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Climate-Change Effects on Groundwater Recharge in the Prairies

Amro Negm[1], Kabir Rasouli[2], Masaki Hayashi[1]
(1) Department of Geoscience, University of Calgary, (2) Environment and Climate Change Canada

Summary

The hydrology of Canadian Prairies is characterized by large spatial variability in terms of topographical and geological formations and land cover. In such environments, numerous topographic depressions accumulate snowmelt runoff and rainfall, resulting in depression-focussed recharge. It is important to assess the variability of hydrological variables under present and future climates. In this work, a soil water balance model and a numerical weather model were used to investigate the hydrological changes for the present climate and pseudo-global warming (PGW) scenario. The results showed that the hydrology of the grassland site will shift to a regime with slightly less surface runoff and groundwater recharge in the PGW climate compared to the present climate. These findings have implications for groundwater resource management in semi-arid regions with seasonally frozen soils.

Objective

The aim of this study is to have a better understanding of how will the changes in air temperature and precipitation phase, soil temperatures and soil moisture affect the hydrological processes (i.e. runoff, and groundwater recharge) in the Canadian Prairies. In this work, a simple soil water balance model, called Versatile Soil Moisture Budget (VSMB) (see below), was used to investigate the hydrological processes in the present climate (2006-2015), including soil moisture, evapotranspiration, snowmelt runoff, snow accumulation, ponded water level and depression-focus recharge which occur in several grassland depressions of the West Nose Creek. The soil water balance model was run under dynamically downscaled climate-change scenarios.

Methods

In this study, the data used for model testing were collected at a grassland site in the Spyhill Farm, near Calgary (51°10'31" N, 114°13'44" W). A weather station was installed in June 2006 to monitor meteorological and soil variables, including relative humidity and air temperature, short and longwave radiation, wind speed, turbulent fluxes, precipitation, soil temperature and water content at different depths. The measured data used to simulate the hydrological process using the VSMB model at present climate (2006-2015) and to assess the model performance. Moreover, the Weather Research and Forecasting (WRF) model (see below) outputs with 4 km resolution for the present climate and pseudo-global warming (PGW) conditions were used to model the future changes in hydrological processes in 2091-2100.

Groundwater recharge model

The VSMB calculates soil water balance on a daily basis for seven soil layers (five for depression) with thicknesses ranging between 0.05 m and 2.0 m. First, water from rainfall and snowmelt calculated by the Utah Energy Balance (UEB) model (Tarboton and Luce, 1996) is added to the top layer, and the runoff is generated only when the top layer becomes saturated; then water infiltrated into the soil is subsequently distributed to the lower layers by gravity drainage and gradient-driven moisture diffusion. The inputs of the VSMB model include hourly data of air temperature and relative humidity, precipitation, wind speed, shortwave incoming radiation, soil and plant properties, and parameters representing the upland-to-depression area ratio and depression geometry. Details of each process algorithm are found in Akinremi et al., (1996), Hayashi et al. (2010), Mohammed et al. (2013), and Noorduijn et al. (2018). Depression-focussed groundwater recharge is estimated using the VSMB Depression-Upland System (VSMB-DUS), which couples vertical soil water balances of depression and upland simulated by the VSMB, via lateral runoff from uplands to a depression (Noorduijn et al., 2018). In the VSMB-DUS, runoff from the upland accumulates in the pond when the volume of water reaching the depression exceeds the infiltration capacity of the soil column (Noorduijn et al., 2018).

Dynamical downscaling of climate change scenario

The outputs of climate models, such as the general circulation model (GCM), are too coarse for hydrological applications. Weather Research and Forecasting (WRF) is a numerical weather prediction system used for atmospheric forecasting and research needs (Skamarock 2008). Various bias correction methods are widely used to reduce biases between atmospheric model outputs and observations (Teutschbein et al., 2012). This study uses a multivariate bias correction method (Cannon, 2018), in which an N-dimensional probability density function transform is used as a bias correction algorithm for correcting the climate model biases in the control period first and then future projections. The bias-corrected WRF model outputs with 4 km horizontal grids and 37 vertical levels were used over the period of 2006-2015 and under PGW dynamical downscaling of future warming projection to study the future changes (2091-20100) in an upland-depression hydrological system. The PGW method was used to dynamically downscale climate model projections (Kawase et al. 2009). In this work, PGW runs from 2006 to 2015 were equivalent to what are expected to occur between 2091-2100.

