°46'	67°39'	4.8
Région Sud-Ouest					
SW13	De la petite nation	1330	45°47'	75°05'	19.1
SW14	Du nord	1170	45°47'	74°00'	21.5
SW15	L'assomption	1340	46°00'	73°25'	23.5
SW16	Matawin	1390	46°41'	73°54'	22.4
SW17	Vermillon	2670	47°39'	72°57'	37.2

DMA = débits moyens annuels

1.4.2 Indices climatiques

Les données des indices climatiques ont été extraites du site web de la NOAA (<http://www.cdc.noaa.gov/ClimateIndices/List> consulté le 23 mars 2012). Cinq indices climatiques ont été retenus en raison de leur influence déjà démontrée sur la variabilité interannuelle en Amérique du Nord, au Canada et au Québec (p. ex. Anctil and Coulibaly, 2004; Assani *et al.*, 2006, 2008, 2010; Coulibaly and Burn, 2004, 2005; Déry and Wood, 2004, 2005; McCabe *et al.*, 2004). Il s'agit des indices suivant : l'oscillation atlantique multi-décennale (OAM), l'oscillation arctique (OA), l'oscillation nord-atlantique (ONA), l'oscillation australe (OAU) et l'oscillation pacifique décennale (OPD).

L'influence qu'ont les indices climatiques sur les débits maximums hivernaux n'est pas négligeable. En effet, ces indices vont interagir quant à la quantité de pluie et de neige tombée et ils vont aussi influencer la date de fonte de la neige au sol. Ces trois variables vont ainsi avoir un impact sur les crues hivernales, selon l'augmentation ou la diminution des précipitations sous forme liquide ou solide ou encore la fonte potentiellement précipitée de la neige à la fin de l'hiver.

Tableau 1.2
Indices climatiques

Indice climatique	Localisation du phénomène	Mode de calcul de l'indice
Oscillation atlantique multi-décennale (OAM)	Océan atlantique nord	Variabilité interannuelle des indices de température de surface de l'océan Atlantique Nord.
Oscillation arctique (OA)	Hémisphère nord extratropicale	Différence des pressions d'une année à l'autre entre le pôle nord et le parallèle de 45°N.
Oscillation nord-atlantique (ONA)	Zone nord-atlantique extratropicale	Différence des pressions entre le Sud (Péninsule Ibérique) et le nord (Islande) du bassin nord atlantique
Oscillation pacifique décennale (OPD)	Océan pacifique nord (au 20°N)	Variation interannuelle des indices de température de surface de l'océan atlantique nord.
Oscillation australe (OAU)	Océan austral tropical	Variation mensuelle de la différence de pressions entre le pacifique austral occidental Darwin (Australie), et le pacifique austral central (Tahiti)

1.4.2.1 Oscillation atlantique multi-décennale

L'oscillation atlantique multi-décennale (OAM) est une variation de la température de surface de la mer qui s'étend sur plusieurs décennies, de 40 à 80 ans, observée dans le Nord de l'Océan Atlantique en soustrayant la variation linéaire due au réchauffement climatique. L'OAM est calculée en soustrayant de la température de surface de la mer la composante due à l'effet de l'augmentation des gaz à effet de serre sur l'atmosphère (NOAA, 2013).

1.4.2.2 Oscillation arctique

L'oscillation arctique (OA) est un mode à grande échelle de la variabilité du climat, également dénommé le mode annulaire de l'hémisphère Nord. L'AO est un

modèle de climat caractérisé par des vents circulant dans le sens anti-horaire autour de l'Arctique, à environ 55° de latitude Nord. Lorsque l'AO est en phase positive, un anneau de vents circulant autour du pôle Nord intervient pour limiter l'air plus froid dans toutes les régions polaires. Cette ceinture des vents s'affaiblit et est plus déformée dans la phase négative de l'AO, qui permet une pénétration plus facile de froid vers le sud et a augmenté l'activité cyclonique dans les latitudes moyennes (NOAA, 2013).

1.4.2.3 Oscillation nord-atlantique

L'oscillation nord-atlantique (ONA) est définie par la variation de la pression atmosphérique au-dessus du bassin nord-atlantique. Il est exprimé par un indice fondé sur la différence de pressions entre le sud (Péninsule Ibérique) et le nord (Islande) du bassin atlantique nord. En pratique, on considère les pressions mesurées à la station de Ponta Delgada (Açores) et à Stykkisholmur ou à Reykjavik (Islande). Les causes climatiques de cette oscillation ne sont pas encore élucidées. Mais selon Leroux (2000), cette variabilité de pression dans l'Atlantique nord est liée aux activités des anticyclones mobiles polaires qui sont des cellules de masses d'air froid qui descendent du pôle nord. Les conséquences climatiques de cette oscillation ont surtout été analysées sur le continent européen bien que leur impact sur le temps en Amérique du Nord a été reconnu (Sheridan, 2003). Ainsi, des indices positifs (Phase haute) de cette oscillation se traduisent par de forts vents soufflant de l'océan Atlantique vers le continent européen. Le climat y est alors sous influence océanique. En Phase basse (indice négatif), les deux centres sont affaiblis, les vents d'ouest le sont aussi et l'Europe subit les rigueurs du climat continental, particulièrement en hiver (Wanner, 1999). L'influence de cette oscillation s'étendrait même en hémisphère sud (Poveda et Mesa, 1996).

1.4.2.4 Oscillation pacifique décennale

L'oscillation pacifique décennale (OPD) est souvent décrite comme un modèle de type El Niño d'une longue durée de vie de la variabilité climatique du Pacifique (Zhang *et al.*, 1997). Les extrêmes dans le modèle d'OPD sont marqués par des variations très

répandues dans le bassin du Pacifique et du climat en Amérique du Nord. En parallèle avec le phénomène ENSO, les phases extrêmes de l'OPD ont été classées comme étant soit chaud ou froid, tel que défini par les anomalies de température de l'océan dans l'océan Pacifique Nord-est et tropical. Lorsque TSM sont anormalement froides dans le Pacifique Nord intérieur et chaudes le long de la côte du Pacifique, et quand les pressions au niveau de la mer sont inférieures à moyenne au-dessus du Pacifique Nord, l'OPD a une valeur positive. Lorsque les configurations d'anomalies climatiques sont inversées ou au-dessus des pressions de moyenne altitude au-dessus du Pacifique Nord, l'OPD a une valeur négative (ONAA, 2013).

1.4.2.5 Oscillation australe

L'oscillation australe (OA) est un phénomène climatique se traduisant dans l'atmosphère par une variation à intervalles irréguliers (de 3 à 7 ans) du champ de la pression atmosphérique moyenne entre l'ouest et le sud-est du Pacifique tropical. On caractérise généralement ce phénomène par un indice exprimant la différence de pression entre Papeete (à Tahiti) et Darwin (au nord-ouest de l'Australie); cet indice est négatif en période El Niño, positif pendant la Niña, car du fait du fort couplage existant entre océan et atmosphère, El Niño et La Niña constituent les deux états extrêmes de l'oscillation australe. L'ensemble de ces phénomènes atmosphériques et océaniques est souvent appelé l'ENSO, abréviation de l'anglais *El Niño - Southern Oscillation* (NOAA, 2013).

1.4.3 Analyse statistique de données

Deux séries hydrologiques ont été constituées : la série de magnitude des débits maximums journaliers et celle de la période d'occurrence de ces débits. La première série a été constituée par la valeur la plus élevée des débits journaliers mesurés de décembre à mars chaque année pendant la période 1934-2010 pour chacune de 17 rivières étudiées. Quant à la seconde série, elle était constituée par des dates

d'occurrence de ces débits les plus élevés. Les dates d'occurrence ont été converties en jours juliens.

