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CHAPITRE I

INTRODUCTION

1.1 Contexte de recherche

Les impacts réels ou potentiels du réchauffement climatique sur les débits des rivières suscitent encore beaucoup de controverse. Cette controverse s'explique en partie par la difficulté des modèles climatiques à simuler adéquatement les précipitations qui génèrent les débits en raison de la diversité des sources d'incertitude dans les simulations climatiques (p. ex. Koutsoyiannis et al., 2008; Kundzewicz et al., 2008; Räisanen, 2007; Sun et al., 2007). Ainsi la prédiction des précipitations demeure encore incertaine. De plus, d'autres facteurs comme l'évapotranspiration, susceptibles d'influencer significativement la variabilité interannuelle des débits, ne sont pas pris suffisamment en compte par les modèles climatiques dans la prédiction des débits.

La prédiction des débits au Québec sous l'influence du réchauffement climatique fait aussi l'objet de controverse. Certains chercheurs prédisent une baisse des débits (p. ex. Croley, 2003); d'autres prédisent au contraire une hausse des débits (p. ex. Dibike and Coulibaly, 2005; Kundzewicz et al., 2008; Labat et al., 2004; McBean and Motiee, 2008; Roy et al., 2001; Singh, 1987). Entre ces deux positions opposées, certains chercheurs prédisent une alternance des périodes de hausse et de baisse des débits (p. ex. Minville et al., 2010). Enfin, d'autres chercheurs soutiennent que les changements des débits vont varier en fonction des saisons (p. ex. Boyer et al., 2010) : une hausse des débits en hiver, consécutive à une augmentation de la fréquence des précipitations sous forme de pluies, mais une baisse des débits au printemps en raison de la diminution de la quantité de neige qui tombe en hiver.

1.2 Problématique, objectifs et hypothèses de recherche

Pour contribuer à clarifier le débat sur la prédiction des débits au Québec, il devient important d'analyser la variabilité interannuelle des débits sur une période suffisamment longue afin de pouvoir détecter les effets du réchauffement climatique. Cette approche a été utilisée récemment par Assani et al. (2010) en ce qui concerne les débits maximums printaniers. Ces auteurs ont conclu que la variabilité interannuelle de ces débits n'est pas influencée par le réchauffement climatique. De plus, ces auteurs ont aussi démontré que la variabilité interannuelle des débits maximums printaniers n'est pas influencée par les mêmes indices climatiques. En effet, en Rive-Nord, les débits sont corrélés à l'oscillation atlantique multidécennale (OAM) et en Rive-Sud, ils le sont respectivement à l'oscillation australe (OAU) au nord du 47^e parallèle nord et à l'oscillation arctique (OA) au sud de ce parallèle. Bien que cette approche soit couramment utilisée dans la littérature scientifique, force est cependant de constater qu'elle présente une faiblesse : elle ne tient pas compte de toutes les caractéristiques fondamentales des débits (magnitude, durée, période d'occurrence, fréquence et variabilité). En effet, chacune de ces cinq caractéristiques joue un rôle important dans le fonctionnement des écosystèmes fluviaux. De plus, on doit admettre le fait que les impacts du réchauffement peuvent ou ne pas affecter, de manière uniforme, les cinq caractéristiques fondamentales. Certaines caractéristiques fondamentales seraient plus sensibles au réchauffement climatique que d'autres. Par conséquent, les études basées sur l'analyse de la variabilité temporelle d'une seule caractéristique fondamentale, en l'occurrence la magnitude, peuvent être considérées comme incomplètes pour détecter le signal du réchauffement climatique sur la variabilité interannuelle des débits.

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

1. Comparer la variabilité interannuelle des cinq caractéristiques fondamentales des débits de fortes crues printanières des 17 affluents naturels ou subnaturels du fleuve Saint-Laurent au Québec. Cet objectif repose sur l'hypothèse

suivante : la variabilité interannuelle n'est pas uniforme pour les cinq caractéristiques, car certaines caractéristiques seraient plus sensibles au réchauffement climatique que d'autres.

2. Analyser les changements qui affectent le lien entre les cinq caractéristiques des débits dans le temps. Cet objectif se fonde sur l'hypothèse suivante : les changements des moyennes et/ou des variances de certaines caractéristiques fondamentales des débits de fortes crues printanières dans le temps affectent peu le degré de dépendance entre ces caractéristiques.

3. Comparer les facteurs climatiques qui influencent la variabilité temporelle de ces cinq caractéristiques. L'hypothèse qui sous-tend cet objectif est la suivante : la variabilité interannuelle de ces cinq caractéristiques n'est pas influencée par les mêmes facteurs (indices) climatiques en raison de leur sensibilité différente à la variabilité climatique.

En ce qui concerne le dernier objectif de notre étude, nous avons proposé une méthode qui permet d'analyser simultanément la relation entre toutes les caractéristiques fondamentales des débits de plusieurs rivières et les indices climatiques.

1.3 Méthodologie de recherche

1.3.1 Méthode de Lombard

Le test de Lombard (1987) a été effectué à l'aide d'un programme en langage MatLab. Dans ce test, on compare les valeurs de la série (S_n) avec celle de la valeur critique (VC), dans le cas de notre étude, la valeur critique est égale à **0.0403** « seuil critique de significativité du test de Lombard de 5 % (Lombard, 1987) », les valeurs S_n supérieures à cette valeur critique de **0.0403** sont statistiquement significatives.

Deux étapes sont à suivre pour compléter le test de Lombard, la première étape consiste à tester la moyenne, et la seconde étape, à tester la variance. La rupture sera détectée entre les temps (t_1,t_2) dans le cas où la valeur de la série statistique (S_n) calculée sur la série est supérieure à la valeur critique de 0.0403.

1.3.2 Méthode canonique de redondance

Pour corréler les cinq caractéristiques des débits (magnitude, durée, période d'occurrence, fréquence et variabilité) aux cinq variables climatiques (OAM, OA, ONA, OPD et OAU), on a appliqué la méthode d'analyse canonique de redondance. Celle-ci a été développée par Rao (1964). Elle est une version canonique de l'analyse en composantes principales (ACP) des variables dépendantes Y (caractéristiques des débits) effectuées sous les contraintes imposées par les variables indépendantes X (indices climatiques). L'objectif de l'analyse est de chercher la combinaison des variables indépendantes (indices climatiques) qui explique le mieux la variation (ou dispersion) des variables dépendantes (caractéristiques des débits). L'Analyse canonique de redondance trouve les axes d'ordination des nuages de points qui sont les plus fortement linéairement liés à l'ensemble des variables explicatives. Selon Makarenkov et Legendre (1999), il existe deux approches pour effectuer une analyse canonique de redondance, mais elles conduisent aux mêmes résultats. La première approche est fondée sur l'utilisation de l'algorithme itératif de calcul des axes principaux. La seconde approche, utilisée notamment par Makarenkov et Legendre (1999), consiste au calcul d'une série de régressions linéaires multiples des variables dépendantes Y sur les variables indépendantes X, suivies d'une analyse en composantes principales de la matrice des valeurs ajustées.

On calcule la régression linéaire multiple de chaque variable dépendante centrée Y, à tour de rôle, sur toutes les variables indépendantes centrées X.

1.4 Résultats de recherche

1.4.1 Résultats de la méthode de Lombard

En ce qui concerne les deux premiers objectifs de notre recherche, les résultats obtenus par la méthode de Lombard pour la moyenne et la variance pour les 17 rivières analysées sont les suivants :

- Un changement de la moyenne de la magnitude a été détecté seulement pour trois rivières (De la petite Nation, Matane et Ouelle). Il se traduit par une hausse de la magnitude de crues printanières. Mais cette hausse n'est pas survenue la même année pour les trois rivières. De plus, aucun changement de la variance de la magnitude n'a été détecté même pour ces trois rivières.

- Un changement de la durée de la magnitude n'a été observé que pour une seule rivière (Eaton). Cette durée a diminué dans le temps. Deux rivières (Beaurivage et Ouelle) ont connu un changement significatif de la variance de la durée.

- Six rivières ont connu un changement significatif de dates moyennes d'occurrence de crues (De la petite Nation et en Matawin 1975, Du loup, Matane et Rimouski en 1978, et Vermillon en 1974). Pour ces rivières, le changement se traduit par une occurrence précoce de crues. En ce qui concerne la variance, une seule rivière (Nicolet du sud-ouest en 1958) a connu un changement significatif de la variance des périodes d'occurrence de crues. Toutefois, pour cette rivière, la moyenne des périodes d'occurrence n'a pas significativement changée. Par ailleurs, contrairement aux autres caractéristiques, tous les changements de la moyenne de période d'occurrence sont quasi synchrones. En effet, ils sont tous survenus durant la décennie 1970.

- Deux rivières (De la petite nation et Matane) ont connu un changement de la moyenne de la variabilité de la magnitude et deux autres (Blanche et Du Sud), celui de la variance de la variabilité de la magnitude. La variabilité de la magnitude de deux premières rivières augmente dans le temps.

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- L'analyse de la variabilité interannuelle de la fréquence des débits de crues au moyen de la régression linéaire a révélé une hausse significative de la fréquence pour trois rivières (Blanche, Nicolet du sud-ouest et Trois-Pistoles) mais une baisse significative de la fréquence pour la rivière Rimouski. De plus, cette méthode a confirmé les changements observés par l'application de la méthode de Lombard en ce qui concerne les moyennes des séries.

1.4.2 Résultats de la méthode canonique de redondance

En ce qui concerne le troisième objectif de notre recherche qui consiste à comparer les facteurs climatiques qui influencent la variabilité temporelle de ces 5 caractéristiques des 17 rivières, les résultats obtenus par la méthode canonique de redondance sont les suivants :

Les variances expliquées cumulées de deux premiers axes canoniques calculés au moyen des indices climatiques hivernaux et printaniers sont respectivement de 78 % et 92 %. Ceci traduit en fait une meilleure corrélation entre les caractéristiques des débits et les indices climatiques printaniers.

En ce qui concerne les axes calculés au moyen des indices climatiques hivernaux, le score de la durée est corrélé négativement au premier axe tandis que celui de la caractéristique fréquence est corrélé positivement au second axe canonique. Quant aux indices climatiques, les scores d'OAM (Oscillation atlantique multi-décennale) et d'OAU (Oscillation australe) sont bien corrélés sur le premier axe canonique alors que ceux d'OA (Oscillation arctique) et ONA (Oscillation nord-atlantique) le sont sur le deuxième axe canonique.

Au niveau des indices climatiques printaniers, la période d'occurrence et la durée sont corrélées négativement au premier axe canonique tandis que la variabilité CV (Coefficient de Variation) est corrélée positivement au second axe. Quant aux indices climatiques, les scores (OAM) et (ONA) sont corrélés au premier axe canonique alors que les indices ONA et OPD (Oscillation Pacifique Décennale) sont corrélés au second axe canonique.

Il ressort de cette analyse que la caractéristique de la durée des débits est corrélée aux indices hivernaux d'OAM et d'OAU et la caractéristique fréquence est corrélée aux indices hivernaux d'OA et d'ONA. En ce qui concerne les indices printaniers, les indices OAM et ONA sont corrélés à la période d'occurrence et à la durée de fortes crues printanières. Cette corrélation est positive entre ONA et les deux caractéristiques, mais négative entre celles-ci et OAM. Enfin, la caractéristique CV est corrélée négativement à ONA, mais positivement à OPD. Ces corrélations sont confirmées par la longueur des flèches associées aux caractéristiques des débits et aux indices climatiques.

Les notes factorielles des stations sur les axes canoniques n'ont pas révélé une organisation spatiale bien précise sur les axes canoniques calculés au moyen des indices climatiques hivernaux. En revanche, en ce qui concerne les indices climatiques printaniers, les notes factorielles de toutes les rivières situées dans les régions hydroclimatiques est et sud-est sont toutes négatives alors que celles des rivières de la région hydroclimatique sud-est sont positives à l'exception d'une seule rivière.

CHAPITRE II

COMPARISON OF THE INTERANNUAL VARIABILITY OF SPRING HEAVY FLOODS CHARACTERISTICS OF TRIBUTARIES OF THE ST. LAWRENCE RIVER IN QUEBEC (CANADA)

Ce chapitre est présenté sous forme d'article, en anglais, et a été publié dans la revue *Advances in Water Resources* sous la référence :

Mazouz R., Assani A.A., Quessy JF. and Légaré G. 2012. Comparison of the interannual variability of spring heavy floods characteristics of tributaries of St. Lawrence River in Quebec (Canada). Advances in Water Resources, 35, 110-120.

Comparison of the interannual variability of spring heavy floods characteristics of tributaries of the St. Lawrence River in Quebec (Canada)

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Résumé

Nous avons comparé la variabilité interannuelle de cinq caractéristiques fondamentales (magnitude, durée, période d'occurrence, fréquence et variabilité) des débits maximums printaniers de 17 rivières naturelles au Québec pendant la période 1934-2004 afin de détecter l'impact de réchauffement climatique sur ces caractéristiques. L'analyse a été effectuée au moyen des méthodes de Lombard et de la régression linéaire. Peu de changements significatifs ont été observés sur les séries de magnitude, de durée, de fréquence et de variabilité des débits de crues printanières. En revanche, nous avons détecté un changement significatif de la période d'occurrence de crues printanières (occurrence précoce) pour 35 % de rivières analysées. Ce changement, survenu de manière quasi synchrone durant la décennie 1970, a été interprété comme un signal de réchauffement climatique.

Mots clés : Caractéristiques des débits, variabilité interannuelle, crues printanières, changement climatique, Méthode de Lombard, Régression linéaire, Québec

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Abstract

Comparison of the interannual variability of five characteristics (magnitude, duration, timing, frequency, and variability) of spring heavy floods was carried out for 17 natural rivers in Quebec for the period from 1934 to 2004 to detect any effect of climate warming on these characteristics. This was done using the Lombard method and Copula. Changes in the mean and variance of all characteristics of streamflow were observed, and all these changes are abrupt. Whereas little significant change was observed in the magnitude, duration and variability (CV) series of spring flood flows. A significant change was noted in the frequency (diminution) for five rivers and in the timing of spring floods for six rivers. However, the change in mean timing is the only one that has a hydroclimatic significance in time and space. This change was observed, on the one hand, in the Eastern hydrological region, located on the south shore of the St. Lawrence River, north of 47°N, and characterized by a maritime climate and, on the other hand, in the South-west hydrological region, located on the north shore and characterized by a continental climate. In both cases, the change took place after the second half of the 1970's and is characterized by the early occurrence of spring floods. In addition, in both hydrological regions, the timing of spring floods is correlated with the same hydroclimatic indices, showing a positive correlation with the North Atlantic Oscillation (NAO) and a negative correlation with the Atlantic Multidecadal Oscillation (AMO). Frequency is the only characteristic for which mean and variance changed significantly over time for the same rivers (4), all located north of 48°N, on both shores of the St. Lawrence. For all flow characteristics, the change in variance can predate, postdate or be synchronous with the change in mean. Finally, the dependence between the various characteristics of spring floods as determined using the Kendall tau statistic remained constant in time for most of the rivers.

Keywords: flow characteristics, spring floods, Lombard method, linear regression, Kendall tau, Quebec

Introduction

A consensus is growing regarding the fact that climate warming might, to some extent, affect flood flows throughout the world. Thus, a growing number of studies attempts to constrain the effect of this warming on the interannual variability of flood flows (e.g. Assani et al., 2010a; Bhutiyani et al., 2008; Burn, 2008; Burn et al., 2004; Carson, 2007; Cayan et al., 2001; Cunderlik and Burn, 2002, 2004; Cunderlik and Ouarda, 2009; Douglas et al., 2000; Jiang et al., 2005; Déry et al., 2009; Dettinger, 2011; Hannarford and Marsh, 2008; Hodgkins et al., 2003; Hodgkins and Dudley, 2006; Leclerc and Ouarda, 2007; Lindström and Bergström, 2004; Petrow and Merz, 2009; Robson, 2002; St George, 2007; Villarini et al., 2009; 2011a, 2011b; Villarini and Smith, 2010; Vogel et al., 2011; Whitfield, 2007; Whitfield and Cannon, 2000; Whitfield et al., 2003; Zhang et al., 2001). Although the most widely accepted notion is that the intensity (magnitude) of flood flows should increase (Kundzewicz et al., 2010), such an increase is still rarely observed. In spite of the increasing global temperature, analysis of many hydrological series of flood flows has revealed no significant change in their mean or variance (e.g. Assani et al., 2010a; Burn and Hag Elnur, 2002; Kundzewicz et al., 2005).

