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Assessing climate change impacts on fresh water resources of the Athabasca River Basin, Canada

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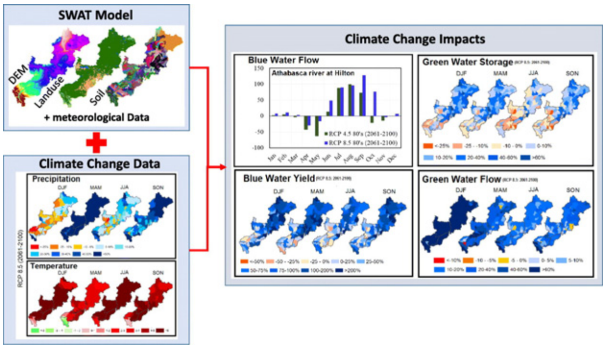
HIGHLIGHTS

- Climate change impact analysis of the Athabasca River Basin (ARB) using the SWAT model
- Explicit consideration of both the blue and green water resources
- Future (mid- and late century) climate data generated by CanRCM4 for RCP 4.5 and 8.5
- Both the blue and green water resources in the ARB are likely to increase in the future.
- Evidences of temporal and spatial heterogeneity of the blue and green water resources

GRAPHICAL ABSTRACT



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ABSTRACT

Proper management of blue and green water resources is important for the sustainability of ecosystems and for the socio-economic development of river basins such as the Athabasca River Basin (ARB) in Canada. For this reason, quantifying climate change impacts on these water resources at a finer temporal and spatial scale is often necessary. In this study, we used a Soil and Water Assessment Tool (SWAT) to assess climate change impacts on fresh water resources, focusing explicitly on the impacts to both blue and green water. We used future climate data generated by the Canadian Center for Climate Modelling and Analysis Regional Climate Model (CanRCM4) with a spatial resolution of 0.22° × 0.22° (~25 km) for two emission scenarios (RCP 4.5 and 8.5). Results projected the climate of the ARB to be wetter by 21–34% and warmer by 2–5.4 °C on an annual time scale. Consequently, the annual average blue and green water flow was projected to increase by 16–54% and 11–34%, respectively, depending on the region, future period, and emission scenario. Furthermore, the annual average green water storage at the boreal region was expected to increase by 30%, while the storage was projected to remain fairly stable or decrease in other regions, especially during the summer season. On average, the fresh water resources in the ARB are likely to increase in the future. However, evidence of temporal and spatial heterogeneity could pose many future challenges to water resource planners and managers.

1. Introduction

The Athabasca River Basin (ARB) is ecologically and economically significant to the development and sustainability of northern Alberta communities. Indeed, the multi-billion dollar oil sands industry requires a large amount of water, approximately 4.4% of the average yearly

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streamflow (Sauchyn et al., 2015). Ever increasing industrialization and a growing population are putting immense pressure on the water resources of the basin and pose a notable threat to the environmental and economic sustainability of the ARB. Moreover, the negative impacts of climate change are evident all over the world. The sustained increase in the emission of greenhouse gases will alter all components of the climate system (IPCC, 2014). By the end of this century, the global surface temperature is likely to be 2 °C warmer, relative to the temperature experienced during the period of 1850–1900. Such increases are alarming, especially for the ARB with its water cycle which primarily depends on glacial melt at its headwater and spring freshet at its other sections. Some evidence of these changes have already been reported in the literature (Eum et al., 2017; Kerkhoven and Gan, 2011; Leong and Donner, 2015; Sauchyn et al., 2015). However, most studies to date have been limited to analyzing stream flow trends. This is reflective of a traditional water resource planning and management approach in which greater emphasis is put on the blue liquid water - the stream flow (Falkenmark and Rockström, 2006). Other forms of water resources, such as green water storage (soil water) and green water flow (evapotranspiration), are equally important to consider. Hence, a comprehensive climate change impact assessment should follow the "Blue and Green Water Paradigm" in which both resources are explicitly examined (Falkenmark and Rockström, 2006).

Furthermore, the ARB is located in a cold-climate region with many impoundments (e.g., lakes). Thus, the hydrology of the basin is snowmelt dominated, meaning its winter flows are low and its spring flows are high. A climate change impact assessment study in such a cold region should take into account both the blue and green water resources, as both resources are affected by climate change. To our knowledge, there has not been a study which considered both water resources at different spatial and temporal scales to make climate change impact assessments of the basin. With this in mind, this study has been carried out with a primary objective of quantifying the impacts of climate change on monthly, seasonal, and annual water balances of blue and green water resources at sub-basin, regional, and basin-wide spatial scales. We addressed this objective with a two-step approach. First, we built a SWAT model of the basin using a spatial and hydro-meteorological data set. We then evaluated the applicability and suitability of the model in the snow-dominated and cold climate in which the ARB basin is located. During the second step, we fed high resolution (~25 × 25 km) future climate data generated by the Canadian Center for Climate Modelling and Analysis Regional Climate Model (CanRCM4) for two emission scenarios (RCP 4.5 and 8.5) into the calibrated and validated model to assess the impacts on blue and green water resources.