Pour analyser la stationnarité de la série de magnitude, on a appliqué la méthode de Lombard qui permet de déterminer les ruptures brusques ou progressives des moyennes ou des variances ainsi que les dates de ces ruptures. Quant à la période d'occurrence des débits maximums journaliers, on a d'abord calculé la fréquence relative de ces dates de 12 décades de la saison hivernale. Ensuite, on a comparé au moyen de la méthode de Khi-carré les fréquences des dates d'occurrence avant et après 1970 de la première et de la dernière décade de la saison. Ces deux décades constituaient les classes modales des fréquences des dates d'occurrence. Enfin, les séries de la magnitude et de la période d'occurrence de 17 rivières ont été corrélées simultanément aux cinq indices climatiques au moyen de l'analyse canonique de corrélation. Les différentes méthodes statistiques utilisées sont décrites en détail dans le prochain chapitre.

1.5 Résultats et conclusions

En analysant la variabilité interannuelle des débits journaliers hivernaux de 1934 à 2010, nous en sommes parvenus aux principaux résultats tirés des différentes méthodes statistiques effectuées.

1. La magnitude des débits maximums journaliers hivernaux a significativement augmenté, et ce, après 1970, pour la plupart des rivières. Notre première hypothèse étant que les débits maximums journaliers hivernaux ont **significativement diminué** après 1970 en raison de la diminution de la quantité de neige, et ce malgré la hausse de la température et de la quantité de pluie, est rejetée, puisque malgré la fonte des neiges et la hausse des températures, les débits ont significativement augmenté.
2. En rive sud, au sud du 47°N (région Sud-Est), les débits maximums journaliers hivernaux surviennent fréquemment à la fin de la saison (dernière décade),

alors qu'en rive nord (région Sud-Ouest) et en rive sud au nord du 47°N (région Est), les débits maximums journaliers hivernaux surviennent fréquemment au début de la saison (première décade). Aucune différence significative de la fréquence d'occurrence des débits maximums n'a été observée avant et après 1970 durant la première décade, ce qui signifie que la fréquence des débits maximums journaliers hivernaux induits par la pluie n'a donc pas significativement augmenté après 1970. Cependant, une différence significative de la fréquence d'occurrence des débits maximums a été observée après 1970 durant la dernière décade, ce qui signifie que la fréquence des débits maximums journaliers hivernaux induits par la fonte des neiges a significativement augmenté après 1970 en raison de la fonte précoce.

3. Il fut démontré que cette fonte précoce des neiges serait la principale cause de la hausse de la magnitude des débits maximums journaliers hivernaux après 1970.
4. Finalement, comme dernier résultat, La magnitude des débits maximums journaliers en hiver est positivement corrélée à OPD alors que la période d'occurrence de ces débits l'est à ONA. Mentionnons que le premier indice climatique influence la quantité de neige au Québec (Brown, 2010). En phase positive, l'ONA provoque une fonte tardive de la neige dans la saison en raison de la persistance de l'air polaire froid au Québec (cas de cet hiver 2014).

Pour conclure cette étude, il convient de répondre à la question principale posée en début de projet, soit « à l'instar des niveaux d'eau du fleuve Saint-Laurent, les débits hivernaux de ses affluents **ont-ils diminué** après 1970? ». La réponse est bien entendu, non, les débits hivernaux des rivières étudiées ont plutôt **augmenté** après 1970. De nombreux aspects sont cependant à considérer dans cette conclusion qui vient réfuter un résultat très récent d'une étude complémentaire à celle-ci, notamment la localisation de l'ensemble des rivières étudiées, la présence de bassins versants pouvant modifier les débits de certaines rivières, de même que la diversité climatique à l'échelle du bassin versant des grands lacs.

CHAPITRE II

TEMPORAL VARIABILITY OF THE MAGNITUDE AND TIMING OF WINTER MAXIMUM DAILY FLOWS IN SOUTHERN QUEBEC (CANADA)

Ce chapitre est présenté sous la forme d'article scientifique, en anglais, et a été soumis dans la revue *Water Resources Research* (Myriam **Beauchamp**, Ali A. **Assani**) sous le titre : « Temporal variability of the magnitude and timing of winter maximum daily flows in southern Quebec (Canada) ».

**Temporal variability of the magnitude and timing of winter maximum daily flows
in southern Quebec (Canada)**

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Abstract

The temporal variability of winter climate in southern Quebec is characterized by increasing temperature and rainfall, but decreasing snowfall. The goal of the study was to analyze the impacts of these changes on the magnitude and timing of winter maximum daily flows. Hydrologic series for seventeen tributaries of the St. Lawrence River were analyzed over the period from 1934 to 2010. The most noteworthy result, obtained using the Lombard method, was to highlight a nearly generalized shift in mean values of the series in the early 1970's. This shift reflects a significant increase in the magnitude of winter maximum daily flows after that decade, interpreted to result primarily from snowmelt, which is increasingly frequent at the end of winter. Indeed, the frequency of the dates of occurrence of winter maximum daily flows increased significantly during the last winter decade (ten days) after the 1970's for most rivers in southern Quebec. The copula method did not, however, bring out any significant change in the dependence between the timing and magnitude of winter maximum daily flows over time. Finally, canonical correlation analysis revealed that the magnitude of winter maximum daily flows is positively correlated with the Pacific Decadal Oscillation (PDO), while their dates of occurrence are correlated with the North Atlantic Oscillation (NAO).

Keywords: Maximum daily flows, timing, winter, climate indices, Lombard method, copula method, canonical correlation analysis, Quebec.

Introduction

In regions with continental temperate climate such as the Province of Quebec, in Canada, winter, which is particularly cold, is the main low-water period due to storage of precipitation as snow on slopes (e.g. Assani and Tardif, 2005; Assani *et al.*, 2012). However, because temperatures are increasing, winter precipitation as rain is more frequent and the amount of winter snow is decreasing. According to most climate models, increasing rainfall frequency should lead to increased frequency and intensity (magnitude) of winter floods as a result of higher runoff on slopes (Boyer *et al.*, 2010a, 2010b). According to Verhaar *et al.* (2010, 2011), the strongest floods will occur more frequently in winter than in spring. Morphologically, one of the main expected impacts of this increase in winter flows is enhanced bank erosion processes and sediment transport for some tributaries of the St. Lawrence River in Quebec (Boyer *et al.*, 2010a; 2010b; Verhaar *et al.*, 2010, 2011). From an ecological standpoint, aside from higher water temperature, the increase in winter flows should have a significant impact on the life cycle of certain aquatic organisms. For instance, the survival rate of juvenile Atlantic salmon (*Salmo salar*) in streams is primarily influenced by winter flows, which determine the available habitat volume (Cunjak *et al.*, 1998). Consequently, given the current climate warming trend, analyzing the changes that affect winter flood regimes in continental temperate regions is of the utmost importance due to the impacts of these changes on aquatic organisms in fluvial ecosystems.

In Quebec, studies looking at the interannual variability of natural streamflow in winter are restricted to the analysis of monthly or seasonal low or mean flows (e.g. Assani et Tardif, 2005; Assani *et al.*, 2011a, 2011b; 2012, Zhang *et al.*, 2001), no study having to date looked at winter maximum daily flows. However, in a recent study, Assani *et al.* (2014) showed that winter maximum daily water levels in the St. Lawrence River have decreased significantly since the 1980's, which they attributed to the decreasing amount of snow highlighted by Brown (2010) in spite of increasing temperatures observed in Quebec since the 1970's (Yagouti *et al.*, 2008). Results of these studies raise the following fundamental question: do winter maximum daily flows decrease over time in

the St. Lawrence River watershed as do winter water levels in the river itself, in spite of increasing temperature and precipitation as rain?