However, all these studies generally deal with peak magnitude and not with other characteristics of floods (frequency, duration, timing, and variability). It is therefore important to determine which flow characteristic is most sensitive to climate variability or climate change in order to monitor its effect on flood conditions. Thus, this study has four objectives:

1. To compare the interannual variability of all fundamental characteristics of spring maximum flows in southern Quebec. The hypothesis to test is the uniformity of the interannual variability of all five fundamental characteristics of spring flood flows.

2. To determine which characteristics of spring maximum flows are most sensitive to climate warming in Quebec. These characteristics can then be used to detect and monitor the climate warming signal and the effect of climate indices.

3. To use the copula method to analyze the dependence between spring maximum flow magnitude (primary characteristic) and the other fundamental characteristics, to see if climate warming has any effect on this dependence. This issue has not yet been addressed in the scientific literature.

4. To determine whether the mean and variance of hydrological series show a similar sensitivity to climate change or climate variability.

Methodology

Choice of rivers and composition of hydrologic series of spring maximum flow characteristics

The St. Lawrence River watershed in Quebec covers a 673,000 km² area. Tributaries of the St. Lawrence for which a continuous record of flow measurements over at least 50 years is available and which are not significantly affected by dams or other major human activity were selected for the study. In total, 17tributaries were selected (Fig. 1 and Table 1). On the south shore, many gauging stations on these rivers are located near their confluence with the St. Lawrence River. The 17 rivers were subdivided into three homogeneous hydrological regions with respect to the interannual variability of flow at the annual, seasonal and daily scales (Assani et al., 2010a, 2010b; 2011a; 2011b). The Eastern region (E), located on the south shore north of 47°N, is characterized by a maritime climate, whereas the South-west region (SW), located on the north shore, is characterized by a continental climate. Finally, the South-east hydrological region (SE) is characterized by a climate that is somewhere a mix between maritime and continental, but with a heavy maritime trend. This region is located on the south shore south of 47°N, and unlike the other two regions, is characterized by extensive agriculture (Table 2).

Assani et al. (2010a and 2010b) showed that streamflow is correlated with the ENSO climate index (El Niño/Southern Oscillation) in the Eastern region, to AO (Arctic Oscillation) in the South-east region and to AMO (Atlantic Multidecadal

Oscillation) in the South-west region. In the present study, two other indices were also correlated with streamflow characteristics, namely the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO). The data for these five indices were extracted from the following websites: http://www.cdc.noaa.gov/ClimateIndices/List (AMO, SOI, NINO3.4 and PDO, extracted 2006 May 15), http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html (NAO, extracted 2006 May 15) and http://jisao.washington.edu/data/ao/ (AO, extracted 2006 May 15). For each index, we calculated the seasonal means (seasonal climate indices) for the following two seasons: winter (January to March) and spring (April to June).These various climate indices affect the interannual variability of winter and spring temperature and precipitation in North America, which therefore affects the five characteristics of spring heavy floods. Numerous authors have described the physical mechanisms underlying the impact of these climate indices on the interannual variability of climate and streamflow (e.g. Curtis, 2008; Enfield et al., 2001; Kingston et al., 2006; McCabe et al., 2004; Sutton and Hobson, 2005; Tootle and Piechota, 2006).

For ease of comparison of the interannual variability of the characteristics of these tributaries, a common time interval over which flows were measured was selected, from 1934 to 2004 (70-year span). Daily flow data were taken from the Environment Canada website (http://www.wsc.ec.gc.ca/hydat/H2O/index_f_cfm?). In Quebec, the hydrologic year begins in October and ends in September. The highest flow is measured during spring snowmelt (April to June).

The procedure developed by Assani et al. (2010b) was used to make up the hydrologic series of spring maximum flow characteristics. This procedure is based on the ecological concept of the natural flow regime (Richter et al., 1996; Poff et al., 1997), according to which streamflow can be decomposed into five characteristics, namely magnitude, frequency, duration, timing, and variability. These five characteristics were subdivided into three categories: primary (magnitude), secondary (duration and timing) and tertiary (frequency and variability) (Assani et al., 2010b). A characteristic is secondary when it serves to define a primary characteristic (e.g., duration or timing of magnitude), and a characteristic is tertiary (frequency, variability and distribution curve shape) when it serves to define the primary and secondary characteristics. Each characteristic may be defined by at least one hydrological variable. Assani et al. (2006a, 2006b) have shown that the number of characteristics to be defined depends on the scale of analysis (annual, seasonal, monthly, or daily) and the hydrologic series type (annual or partial). At the daily scale, these five characteristics can only be defined for a partial series. Definition of the five characteristics involved the following steps (Assani et al., 2010a):

- In the first step, we constructed a spring seasonal streamflow series (series constructed by the highest streamflow values measured each year between April and June).

- In the second step, for each year, we selected all streamflow values equal to or greater than Qm, Qm being the lowest value of the seasonal series constituted in Step 1. Thus, for each year, we have at least one streamflow value ≥ Qm. Parallel to the streamflow magnitude series, we also constructed the series of four other characteristics, namely timing, duration, frequency and variability, this latter characteristic being defined with the coefficient of variation. The dates of occurrence of the flood were converted into Julian days (from January 01). Duration was defined as the number of days during which streamflow magnitude remained ≥ Qm during a spring season. It is expressed as a percentage of the total number of days in the spring season. This type of transformation had no effect on the long-term trend of the hydrologic series. In fact, the original and the transformed series yielded the same results. The values of the coefficients of variation were calculated based on the flood magnitude values. Frequency was defined as the number of times streamflows ≥ Qm were measured during a spring season. Frequency data were converted to probability and expressed in percent using the following formula: FMi = Nix100/Nt, where FMi is the frequency expressed in percent, Ni is the number of events ≥ Qm observed during a given year, and Nt is the total number of events ≥ Qm observed over the 1934-2004 period. An event is a flood with flows equal or greater than Qm during one or more consecutive days.

- In the last step, when several floods occurred in the same season (from April to June), we calculated their average duration and timing. However, concerning the magnitude and coefficients of variation, this average was calculated when the streamflow $\geq$ Qm lasted more than one day. In all, we constituted five series of fundamental spring flood characteristics during the period from 1934 to 2004 (Table 3).

Statistical analysis

Detection of breakpoints in a univariate series

As previously mentioned, linear regression and the Mann-Kendall test, the two methods commonly used in hydrology, are not capable of detecting the nature (abrupt or smooth), nor the exact timing (year) of changes in the mean or variance of a hydrological series. Instead, the method developed by Lombard (1987) was used.

Let $X_1, \ldots, X_n$ be a sequence of independent observations, 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

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

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 $X_1,\ldots X_n$. Introduce the Wilcoxon score function $\phi(u) = 2u - 1$ and define the rank score of X_i by

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

where

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

Lombard's test statistic is

$$S_n = \frac{1}{n^5}\sum_{T_1=1}^{n-1}\sum_{T_2=T_1+1}^{n} L^2_{T_1T_2}, \tag{4}$$

where

$$L_{T_1T_2} = \sum_{j=T_1+1}^{T_2}\sum_{i=1}^{j} Z_i \tag{5}$$

At the 5% significance level, one concludes that the mean of the series changes significantly according to a pattern of type (1) whenever $S_n > 0.0403$. At the 10% significance level, the mean of the series changes significantly whenever $S_n > 0.0287$ (Lombard, 1987). The test is suitable for the detection of all kinds of patterns in equation (1), including abrupt changes. It is also possible to test whether the variance of the series changes by using the so-called Mood score function, namely $\phi(u) = (2u-1)^2$. A complete investigation of the power and robustness of S_n and of five other test statistics proposed by Lombard is given in Quessy et al. (2011a).

Lombard (1987) also proposed another test which allows detection of multiple changes in the mean of a hydrological series. However, because graphical analysis of the data did not reveal the presence of multiple changes in the mean values of streamflow characteristics, this test was not used. This was confirmed by separately analyzing sub-series of the main series (before and after the year a change took place).

Duration and frequency data were also analyzed with the classic Mann-Kendall test, using the graphical approach proposed by Sneyers (1975). This test yielded similar results to those obtained with the Lombard method.

Detection of breakpoints in the dependence of a bivariate series

The copula is increasingly used in hydrology to describe the dependence between two variables to get around the limitations of conventional methods which consist in characterizing the individual behaviour of the two variables by the same parametric family of univariate distributions (e.g., De Michele and Salvadori; Favre et al., 2004; Genest and Favre, 2007; Genest et al., 2007; Grimaldi and Serinaldi, 2006; Renard and Lang, 2007; Salvadori and De Michelle, 2004; 2007). It is now well-established that 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

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

Quessyet al. (2011b) developed a testing procedure to identify a change in the copula (*i.e.* dependence structure) of a bivariate series $(X_1, Y_1), \ldots, (X_n, Y_n)$. The idea is based on Kendall's tau, which is a nonparametric measure of dependence; see Lee (1990) for more details. Let $\hat{T}_{1:T}$ be Kendall's tau measured for the first T observations and $\hat{T}_{T+1:n}$ be Kendall's tau for the remaining $n-T$ observations. The proposed test statistic is

$$M_n = \max_{1<T<n} \frac{T(n-t)}{n\sqrt{n}} \left| \hat{T}_{1:T} - \hat{T}_{T+1:n} \right| \tag{7}$$

i.e. a maximum weighted difference between the Kendall 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 $M_n^{(1)},...M_n^{(N)}$ 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. (2011b). Usually, one can expect that the series $X_1,...,X_n$ and $Y_1,..., Y_n$ are subject to changes in the mean and / or variance following, e.g. the smooth-change model (1). If such changes are detected, the series must be stabilized in order to have (approximately) constant means and variances. The procedure is shown to be valid by Champagne et al. (2010).

Results

Detection of breakpoints in a univariate series

Results obtained using the Lombard method is presented in Table 4 for mean and Table 5 for variance values. Although the mean value of all five characteristics analyzed shows a significant change over time, this change does not affect all rivers. A change in magnitude was only observed for three rivers, two of these (Ouelle and Matane) being located in the Eastern hydrological region, and the third (De la Petite Nation), in the South-west region. This change consists in an increase in the magnitude of spring floods (Fig. 2). A significant change (decrease) in the mean duration of spring floods over time is observed for a single river (Eaton), located in the South-east hydrological region (Fig. 3). Six rivers show a significant change in the average date (timing) of spring flood occurrence (Fig. 4). Three of these rivers are in the South-west region, and the other three, in the Eastern region. This change corresponds to earlier spring floods over time (decrease in the mean of the dates of change). Five rivers show a change in the mean of the frequency of spring heavy floods (Fig. 5a, 5b). For all five rivers, this change is an increase in frequency. Three of the five rivers are located in the Eastern hydrological region, while the other two rivers are located respectively in each of the other two regions. Finally, two rivers (Beaurivage and Matane) show a change in the mean coefficient of variation (CV), variability of magnitude (Fig. 6), which increases significantly in both cases.

As for variance, no change in that of the magnitude is observed (Table 5). The variance of spring flood duration for the Beaurivage and Ouelle rivers (Fig. 7) and of the timing of spring heavy floods in the Nicolet SW River decreased significantly over time (Fig. 8a). And although the variance of the frequency of spring heavy floods in four rivers (Trois-Pistoles, Rimouski, Blanche and Vermillon) also decreased significantly over time, that change did not take place synchronously in the four rivers. Finally, the variance of CV for the Du Sud River increased, while for the Blanche River, this value decreased (Fig. 8b, 8c). For none of the rivers analyzed is a change in the mean or the variance of all five characteristics observed. Four rivers (Trois-Pistoles, Rimouski, Blanche and Vermillon) show a change in mean and variance of the same characteristic, namely frequency.

Changes in mean and variance are abrupt for all rivers. The dates (timing) of these changes depend on the actual statistical variable (mean or variance) and streamflow characteristic (magnitude, duration, timing, frequency or variability). For the four rivers which show a change in the mean and variance of the same characteristic (frequency), the change in variance occurred before the change in mean for two rivers (Blanche and Vermillon), and after the change in mean for the Trois-Pistoles river. The Rimouski River is the only one for which changes in the mean and variance of spring flood timing is synchronous.

Of all changes in mean and variance values, the change in mean timing is the only one which is more spatially and temporally coherent. Thus, the change in mean timing took place during the second half of the 1970's for six rivers (Table 4). From a spatial standpoint, the timing of floods changed significantly in two hydrological regions, the Eastern region (3 out of 6 rivers) characterized by a maritime climate, and the South-west region (3 out of 5 rivers) characterized by a continental climate. The change took place earlier in the latter region than in the former. However, in each of these two regions taken individually, the date of the change in mean timing is the same for all rivers in which this change is observed. Finally, the four rivers for which the mean and variance of frequency have changed significantly are all located north of 48°N on either shores of the St. Lawrence.

Detection of breakpoints in the dependence of a bivariate series

The dependence between the primary flood characteristic (magnitude) and other characteristics (duration, timing, frequency and variability) was the only dependence relationship analyzed. A change in the dependence between magnitude and the other three fundamental characteristics was observed for only two rivers (Châteauguay and De la Petite Nation) (Figs. 9-11 and Table 6). For the former, the change occurred in 1963, whereas for the De la Petite Nation River, a change in the dependence between magnitude and variability took place in 1960, and a change in the dependence between magnitude and the other two characteristics (duration and timing) occurred in 1976 (Figs. 10, 11 and Table 7). The Nicolet du Sud-Ouest River shows a change in the dependence between magnitude and duration, but this change, which took place in 1982, is only significant at the 10% level. Finally, for the Rimouski River, a significant (at the 1% level) change in the dependence between magnitude and variability occurred in 1988.

Comparison of Kendall's tau values before and after the date of a change in dependence between flood flow characteristics reveals that, for the Châteauguay River, this value increased after that date (Table 7). This means that the level of dependence or link between magnitude and the other flood characteristics increased over time. In contrast, this dependence decreased over time for De la Petite Nation River, as Kendall's tau values decrease after the date of change. For magnitude-duration and magnitude-timing, these values even become negative after the year of change, as is also the case for two other rivers, the Southwest Nicolet and the Rimouski (Table 5).

Discussion and conclusions

This is the first study to compare simultaneously the interannual variability of five fundamental characteristics of flow for 17 rivers. Some of its novel results are listed below.

1. Change does not affect the mean and variance of all five characteristics in the same way, some characteristics being more sensitive to change than others. In this study, a change in the mean of the date of occurrence (6 out of 17) and frequency (5 out of 17) of spring floods was observed for several rivers, whereas only one river showed a change in the mean of the duration of spring floods.

2. For the sample of rivers analyzed, more rivers are affected by a change of mean than by a change in variance. This result is consistent with results obtained by Villarini et al. (2011a, 2011b) for rivers in the Midwestern United States and Central Europe. This could be due to the difficulties in detecting changes in the second order statistic, for which a stronger signal would be needed or a larger sample size. However, in the Eastern United States, the proportion of rivers which show a significant change in variance is higher than that of rivers showing a significant change in mean (Villarini and Smith, 2010). For the United States, the length of the period over which streamflow was measured cannot account for this difference.

3. Timing is the only characteristic for which the change in mean shows some spatial and temporal coherence. Thus, the change in the mean of timing took place during the second half of the 1970's, on one hand, and was only observed in the two hydrological regions characterized respectively by a maritime climate on the south shore, North of 47°N (E), and a continental climate on the south shore (SE), on the other. Although many studies in North America have noted the early occurrence of spring floods (e.g. Burn, 2008; Cayan et al., 2001; Cunderlik and Ouarda, 2009; Déry et al., 2009; Hodgkins et al., 2003; Hodgkins and Dudley, 2006), the actual cause of this phenomenon remains unclear. Two hypotheses are commonly put forward:

- Climate warming resulting from a CO2 increase is the hypothesis most commonly mentioned. In Canada, for instance, analysis of temperature variability over the last century revealed that a significant increase took place during the 1970's (Zhang et al., 2001). However, the lack of temperature data for many of the analyzed watersheds makes it impossible to conclusively demonstrate a link between temperature increase and the earlier occurrence of spring floods.

