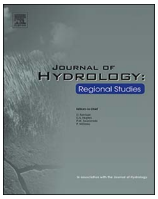
Journal of Hydrology: Regional Studies 15 (2018) 134–148

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh



Modelling the Athabasca watershed snow response to a changing climate

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ARTICLE INFO

Keywords:
Climate change
Snow cover
SWE
Snow melt
Athabasca watershed
VIC model

ABSTRACT

Study region: The Athabasca River basin (ARB) with its head-waters located within the Canadian Rockies.

Study focus: Investigating the snow response of the Athabasca watershed to projected climate using the Variable Infiltration Capacity (VIC) hydrologic model and statistically downscaled future climate data from a selected set of CMIP5 GCMs forced with RCP4.5 and RCP8.5 emissions scenarios.

New hydrological insights for the region: High resolution end-of-century projections of SWE over the Athabasca watershed show an overall decreasing trend in the mean monthly SWE over the watershed, with the largest decreases occurring in March and April, especially in the high-elevation sub-basin. There are also widespread decreases in annual maximum SWE (SWEmax), with the middle-basin showing slight increases under the RCP4.5 scenario. The dates of SWEmax are generally getting earlier, with RCP4.5 showing a less linear response than RCP8.5. Increases in early spring snowmelt are followed by decreases during the late spring and summer months mainly as a result of earlier start of snowmelt. An overall decrease in snow-cover duration of up to fifty days is projected with the largest decrease occurring in the high elevation sub-basin. Such projected declines in snow water storage and a shift to earlier peak SWE and snowmelt over the ARB have significant implications for the magnitude and timing of the watershed soil-moisture content and hydrologic regime of the Athabasca River.

1. Introduction

Snowfall and seasonal snow cover are important components of the hydrologic cycle in cold regions because of their strong linkages with the regional climate and hydrology through their significant effects on energy and moisture budgets. Specifically, snow cover depth plays a significant role because of its water storage effect and role in generating spring snowmelt. Streamflow originating from mountainous-headwater catchments are primarily dependent on snow accumulation and melt from the higher elevations, which provide the major contributions to total basin flow. After the snowmelt, various processes, such as refreezing of water within the cold snow cover (Marsh and Woo 1985) and frozen soil infiltration (Gray et al., 1985) will affect the movement of water into the soil column below and to the stream channels. The relatively high albedo and low thermal conductivity of snow cover also have major influences on surface energy exchanges and the ground thermal regime with important consequences for snowmelt and soil hydraulic properties. After reviewing the potential impacts of a warming climate in snow-dominated regions, Barnett et al. (2005) indicated

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https://doi.org/10.1016/j.ejrh.2018.01.003
Received 5 May 2017; Received in revised form 9 January 2018; Accepted 14 January 2018

that less winter precipitation will occur as snow and the melting of winter snow will occur earlier in the spring. Berghuijs et al. (2014) have also indicated that one of the most widely anticipated changes in the hydrological cycle is the temperature-induced shift of precipitation from snow to rain that will affect snowpacks mostly in the mid to later part of the snow season. This shift has the potential to alter the frequency of rain-on-snow events that have a number of implications for hydrological processes over the land surface, including snow melt and streamflow (Cohen et al., 2015).

Snow response to projected changes in temperature and precipitation in northern and alpine dominated watersheds is complex, with the rate and sign of changes varying with local climate regime and elevation. Locally, snow water equivalent (SWE) responds to changes in both precipitation and air temperature, and the magnitude and seasonal characteristic of the change depends on the various interplay between a shortened snow-accumulation period, the fraction of precipitation that falls as snow, and the frequency and intensity of winter thaw events (Räisänen, 2008; Brown and Mote, 2009). Beniston and Stoffel (2016) identified that rain on snow events are major drivers of alpine flood events and future trends show that these events may increase as a first response to sustained warming but may decline thereafter. A global scale assessment of mountainous systems by Huss et al. (2017) shows the major shifts in seasonal runoff regimes around the world that will result from the effect of reduced snow cover and ice. Based on recent evidence over the European Alps, Marty et al. (2017) also reported a widespread reduction in snow mass, which is more pronounced for spring than for winter with even the highest elevation sites showing a decline in spring SWE. Using recently updated data to provide a comprehensive view of climate variability and long-term changes for the period of instrumental record over Canada, Vincent et al. (2015) reported a decrease in the amount of precipitation falling as snow in the south, fewer days with snow cover, an earlier start of the spring high-flow season, and an increase in April streamflow, all consistent with the observed warming and precipitation trends. They have also demonstrated that the different modes of low-frequency variability resulting from atmospheric teleconnections modulate the spatial distribution and strength of the trends; however, they alone cannot explain the observed long-term trends in these climate variables.