In addition, there is still some debate over which climate index primarily influences the spatial and temporal variability of winter temperature and precipitation (snow and rain) in Quebec. Some workers are of the opinion that the El Niño/Southern Oscillation (ENSO) is the main variability factor (e.g., Shabbar, 2006), while others attribute it to the North Atlantic/Arctic Oscillation (NAO), (e.g., Kingston *et al.*, 2006; Qian *et al.*, 2008), the Atlantic Multidecadal Oscillation (AMO) (Assani *et al.*, 2014), or the Pacific Decadal Oscillation (PDO) (Brown, 2010). It is important to establish which of these climate indices affects the spatial and temporal variability of these characteristics (timing and magnitude) of winter maximum daily flows in Quebec.

Consequently, the three goals of the study are as follows:

1. To compare the interannual variability of the magnitude of maximum daily flows in the three hydroclimatic regions of southern Quebec, the underlying hypothesis being to test whether decreasing amounts of snow resulted in a decrease in maximum daily flows in winter in southern Quebec akin to the observed decrease in water levels in the St. Lawrence River.
2. To compare the interannual variability of the dates of occurrence of these winter maximum daily flows in the three hydroclimatic regions of Quebec to determine whether the increased frequency of precipitation as rain has affected these dates in southern Quebec.
3. To establish which climate indices are significantly correlated with the magnitude and timing of winter maximum daily flows in Quebec.

Methods

Station location and sources of flow data

Southern Quebec can be divided into three homogeneous hydroclimatic regions (e.g. Assani *et al.*, 2010a, 2010b; 2011), the first two being located on the south shore (right bank) of the St. Lawrence River to the north (Eastern region) and south (Southeastern region), respectively, of latitude 47°N (Fig. 1). These two regions are characterized by a maritime mixed climate. The third region is located on the north shore (left bank), and its climate is continental. At least five hydrologic stations were selected in each of these three regions, the choice of these stations resting on (1) the existence of flow data measured over a relatively long period and (2) the absence of dams or other human activity that might have significantly modified the natural hydrologic regime of the rivers. Characteristic features of the selected stations are shown in Table 1 and their location is shown in Figure 1. Winter in Quebec generally extends from December to March.

Daily flow data were taken from the Environment Canada website (<http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm>, viewed in March 2012) and climate data were taken from the NOAA website (<http://www.cdc.noaa.gov/ClimateIndices/List>, viewed in June 2013). As part of the study, we selected five climate indices which have been shown to affect the spatial and temporal variability of hydroclimatic variables in North America in general, and in Quebec in particular (e.g., Anctil et Coulibaly, 2004; Assani *et al.*, 2010, 2011, 2012; Mazouz *et al.*, 2012, 2013). These climate indices are the following: AMO (Atlantic Multi-decadal Oscillation), AO (Arctic Oscillation), NAO (North Atlantic Oscillation), PDO (Pacific Decadal Oscillation), and SOI (Southern Oscillation Index). Climate indexes for the AMO and PDO were taken from the following website: <http://www.cdc.noaa.gov/ClimateIndices/List> (viewed on 10-06-2013), the NAO from <http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html> (viewed on 10-06-2008), the AO from <http://jisao.washington.edu/data/ao/> (viewed on 10-02-2007), and the SOI from <http://www.cgd.ucar.edu/cas/catalog/climind/soi.html> (viewed on 10-02-2007). Data for

these climate indices (NAO, AO and SOI) after 2006 were taken from the NOAA website: <http://www.esrl.noaa.gov/psd/data/climateindices/list/>. For each index, an annual mean was derived using monthly values from January to December. Data for all these indices since 1950 are available on the NOAA website: <http://www.esrl.noaa.gov/psd/data/climateindices/list/>. Annual means were calculated over the period from 1918 to 2012.

Statistical analysis

Hydroclimatic series

Two streamflow data series were produced for each river: a series of winter maximum daily flows and a series of dates of occurrence of these flows. The first series comprises the largest daily flow value measured from December to March for each year from 1934 to 2010. This period allowed the analysis of the largest number of rivers over a relatively long time period (more than 70 years of flow measurements). The second series comprises the dates of occurrence of maximum daily flows. These dates of occurrence were first converted to Julian days, with the first of these set as July 1, and the last, as June 30, in order to avoid a sharp break in date values from December 31 to January 1. Then the frequencies per decade (10-day intervals) from December to March of the dates of occurrence of maximum daily flows were calculated for each river over the period from 1934 to 2010. Thus, the winter season was divided into 12 decades, the first of which consisting of the first 10 days of December, and the last, of the last 10 days of March. This breakdown of the winter season into decades was used because it is the only breakdown that brought out changes in the dates of occurrence of maximum daily flows over time. Other breakdown approaches and other methods used in the literature (e.g., Burn, 2008; Cayan *et al.*, 2001; Cunderlik and Ouarda, 2009; Déry *et al.*, 2009; Hodgkins *et al.*, 2003; Hodgkins and Dudley, 2006; Magillan and Graber, 1996) did not yield conclusive results.

For each climate index, four data series were produced: two series of mean values calculated over three fall months (SON) and three winter months (JFM), on one hand, and over four fall months (SOND) and four winter months (DJFM), on the other, with a view to determine which seasonal series of climate indices best correlates with the hydrologic series.

Analysis of shift in mean values of hydrologic series

In the scientific literature, analysis of shifts in mean values is usually preceded by a long-term trend analysis. However, Assani *et al.* (2014) recently showed that this step is not important because interpreting the results of a long-term trend analysis is always difficult in hydroclimatology due to the difficulty of determining which factors explain changes in the long-term trend of a hydroclimatic series. Moreover, from a statistical standpoint, unlike shifts in means, there is still some debate as to which statistical methods are most appropriate for detecting changes in the long-term trend of hydroclimatic series (e.g., Önöz and Bayazit, 2012). For this reason, the study only focuses on shifts in mean values. From a hydrological standpoint, interpreting these shifts in mean and/or variance values is easier than interpreting changes in the long-term trend.

Shifts in mean values were analyzed using the Lombard method (e.g., Assani *et al.*, 2011, 2012, 2014). This method was chosen because of its demonstrated effectiveness for detecting shifts and characterizing them to facilitate their hydrological interpretation.

Suppose a series of observations, noted $X_1, \dots, X_n$, where X_i is the observation taken at time $T = i$. These observations are supposed to be independent. One question of interest is to see whether the mean of this series has changed. If μ_i refers to the theoretical mean of X_i , then a possible pattern for the mean is given by Lombard's smooth-change model

where

$$\mu_i = \begin{cases} \theta_1 & \text{if } 1 \leq i \leq T_1 \\ \theta_1 + \frac{(i - T_1)(\theta_2 - \theta_1)}{T_2 - T_1} & \text{if } T_1 < i \leq T_2 \\ \theta_2 & \text{if } T_2 < i \leq n \end{cases} \quad (1)$$

In other words, the mean changes gradually from θ_1 to θ_2 between times T_1 and T_2 . As a special case, one has the usual abrupt-change model when $T_2 = T_1 + 1$.