- The second hypothesis relates to a change in climate oscillation phase (AMO, AO, NAO, PDO and SOI). Such a change in phase affects rainfall and temperature regimes in North America, among other places. Analysis of the correlation between timing of flood flows in rivers reveals that this characteristic is significantly correlated with AMO and NAO (Table 8) in the Eastern and South-west hydrological regions. In both cases, this correlation is negative. AMO is known to have undergone a phase change from positive to negative during the 1970's (e.g. McCabe et al., 2004), reaching maximum values around the mid-1970's. The climatic effects of this index in North America are well documented (e.g. Enfield et al., 2001; Goldenberg et al., 2001; Gray et al., 2004; McCabe et al., 2004; Sutton and Hodson, 2005). During its negative phase, temperature is generally higher than normal in a large part of the continent, an increase which could account for earlier spring floods as a result of earlier snowmelt in the spring. As for NAO, it is positively correlated with the timing of spring floods. Kingston et al. (2006) identified two regions in North-eastern North America (including Quebec) based on the sign of the correlation between the hydroclimatic variables (temperature, precipitation and streamflow) and the NAO index: a region characterized by a negative correlation (Eastern Canada) and a region characterized by a positive correlation (Northeastern United States) between these two variables. Our study shows that in Quebec, the timing of spring flood is correlated positively to NAO. Therefore, this region behaves the same as the Northeastern United States. According to the scheme proposed by these authors, in regions characterized by a positive correlation between NAO and hydroclimatic variables, when NAO is in positive phase (high values), an increase in SSTs (Sea Surface Temperatures) is observed (more northerly Gulf Stream position), along with a reduced influence of the East Coast trough. As a result, the frequency of southerly airflow increases, and storm tracks coincide with the coast more often. Thus, temperature and precipitation are above average. This can lead to early snowmelt and, in turn, early spring floods.

4. Incidentally, the link between timing measured at different stations and climate indices suggests a spatial correlation. Douglas et al. (2000) have shown that such a spatial correlation can affect the significance of the trend. However, as previously mentioned, numerous studies have shown the early occurrence of nival spring floods in many regions of North America. Thus, this is a significant trend at the regional scale which cannot be assigned to the existence of a spatial correlation.

5. Frequency is the only characteristic for which the mean and variance changed significantly over time. This change is observed for four rivers, all located north of 48°N. This may suggest that the interannual variability of frequency in Quebec is dependent on latitude. However, changes in mean and variance values did not take place synchronously for these four rivers.

6. The degree of dependence between flood characteristics remains constant over time for most rivers analyzed, although for some rivers, it decreases, while for others, it increases over time. However, given the current state of understanding, it is difficult to establish which factors account for this type of change in Quebec.

7. This study supports the conclusion by Assani et al. (2010a) that there is currently no statistically significant generalized in the magnitude of spring flood flows in Quebec. On the other hand, climate and hydrological models predict a decrease in the amount of snow in winter (Boyer et al. 2010). This decrease will lead to a decrease in the magnitude of spring floods, which are almost exclusively derived from melting of snow accumulated in winter. Such a decrease in the magnitude of spring flood flows has been observed in several other Canadian provinces (Cunderlik and Ouarda, 2009).

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Table 1. Hydrometric stations analyzed.

No	River	Area (km^2)	Latitude (N)	Longitude (W)	MAF (m^3/s)
		South-East Hydrologic Region			
1	Châteauguay	2500	45°17’	73°48’	26.0
2	Eaton	642	45°28’	71°39’	8.6
3	Etchemin	1130	46°38’	71°02’	28.5
4	Nicolet SW	544	45°47’	71°58’	8.4
5	Beaurivage	709	46°39’	71°17’	10.5
6	Du Sud	826	46°49’	70°45’	14.7
		East Hydrologic Region			
7	Ouelle	802	47°25’	69°56’	15.6
8	Du Loup	1050	47°49’	69°31’	15.4
9	Trois-Pistoles	932	48°05’	69°11’	13.4
10	Rimouski	1610	48°24’	68°33’	26.5
11	Matane	826	48°46’	67°32’	33.4
12	Blanche	208	48°46’	67°39’	4.8
		South-west Region			
13	De La Petite Nation	1330	45°47’	75°05’	19.1
14	Du Nord	1170	45°47’	74°00’	21.5
15	L’Assomption	1340	46°00’	73°25’	23.5
16	Matawin	1390	46°41’	73°54’	22.4
17	Vermillon	2670	47°39’	72°57’	37.2

MAF = meanannual flow.

Table 2. Comparison of percent forest covers in catchments of the three Hydrologic Regions (Assani et al., 2011b).

Region	Number of rivers	Mean of drainage area (km^2)	Mean area covered by forest (%)
South-East	6	5279	52*
East	6	893	85
South-West	5	1580	88

*= In the Region, Forest area changed to agriculture land use.

Table 3. Streamflow characteristics defined on the partial series of spring floods of the Vermillon River (1934-2000). (Assani et al., 2010b).

Characteristics	Code	Hydrologic variable
Magnitude	M	Average of streamflows ≥ Qm measured in spring (April to June) of each year
Duration	DM	Number of days during which streamflows ≥ Qm were measured in spring of each year
Timing	TM	Average timing (in Julian days) of streamflows ≥ Qm measured in spring of each year
Frequency	FM	Number of times that streamflows ≥ Qm were reached or exceeded in spring of each year
Variability	CV	Coefficient of variation of streamflows ≥ Qm measured in spring of each year
Coefficient of skewness	CS	Coefficient of skewness of streamflows ≥ Qm measured in spring of each year

Qm = is the lowest value of the maximum seasonal series of spring floods.

Table 4. Sn values calculated using the Lombard test applied to spring maximum flow characteristics (1934-2004). Mean.

River	Magnitude		Duration		Timing		Frequency		Variability (CV)	
	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2
South-East Hydrologic Region										
Châteauguay	0.007	-	0.001	-	0.015	-	0.002	-	0.002	-
Eaton	0.005	-	**0.051**	**1954/1955**	0.003	-	0.004	-	0.008	-
Etchemin	0.002	-	0.010	-	0.006	-	0.008	-	0.006	-
NicoletSw	0.007	-	0.034	-	0.003	-	**0.066**	**1988/1989**	0.006	-
Beaurivage	0.004	-	0.005	-	0.009	-	0.024	-	0.008	-
Du Sud	0.003	-	0.011	-	0.026	-	0.000	-	0.009	-
East Hydrologic Region										
Ouelle	**0.106**	**1971/1972**	0.001	-	0.019	-	0.005	-	0.019	-
Du Loup	0.004	-	0.004	-	**0.056**	**1978/1979**	0.021	-	0.004	-
Trois-Pistoles	0.002	-	0.019	-	0.008	-	**0.046**	**1974/1975**	0.005	-
Rimouski	0.001	-	0.020	-	**0.202**	**1978/1979**	**0.101**	**1962/1964**	0.019	-
Matane	**0.066**	**1976/1977**	0.006	-	**0.068**	**1978/1979**	0.002	-	**0.068**	**1978/1979**
Blanche	0.015	-	0.0014	-	0.020	-	**0.047**	**1974/1975**	0.008	-
South-West Hydrologic Region										
De la Petite Nation	**0.085**	**1967/1969**	0.038	-	**0.052**	**1975/1976**	0.004	-	**0.054**	**1965/1966**
Du Nord	0.005	-	0.004	-	0.010	-	0.000	-	0.004	-
L'Assomption	0.006	-	0.003	-	0.023	-	0.000	-	0.0125	-
Matawin	0.038	-	0.010	-	**0.122**	**1975/1976**	0.005	-	0.031	-
Vermillon	0.023	-	0.000	-	**0.077**	**1975/1976**	**0.058**	**1967/1968**	0.018	-

Note: Values of Sn which are statistically significant at the 5% level are shown in red bold. T1 and T2 are year's corresponding to beginning and end, respectively, of a significant change in mean.

Table 5. Sn values calculated using the Lombard test applied to spring maximum flow characteristics (1934-2004). Variance.

River	Magnitude		Duration		Timing		Frequency		Variability (CV)	
	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2	Sn	T1/T2
South-East Hydrologic Region										
Châteauguay	0.002	-	0.011	-	0.009	-	0.007	-	0.016	-
Eaton	0.008	-	0.013	-	0.011	-	0.000	-	0.005	-
Etchemin	0.012	-	0.014	-	0.040	-	0.006	-	0.040	-
Nicolet Sw	0.030	-	0.011	-	**0.057**	**1958/1959**	0.001	-	0.026	-
Beaurivage	0.028	-	**0.097**	**1961/1962**	0.014	-	0.008	-	0.005	-
Du Sud	0.010	-	0.006	-	0.016	-	0.001	-	**0.070**	**1958/1959**
East Hydrologic Region										
Ouelle	0.006	-	**0.044**	**1977/1978**	0.008	-	0.002	-	0.008	-
Du Loup	0.024	-	0.024	-	0.004	-	0.009	-	0.014	-
Trois-Pistoles	0.022	-	0.038	-	0.007	-	**0.042**	**1980/1981**	0.000	-
Rimouski	0.004	-	0.003	-	0.005	-	**0.111**	**1962/1963**	0.027	-
Matane	0.002	-	0.009	-	0.006	-	0.005	-	0.006	-
Blanche	0.028	-	0.034	-	0.004	-	**0.048**	**1971/1972**	**0.083**	**1959/1960**
South-West Hydrologic Region										
De la Petite Nation	0.025	-	0.000	-	0.020	-	0.004	-	0.016	-
Du Nord	0.006	-	0.006	-	0.019	-	0.001	-	0.002	-
L'Assomption	0.027	-	0.003	-	0.009	-	0.000	-	0.003	-
Matawin	0.013	-	0.000	-	0.036	-	0.009	-	0.014	-
Vermillon	0.012	-	0.003	-	0.025	-	**0.062**	**1935/1936**	0.004	-

Note: Values of Sn which are statistically significant at the 5% level are shown in red bold. T1 and T2 are year's corresponding to beginning and end, respectively, of a significant change in mean.

Table 6. Results of the analysis of dependence between spring maximum flow characteristics.

Rivers	Magnitude-Duration	Magnitude-Timing	Magnitude-Variability
South-East Hydrologic Region			
Châteaugay	0.0689	**0.0000**	**0.0330**
Eaton	0.4720	0.2020	0.1820
Etchemin	0.2420	0.1570	0.1410
Nicolet du sud-ouest	0.0960	0.3300	0.2840
Beaurivage	0.1950	0.1070	0.5440
East Hydrologic Region			
Du Sud	0.4720	0.7860	0.1710
Ouelle	0.1440	0.8510	0.8530
Du Loup	0.2920	0.2960	0.5050
Trois-Pistoles	0.4820	0.8790	0.1570
Rimouski	0.3700	0.6040	**0.0080**
Matane	0.7410	0.3200	0.3550
Blanche	0.4520	0.1890	0.3420
South-West Hydrologic Region			
De La Petite Nation	**0.0000**	**0.0000**	**0.0290**
Du Nord	0.1900	0.1690	0.2520
L'Assomption	0.5130	0.2750	0.5160
Matawin	0.4520	0.5370	0.3650
Vermillon	0.5180	0.2100	0.8800

p-values calculated using the copula method. Statistically significant (at the 5% level) p-values are shown in red bold.

Table 7. Comparison of Kendall's tau values before and after a change in dependence between flood flow characteristics.

	Magnitude-Duration			Magnitude-Timing			Magnitude-CV		
	Year	Before	After	Year	Before	After	Year	Before	After
Châteauguay	1963	0.1019	0.2190	1963	-0.0421	0.1772	1963	0.1571	0.2455
De la Petite Nation	1976	0.2396	-0.1605	1976	0.1643	-0.1675	1960	0.4123	0.0547
Nicolet du sud-ouest	1982	0.0385	-0.0736	-	-	-	-	-	-
Rimouski	-	-	-	-	-	-	1988	0.1371	-0.0556

CV = coefficient of variation.

Table 8. Coefficients of correlation calculated between spring climate indices (April to June averages) and the timing of spring flood flows.

Rivers	AMO	AO	NAO	PDO	SOI
East Hydrologic Region					
Ouelle	**-0.263**	0.112	0.075	0.012	0.180
Du Loup	**-0.302**	0.164	**0.299**	-0.156	0.184
Trois-Pistoles	**-0.344**	0.153	**0.324**	-0.037	-0.032
Rimouski	**-0.246**	0.204	**0.334**	**-0.256**	0.221
Matane	**-0.316**	0.161	**0.315**	-0.207	0.127
Blanche	**-0.278**	0.201	**0.261**	-0.151	0.098
South-West Hydrologic Region					
De la Petite Nation	**-0.233**	0.149	**0.313**	0.020	0.211
Du Nord	**-0.254**	0.136	0.226	-0.002	0.161
L'Assomption	**-0.282**	0.037	0.218	-0.017	0.194
Matawin	-0.165	0.031	**0.253**	-0.011	**0.259**
Vermillon	**-0.307**	0.158	**0.340**	-0.072	**0.243**
South-East Hydrologic Region					
Châteauguay	-0.022	-0.126	0.046	0.047	-0.074
Eaton	-0.109	-0.093	-0.106	0.148	-0.137
Etchemin	-0.182	-0.004	0.159	0.169	-0.055
Nicolet SW	0.030	0.040	0.166	0.030	-0.075
Beaurivage	-0.223	0.009	0.014	0.056	0.145
Du Sud	**-0.276**	0.140	**0.380**	-0.004	0.095

Significant coefficient of correlation values at the 5% level are shown in red bold.

List of figures

Figure 7. Shift of variance. Interannual variability of duration of the magnitude of spring floods. a = Beaurivage River, b = Ouelle River. The vertical red bar indicates the year of variance shift.

Figure 8. Shift of variance. Interannual variability of timing (a) and CV (b and c) of the magnitude of spring floods. a = Nicolet SW River; b = Du Sud River; c = Blanche River. The vertical red bar indicates the year of variance shift.

Figure 9. Shift in dependence. Interannual variability of magnitude (black curve) and duration (red curve) of the magnitude of spring floods. The vertical red bar indicates the year of change in dependence between the two characteristics.

Figure 10. Shift in dependence. Interannual variability of magnitude (black curve) and timing (red curve) of the magnitude of spring floods. The vertical red bar indicates the year of change in dependence between the two characteristics.

Figure 11. Shift in dependence. Interannual variability of magnitude (black curve) and CV (red curve) of the magnitude of spring floods. The vertical red bar indicates the year of change in dependence between the two characteristics.

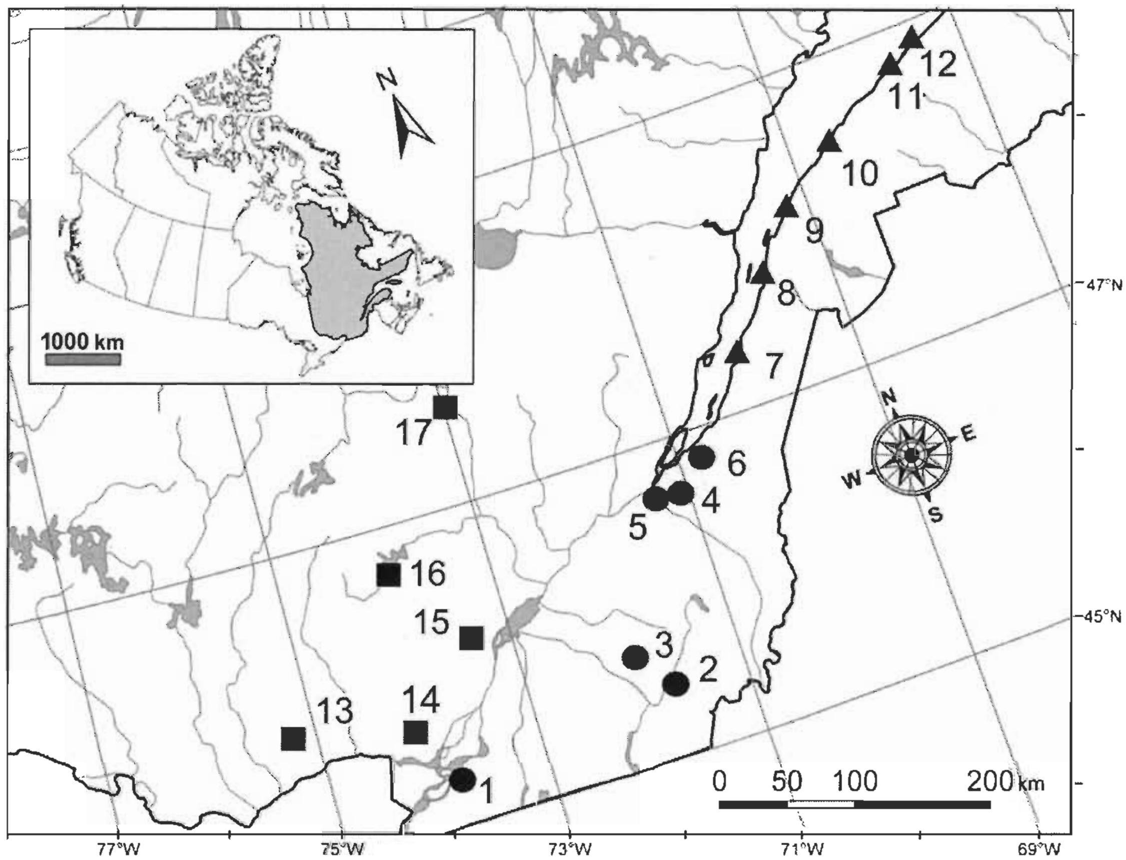

1000 km
N
12
11
10
9
8
7
6
5
4
3
2
1
13
14
15
16
17
N
E
W
S
0 50 100 200 km
47°N
45°N
77°W
75°W
73°W
71°W
69°W

Fig. 1.

