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Impacts of future climate change on river discharge based on hydrological inference: A case study of the Grand River Watershed in Ontario, Canada

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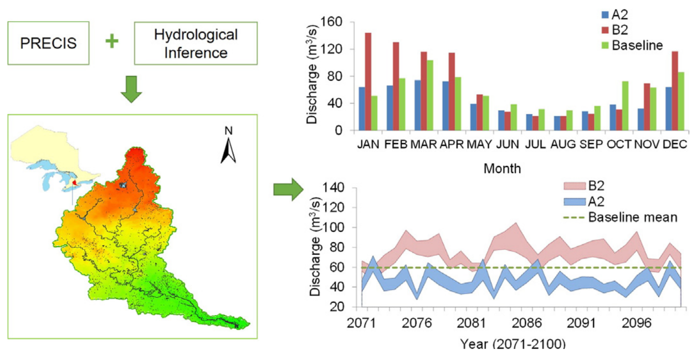
HIGHLIGHTS

- A case study in the Grand River Watershed, Canada was conducted.
- Two PRECIS runs were conducted to generate climate projections during 2071–2100.
- A Hydrological Inference Model was proposed to assess climate change impacts.
- Results show that water availability will increase in winter and decrease in summer.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the recent years, climate change impacts have been increasingly studied at the watershed scale. However, the impact assessment is strongly dependent upon the performance of the climatic and hydrological models. This study developed a two-step method to assess climate change impacts on water resources based on the Providing Regional Climates for Impacts Studies (PRECIS) modeling system and a Hydrological Inference Model (HIM). PRECIS runs provided future temperature and precipitation projections for the watershed under the Intergovernmental Panel on Climate Change SRES A2 and B2 emission scenarios. The HIM based on stepwise cluster analysis is developed to imitate the complex nonlinear relationships between climate input variables and targeted hydrological variables. Its robust mathematical structure and flexibility in predictor selection makes it a desirable tool for fully utilizing various climate modeling outputs. Although PRECIS and HIM cannot fully cover the uncertainties in hydro-climate modeling, they could provide efficient decision support for investigating the impacts of climate change on water resources. The proposed method is applied to the Grand River Watershed in Ontario, Canada. The model performance is demonstrated with comparison to observation data from the watershed during the period 1972–2006. Future river discharge intervals that accommodate uncertainties in hydro-climatic modeling are presented and future river discharge variations are analyzed. The results indicate that even though the total annual precipitation would not change significantly in the future, the inter-annual distribution is very likely to be altered. The water availability is expected to increase in Winter while it is very likely to decrease in Summer over the Grand River Watershed, and adaptation strategies would be necessary.

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1. Introduction

Over the past decade, the assessment of climate change impacts on water resources has been a major research effort (Jordan et al., 2014; Li et al., 2015; Vezzoli et al., 2015). Climate change is expected to affect the hydrological cycle, and consequently, water balances and local water supplies (Ling et al., 2014; López-Moreno et al., 2014). Predicting water availability under changing climatic conditions and hydrological variations, for both short-term and long-term, are essential for many social, economic and environmental sectors such as agriculture, industry, and biodiversity conservation (Kisi and Cimen, 2011; Pasini et al., 2012; Wu et al., 2012; Vezzoli et al., 2015; Pasini et al., 2012; Wu et al., 2012).

The Grand River Watershed is the largest watershed in southern Ontario, Canada and faces pressing challenges in climate change adaption and water resources management (Jyrkama and Sykes, 2007). It is one of the richest agricultural areas in Canada with approximately 79% of land being actively farmed, which leads to a large demand in irrigation water (GRCA, 2014). Moreover, several of the fastest growing cities in the province, with a total population of about 960,000 residents, are located in the watershed; and many southern Ontario cities depend entirely on surface water from the Grand River (Koycheva, 2003). Recent studies in regional climate modeling have demonstrated the future change of climate conditions such as temperature, precipitation and wind over the province of Ontario (Cheng et al., 2011; Wang et al., 2014a). Accordingly, several studies were conducted to assess the impacts of such changes on the Grand River (Grillakis et al., 2011). Jyrkama and Sykes (2007) characterized both the temporal and spatial effects of climate change on groundwater recharge in the Grand River Watershed. Colautti (2010) conducted a steady-state simulation of the Grand River Watershed hydrology using five future climate change scenarios where precipitation in the Grand River Watershed changed −5%, +5%, +10%, +15%, and +20%, respectively. Disch et al. (2012) interviewed 13 team members from Ontario's Low-Water Response (OLWR) program in the Grand River Watershed and assessed the resilience of their communities under potential future climate change scenarios. However, these studies were based on simple climate scenarios, and they did not conduct a relevant impact study through an ensemble of climatic and hydrological models. Given the Grand River's vital role as a regional resource for socio-economic development and the magnitude of future climatic changes, there is a clear need for an improved assessment of the potential impacts of climate change on future water availability in the Grand River Watershed.