In order to test formally whether the mean in a series is stable or rather follows model (1), one can use the statistical procedure introduced by Lombard (1987). To this end, define R_i as the rank of X_i among $X_1, \dots, X_n$. Introduce the Wilcoxon score function $\phi(u) = 2u - 1$ and define the rank score of X_i by

$$Z_i = \frac{1}{\sigma_\phi} \left\{ \phi \left(\frac{R_i}{n+1} \right) - \bar{\phi} \right\}, \quad i \in \{1, \dots, n\} \quad (2)$$

where

$$\phi = \frac{1}{n} \sum_{i=1}^n \phi \left(\frac{i}{n+1} \right) \quad \text{and} \quad \sigma_\phi^2 = \frac{1}{n} \sum_{i=1}^n \left\{ \phi \left(\frac{i}{n+1} \right) - \bar{\phi} \right\}^2 \quad (3)$$

Lombard's test statistic is

$$S_n = \frac{1}{n^5} \sum_{T_1=1}^{n-1} \sum_{T_2=T_1+1}^n L_{T_1 T_2}^2 \quad (4)$$

where

$$L_{T_1 T_2} = \sum_{j=T_1+1}^{T_2} \sum_{i=1}^j Z_i \quad (5)$$

At the 95% confidence interval, one concludes that the mean of the series changes significantly according to a pattern of type (1) whenever $S'_n > 0.0403$. This value correspond to the theoretical (critical) values (see Lombard, 1987) defining the significance level at 5% for the test. Note that the equation proposed by Lombard (1987) to detect multiple abrupt changes in the mean of a statistical series was also applied. This formula confirmed results obtained using equation 1. It is important to note that the assumptions regarding the Lombard method (see Lombard, 1987; Quessy *et al.*, 2011) are valid for this application. Among these hypotheses, we checked for autocorrelation between values using the method proposed by Von-Storch and Navarra (1995), among others.

Analysis of the temporal variability of the dependence between the magnitude and timing of winter maximum daily flows using the copula method

In southern Quebec, winter floods may result from rainfall events and/or snowmelt. Floods caused by rainfall are frequent in early (December) and mid- (January and February) winter, while those caused by snowmelt occur toward the end of the season (March). In addition, the intensity of the magnitude of these floods varies as a function of their timing, being generally greater at the end of the winter season than at the beginning. Although there is a link between the timing and magnitude of winter daily floods in Quebec, this link may be changing over time due to a potential increase in frequency and amount of precipitation as rain resulting from increased winter temperatures. We used the copula method to quantify the temporal evolution of this dependence. This method may be used to analyze the temporal variability of the link between two variables. The dependence in a random vector (X, Y) is contained in its corresponding copula function C . Specifically, the celebrated theorem of Sklar (1959) ensures that there exists a unique $C : [0, 1]^2 \longrightarrow [0, 1]$ such that

$$P(X \leq x, Y \leq y) = C\{P(X \leq x), P(Y \leq y)\}. \quad (6)$$

Quessy *et al.* (2012) developed a testing procedure to identify a change in the copula (*i.e.* dependence structure) of a bivariate series $(X_1, Y_1), \dots, (X_n, Y_n)$. The idea is based on Kendall's tau, which is a nonparametric measure of dependence. Let $\hat{T}_T$ be Kendall's tau measured for the first T observations and $\hat{T}_{T+Ln}$ be Kendall's tau for the remaining $n-T$ observations. The proposed test statistic is

$$M_n = \max_{1 \leq T \leq n} \frac{T(n-T)}{n\sqrt{n}} |\hat{T}_T - \hat{T}_{T+Ln}| \quad (7)$$

i.e. a maximum weighted difference between the Kendall's tau. Since M_n depends on the unknown distribution of the observations, the so-called multiplier re-sampling method is used for the computation of p -values. Specifically, for n sufficiently large ($n > 50$), this method yields independent copies $M_n^{(1)}, \dots, M_n^{(N)}$ of M_n . Then, a valid p -value for the test is given by the proportion of $M_n^{(i)}$'s larger than M_n . For more details, see Quessy *et al.* (2012). Usually, one can expect that the series $X_1, \dots, X_n$ and $Y_1, \dots, Y_n$ are subject to changes in the mean and / or variance following, *e.g.* the smooth-change model (Lombard, 1987). If such changes are detected, the series must be stabilized in order to have (approximately) constant means and variances. Finally, a change in the degree of dependence between two series is statistically significant when $M_n > Vc$, where Vc is the critical value derived from the multiplier resampling method.

As part of this study, the copula method was applied to standardized dates of occurrence and magnitude data for winter maximum daily flows. It should be noted that this method was applied after removing any statistically significant shift in mean values.

Analysis of the link between climate indices and characteristics (magnitude and timing) of winter maximum daily flows

Canonical correlation analysis (CCA) was used to analyze the link between the five climate indices and the two characteristics (magnitude and timing) of winter maximum

daily flows. This statistical method was applied using the approach recently proposed by Mazouz *et al.* (2013), because all stations can be analyzed simultaneously without requiring prior regionalization of the hydrological variables.

CCA was described in particular by Afifi and Clark (1996). If one wishes to calculate the relation between two groups, one of X variables ($X_1, X_2, \dots, X_p$) and the other of Y variables ($Y_1, Y_2, \dots, Y_q$), one must calculate the canonical variables V ($V_1, V_2, \dots, V_p$) and ($W_1, W_2, \dots, W_q$), which are linear combinations of the X variables of the first group (in this case, the two flow characteristics) and the Y variables of the second group (in this case, the climatic indices). Then, the canonical variables U and V are correlated between themselves, that is to say, V_1 is correlated to W_1 , V_2 to W_2 and so on, in order to obtain the canonical correlation coefficients. After that, the canonical variables U and V are correlated to the variables X and Y , so as to obtain what are called structure coefficients. In fact, these coefficients measure the link (the correlation) between the canonical variables (U and V) and the original variables of groups X and Y . Thus, if X_1 and X_2 are correlated, for example, to V_1 , Y_1 is correlated to W_1 . Y_1 is therefore correlated to the original variables X_1 and X_2 , since the canonical variables V_1 and W_1 are correlated. The main purpose of canonical correlation analysis is to maximize the correlations between the two groups of variables. For our purposes, the group of independent variables X comprises the five climate indices, and the group of dependent variables Y comprises the magnitude and timing of winter maximum daily flows. All these independent and dependent variables were first standardized to remove any effect of size on the coefficient of correlation values. For magnitude, this standardization was applied to specific discharge data, thus allowing watersheds of different sizes to be compared. Timing data were converted to Julian days prior to their standardization. Finally, CCA was applied to a matrix comprising 1292 rows (76 years of observation $\times$ 17 rivers) by 8 columns (river + 5 climate indices + 2 hydrologic variables). The clear statistical advantage of this approach is that CCA can be applied to a matrix comprising a very large number of data (1292) rather than to one comprising only 76 rows (number of years of observation).

Results

Analysis of shift in mean values of hydrologic series

Autocorrelation values of order 1 are shown in Figure 2. No autocorrelation coefficient is statistically significant at the 5% level, which implies that the series are random and the Lombard method may therefore be used. Results obtained using this method are shown in Table 2, from which it can be seen that most hydrological series are affected by a shift in mean values. Only the Nicolet du Sud-Ouest and Du Loup rivers, located on the south shore, show no shift. For nearly all rivers, this shift in mean values is abrupt (aside from the Châteauguay and Trois-Pistoles rivers, which show smoothed shifts). As for the timing of these shifts, most of them took place during the first half of the 1970's decade. Thus, these shifts in mean are synchronous. At the scale of southern Quebec as a whole, mean values of winter maximum daily flows increased significantly after these shifts (Fig. 3). This increase in mean values ranged from 31% (Du Sud river) to 134% (Matane river), the mean value of winter maximum daily flows for the latter river more than doubling after the 1970's. The relative increase in mean values (R), however, is not of function of watershed surface area (Fig. 4), as correlation coefficients calculated between the two variables are not statistically significant at the 5% level.