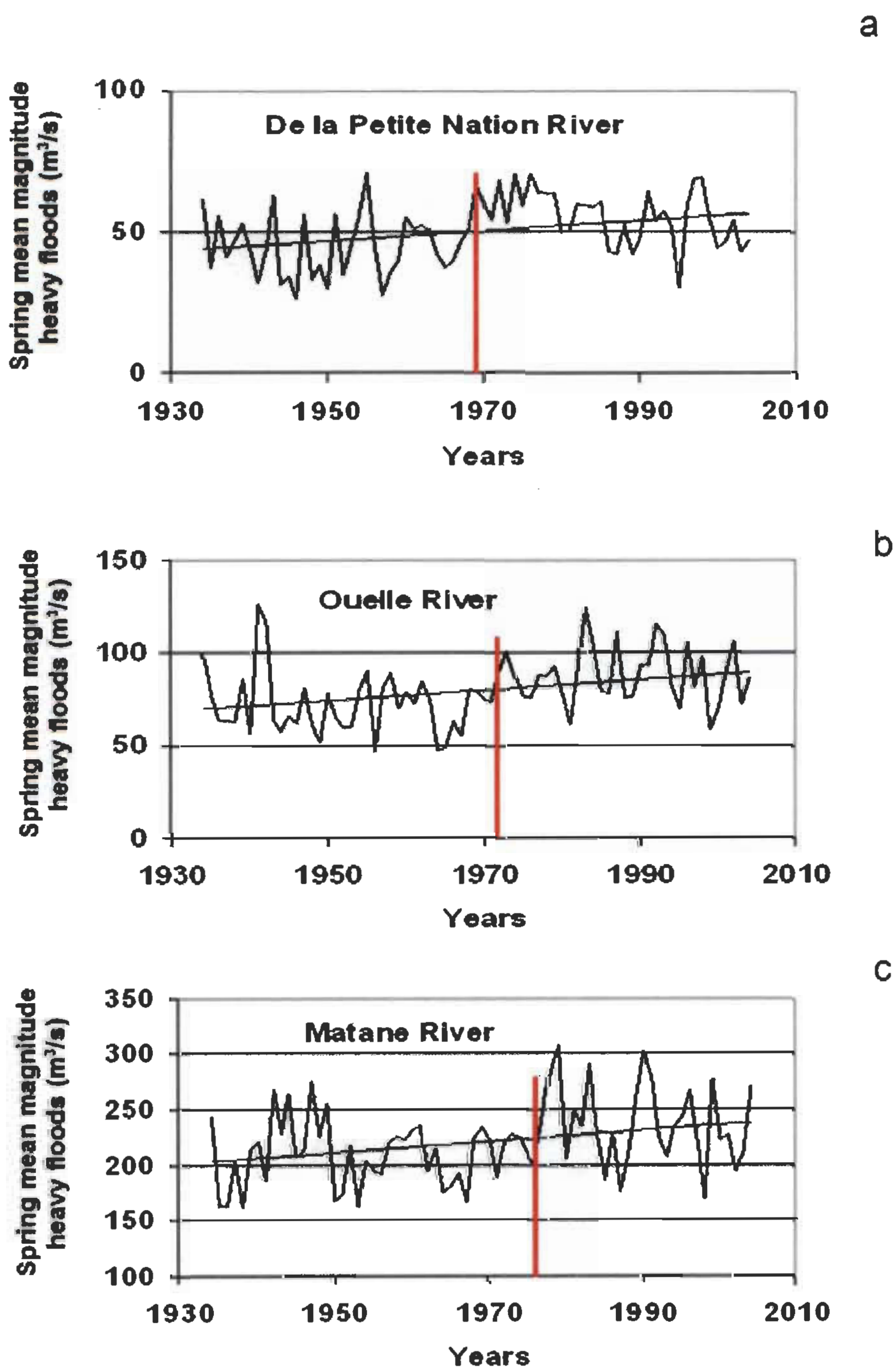

a
Spring mean magnitude heavy floods (m³/s)
100
50
0
De la Petite Nation River
1930
1950
1970
1990
2010
Years
b
Spring mean magnitude heavy floods (m³/s)
150
100
50
0
Ouelle River
1930
1950
1970
1990
2010
Years
c
Spring mean magnitude heavy floods (m³/s)
350
300
250
200
150
100
Matane River
1930
1950
1970
1990
2010
Years

Fig. 2.

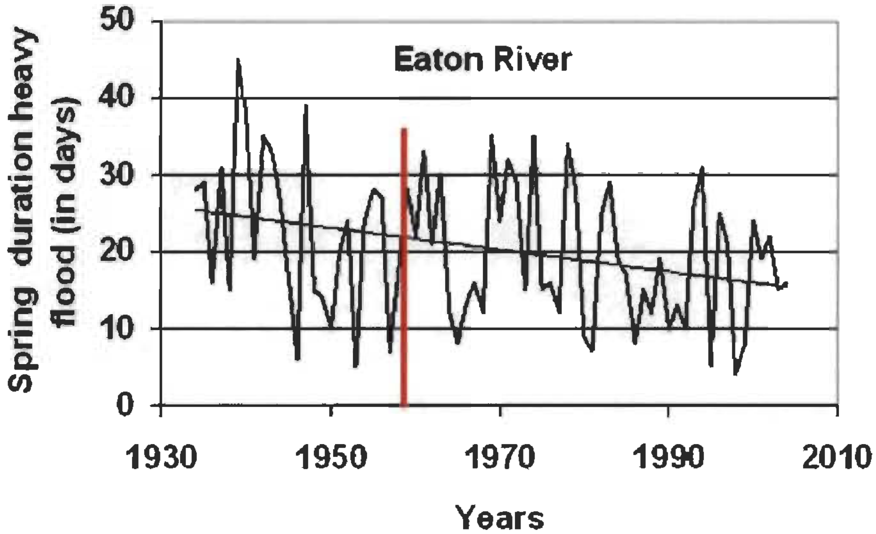
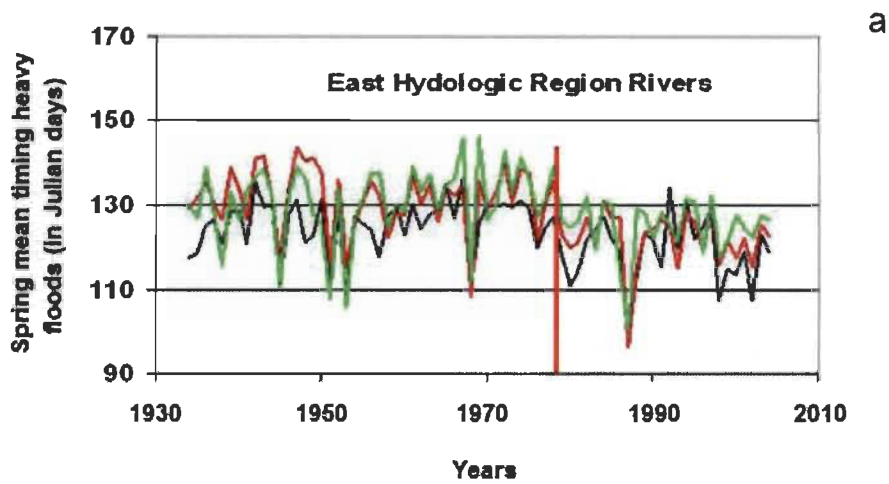

Eaton River
Spring duration heavy flood (in days)
0
10
20
30
40
50
1930
1950
1970
1990
2010
Years

Fig. 3.


a
East Hydologic Region Rivers
Spring mean timing heavy floods (in Julian days)
170
150
130
110
90
1930
1950
1970
1990
2010
Years

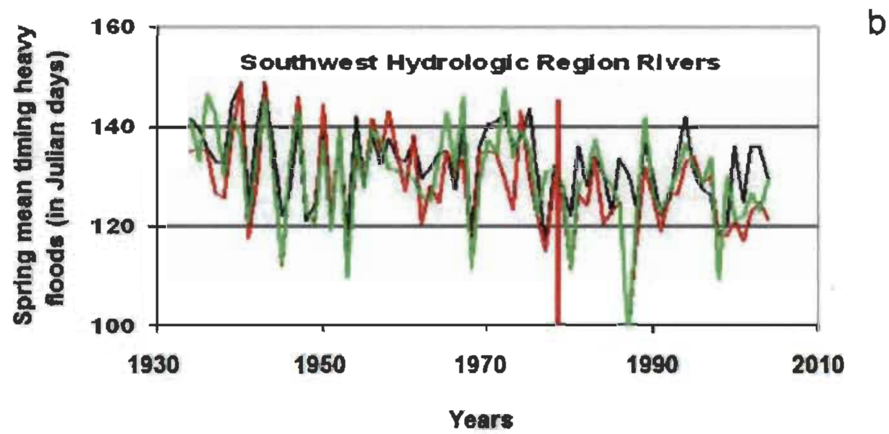

b
Southwest Hydrologic Region Rivers
Spring mean timing heavy floods (in Julian days)
160
140
120
100
1930
1950
1970
1990
2010
Years

Fig. 4.

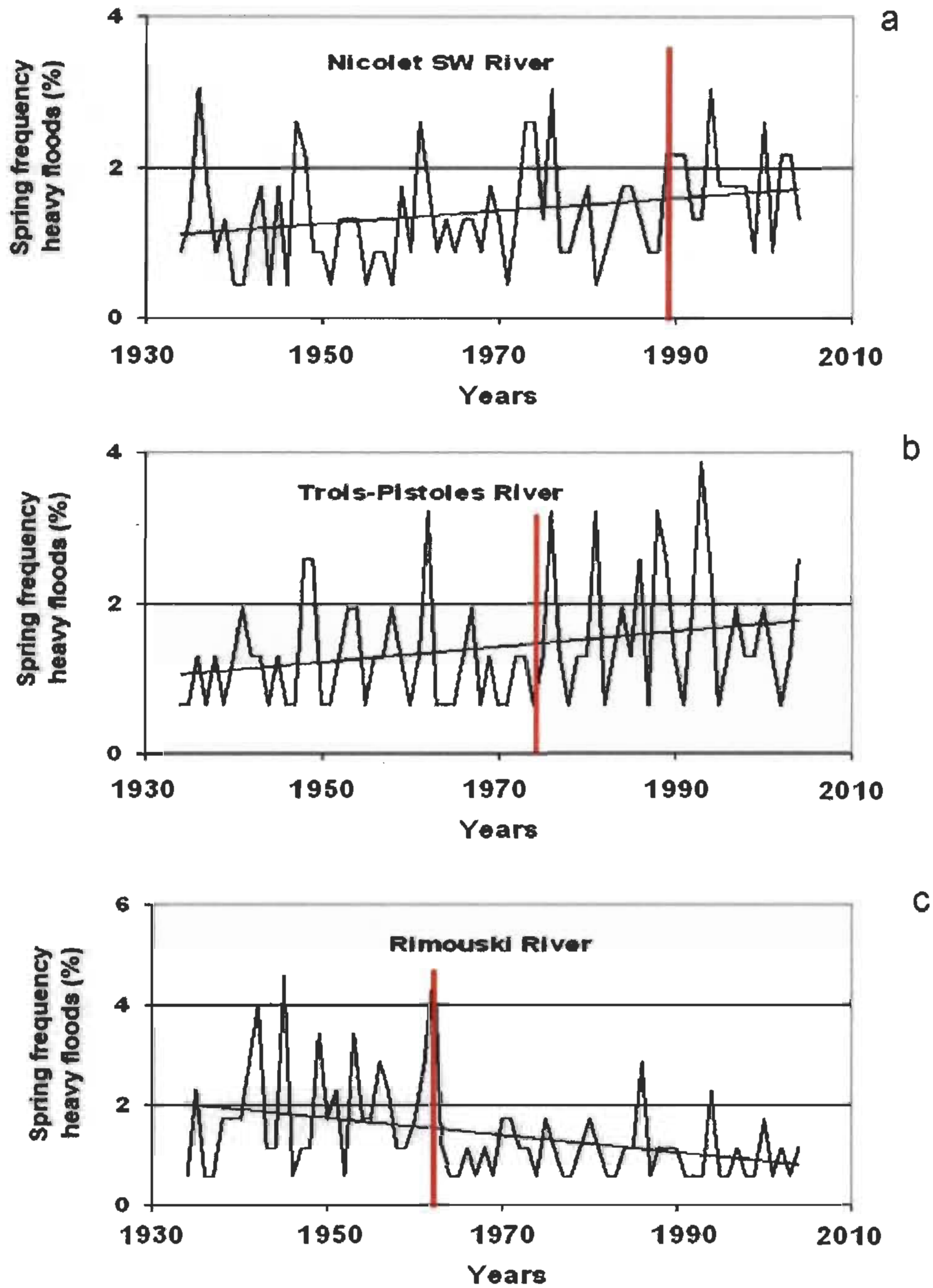

a
Nicolet SW River
Spring frequency heavy floods (%)
Years
b
Trois-Pistoles River
Spring frequency heavy floods (%)
Years
c
Rimouski River
Spring frequency heavy floods (%)
Years

Fig. 5a.

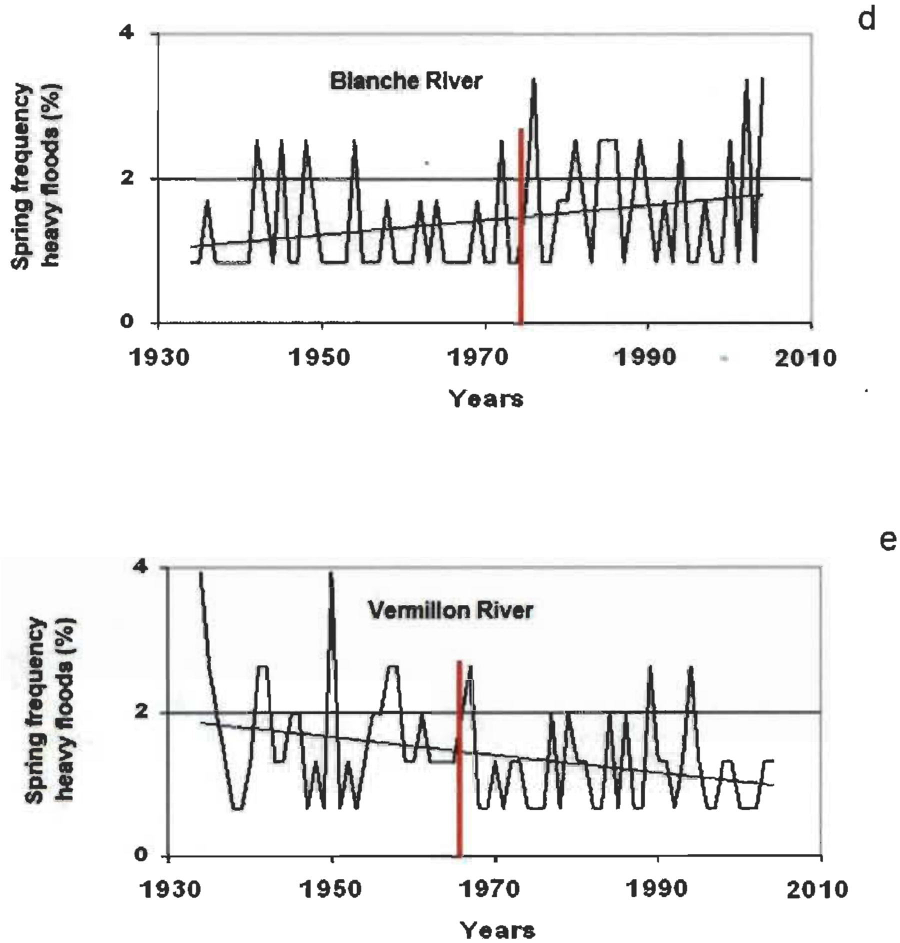
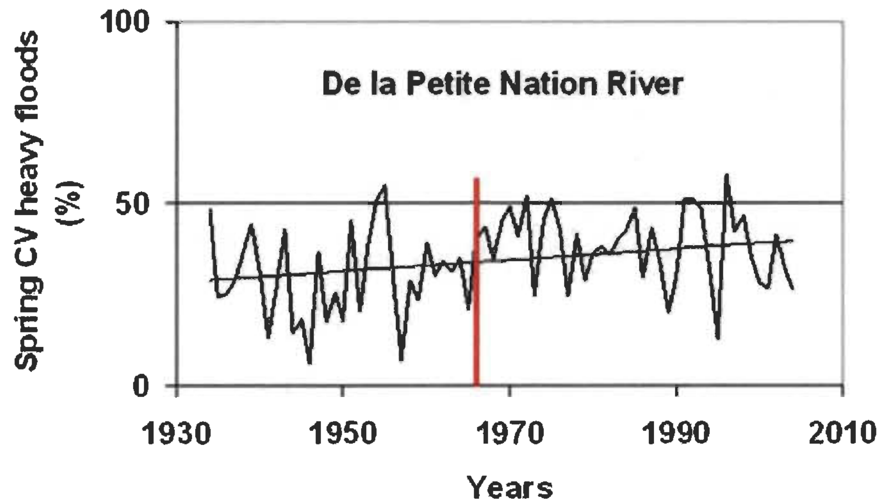

d
Blanche River
Spring frequency heavy floods (%)
4
2
0
1930
1950
1970
1990
2010
Years
e
Vermillon River
Spring frequency heavy floods (%)
4
2
0
1930
1950
1970
1990
2010
Years

Fig. 5b.


