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Quantifying the spatial temporal variability of annual streamflow and meteorological changes in eastern Ontario and southwestern Quebec using wavelet analysis and GIS

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ABSTRACT

To make good policy decisions, knowledge of the trends and patterns in regional and local fluctuations in water resources and the influence of regional meteorological conditions are required. This study quantified the spatial–temporal variability of annual streamflow variations and meteorological changes in parts of eastern Canada. Time series and Geographic Information System (GIS) methods were used to evaluate the potential influence of low frequency climate change on annual spring flood onset and streamflow amplitude over a 24 year period. Continuous wavelet (CWT) and cross-wavelet transforms (XWT) were used to detect and extract temporal changes in the annual streamflow cycle amplitude, and to determine its relative phase shift to a standing 1-year sine wave through time. This was done to determine spatial–temporal differences and trends in the annual flood onset, and to determine the differences in the range between flood and background levels in 23 hydrological stations in eastern Canada. The study was carried out in the eastern Ontario/southwestern Quebec region of Canada because of the relatively high spatial density of hydrological stations from generally pristine waterways, as well as the high density of meteorological stations with uninterrupted recordings for a 24 year period from 1/1969 to 12/1992. This research indicates that over this 24 year period, the southwestern part of the region, along the US border, experienced an increase in temperature of up to 0.05 °C/year, and a decrease in precipitation of ~0.5 mm/month; the predominantly rural northwest region warmed only <0.02 °C/year and became <0.2 mm/year wetter. During the same time interval, the annual streamflow shifted on average to a ~20 days earlier flood onset, following the similar northwest–southeast trend of the meteorological records. In the northwest, along the Ottawa River, flooding occurred approximately 50 days earlier in the early 1990s than in the late 1960s, while it was less than 10 days earlier in the southeastern streams. The streamflows of the Ottawa and Rideau River, the main waterways that were studied, have generally lower annual streamflow amplitudes than the smaller and more pristine waterways that experience more seasonality, while the annual streamflow amplitude does not show any significant trend in time and space.

1. Introduction

Knowledge of the relationship between climate and water resource fluctuations is important for water resource predictions and management in a changing climate. The worldwide observational temperature records have revealed a global temperature increase of 0.3–0.7 °C in the last century (IPCC, 2007). In the northern hemisphere, most of this increase has been attributed to an increase in diurnal and annual temperatures, suggesting that conditions are actually 'less cold' rather than 'warmer' (e.g., Bonsal et al., 2001). It has been estimated that southern Canada warmed between 0.5 and 1.5 °C through the 20th century due to several sources of anthropogenic warming, in particular greenhouse gas output (Bonsal et al., 2001; Zhang et al., 2000). In the same time interval, precipitation and streamflow patterns underwent significant, albeit regional, variations (Ehsanzadeh and Adamowski, 2010; Coulibaly, 2006; Coulibaly and Burn, 2005). For example, over the last 50 years, a large decrease in annual mean streamflow has been observed in British Columbia (Western Canada), which can be linked to a large increase in spring temperatures (Zhang et al., 2001).

The climate in eastern Ontario/southwestern Quebec is continental, with long, cold winters, short hot-humid summers, and slightly moderated by the effects of the Great lakes and the St. Lawrence River. The general climate pattern in the region is controlled

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by the jet stream with predominant westerly winds, and to a weaker degree by El Nino's and the North Atlantic Oscillation (NAO), and in the summer by moisture from the Gulf of Mexico (e.g., Zhang et al., 2001). The climate in the metropolitan area of Ottawa, the area of focus in this study, is overprinted by urban heat island warming of ~1 °C through the last century (Prokoph and Patterson, 2004). The streamflow pattern in and around Ottawa is characterized by strong spring flooding, with relatively constant low streamflows during the rest of the year (Adamowski, 2008). Occasionally, large rainfall events or warm spells in winter lead to additional flooding, providing generally weaker peaks in the streamflow than the main spring flood.

Several studies have incorporated both spatial and temporal information, and combined streamflow patterns (means and extremes) with climate records (Adamowski and Bocci, 2001; Coulibaly and Burn, 2005). The results of several spatial–temporal studies using Geographic Information Systems (GIS) in watersheds in Canada have found that trends differ significantly from region to region, or there may not be any detectable trends. While GIS based climate and water resource studies on a large scale are common for Canada, only a few have examined water resources in the Ottawa region. Those studies focused on water quality such as chemical composition (e.g., Telmer and Veizer, 1996), while other GIS studies focused on geological mapping in eastern Ontario, Canada (e.g., Couture et al., 2006).