Analysis of the timing of winter maximum daily flows

Table 3 shows the relative frequencies of occurrence of maximum daily flows during the twelve decades of winter in southern Quebec. In general, maximum daily flows can occur during any winter decade, aside from the first two dekads of February for some of the rivers. They do, however, occur more frequently during the first decade (Decade I) of the season on the north shore and on the south shore north of 47°N, and during the last decade (Decade XII) on the south shore south of 47°N.

To analyze the temporal variability of the dates of occurrence of winter maximum daily flows, we compared the frequency of these dates before and after the 1970's decade, which is when the shifts in mean values took place for the bulk of rivers. This

comparison is restricted to the first and last decades, which are the two modal classes of frequency of occurrence. Results of this comparison are shown in Table 4. Application of the Chi-square method did not reveal any statistically significant change in the frequency of occurrence of maximum daily flows after 1970 for the first decade. In contrast, this frequency increased significantly after 1970 for the last decade. This significant increase in frequency is larger for south shore rivers located north of 47°N and north shore rivers. Since these rivers are characterized by more frequent occurrence of maximum daily flows during the first decade than during the last decade, as mentioned based on data in Table 3, this increase clearly reflects a change in the date of occurrence of maximum daily flows in these two hydroclimatic regions. Thus, after the 1970's, these maximum flows are now much more frequent during the last decade than during the first.

Analysis of the dependence between the magnitude and date of occurrence of winter maximum daily flows

The coefficient of correlation values calculated between the two variables are shown in Table 5. Half of the coefficients of correlation are statistically significant at the 5% levels. Correlation between the two variables is positive, which means that the magnitude of maximum daily flows occurring late in the season is higher than that of flows occurring early in the season. One key point of the analysis was to check whether the changes in mean values of maximum daily flows and in the frequency of the dates of occurrence of these flows affected the evolution of this dependence over time. This evolution was therefore analyzed using the copula method, the results of which are presented in Table 6. From these, it can be seen that changes are only observed for two rivers (Châteauguay and Blanche). The case of the Châteauguay river is highlighted in Figure 5. Thus, it appears that for many rivers, the evolution of the dependence of the magnitude and date of occurrence of maximum daily flows did not change significantly over time.

Link between the magnitude and date of occurrence of maximum daily flows

Table 7 shows the coefficients of structure calculated between the two hydrological variables and the five climate indices. While the two hydrological variables were correlated with the five fall (SON and SOND) and five winter (JFM and DJFM) climate indices, the best correlation obtained was for winter climate indices calculated over four months (DJFM). As far as hydrological variables are concerned, the date of occurrence is strongly correlated with V1, and the magnitude, with V2. For climate indices, winter NAO is correlated with W1 and winter PDO, with W2. Consequently, NAO is positively correlated with the dates of occurrence of the magnitude of maximum daily flows, this magnitude being in turn positively correlated with PDO.

Discussion and conclusions

Studies looking at the temporal variability of winter temperature and precipitation in Quebec have highlighted a significant increase in temperature and rainfall, with a decrease in snowfall (e.g., Brown, 2010; Yagouti *et al.*, 2008). The temperature increase was particularly strong for minimum temperatures, while low-intensity rainfall events increased significantly.

The impacts of these changes in climate variables on winter flood flows in St. Lawrence River tributaries in southern Quebec have never been studied. However, Assani *et al.* (2014) showed in a recent study that winter maximum and minimum daily water levels in the St. Lawrence have decreased significantly after the 1980's. Thus, it is very important to determine if the decrease in snowfall also caused a decrease in daily flood flows in St. Lawrence River tributaries.

An analysis of the stationarity, using the Lombard method, of maximum daily flows in 17 tributaries of the St. Lawrence River in southern Quebec over the period from 1934 to 2010 revealed a significant increase in flow magnitude for nearly all tributaries analyzed, this increase having generally occurred during the first half of the 1970's

decade. This increase cannot be caused by a decrease in amount of snow, which should result in a decrease in flow magnitude. Moreover, this decrease in the amount of snow occurred during the 1980's (Brown, 2010) and therefore after the change in flood magnitude.

Analysis of the temporal variability of the dates of occurrence of winter maximum daily flows highlighted a significant increase in the frequency of occurrence of these dates after 1970. As previously mentioned, due to Quebec's continental temperate climate, winter floods associated with maximum daily flows can be the result of rainfall and/or snowmelt. Floods resulting from rainfall mainly occur in early and mid-winter, while those caused by snowmelt primarily occur toward the end of winter. A comparison of the frequencies of the dates of occurrence of maximum daily flows by decade shows that, for the first decade of winter, these frequencies did not increase significantly after 1970, implying that the frequency of winter floods resulting from rainfall did not increase significantly after that year. In contrast, for the last decade of winter, winter flood frequencies did increase significantly after 1970, which suggests that the frequency of maximum daily flows resulting from snowmelt increased significantly after 1970 as a result of early snowmelt, rather than an increase in the amount of snow. Prior to the 1970's, this snowmelt often occurred in April, or early spring. But after the 1970's, snowmelt occurs relatively early, toward the end of March (winter). This earlier melting phenomenon has been observed in many regions of North America (e.g., Burn, 2008; Cayan *et al.*, 2001; Cunderlik and Ouarda, 2009; Déry *et al.*, 2009; Hodgkins *et al.*, 2003; Hodgkins and Dudley, 2006) and is also observed in Quebec in the dates of occurrence of the magnitude of spring freshets (Mazouz *et al.*, 2012). As a consequence, the increase in magnitude of winter maximum daily flows after the 1970's is simply the result of early snowmelt that is now frequently observed near the end of winter in southern Quebec, which explains why the magnitude of winter maximum daily flows has increased significantly over time in spite of decreasing amounts of snow.

Analysis of the correlation between climate indices and the magnitude of maximum daily flows using CCA showed that this hydrologic variable is positively correlated with

PDO. Brown (2010) has already shown that, in southern Quebec, this is the climate index that best correlates with the amount of the snow. However, the climate mechanisms through which PDO affects the snowfall in Quebec remain poorly constrained. As far as the dates of occurrence of maximum daily flows are concerned, they are positively significantly correlated with NAO. Kingston *et al.* (2006) proposed a conceptual framework to explain the effect of this index on the spatial and temporal variability of temperature, precipitation and streamflow in the northeastern United States and eastern Canada, among other places. When this index is in a positive phase, the persistence of polar air over Quebec, in particular, tends to result in delayed snowmelt, and thus winter floods tend to occur later in the season (toward the end of winter).

This study highlights the fact that, unlike spring flood flows, the magnitude of winter flood flows increased significantly over time after the 1970's as a result of early snowmelt increasingly occurring at the end of March. Thus, the decrease in amount of snow observed since the 1980's in southern Quebec has no impact on the temporal variability of the magnitude of winter floods.

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Tables and Figures

Table 1 Rivers analyzed.