De la Petite Nation River
Spring CV heavy floods (%)
100
50
0
1930
1950
1970
1990
2010
Years

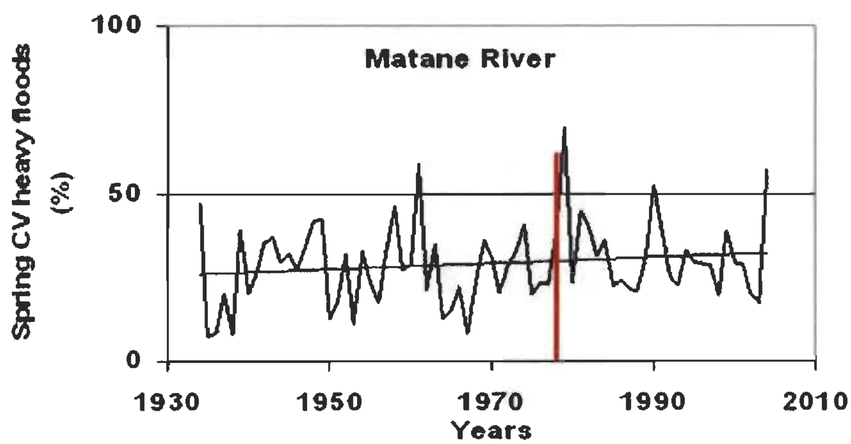

Matane River
Spring CV heavy floods (%)
100
50
0
1930
1950
1970
1990
2010
Years

Fig. 6.

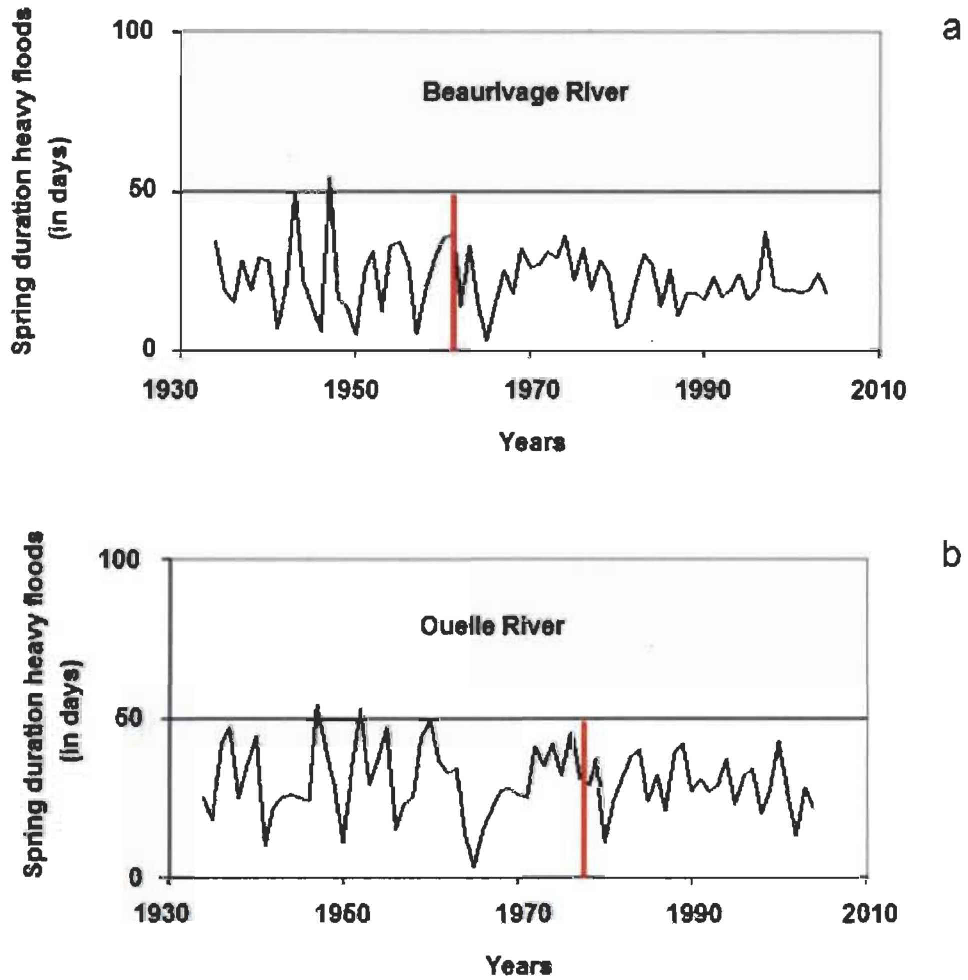

a
Beaurivage River
Spring duration heavy floods (in days)
100
50
0
1930
1950
1970
1990
2010
Years
b
Ouelle River
Spring duration heavy floods (in days)
100
50
0
1930
1950
1970
1990
2010
Years

Fig. 7.

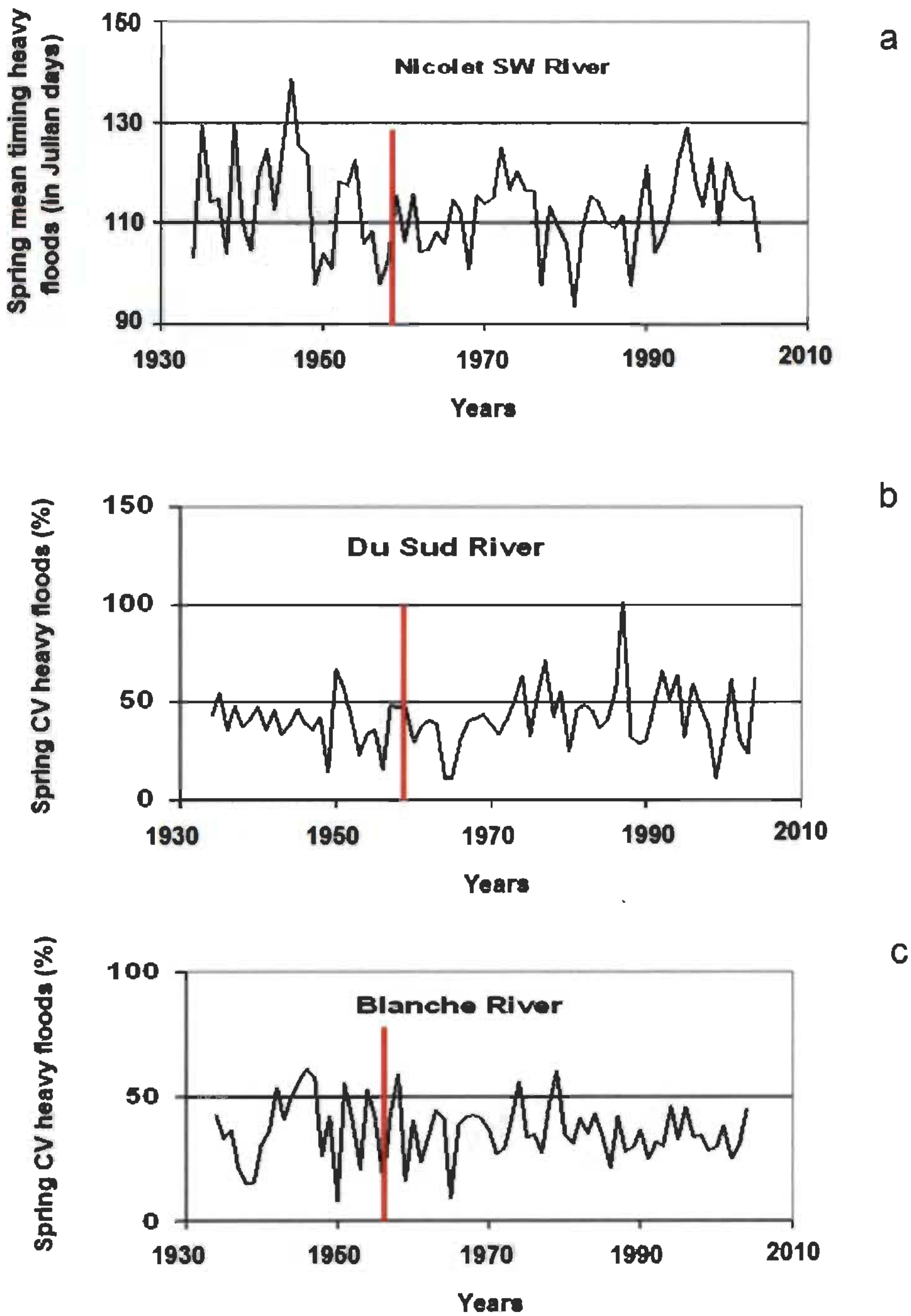

a
Nicolet SW River
Spring mean timing heavy floods (in Julian days)
150
130
110
90
1930
1950
1970
1990
2010
Years
b
Du Sud River
Spring CV heavy floods (%)
150
100
50
0
1930
1950
1970
1990
2010
Years
c
Blanche River
Spring CV heavy floods (%)
100
50
0
1930
1950
1970
1990
2010
Years

Fig. 8.

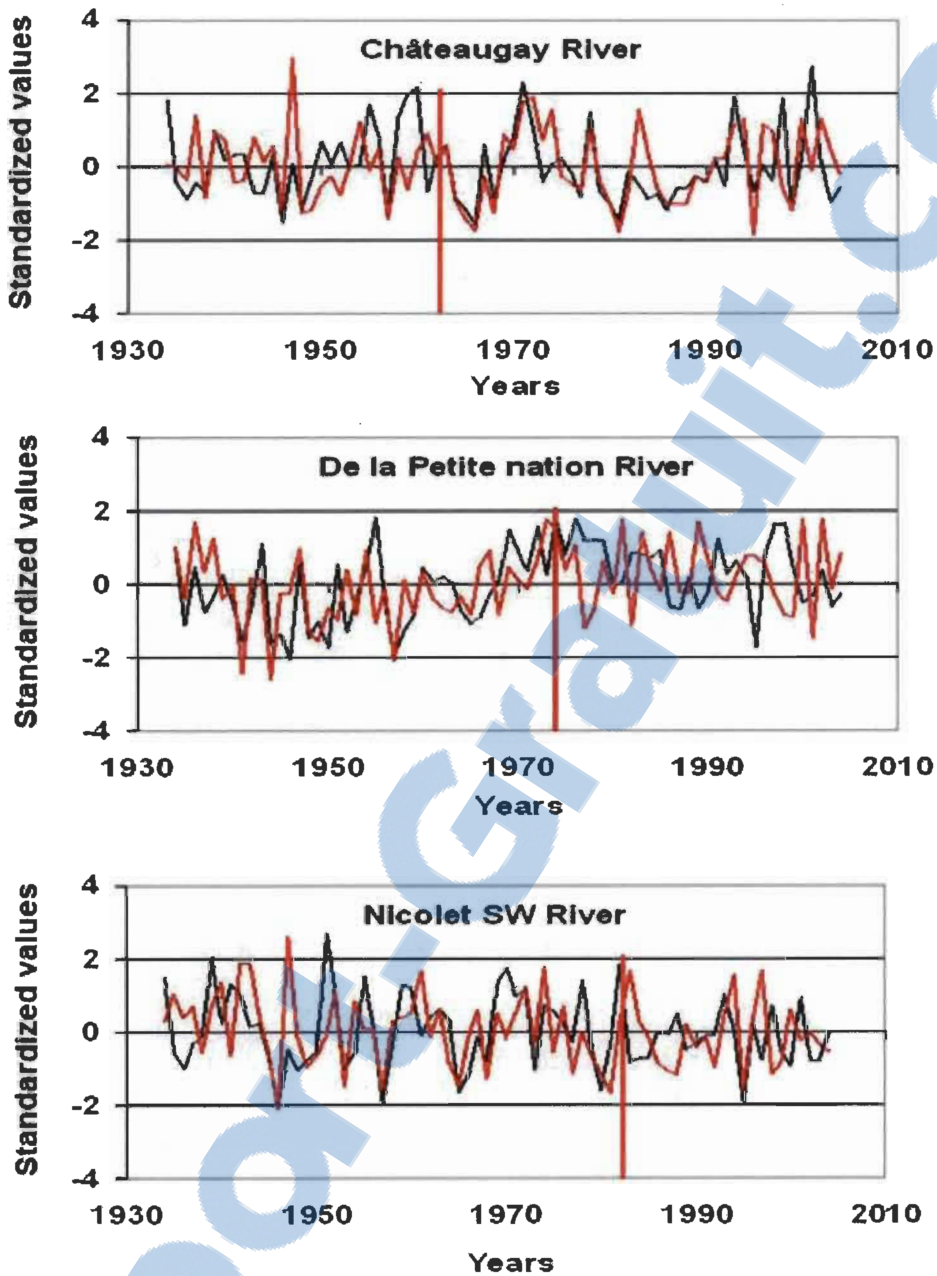


Fig. 9.

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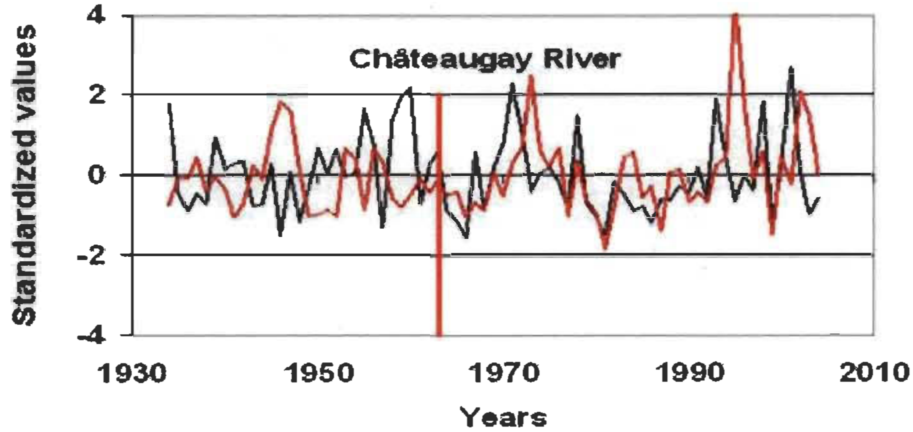
LE NUMERO 1 MONDIAL DU MÉMOIRES


Châteaugay River
Standardized values
4
2
0
-2
-4
1930
1950
1970
1990
2010
Years

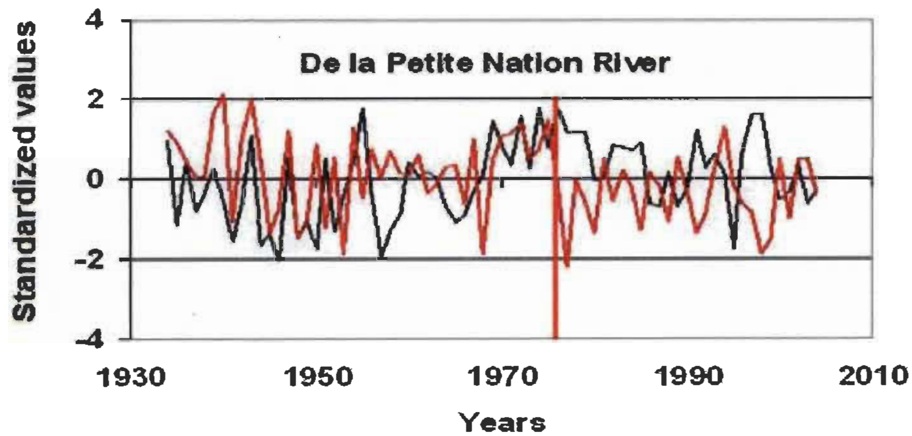

De la Petite Nation River
Standardized values
4
2
0
-2
-4
1930
1950
1970
1990
2010
Years

Fig. 10.