2. Materials and methods

2.1. The study area

The Athabasca River Basin (ARB) originates at the Columbia Icefields, located in the Canadian Rocky Mountains in the province of Alberta. The river flows toward the North-East and drains first into Lake Athabasca (Fig. 1) before eventually reaching the Arctic Ocean. The catchment area of the mouth of the ARB is approximately 161,000 km^2. The river crosses through the municipalities of Jasper, Hinton, Whitecourt, Athabasca, and Fort McMurray (AWC, 2011). Forest is the dominant land-use type in the basin at almost 82% coverage, followed by agriculture land with about 10% coverage (Fig. S1). Major industries with activities occurring in the basin include agriculture, pulp mills, coal, and oil sand mining (AWC, 2013).

2.2. The hydrologic simulator - Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT), developed by the United States Department of Agriculture (USDA), is a semi-distributed hydrological simulator used for continuous long term simulation of a variety of processes which are primarily from rural catchments (Arnold et al., 1998). The SWAT is one of the most widely used simulators for hydrologic modelling (Arnold et al., 2012). This is partially because it is an open-source tool containing various add-ons, such as SWAT calibration and uncertainty or sensitivity analysis programs – SWAT CUP (Abbaspour et al., 2007). The simulator has also been recognized by the US Environmental Protection Agency (Abbaspour et al., 2015). Moreover, the simulator has been used to simulate hydrological processes (Leta et al., 2015), water quality processes (Santhi et al., 2001; Shrestha et al., 2017), and erosion sediment transport modelling (Shrestha et al., 2013), in addition to being utilized as a component model in the integrated modelling chain (Shrestha et al., 2014). The SWAT uses spatial datasets for elevation, land-use, and soil, along with several hydro-meteorological datasets which are typically integrated using the Geographic Information System (Winchell et al., 2010). SWAT compartmentalizes a watershed into sub-basins that are further divided into Hydrological Response Units (HRUs) which are unique combinations of soil, land-use, and slope (Arnold et al., 2011).

The hydrological component of SWAT considers precipitation, infiltration, deep aquifer, channel transmission and evapotranspiration (ET) losses, surface runoff (Q_{surf}), and lateral and return flow ($Q_{sub\text{-}surf}$) for water balance calculations (Eq. (1)). SWAT differentiates precipitation as rainfall or snowfall while comparing air temperature with a snowfall temperature parameter (SFTMP). As a result, the model keeps track of the volume and areal extent of snowpack, as well as the corresponding snowmelt as per Eqs. (2)–(4). Snow accumulation and melting are processes that can be spatially varied using elevation bands in a sub-basin. A maximum of 10 elevation bands can be defined at each sub-basin. The model allows for the consideration of two lapse rates, the temperature (TLAPS) and precipitation (PLAPS), in order to, respectively, vary the temperature and precipitation with elevation (Eqs. (5)–(8)). The model employs either the SCS curve number or the modified Green-Ampt method to determine the infiltration and runoff volumes for each HRU. Infiltrated water percolates through each soil layer, as estimated using a storage routing technique. SWAT offers a variable storage method or Muskingum method to route the streamflow generated as a result of runoff coming from each of the HRUs of the sub-basins (Neitsch et al., 2011).

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(P_i - ET_i - Q_{i,seep} - Q_{i,surf} - Q_{i,gw}\right) \tag{1}$$

$$SNO_t = SNO_0 + \sum_{i=1}^{t} \left(P_i - E_{i,sub} - SNOMLT_i\right) \tag{2}$$

$$SNOMLT_i = b_{i,mlt} \cdot SNOCOV_i + \left(\frac{T_{i,snow} + T_{i,\,max}}{2} - SMTMP\right) \tag{3}$$

$$b_{i,mlt} = \left(\frac{SMFMX + SMFMN}{2} + \frac{SMFMX - SMFMN}{2}\right) \cdot \sin\left(\frac{2\pi}{365}(i - 81)\right) \tag{4}$$

$$P_{band} = P_{day} + \left(EL_{band} - EL_{gauge}\right) \cdot \left(\frac{PLAPS}{days_{pcp,yr} \cdot 1000}\right) \tag{5}$$

$$P_{day} = \sum_{band=1}^{k} P_{band} \cdot FR_{band} \tag{6}$$

$$T_{mx,mn,avg,band} = T_{mx,mn,av,day} + \left(EL_{band} - EL_{gauge}\right) \cdot \left(\frac{TLAPS}{1000}\right) \tag{7}$$

$$T_{mx,mn,av,day} = \sum_{band=1}^{k} T_{mx,mn,avg,band} \cdot FR_{band} \tag{8}$$

where, SW_t = soil moisture at time t (mm); SW_0 = initial soil moisture (mm); i = day counter; P_i = precipitation (mm); ET_i =