No	Code	River	Area (km ²)	Latitude (N)	Longitude (W)	MAF (m ³ /s)
Southeastern Hydroclimate Region						
R1	SE1	Chateaugay	2500	45°17'	73°48'	26.0
R2	SE2	Eaton	642	45°28'	71°39'	8.6
R3	SE3	Nicolet SW	544	45°47'	71°58'	8.4
R4	SE4	Etchemin	1130	46°38'	71°02'	28.5
R5	SE5	Beaurivage	709	46°39'	71°17'	10.5
R6	SE6	Du Sud	826	46°49'	70°45'	14.7
Eastern Hydroclimate Region						
R7	E1	Ouelle	802	47°25'	69°56'	15.6
R8	E2	Du Loup	1050	47°49'	69°31'	15.4
R9	E3	Trois-Pistoles	932	48°05'	69°11'	13.4
R10	E4	Rimouski	1610	48°24'	68°33'	26.5
R11	E5	Matane	826	48°46'	67°32'	33.4
R12	E6	Blanche	208	48°46'	67°39'	4.8
Southwestern Hydroclimate Region						
R13	SW1	De La Petite Nation	1330	45°47'	75°05'	19.1
R14	SW2	Du Nord	1170	45°47'	74°00'	21.5
R15	SW3	L'Assomption	1340	46°00'	73°25'	23.5
R16	SW4	Matawin	1390	46°41'	73°54'	22.4
R17	SW5	Vermillon	2670	47°39'	72°57'	37.2

MAF = Mean annual flow

Table 2 Results of the Lombard method applied to winter maximum daily flow series for the period from 1934 to 2010.

No	Code	Sn	T1	T2	M1 (m ³ /s)	M2 (m ³ /s)	R (%)
R1	SE1	0.1447a	1956	1973	210.3	345.5	+64.2
R2	SE2	0.1040a	1974	1975	98.4	145.5	+47.9
R3	SE3	0.0193	-	-	-	-	-
R4	SE4	0.0539a	1971	1972	92.8	136.8	+47.4
R5	SE5	0.1644a	1970	1972	47.1	99.6	+111.4
R6	SE6	0.1267a	1971	1972	80.2	105.1	+31.0
R7	E1	0.1267a	1971	2000	29.9	53.6	+79.3
R8	E2	0.0066	-	-	-	-	-
R9	E3	0.0997a	1959	1973	45.4	67.2	+48.0
R10	E4	0.0903a	1971	1973	41.0	58.5	+42.7
R11	E5	0.1090a	1948	1949	29.7	69.5	+134.0
R12	E6	0.1614a	1972	1973	5.5	12.3	+123.6
R13	SW1	0.2417a	1961	1974	20.7	38.5	+86.0
R14	SW2	0.0839a	1971	1972	54.6	84.9	+55.5
R15	SW3	0.0864a	1971	1972	48.5	66.1	+36.6
R16	SW4	0.1914a	1971	1972	26.0	50.4	+93.8
R17	SW5	0.0997a	1962	1963	33.2	51.9	+56.3

a = Sn values > 0.0403 are statistically significant at the 5% level and are shown in bold and red. T1 and T2 are the years of beginning and end, respectively, of changes in mean values. M1 = mean value before the shift; M2 = mean value after the shift. R = Increase rate (%) in mean after the shift.

Table 3 Comparison of the relative frequencies (%) of decadal occurrences of winter maximum daily flows during the winter season.

Code	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
SE1	6.6	5.3	3.9	3.9	6.6	1.3	1.3	1.3	2.6	9.2	15.8	42.1
SE2	5.3	3.9	5.3	2.6	2.6	6.6	6.6	0	3.9	5.3	19.7	38.2
SE3	11.8	7.9	9.2	2.6	5.3	5.3	0	0	1.3	6.6	18.4	31.6
SE4	19.7	5.3	6.6	5.3	6.6	2.6	1.3	1.3	1.3	2.6	9.2	38.2
SE5	23.7	7.9	3.9	5.3	1.3	3.9	0	1.3	1.3	5.3	13.2	32.9
SE6	25.0	10.5	7.9	1.3	5.3	2.6	0	0	2.6	1.3	6.6	36.8
E1	38.2	7.9	5.3	2.6	3.9	3.9	0	0	1.3	6.6	6.6	23.6
E2	34.2	10.5	5.3	2.6	3.9	2.6	0	0	5.3	0	7.9	27.6
E3	43.4	7.9	5.3	1.3	6.6	1.3	1.3	1.3	1.3	2.6	6.6	21.1
E4	47.4	14.5	3.9	3.9	2.6	0	1.3	1.3	3.9	1.3	0	19.7
E5	57.9	9.2	3.9	3.9	2.6	1.3	1.3	0	2.6	0	1.3	15.8
E6	15.8	6.6	2.6	15.8	5.3	2.6	0	0	3.9	2.6	17.1	27.6
SW1	31.6	6.6	7.9	5.3	6.6	3.9	0	1.3	0	5.3	0	31.6
SW2	30.3	10.5	5.3	3.9	3.9	2.6	0	1.3	3.9	1.3	3.9	32.9
SW3	35.5	9.2	6.6	2.6	3.9	1.3	1.3	1.3	2.6	1.3	6.5	27.6
SW4	52.6	9.2	2.6	3.9	2.6	3.9	1.3	1.3	2.6	1.3	1.3	18.4
SW5	64.5	3.9	2.6	6.6	1.3	3.9	0	0	1.3	0	3.9	11.8

The highest (modal) frequencies are highlighted in bold and red.

Table 4 Comparison of the relative frequencies (%) of decadal occurrences of winter maximum daily flows before and after the 1970's for the first and last decades of winter (1934-2010).

Code	First decade		Last (twelfth) decade	
	Before 1970	After 1970	Before 1970	After 1970
SE1	60	40	56.3	43.7
SE2	50	50	55.2	44.8
SE3	71.4	28.6	41.4	58.6
SE4	55.6	46.4	50	50
SE5	66.7	33.3	24	76
SE6	61.1	38.9	41.3	58.7
E1	60.7	39.3	22.2	77.8
E2	53.8	46.2	23.8	76.2
E3	53.1	46.9	18.8	81.9
E4	48.6	51.4	40	60
E5	50	50	33.3	66.7
E6	0	100	25	75
SW1	39.1	61.9	41.7	58.3
SW2	47.8	52.2	48	52
SW3	46.2	53.8	38.1	61.9
SW4	60	40	40	60
SW5	47.9	52.1	22.2	77.8

Table 5 Coefficient of correlation values calculated between the magnitude and timing of winter maximum daily flows from 1934 to 2010.

Rivers (Code)	Coefficients of correlation
SE1	0.2055
SE2	0.1750
SE3	0.2226
SE4	0.3197a
SE5	0.2640a
SE6	0.384a
E1	0.2868a
E2	0.1650
E3	0.1860
E4	0.1506
E5	0.1541
E6	0.0195
SW1	0.0189
SW2	0.2896a
SW3	0.3648a
SW4	0.3133a
SW5	0.3140a

a = Statistically significant coefficient of correlation values at the 5% level.

Table 6 Analysis of the dependence between the dates of occurrence and the magnitude of winter maximum daily flows (1934-2010).

Code	Mn(max)	VC	p-value
SE1	1.0878	0.8497	0.0130a
SE2	0.5487	0.9182	0.4660
SE3	0.3954	0.8078	0.7180
SE4	0.5487	0.8739	0.4350
SE5	0.5376	0.7911	0.3170
SE6	0.5312	0.9092	0.4940
E1	0.6020	0.8788	0.3010
E2	0.6071	0.9401	0.3200
E3	0.3542	0.8528	0.8160
E4	0.5456	0.8829	0.4670
E5	0.8859	0.9165	0.0620
E6	0.9142	0.8949	0.0390a
SW1	0.9511	0.8315	0.0200
SW2	0.4886	0.8853	0.5170
SW3	0.7537	0.7735	0.0590
SW4	0.7050	1.0192	0.3010
SW5	0.8794	0.9076	0.0650

a = Statistically significant p-values.

Table 7 Coefficient of structure values calculated between winter climate indices (4 months) and hydrological variables (dates of occurrence and magnitude) for maximum daily flows from 1934 to 2010.