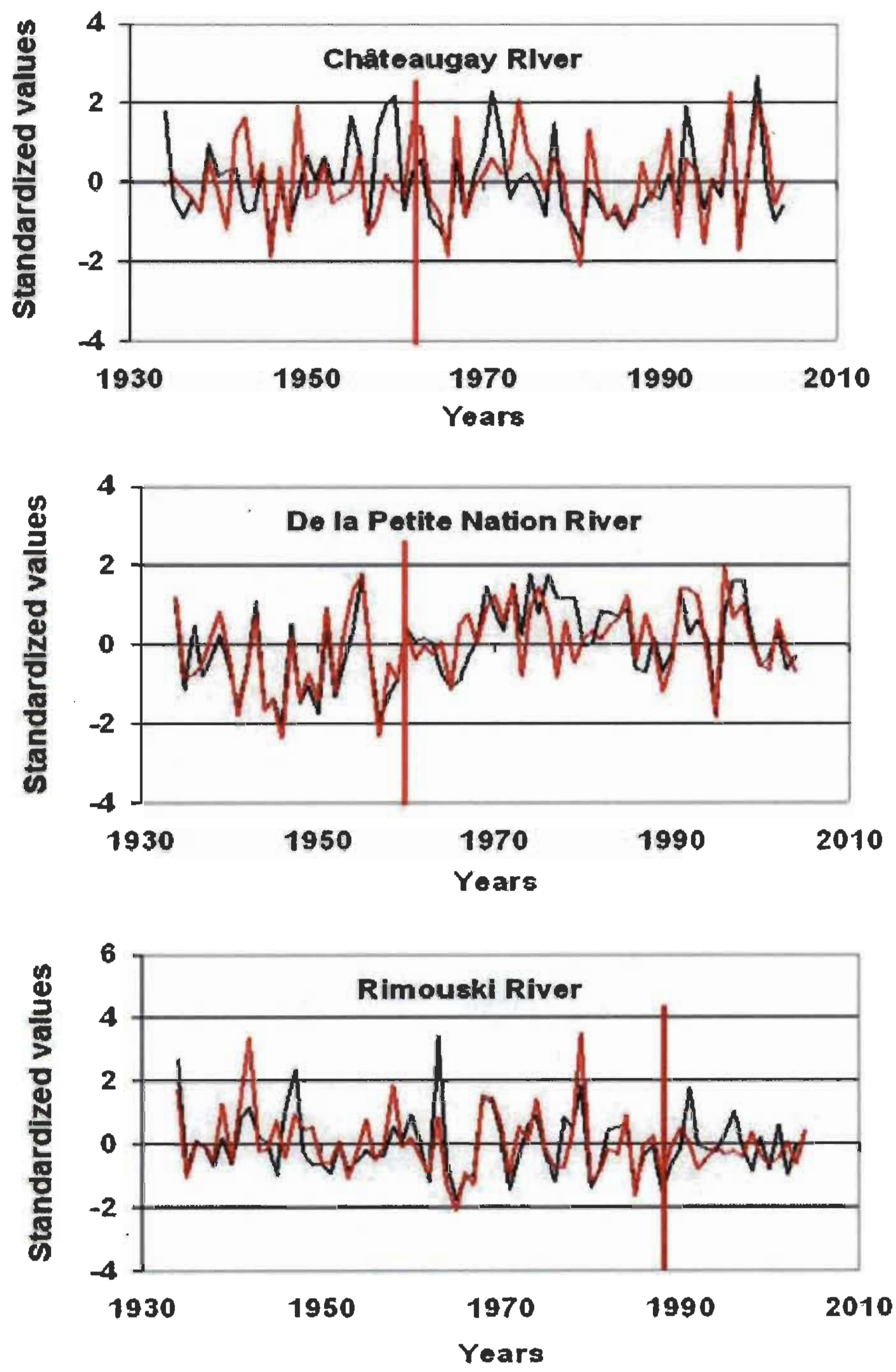

Châteaugay River
Standardized values
4
2
0
-2
-4
1930
1950
1970
1990
2010
Years
De la Petite Nation River
Standardized values
4
2
0
-2
-4
1930
1950
1970
1990
2010
Years
Rimouski River
Standardized values
6
4
2
0
-2
-4
1930
1950
1970
1990
2010
Years

Fig. 11.

CHAPITRE III

APPLICATION OF REDUNDANCY ANALYSIS TO HYDROCLIMATOLOGY: A CASE STUDY OF SPRING HEAVY FLOODS IN SOUTHERN QUÉBEC (CANADA)

Manuscrit en attente de soumission au *Journal of Hydrology*.

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Application of redundancy analysis to hydroclimatology: a case study of spring heavy floods in Southern Québec (Canada)

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Résumé

On a appliqué l'analyse canonique de redondance pour explorer le lien complexe entre les cinq caractéristiques (magnitude, durée, période d'occurrence, fréquence et variabilité) des débits de fortes crues printanières, définies selon le paradigme écologique de « régime des débits naturels » et cinq indices climatiques (AMO, AO NAO, PDO et SOI) au Québec méridional pendant la période 1934-2004. NAO apparait comme le principal indice qui est corrélé aux quatre caractéristiques des débits suivantes : Durée (corrélation positive), période d'occurrence (corrélation positive), Fréquence (corrélation positive) et CV (corrélation négative). Ainsi, les anomalies positives de NAO sont associées à une occurrence tardive, une durée relativement longue, une variabilité relativement forte et une faible fréquence des débits de fortes crues printanières au Québec. Cette relation traduit la persistance des conditions climatiques caractérisées par des basses températures et des faibles précipitations en hiver et au début du printemps dans la partie orientale du Canada lorsque NAO est en phase positive. Aucun lien n'a été observé entre les indices climatiques et la magnitude des débits de fortes crues printanières au Québec.

Mots clés : Analyse canonique de redondance, débits printaniers, indices climatiques, Québec

Abstract

Redundancy analysis (RDA) and Canonical correlation analysis (CCA) were used to examine the complex links between the five characteristics of flow (magnitude, duration, timing, frequency, and variation), defined as part of the "natural flow regime" ecological paradigm, for spring heavy flood, and five climate indices (Atlantic Multi-decadal Oscillation (AMO), Arctic Oscillation (AO), Nord Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) and Southern Oscillation Index (SOI)) in southern Québec, over the period from 1934 to 2004. The two methods yield similar results. AMO and NAO appear to be the main index correlated with the following four flow characteristics: duration, timing, frequency and coefficient of variation. Thus, positive AMO and NAO anomalies are associated with delayed timing, higher frequency, relatively long duration and relatively weak variability of spring heavy floods in Québec. This relationship reflects sustained climate conditions characterized by low temperature in winter and early spring in eastern Canada during negative phases of AMO and positives phases NAO. No link was noted between climate indices and the magnitude of spring heavy floods in Québec.

Keywords: Redundancy analysis, canonical correlation analysis, spring flows characteristics, climate indices, Québec

Introduction

The natural flow ecological paradigm developed in aquatic ecology in the 1990's (Richter et al., 1996; Poff et al., 1997) is widely used in aquatic science. According to it, streamflow can be decomposed into five fundamental characteristics: magnitude, timing, duration, frequency, and variation. A hierarchy of these characteristics was defined by Assani et al. (2010a) in which each is assigned to one of three categories: primary (magnitude), secondary (duration and timing) and tertiary (frequency and variation). Each characteristic plays a specific role in the function of fluvial ecosystems (Richter et al., 1996; Poff et al., 1997).

In hydrology, this concept is increasingly used to various ends, including the following:

- to quantify the effects of human activity (e.g., dams, farming, urbanization) on flow in rivers (e.g. Assani et al., 2005, 2006a, 2007; Carlisle et al., 2010; Gao et al., 2009; Lajoie et al., 2007; McManamay et al., 2012; Monk et al., 2007; Mushombe et al., 2011; Poff and Zimmerman, 2010; Richter et al., 1996; Small et al., 2009; Suen and Eheart, 2005; Yang et al., 2008);
- to characterize natural or regulated hydrological regimes (e.g. Assani and Tardif, 2005; Enders et al., 2009; Kenn et al., 2008; Merritt et al., 2010; Olden and Poff, 2003; 2006; Pyron and Neuman, 2008; Zhang et al., 2011);
- to identify factors affecting the spatial variability of flow in natural or regulated rivers (e.g. Assani et al., 2006b; Detenbeck et al., 2005; Matteau et al., 2009). Insight gained from these studies can be used to improve water, plant, and wildlife resource management for rehabilitation or conservation of the ecological integrity of fluvial ecosystems;
- Finally, to estimate streamflow at ungauged sites (e.g. Shiau and Wu, 2009).

Assani et al. (2010a) have shown the potential usefulness of this concept in hydroclimatology by analyzing the link between spring flow characteristics of a river (the Vermillion, in Québec) and five climate indices. These authors restricted the analysis to a single river, because in trying to simultaneously correlate climate indices to the five streamflow characteristics measured for multiple rivers, they were faced with the problem that time series of streamflow measurements are naturally nested within rivers. More generally, in nested sampling designs units within a group usually tend to be more similar to other units within their group than to units in other groups. The resulting intra-group correlation implies that individual observations are not entirely independent as required by conventional statistical models. Furthermore, samples collected in consecutive years are generally subject to temporal autocorrelation, which further undermines the assumption of independence. Hydroclimatological analyses often require both the spatial (flow characteristics measured for multiple rivers) and temporal (flow characteristics measured each year for each river analyzed, as well as climate indices) components to be included in the analysis. However, samples collected under this design are not freely exchangeable and may show both intra-group correlation and serial dependence. From a statistical standpoint, multivariate statistical methods normally used in hydroclimatology (i.e., multiple regression, principal component analysis, independent component analysis, empirical orthogonal function, canonical correlation analysis, etc.) are based on the hypothesis that the samples are independent from one another. However, because of the nesting of samples within rivers and the autocorrelation of the time series, this independence condition is not met.

The goal of this study is to propose a method, namely redundancy analysis (RDA), combined with restricted permutation tests that match the study design, which solves this problem. "Redundancy" expresses how much of the variance in one set of variables can be explained by the other; it is a measure of the average proportion of variance in the Y set that is accounted for by the X set, and is comparable to the squared multiple correlation in multiple linear regression (Afifi and Clark 2001). RDA is an asymmetrical analysis that examines how a set of dependent variables Y relates to a set of independent variables X. The complex relationships between the five characteristics of spring heavy floods (magnitude, duration, timing, frequency and duration) in 17 rivers and five climate indices over the period from 1934 to 2004 in southern Québec are explored using this method, in order to answer the following question: what climate indices affect the interannual variability of spring heavy flood flow characteristics in this region? A secondary objective is to test whether this method yields similar results to those obtained using canonical correlation analysis (CCA). CCA is a multivariate extension of correlation analysis that has as main purpose to maximize the correlations between two sets of variables. The two sets of variables are treated symmetrically and thus there is no fundamental distinction between the dependent (streamflow characteristics) and independent (climate indices) variables. In principle, RDA and CCA may yield different results because in the former, emphasis is on the effect of the independent set on the dependent set (maximizing the % variance in Y explained by X, rather than the correlation between Y and X as in CCA). It is therefore important from a hydroclimatic standpoint to check whether the two canonical methods (RDA and CCA) can yield similar results regardless the inherent asymmetry between dependent and independent variables in the data set. Multiple regression was excluded from this comparison because it does not link the independent ("predictor") variable set simultaneously to several, potentially correlated, dependent variables. It does not account for the effect of intragroup relationships on intergroup relationships. Consequently, it cannot be used to explore the complex links that may exist between climate indices and streamflow characteristics measured at multiple stations.

Methods

Choice of rivers and climate indices

The St. Lawrence River watershed in Québec covers a 673,000 km^2 area. Tributaries of the St. Lawrence for which a continuous record of flow measurements over at least 50 years is available and which are not significantly affected by dams or other major human activity were selected for the study. In total, 17 tributaries were selected (Fig. 1 and Table 1). On the south shore, many gauging stations on these rivers are located near their confluence with the St. Lawrence River. The 17 rivers are representative of three homogeneous hydrological regions with respect to the interannual variability of flow at the annual, seasonal and daily scales (Assani et al., 2010a, 2010b; 2011a; 2011b). The Eastern region (E), located on the south shore north of 47°N, is characterized by a maritime climate, whereas the South-West region (SW), located on the north shore, is characterized by a continental climate. Finally, the South-East hydrological region (SE) is characterized by a climate that is a mix between maritime and continental, but with a heavy maritime trend. This region is located on the south shore south of 47°N, and unlike the other two regions, is characterized by extensive agriculture. Flow measurements for the 17 rivers span the period from 1934 to 2004. The largest number of rivers to analyze is for this period.

As for climate indices, they were chosen because they have been shown to influence the interannual variability of streamflow and climate in Québec in particular, and in North America in general (e.g. Anctil and Coulibaly, 2004; Assani et al., 2010b, 2010c; 2011a, 2011b; Coulibaly and Burn, 2005; Déry and Wood, 2004, 2005; Kingston et al., 2006; Lin et al., 2010). They are the following five indices: AMO (Atlantic Multidecadal Oscillation), AO (Artic Oscillation), NAO (North Atlantic Oscillation), PDO (Pacific Decadal Oscillation) et SOI (Southern Oscillation Index). The data for these five indices were extracted from the following websites: http://www.cdc.noaa.gov/ClimateIndices/List (AMO, SOI, and PDO, extracted 2010 May 15). http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html (NAO, extracted 2009 May 15) and http://jisao.washington.edu/data/ao/ (AO, extracted 2009 May 15). For each index, we calculated the seasonal means (seasonal climate indices) for the following two seasons: winter (January to March) and spring (April to June).A seasonal series of climate indices for the period from December to February was also constructed, which yielded similar results to those obtained from the original winter seasonal series.

Composition of hydrologic series of spring maximum flow characteristics

A detailed description of the method used to compose time series of flow characteristics is presented in Assani et al. (2010a) and in Mazouz et al. (2012). The bulk of this description is reproduced here. Note that these characteristics were defined as part of the "natural flow regime" concept (Poff et al., 1997). Definition of the five characteristics involved the following steps:

- In the first step, we constructed a spring seasonal streamflow series (series constructed by the highest streamflow values measured each year between April and June).

- In the second step, for each year, we selected all streamflow values equal to or greater than Qm, Qm being the lowest value of the seasonal series constituted in Step 1. Thus, for each year, we have at least one streamflow value ≥ Qm. Parallel to the streamflow magnitude series, we also constructed the series of four other characteristics, namely timing, duration, frequency and variability, this latter characteristic being defined with the coefficient of variation. The magnitude was defined as the daily flow volume measured at a gauging station (expressed inm^3/s). The dates of occurrence of the flood were converted into Julian days (from January 01). Duration was defined as the number of days during which streamflow magnitude remained ≥ Qm during a spring season. It is expressed as a percentage of the total number of days in the spring season. This type of transformation had no effect on the long-term trend of the hydrologic series. In fact, the original and the transformed series yielded the same results. The values of the coefficients of variation were calculated based on the flood magnitude values. Frequency was defined as the number of times streamflows ≥ Qm were measured during a spring season. Frequency data were converted to probability and expressed in percent using the following formula: $FMi = Nix100 / Nt$, where FMi is the frequency expressed in percent, Ni is the number of events ≥ Qm observed during a given year, and Nt is the total number of events ≥ Qm observed over the 1934-2004 period. An event is a flood with flows equal or greater than Qm during one or more consecutive days.

- In the last step, when several floods occurred in the same season (from April to June), we calculated their average duration and timing. However, concerning the magnitude and coefficients of variation, this average was calculated when the streamflow ≥ Qm lasted more than one day. In all, we constituted five series of fundamental spring flood characteristics during the period from 1934 to 2004 (Table 2).

Statistical Analysis

RDA was used to correlate the five characteristics of flow to the five climate indices. This method, which was developed by Rao (1964), is a canonical version of principal component analysis (PCA) of dependent variables *Y* (flow characteristics) constrained by independent variables *X* (climate indices). The goal of the analysis is to find the combination of independent variables (climate indices) that best explains the variation (or dispersion) of dependent variables (flow characteristics). It consists in finding the ordination axes of the clouds of points which are most strongly linearly linked to the set of explanatory variables, and is in that sense a multivariate extension of ordinary regression. According to Makarenkov and Legendre (1999), there are two approaches to RDA, which yield the same results. The first is based on the use of an iterative algorithm for obtaining the principal axes. The second, used by Makarenkov and Legendre (1999), consists in deriving a series of multiple linear regressions of the dependent variables *Y* on the independent variables *X*, followed by principal component analysis of the matrix of fitted values.