Most of the major rivers crossing the Canadian prairies originate in the Rocky Mountains, where deep snowpacks and melting glaciers maintain river and groundwater supplies (Schindler and Donahue, 2006). However, quantifying the volume of snow on the ground is challenging owing to its high spatial variability and sparse surface observations, as well as difficulties in retrieving relevant snow information from raw satellite data. Long-term observational data sets for snow cover extent have only recently been reconciled, and considerable observational uncertainty remains (Brown et al., 2010). Lapp et al. (2005) have demonstrated that the projected increase in winter precipitation over the upper Oldman River basin in southwestern Alberta, will not compensate for regional changes in the rain-to-snow ratios, and the net result will be a decline in winter accumulations of precipitation as snow, and hence, an expected decline in spring runoff. Pomeroy et al. (2015) have reported that a 2 °C warming in the Canadian Rockies will lead to a shift from snowfall to rainfall dominance, a substantial decline in snowpack magnitude, and a shortening of the duration of snow-season at all elevations. However, in many regions including the Athabasca River basin, the spatial and seasonal response of SWE to a warming climate has not been addressed in detail, with most previous studies focusing only on season average or annual maximum SWE (SWEmax).

The main objective of this paper is to present the findings of a detailed investigation conducted as part of the governments of Alberta and Canada Joint Oil-Sands Monitoring Program (JOSMP, 2012) on the Athabasca watershed snow response to a changing climate. With its head-waters located within the Canadian Rockies, snow accumulation and melt constitute a larger proportion of the Athabasca River discharge which plays an important role in sustaining aquatic habitats and in supporting various industrial activities in the region. The scenario based study is conducted using the Variable Infiltration Capacity (VIC) process-based and distributed hydrologic model (Liang et al., 1994) and the CMIP5 climate projection (Maloney et al., 2014). The VIC model has been used in numerous climate studies including evaluation of declines in western snowpack (Mote et al., 2005; Mao et al., 2015) and it has also been successfully applied for evaluating the effects of climate change on hydrologic regimes for watersheds with different basin size, climatology and hydrologic processes (Cuo et al., 2011; Christensen and Lettenmaier, 2007; Elsner et al., 2010; Werner et al., 2013). The VIC performance in modelling snow over the Athabasca watershed is first evaluated by comparing the SWE values simulated using gridded observed climate data with measured SWE data from snow course observations as well as an observation-based gridded snow product over the baseline period. This is followed by an assessment of the projected changes in the driving hydro-climatic variables (temperature and precipitation) over the watershed using the bias-corrected and spatially-downscaled climate projections from the latest CMIP5 data set. The CMIP5 daily precipitation and temperature data were also used to drive the VIC model to simulate the hydrologic response of the Athabasca River Basin (ARB) for the baseline and future periods, and compute the projected changes in the SWE over the entire watershed. This analysis focuses primarily on the spatial and seasonal changes in the magnitude and timing of the mean monthly and annual maximum SWE, snowmelt and Snow cover duration (SCD) in the 21 st century corresponding to the RCP4.5 and RCP8.5 emissions scenarios. The study area considered for this analysis, the ARB, is described in Section 2 followed by a description of the hydrologic modelling approach and the input data sets in Section 3. The results of the investigation are presented and discussed in Section 4 and a summary of key findings and final conclusions are presented in Section 5.

2. Studied basin description

The Athabasca River basin (ARB) originates in the Canadian Rockies from the Athabasca Glacier at over 3700 m above mean sea level (amsl) and flows approximately 1500 km north-eastward to Lake Athabasca at 187 m amsl. Its total drainage area attains approximately 156,000 km^2 near Old Fort before it flows into Lake Athabasca. Mean annual precipitation in the watershed ranges from around 300 mm at the downstream end near Lake Athabasca to over 1000 mm at the high elevation head-waters. The ARB has been divided into three hydro-physiographic regions based on differing climatic, hydrologic and topographic characteristics