Variables	V1	V2	W1	W2
Magnitude	0.6162	0.7876		
Timing	0.9295	-0.3688		
AMO			-0.6474	-0.3533
AO			0.6181	0.1081
NAO			0.8094	-0.1074
PDO			-0.1519	0.8289
SOI			0.3766	-0.4921
EV (%)	62.2	37.8	32.4	21.5

The highest coefficients of structure that are statistically significant at the 1% level are shown in bold. EV= explained variance.

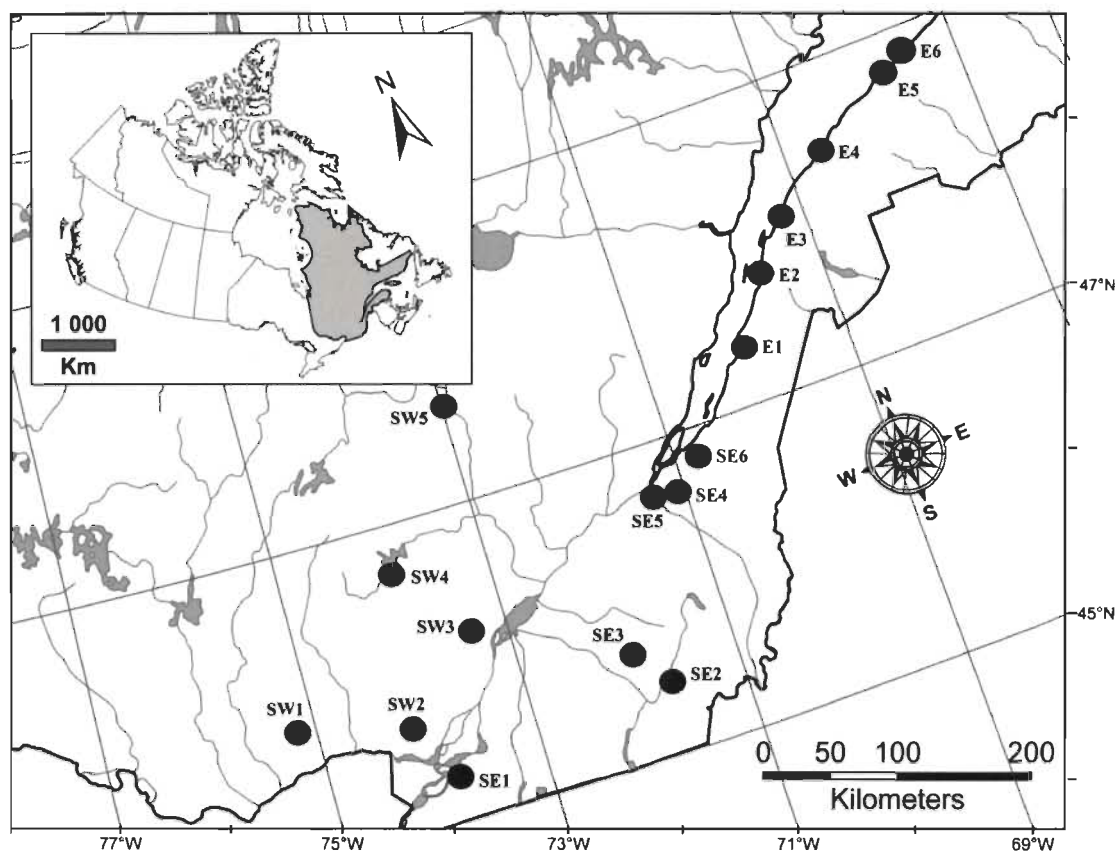


Figure 1 Location of stations.

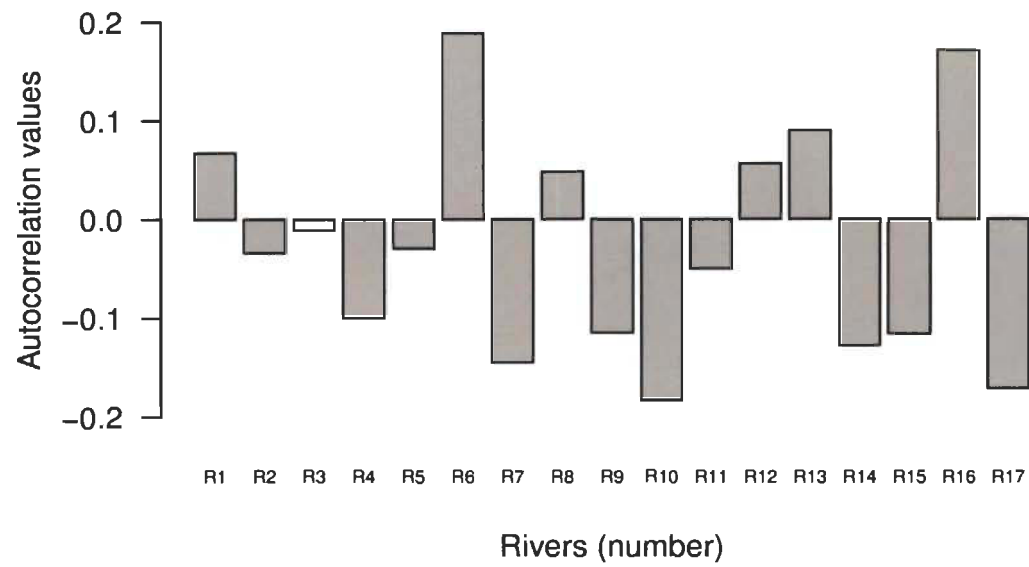


Figure 2 Autocorrelation coefficient values. No coefficient is statistically significant at the 5% level.

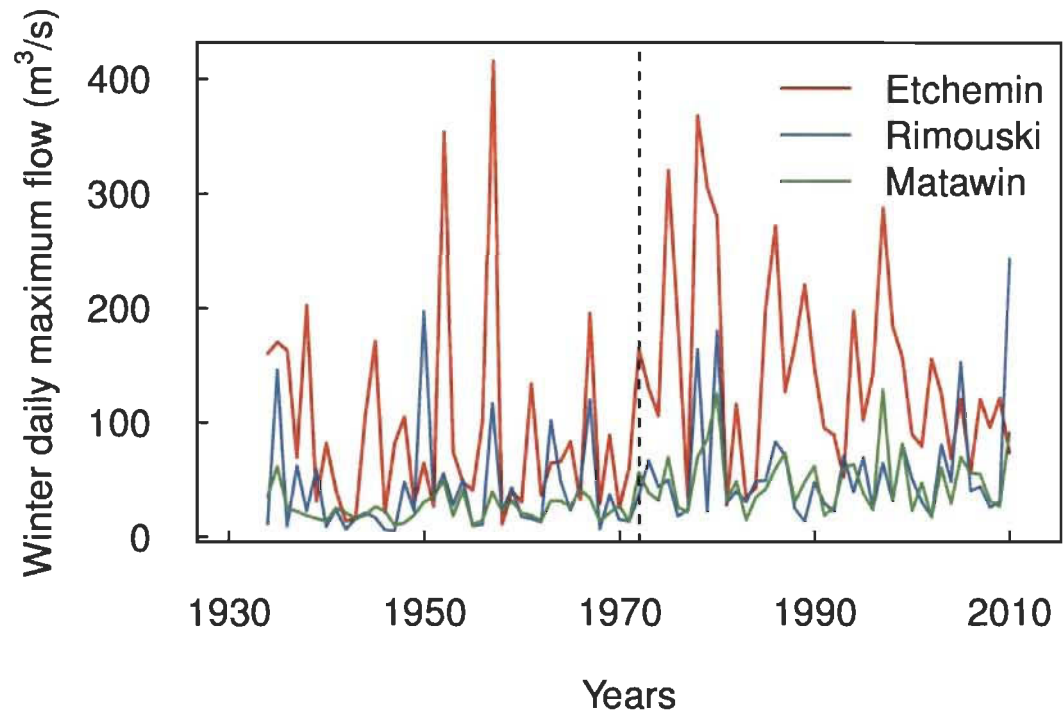


Figure 3 Temporal variability of the magnitude of winter maximum daily flows in the Etchemin (blue), Rimouski (red) and Matawin (green) rivers over the period from 1934 to 2010.