The main steps in a RDA, which are described in Makarenkov and Legendre (1999), are as follows:

- a multiple linear regression is computed for each centered variable *Y*, one by one, on all centered independent variables *X*. This step yields the fitted values $\hat{Y}$ through the following formula:

$$\hat{Y} = XB = X\left[X'X\right]^{-1} X'Y \tag{1}$$

- the covariance matrix S of the matrix of fitted values $\hat{Y}$ is computed using the following formula:

$$S=\left[1/(n-1)\right]\hat{Y}'\hat{Y}=\left[1/(n-1)\right]Y'X\left[X'X\right]^{-1}X'X\left[X'X\right]^{-1}X'Y \qquad (2)$$

- eigenvalue and eigenvector decomposition of the covariance matrix S of $\hat{Y}$ is carried out by solving the following matrix equation:

$$\left(S-\lambda_k I\right)u_k=0 \qquad (3)$$

where λ_k is a canonical eigenvalue and u_k, the related canonical eigenvector. The matrix containing the normalized canonical eigenvectors u_k is calledU;

- the ordination of objects (Y rows) in dependent variable space is obtained directly from the centered matrix Y, using the standard equation for computing principal components:

$$Ord_{(\text{response variable Y space})_k}=Yu_k \qquad (4)$$

The ordination vectors defined by equation (4) are called "site scores". Their variance is similar, although not necessarily equal to the corresponding eigenvalues Likewise, the ordination of objects in X space is obtained using the following equation:

$$Ord_{(\text{explanatory variable X space})_k}=\hat{Y}u_k XBu_k \qquad (5)$$

The ordination vectors, called "fitted site scores", are the linear combinations of the explanatory variables X. Their variance is equal to the corresponding eigenvalues.

- The contribution of explanatory variables to the various canonical axes is estimated by computing the linear correlations between variables X and the ordination axes, either in Y space, using equation (4) axes, or in X space, using equation (5) axes.

- Finally, biplot diagrams can be drawn to represent three types of datasets: site scores (rivers) derived from equations (4) and (5), dependent variables Y (flow characteristics), and explanatory or independent variables X (climate indices). Two types of scaling are most commonly used for biplots: type 1 scaling produces a plot in which distances between objects are conserved (distance biplot) by emphasizing the relationships between sites, whereas type 2 scaling produces a plot in which correlations are conserved (correlation biplot) by emphasizing the relationships between dependent and independent variables. In this study, type 2 scaling was used because the main goal was to constrain the link between flow characteristics and climate indices.

RDA was applied to standardized (centered and reduced) data. For each of the five spring heavy flood characteristics, a series of data measured at the 17 stations from 1934 to 2004 (17 rivers × 71years) was first assembled. This was followed by standardizing each series for each of the five flow characteristics. For climate indices, a series was assembled of each of the five indices, the length of which is equal to that of each of the flow characteristic series (17 rivers × 71 years), by repeating the same set of climate index for each river. Ultimately, RDA was applied to a matrix with 1207 rows (17 rivers × 71 years) and 11columns (1 column for river sites + 5 columns for flow characteristics + 5 columns for climate indices).

An overall test of significance of the canonical relationshipwas based on the sum of all constrained eigenvalues. The test statistic was a "pseudo-*F*", obtained as the ratio of constrained and unconstrained total variances, each divided by their respective ranks (Miller, 1975). Permutation tests were used because they provide a robust alternative when multivariate normality assumptions do not hold (Takane and Hwang 2005). Permutations were restricted to match the study design, in which samples were stratified by river and were collected in consecutive years. Samples collected under this design are not freely exchangeable and may show both intra-group correlation and serial dependence (temporal autocorrelation). To account for this potential lack of independence, samples were arranged in temporal order within rivers, and sample permutations were allowed only as cyclical shifts ("loop" rotations) of samples within rivers.

Canonical correlation analysis (CCA), is a multivariate extension of correlation analysis that has as main purpose to maximize the correlations between two groups of variables. In contrast with RDA, CCA examines the relationships between two sets of variables that are treated symmetrically. To calculate the canonical correlations between two groups, one comprising X variables (X1, X2,..., Xp) and the other Y variables (Y1, Y2,..., Yq), one must obtain the canonical variables V (V1, V2,..., Vp) and (W1, W2,..., Wq), that are linear combinations of the X variables of the first group (in this present study, the five flow characteristics) and the Y variables of the second group (in this present study, the climatic indices). The linear combinations maximize the correlations (canonical correlation coefficients) between the canonical variables U and V, i.e., between V1 and W1; V2 and W2, and so on. The canonical variables U and V are then correlated to the variables X and Y, to obtain the structure coefficients that measure the link (correlations) between the canonical variables (U and V) and the original variables of groups X and Y.

For both RDA and CCA, structure coefficients were interpreted as correlation coefficients between the original variables and the canonical axes, and were tested for statistical significance. In the CCA, the number of degrees of freedom was lowered to 68 (70 years of measurements of streamflow – 2) and the significance level to test structure coefficients was reduced from 5% to 1%. This adjustment is intended as a conservative measure, in lieu of permutation tests, to compensate for the lack of independence of samples that arises from temporal and within-group correlation.

Results

The eigenvalues of five RDA axes and their explained variance derived from the data matrices are shown in Table 3. Structure coefficients calculated between spring climate indices and streamflow characteristics are shown in Table 4. Only the first two canonical axes were retained for evaluation, following Makarenkov and Legendre (1999). The overall test of the canonical relationship was significant for the spring climate indices (pseudo-F = 5.84; P = 0.014), but not for the winter climatic indices (pseudo-F = 3.15; P = 0.423). Cumulative explained variance values for the first two RDA axes calculated between spring climate indices and streamflow characteristics reach 92%. Structure coefficients calculated between spring climate indices and streamflow characteristics are shown in Table 4. Note that, in general, only the first two canonical axes are retained (Makarenkov and Legendre, 1999). In this study, the choice of the first two axes is justifiedby the fact that only the eigenvalues for the first two axes of related principal components are > 1, a criterion proposed by Kaiser (1960) for statistically significant principal components. As for streamflow characteristics, three are significantly correlated with the first axis at the 1% level, namely timing, duration and frequency. This correlation is negative. The strongest correlation observed is between timing and the first RDA axis. The second RDA axis is only significantly correlated with the coefficient of variation (CV). As for climate indices, three are significantly correlated with the first RDA axis, namely AMO, NAO and SOI, this correlation being positive for AMO, but negative for the other two indices.TheAMO score is highest on the first RDA axis. The second RDA axis is correlated with four climate indices. Aside from the three indices mentioned above, the second axis is also positively correlated with the PDO index. This correlation is negative, however, between the second axis and AMO. It follows that CV is negatively correlated with AMO, NAO and SOI, but positively correlated with PDO. The strongest correlation observed is between timing and AMO. The lengths of the arrows associated with flow characteristics and climate indices confirm these correlations (Figure 2). The alignment and length of arrows also shows that the streamflow characteristics tend to be correlated positively, strongly so in the case of timing and duration.

These RDA results are nearly identical to the CCA results shown in Tables 5 and 6.

- Like RDA, only the first two CCA axes are statistically significant (Table 5). The total variance explained by these two axes is nearly the same as that explained by the first two RDA axes (see Table 3).
- In regards to canonical structure coefficients (Table 6), timing, duration and frequency are significantly correlated with V1 on the one hand, while AMO, NAO and, to a lesser extent, SOI, are significantly correlated with W1, on the other. Thus, the three spring heavy flood flow characteristics are negatively correlated with AMO, but positively correlated with NAO and SOI, since canonical axes V1 and W1 are significantly correlated. As for the CV characteristic, it is significantly correlated with V2 on the one hand, and the AMO, NAO and SOI climate indices are significantly correlated with W2, on the other. Thus, CV is significantly correlated with these three indices.

Discussion and Conclusion

The goal of the study was to use RDA to look at the complex relationship between the five characteristics (magnitude, duration, timing, frequency, and variation) of spring heavy floods and five climate indices. The use of this statistical approach is warranted by 1) the lack of independence caused by within-group and temporal correlations in climate index time series data, and 2) the emphasis of RDA on explaining the effect of the independent set on the dependent set, rather than the correlation between the two sets as in CCA. Redundancy analysis was compared to the canonical correlation analysis method widely used in hydrology and climatology to investigate the links between two groups of variables. This comparison shows that the two methods can yield similar results. Thus, this conclusion justifies the use of RDA in hydroclimatology. As for multiple regression, as previously mentioned, it cannot be used to explore the complex link between climate indices and streamflow characteristics measured at multiple stations.

As far as this link is concerned, the study reveals that four of the five flow characteristics of spring heavy floods in Québec are primarily correlated with two indices, namely AMO and NAO. Thus, timing, duration and frequency are negatively correlated with AMO, but positively correlated with NAO, while the opposite is true for the variability (CV) of spring heavy flood flows.

The effect of AMO on the interannual variability of hydroclimatic variables in North America is well documented (e.g., Enfield et al., 2001; McCabe et al., 2004, 2008; Sutton and Hodson, 2005; Ting et al., 2011). According to McCabe et al. (2008), AMO is the main climate factor affecting the interannual variability of streamflow in North America. Thus, all known periods of intense drought (1930 and 1950) on this continent are thought to be linked to positive phases of AMO. Although this conclusion was corroborated by Feng et al. (2011), it is not accepted by all, some authors linking large periods of drought with the La Niña phenomenon (see works by Cook et al., 2009a, 2009b; 2011a, 2011b). Whatever the case may be, the effect of AMO on the interannual variability of the magnitude of streamflow has been demonstrated in hydroclimatology. According to these studies, AMO is negatively correlated with this streamflow characteristic. Note that these studies looked at annual series (annual daily maximum flows) or annual or seasonal mean flow series. Partial series (POT) were analyzed in the present study, which may account for the lack of correlation between flow magnitude and AMO. However, it was shown that this climate index is significantly correlated with the other four flow characteristics of spring heavy floods in Québec (timing, duration, frequency and variability). This correlation is negative for the first three characteristics, while for the last one, it is positive, albeit relatively very weak.

As for NAO, according to many authors, this index is the most important mode of atmospheric variability over the North Atlantic Ocean, and plays a major role in weather and climate variations over eastern North America, the North Atlantic and the Eurasian continent (van Loon and Rogers, 1978; Wallace and Gutzler, 1981; Hurell, 1995, 1996; Kushnir, 1999; Greatbach, 2000). In eastern Canada (including Québec), NAO is the leading mode of atmospheric variability (Qian et al., 2008). Based on these studies, Kingston et al. (2006) proposed a conceptual representation of the effect of this index on temperature, precipitation, and streamflow in this part of North America. In this representation, the northeastern part of the continent can be divided into two distinct regions: a region characterized by a negative correlation between the hydroclimatic variables and the NAO index (Eastern Canada) and a region characterized by a positive correlation between these two variables (Northeastern United States). However, because other flow characteristics have never been systematically analyzed, this relationship has only been validated for flow magnitude. Our analysis demonstrates the absence of a link between the magnitude of spring heavy floods and NAO in Québec, where, it should be recalled, these flows mainly result from the melting of snow accumulated in winter. Thus, the Kingston et al. (2006) scheme cannot be indiscriminately used to explain the relationship between NAO and the other flow characteristics. Analysis of the sign of the correlation between NAO and these other flow characteristics reveals that this climate index is positively correlated with timing, duration, and frequency of spring heavy floods, but negatively correlated with the variation (CV) of those flows. In other words, the positive phases of NAO are associated with delayed spring heavy floods of relatively long duration, but relatively low variability. Furthermore, these positive phases would be related to more frequent spring heavy floods.

It should be recalled that the AMO index reflects the interannual variability of sea surface temperature in the Atlantic Ocean in the northern hemisphere, while NAO reflects the variability of pressure (atmosphere flow) above the Atlantic. Theoretically, from a strictly physical standpoint, there is a link between sea surface temperature and atmospheric pressure above an ocean basin. When surface water temperatures are low (cooling), the air is cooled and air pressure increases above the ocean and vice versa. Given this theoretical link, negative phases of AMO (low Atlantic Ocean sea surface temperatures) theoretically coincide with positive phases of NAO (increased pressure above the Atlantic Ocean in the temperate zone). This accounts for the negative correlation observed between AMO and NAO on the first canonical axis (Tables 4 and 6). However, phase durations for the two indices differ, positive and negative phases (cycles) of AMO being longer (40 to 60 years) than those for NAO (< 10 years). Given the long duration of AMO phases, NAO can cycle through a positive then a negative phase during a single AMO phase (positive or negative). Thus, such NAO phase changes imply that positive (negative) phases of AMO and NAO may occur simultaneously during periods of less than 20 years. As a result, AMO and NAO can also be positively correlated, as is the case on the second canonical axis, on which the sign of both indices is the same (see Tables 4 and 6). It must be pointed out, however, that the theoretical relationship between AMO and NAO is very complex, and the dynamic link between the two indices is not well established.

In any case, analysis of the correlation between climate indices and spring heavy flood flow characteristics highlights the effect of the Atlantic Ocean on the interannual variability of these flow characteristics in Québec. Thus, AMO and NAO are the two climate indices that are most strongly correlated with flow characteristics. For timing, duration and frequency, the only factor which can account for the relationship between AMO (negative correlation) and NAO (positive correlation) and these three flow characteristics is the occurrence of low temperatures in winter and early spring (when AMO is in a positive phase and NAO, in a negative phase), which delay snowmelt, making it slow and gradual. Furthermore, low temperature results in significantly reduced snow sublimation and snowmelt evaporation, which leads to sustained relatively high flows lasting many days. Moreover, such low temperatures lead to more frequent advection of cold polar air in Québec in springtime. These advection events can stop or significantly slow down snowmelt during several days, resulting in multiple floods associated with different snowmelt events. These floods are separated by intervals (two days on average) when advection of cold polar air interrupts or slows down snowmelt. This accounts for the increased frequency of spring heavy floods (positive correlation with NAO, but negative correlation with AMO). In contrast to the commonly held view, spring snowmelt is not always continuous (a single spring flood). It can be discontinuous (many floods). This discontinuity is due to the interruption or slowing down of snowmelt as a result of low temperatures linked with cold polar air advection, which lower air temperature.

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According to Hurrell (1995, 1996), low temperatures in positive NAO (negative AMO) years are due to the Iceland Low that is anomalously deep, resulting in cold Arctic air moving southward to the area west of Iceland and Greenland, inducing cold anomalies over eastern Canada. This would lead to persistent cold and dry weather over Québec in winter and early spring. This situation is entirely consistent with observations by Ikeda et al. (1998) confirmed by simulations by Qian et al. (2008). Thus, Ikeda et al. (1998) noted that, in the Labrador and Newfoundland region northeast of Québec, the positive phase of NAO is associated with spreading of the sea ice cover. This spreading can only result from sustained very low temperatures in the fall, winter, and early spring. This relationship between negative temperature anomalies and positive NAO anomalies was also observed and simulated in several regions of eastern Canada by Qian et al. (2008). As for the variability (CV) of spring heavy floods, it decreases during positive phases of NAO (the index most strongly correlated with CV), likely as a result of slowed down melting of snow due to low temperatures. In addition, CV is also correlated with PDO, which reflects the interannual variability of sea surface temperatures (SST) in the northern Pacific Ocean. Positive phases of PDO are characterized by cooler SST than normal in the east-central North Pacific and warmer SST along the west coast of North America, and vice versa. In light of these considerations, it is postulated that, unlike the other three characteristics, CV is affected by SST in both the Pacific and the Atlantic, reflecting the influence of the Pacific-North American teleconnection pattern.

This study shows the usefulness of taking all flow characteristics into consideration to better constrain the effect of different climate indices on the spatial and temporal variability of those characteristics. Thus, studies which only look at flow magnitude may no be able to bring out the effects of some climate indices on the interannual variability of other flow characteristics. For spring heavy floods in Québec, while AMO and NAO have no impact on flow magnitude, it does affect the interannual variability of the other flow characteristics. Without an analysis of these characteristics, it would be impossible to highlight the effect of these two climate indices on the interannual variability of spring heavy floods. That, in itself, is ample justification for using the "natural flow regime" paradigm in hydroclimatology to analyze, among other things, the relationship between climate indices and flow characteristics. This study illustrates the efficiency of RDA as a tool for exploring the complex links between flow characteristics and climate indices. When dependent variables such as streamflow characteristics are correlated, multivariate techniques for analyzing the joint variation in these characteristics generally have greater power and provide more compact results than techniques that analyze the dependent variables individually, such as multiple regression. A key advantage of RDA combined with restricted permutation tests as a method for establishing relationships between two multivariate data sets is that it takes into account the asymmetric nature of the relationship between dependent and independent data sets and the dependence structure in time series collected at multiple sites. This contrasts with other commonly used tools in hydrology, which do not lend themselves to asymmetric analysis of strongly dependent data.