A common approach for studying climate-change impacts on water resources is to use climate and hydrological models (Koutsouris et al., 2010; Marvel and Bonfils, 2013; Krakauer and Fekete, 2014; Wu et al., 2014). There are many complexities in the climate modeling processes (Jones et al., 2004; Kingston et al., 2011). The lack of understanding of climate dynamics, as well as various uncertainties associated with the future emission scenarios and their spatial and temporal details, hinder the capability to provide reliable climate change scenarios (Mearns et al., 2001; Henriques et al., 2015). As for hydrological modeling, physically-based models and data-driven models are the two major approaches. Physically-based models can provide information about the flow characteristics at points within the watershed (Grayson et al., 1992; Ma et al., 2014). The drawback of these models is that their representations of hydrologic processes are often too crude to enable accurate modeling and that the parameterization is rather difficult due to nonlinearities of processes and spatial heterogeneity (Barnett et al., 2005). Data driven models analyze the concurrent input and output time series rather than the physical process, but there is certain skepticism about whether it is adequate to build hydrological models without key knowledge of the inherent relationships (Solomatine and Ostfeld, 2008). Various complexities in the climate system and water cycle, as well as their dynamic interactions, have posed a great challenge for the prediction of future river runoff (Piao et al., 2010; Li et al., 2013; Zhang et al., 2014; Henriques et al., 2015). It is thus desired to integrate advanced climate modeling and hydrological modeling techniques and provide bases for the assessment of the climate change impacts on future water resources (Lin et al., 2006; Koutroulis et al., 2013).

Therefore, the objective of this study is to develop an effective hydro-climatic modeling chain. The Providing Regional Climates for Impacts Studies (PRECIS) modeling system will be used to simulate future temperature and precipitation patterns. Uncertainties in future emissions will be tackled by running PRECIS for two emission scenarios. A Hydrological Inference Model (HIM) will be proposed to map the complex nonlinear relationships between river discharge and related climatic factors, and monthly river discharge forecast will be generated to provide decision support for water resources management and planning. The developed method will be used to assess the impacts of future climate change on the monthly river discharge in the Grand River Watershed in Ontario, Canada. Future discharge intervals will be generated and changes of intra-annual and inter-annual discharge variations will be analyzed. The results will reveal changes of future climate patterns based on the insights gained in terms of dynamic variations of climate over the Grand River Watershed. This study will provide desired support for water resources management and watershed-scale climate adaptation.

2. Methods

2.1. Study area

The Grand River Watershed is the largest watershed in southern Ontario, draining an area of 6800 km^2 into Lake Erie (Fig. 1). The Grand River is approximately 280 km in length from its source near the town of Dundalk to the mouth at Port Maitland, with an elevation difference of 352 m. There are four major tributaries, including the Conestogo River, the Eramosa River, the Speed River and the Nith River. The climate is affected by the lake effects of the Great Lakes, as well as the climate patterns in the Arctic and the Gulf of Mexico. The temperature is generally moderate to cool, compared to other parts of Canada. During the past decade, the average monthly temperate ranged from −9.2 °C to 21 °C, and the annual mean precipitation is approximately 900 mm. There is no rainy season and the majority of precipitation in Winter is in the form of snow. The land cover is primarily agricultural (79%) and natural hardwood forest (19%) (Reid et al., 2008). The soil types and topography are heterogeneous: the upper watershed is mainly formed of lower permeability till plains with varying surface relief; the middle watershed consists of higher permeability sand and gravel kame moraines with moderately high relief; and the lower watershed is comprised of low permeability lacustrine clay deposits with low topographic relief (Jyrkama and Sykes, 2007).

Different from many large watersheds in Canada that are mainly located in sparsely populated areas, the Grand River Watershed, particularly the central portion of the watershed, is highly urbanized and densely populated. Its eastern boundary is located approximately 80 km west of Toronto, and it contains five fast-growing cities including Brantford, Cambridge, Kitchener, Waterloo, and Guelph (Bouda et al., 2012). The total population is over 960,000 and is expected to be more than 1,400,000 in 2031 (Farwell et al., 2008). The rapid urbanization has posed major challenges for water supply, and there is a growing concern about the potential impacts of climate change on water resources.

2.2. Data collection

Watershed boundary data were extracted from the National Hydro Network (NHN) on the GeoBase Web portal (www.geobase.ca). Stream network data were obtained from the Grand River Watershed basic map layers provided by Wilfrid Laurier University's Department of Geography and Environmental Studies. Meteorological and hydrometric data