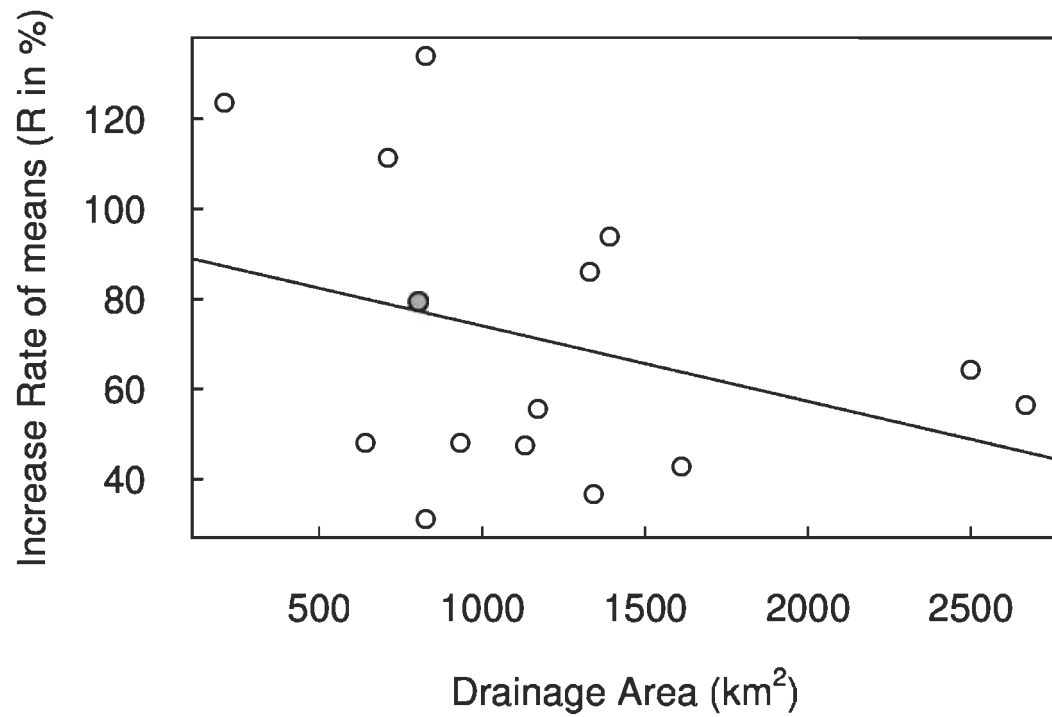


Figure 4 Link between the increase rate (R) in mean value of winter maximum daily flows and watershed surface area.

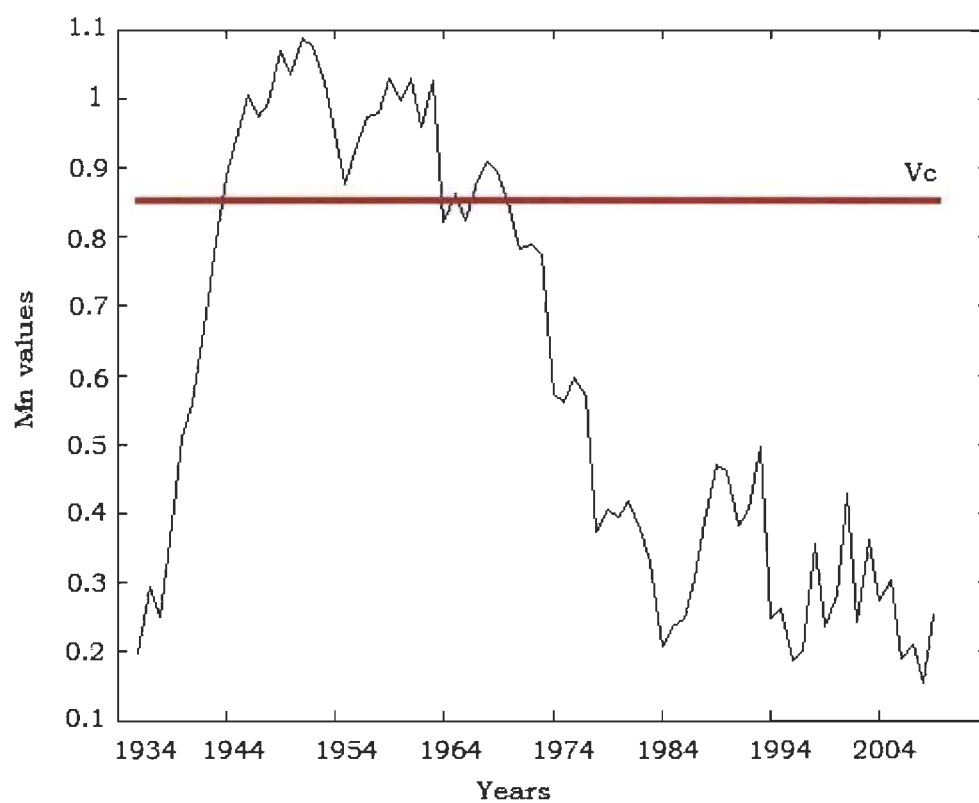


Figure 5 Temporal variability of M_n values for the Châteauguay river from 1934 to 2010. The red line is the VC value.

CHAPITRE III

CONCLUSION

De nombreuses études démontrent une augmentation des températures à partir des années 1970 au Québec. De ce fait, il est plausible de penser que la neige fond de façon plus précoce et que les précipitations se fassent plus sous forme de pluie que de neige. Ces conclusions nous portent alors à nous interroger sur le lien entre ces faits et les débits des rivières tributaires au fleuve St-Laurent. Des études ont déjà porté sur les crues estivo-automnales et printanières, alors qu'aucune n'a été réalisée sur les crues hivernales. L'originalité de la présente étude repose précisément sur cet aspect. L'objectif de notre projet est d'étudier la variabilité spatio-temporelle de la magnitude et de la période d'occurrence des débits maximums journaliers hivernaux ainsi que leur relation avec les indices climatiques. Nos hypothèses étaient que ces débits avaient significativement diminué après 1970 en raison de la diminution de la quantité de neige, qu'ils surviennent fréquemment à la fin de la saison et que la magnitude tout comme la période d'occurrence sont corrélés aux mêmes indices. De toutes ces hypothèses, uniquement celle relative au moment de la saison où surviennent les débits s'est avérée retenue.

Il faut donc en conclure que la hausse des températures des années 1970 a effectivement eu un impact sur la fonte des neiges, rendant celle-ci plus précoce vers le mois de mars. Cependant, la diminution de la quantité de neige n'influence pas la variabilité spatio-temporelle des débits maximums hivernaux. Il reste ainsi à analyser les impacts de cette hausse de la magnitude des crues hivernales sur l'évolution morphologique des chenaux d'une part et, sur la dynamique des espèces aquatiques et semi-aquatiques des écosystèmes fluviaux au Québec, d'autre part.