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Table 1. Hydrometric stations analyzed

Code	River	Area (km^2)	Latitude (N)	Longitude (W)	MAF (m^3/s)
		South-East Hydrologic Region			
SE1	Châteaugay	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
		East Hydrologic Region			
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
		South-West Hydrologic Region			
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

MAF = mean annual flow

Table 2. Streamflow characteristics defined on the partial series of spring floods of the Vermillon River (1934-2000). (Mazouz et al., 2012)

Characteristics	Code	Hydrologic variable
Magnitude	MAG	Average of streamflows ≥ Qm measured in spring (April to June) of each year
Duration	DM	Number of days during which streamflows ≥ Qm were measured in spring of each year
Timing	TM	Average timing (in Julian days) of streamflows ≥ Qm measured in spring of each year
Frequency	FM	Number of times that streamflows ≥ Qm were reached or exceeded in spring of each year
Variability	CV	Coefficient of variation of streamflows ≥ Qm measured in spring of each year

Qm = is the lowest value of the maximum seasonal series of spring floods.

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Table 3. Eigenvalues and explained variance of the RDA axes. Winter and spring climate indices

	Winter climate indices					Spring climate indices				
	RDA1	RDA2	RDA3	RDA4	RDA5	RDA1	RDA2	RDA3	RDA4	RDA5
Eigenvalues	0.0361	0.0243	0.0143	0.0027	0.0000	0.0920	0.0170	0.0060	0.0030	0.0000
EV (%)	46.6	31.4	18.4	3.5	0.0	77.4	14.2	5.7	2.4	0.3
CEV (%)	46.6	78.1	96.5	99.9	99.9	77.4	91.6	97.3	99.7	100
Pseudo-F values	3.15					5.840				
p-values	0.423					0.014				

Table 4. Flow characteristics and climate indices loadings on the first two significant RDA axes

Variables	RDA1	RDA2
	Flow characteristics	
MAG	-0.161	0.200
TM	**-0.947**	-0.146
DM	**-0.606**	0.077
FM	**-0.352**	0.031
CV	-0.111	**0.441**
	Climate indices	
AMO	**0.763**	**-0.390**
AO	-0.239	-0.071
NAO	**-0.547**	**-0.549**
PDO	0.008	**0.502**
SOI	**-0.376**	**-0.359**

Values of statistically significant structure coefficients at the 1% level are shown in bold.

Table 5. Eigenvalues and explained variance of the CC axes. Spring climate indices

	CC1	CC2	CC3	CC4	CC5
Values	0.2690	0.1348	0.0747	0.0659	0.0212
Eigenvalues	0.0780	0.0185	0.0056	0.0044	0.0005
EV (%)	72.9	17.3	5.3	4.1	0.4
CEV (%)	72.9	90.3	95.5	99.6	100
F-values	5.04	2.16	1.39	1.44	0.54
p-values	0.0001	0.0046	0.1873	0.2176	0.4619

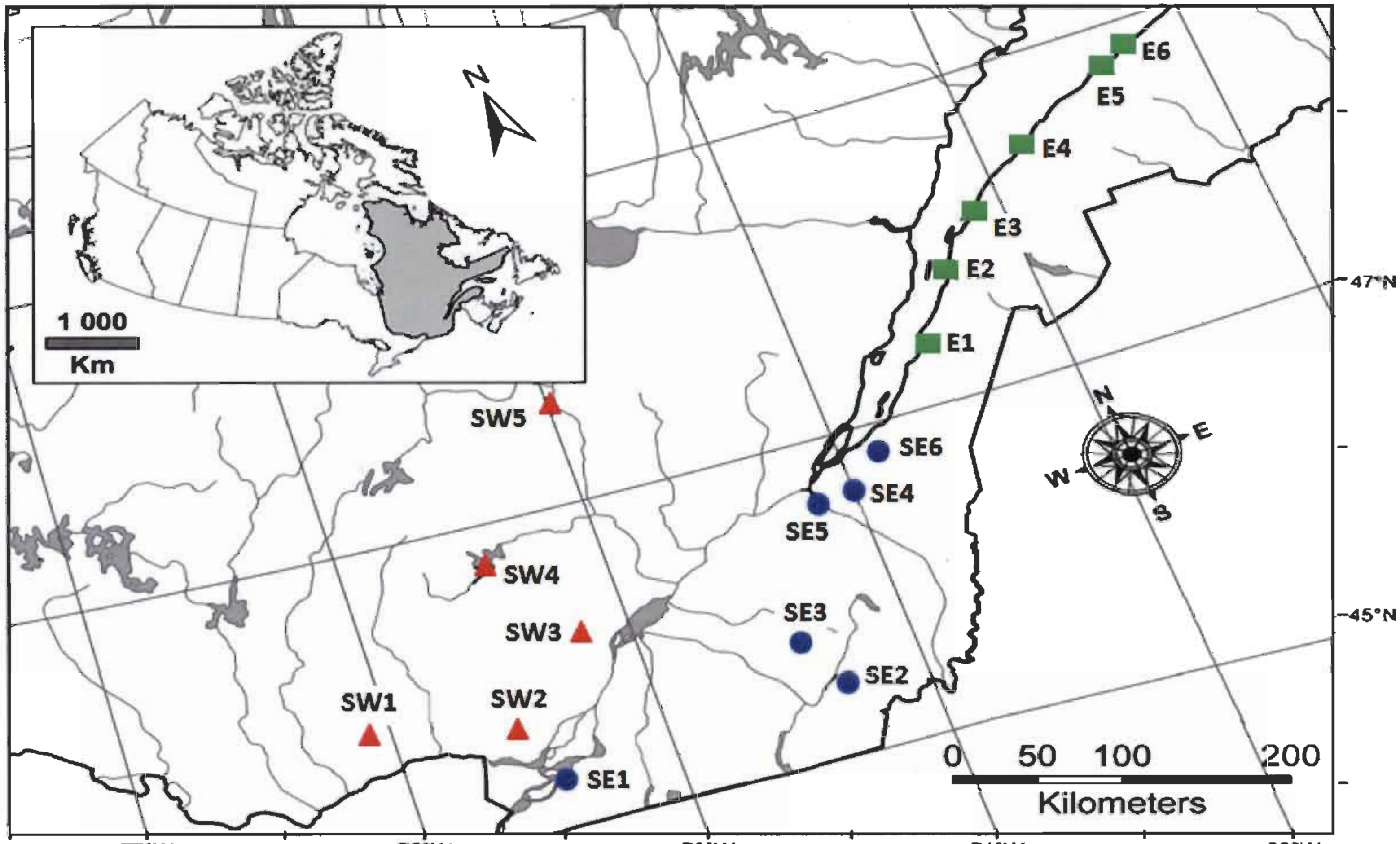
EV = explained variance; CEV = cumulated explained variance.

Table 6. Canonical structure coefficients calculated between flow characteristics and spring climate indices on the first two significant CONCAR axes

Variables	V1	V2	W1	W2
MAG	0.1380	0.1917		
TM	**0.8986**	-0.2177		
DM	**0.5440**	0.2462		
FM	**0.3446**	-0.0206		
CV	0.0581	**0.6229**		
AMO			**-0.7357**	**-0.4683**
AO			0.2880	-0.2033
NAO			**0.6067**	**-0.6072**
PDO			0.0219	**0.4011**
SOI			**0.3279**	0.2975

Values of statistically significant structure coefficients at the 1% level are shown in bold.

List of figures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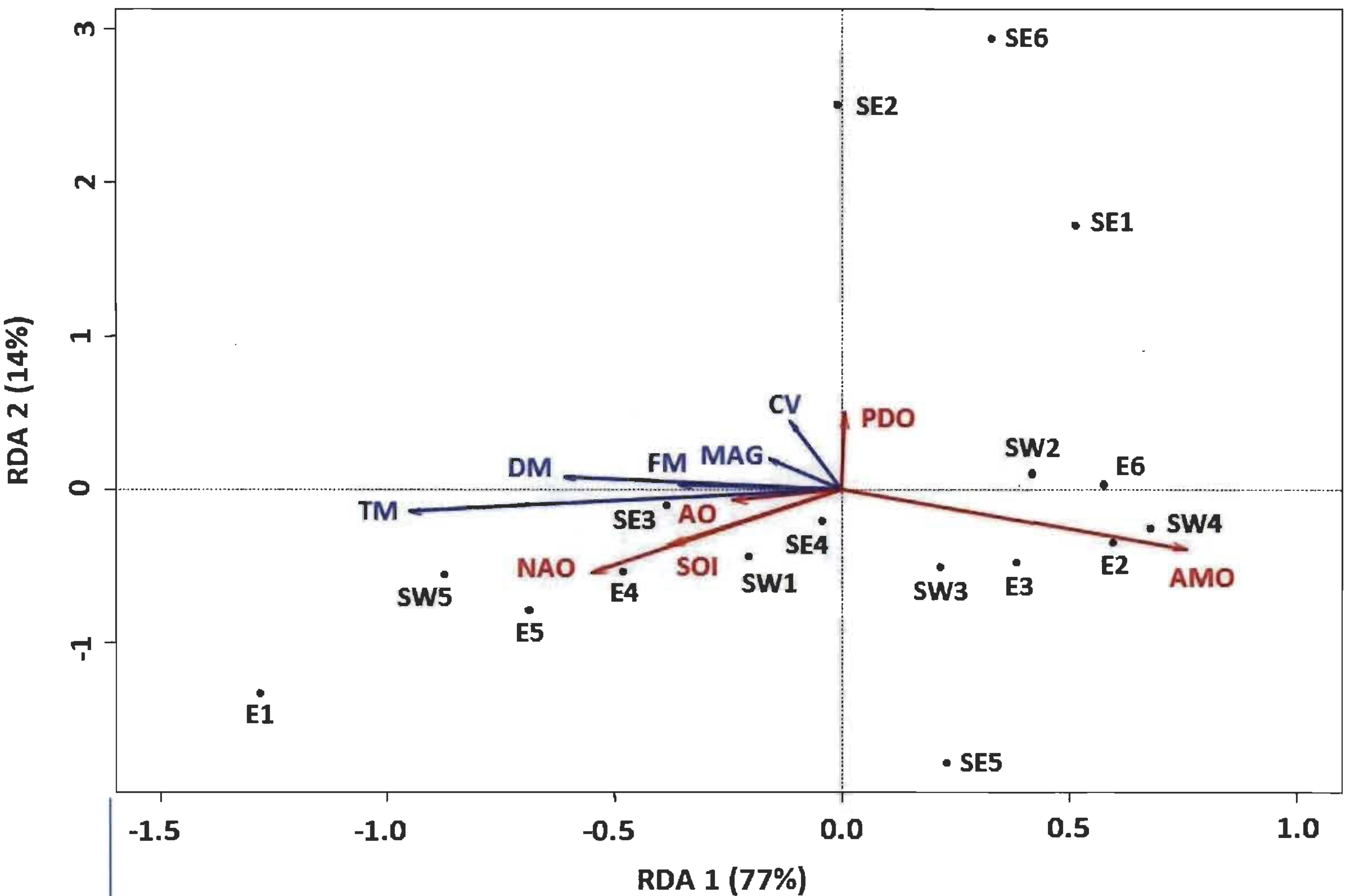
71°W
69°W

Figure 1


SE6
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E2
AMO
SW5
E4
SW3
E3
E5
E1
SE5
3
2
1
0
-1
RDA 2 (14%)
-1.5
-1.0
-0.5
0.0
0.5
1.0
RDA 1 (77%)

Figure 2

CHAPITRE IV

CONCLUSION GÉNÉRALE

Cette étude est la première qui compare simultanément la variabilité interannuelle de cinq caractéristiques fondamentales des débits de nombreuses rivières en relation avec les indices climatiques. En ce qui concerne la variabilité interannuelle, nous avons mis en évidence quelques résultats originaux.

1. Le changement de moyenne et de variance n'affecte pas de manière uniforme toutes les cinq caractéristiques. En effet, il est apparu que certaines caractéristiques sont plus sensibles au changement que d'autres. Dans le cas de notre étude, le changement de la moyenne de la période d'occurrence de crues a été détecté pour plusieurs rivières alors que celui de la moyenne de la durée n'a été observé que pour une seule rivière.

2. Le changement de la moyenne et de la variance d'une même caractéristique ne se produit pas de manière synchrone. Aucune rivière analysée n'a connu à la fois le changement de la moyenne et de la variance de la même caractéristique de débits. La fréquence de changement de moyenne a été plus élevée que celle de la variance dans l'échantillon de rivières analysées. Il s'ensuit que la moyenne apparait comme la variable hydrologique la mieux indiquée pour analyser le changement des séries hydrologiques dans le temps que la variance.

3. Si on considère l'ensemble de toutes les caractéristiques des débits, on ne peut pas attribuer les changements de moyenne et variance observés pour certaines rivières au réchauffement climatique, car les dates de changement ne sont pas synchrones pour toutes les rivières. De plus, ce changement n'a été observé que pour quelques rivières. Par conséquent, il ne s'agit pas d'un changement généralisé de toutes les caractéristiques fondamentales des débits. Toutefois, lorsqu'on considère seulement

« la période d'occurrence » de crues, on peut tenter d'établir un lien avec le réchauffement climatique, car tous les changements observés de moyennes de séries hydrologiques sont survenus de manière quasi synchrone, c'est-à-dire durant la décennie 1970. Cette décennie est considérée comme le début du réchauffement climatique au Québec et au Canada (Zhang et al., 2001). De plus, plusieurs études effectuées en Amérique du Nord ont démontré que le réchauffement climatique se traduisait principalement par une occurrence de plus en plus précoce de « la date d'occurrence » des crues provenant de la fonte de neige ou de glace (p. ex. Burn, 2008; Cayan et al., 2001; Cunderlik et Ouarda, 2009; Déry et al., 2009; Hodgkins et al., 2003; Hodgkins et Dudley, 2006). Cette observation est compatible avec nos résultats. Il s'ensuit que la période d'occurrence apparait comme la caractéristique la plus sensible au réchauffement climatique. Cette caractéristique est la plus appropriée pour détecter le signal de changement climatique sur les séries des débits maximums printaniers au Québec.

4. Cette étude confirme la conclusion déjà tirée par Assani et al. (2010a) sur l'absence d'une hausse généralisée de la magnitude des débits de crues printanières à l'échelle du Québec à cause du réchauffement climatique. Pourtant, les modèles climatiques et hydrologiques prédisent une baisse de la quantité de neige en hiver (Boyer et al., 2010). Cette baisse entraînera celle de la magnitude des crues printanières qui proviennent quasi exclusivement de la fonte de neige accumulée en hiver. Toutefois, cette baisse de « la magnitude des débits » de crues printanières a été observée dans plusieurs autres provinces du Canada (Cunderlik et Ouarda, 2009).

Quant à la relation entre les indices climatiques et les caractéristiques des fortes crues printanières, elle a été analysée au moyen de l'analyse canonique de redondance. Il s'agit d'une première application de cette méthode en hydroclimatologie. Bien que le degré de lien entre les variables varie en fonction des caractéristiques des débits et des indices climatiques, il ressort de cette étude que l'indice climatique ONA est le seul qui est corrélé aux quatre de cinq caractéristiques des débits : durée (corrélation positive), période d'occurrence (corrélation positive), fréquence (corrélation positive) et variabilité (corrélation négative). Aucun lien n'a été observé entre la magnitude des débits et les cinq indices climatiques.

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Quand ONA est en phase positive, le Québec est dominé par l'air polaire froid qui génère des basses températures. Celles-ci réduisent la quantité de neige en hiver et retardent la fonte de neige au printemps, mais en allongeant la durée de cette fonte.

Cette étude démontre l'intérêt de tenir compte de toutes les caractéristiques des débits afin de mieux cerner l'influence des différents indices climatiques sur leur variabilité spatio-temporelle. Les études qui se limitent exclusivement à la magnitude des débits peuvent ainsi ne pas pouvoir mettre en évidence l'influence de certains indices climatiques en raison de l'absence d'un lien entre ces variables hydroclimatiques. Dans le cas des débits de fortes crues printanières au Québec, l'influence de NAO n'affecte pas la magnitude de ces débits alors que les autres caractéristiques le sont à des degrés divers. Sans l'analyse des autres caractéristiques, l'influence de cet indice climatique sur la variabilité interannuelle des débits de fortes crues printanières ne serait jamais mise en évidence. Ceci justifie pleinement l'application du paradigme du « régime des débits naturels » en hydroclimatologie pour analyser notamment la relation entre les indices climatiques et les caractéristiques des débits.

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