The temporal trends in streamflow and climate are of a similar complexity. Ko and Cheng (2004) related meteorological data to hydrological data showing different response times of streamflow in a relatively small area in southern Ontario. In addition, there are only a few regional studies on potential climate-streamflow connections, such as on trends in the onset of floods in the western USA (e.g., Steward et al., 2005), or on changes in the amplitude of the annual streamflow cycles relative to precipitation in southern Canada (Adamowski et al., 2011). There are indications of a significant increase in precipitation and streamflow in the northeastern USA through the last century (e.g., Krakauer and Fung, 2008).

The combined spatial–temporal analysis of coeval meteorological and streamflow fluctuation are complicated by several issues. These include:

(a) Dams and other man-made land-use changes influence streamflows independent of climate changes.
(b) Coeval records from both meteorological and streamflow measurements do not exist in close proximity and over long time intervals.
(c) Local meteorological records represent local conditions while streamflow patterns reflect conditions along the entire drainage system.
(d) Local warming due to urbanization ('urban heat island effect', e.g., Karl et al., 1988) overprints regional and global climate patterns.
(e) Only a few streamflow records are complete.

Thus, this may make it very difficult to draw solely data-based conclusions on future streamflow levels in Canada and their link to global climate change for both annual mean flow (e.g., Burn and Hag Elnur, 2002; Pilon and Yue, 2002; Adamowski and Bocci, 2001; Zhang et al., 2001), as well as streamflow extremes (e.g., Burn et al., 2010; Cunderlik and Burn, 2002).

In this study, changes in the annual streamflow amplitude and streamflow distributions were compared with changes in mean temperature and precipitation in eastern Ontario and southwestern Quebec, Canada, through the use of time series analysis techniques (trend, wavelet, cross-wavelet analysis) and spatial analysis using ArcGIS©. Eastern Ontario and southwestern Quebec have the advantage of having many, still pristine streamflows, with a relatively high density of meteorological and streamflow gauge stations where data has been recorded without interruptions for over 24 years (Fig. 1). Data was sampled from different locations in the same region, as well data representing surface hydrology and atmospheric conditions, and were combined and analyzed to allow for the interpretation of their spatial–temporal relationship. Knowledge of such relationships can help policy makers to mitigate water supply and flood problems based on knowledge of the regional meteorological trends and other temporal patterns. At the same time, it is possible to determine which hydrological regions are more susceptible to short and long term meteorological fluctuations.

2. Data

Complete monthly precipitation and temperature records from 9 stations in eastern Ontario and southwestern Quebec, for the time interval from January 1969 to December 1992, were

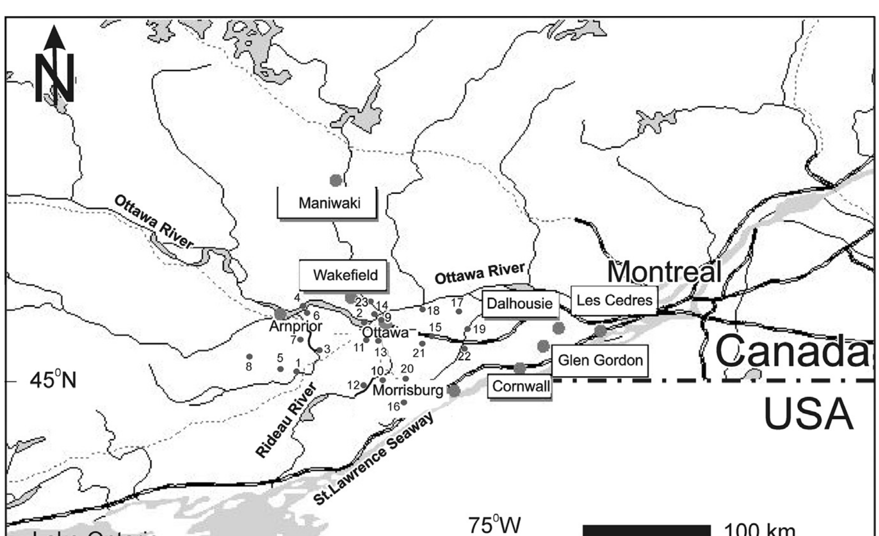

Fig. 1. Map eastern Ontario/southwestern Quebec, Canada: Red dots mark 23 streamflow gauge stations (for names and ID's see Table 1) and gray dots (except for Ottawa) mark meteorological stations used in this study.