Conclusions

Hydrological response of a grassland site with seasonally frozen soils in the Canadian Prairies was assessed in the present climate (2006-2015) and compared to PGW under the RCP8.5 scenario for 2091-2100. A soil water balance model coupling the hydrology of a topographic depression and its upland catchment, VSMB-DUS, was used to simulate hydrological processes and estimate depression-focussed groundwater recharge. The bias-corrected regional climate model, WRF, was used to dynamically downscale the climate predictions provided by global circulation models. The outputs of WRF under the PGW scenario showed an increase of mean annual air temperature from 4.0 to 8.9 °C, and an increase of annual precipitation from 491 mm to 637 mm. The outputs of VSMB-DUS showed an increase of soil temperature by 4-7°C (Fig.1), a decrease of the number of frozen soil days from 158 days to 32 days, and a decrease in total soil water content by 0.05-0.10 in spring and summer at Spyhill site. Warming led to a 29% reduction in peak snowpack and a decrease in the proportion of precipitation that falls as the snow

Under the PGW scenario, an increase in air temperature resulted in the increased prominence of rainfall to snowfall and decreased soil frost. These changes along with the rise in soil temperature and changes in soil moistures have substantial impacts on the hydrology of the study area. The main hydrological processes and most importantly the runoff generation mechanism changed from being snowmelt-dominated to rainfall dominated. The depression focused recharge was affected as a result of earlier snowmelt and lower runoff when compared to the present climate. Despite a precipitation increase, the groundwater recharge in the grassland of the Spyhill site was slightly reduced under the warmer climate (Fig. 2). Future investigations are needed to investigate the effect of warming on croplands of the Canadian Prairies which contribute with Changes in depression-focused groundwater recharge have important consequences in the hydrological regime of the upland-depression systems and availability of groundwater resources in the Canadian Prairies.

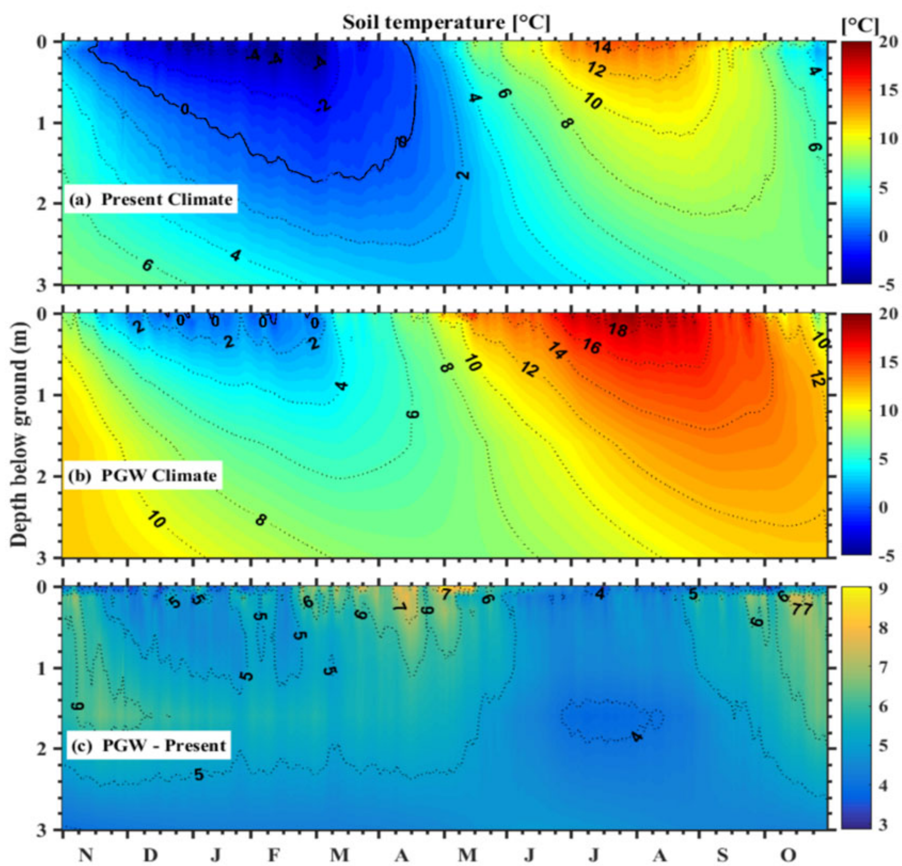

Figure 1 – The annual cycle of the soil temperature in °C with soil depth in the Spyhill site under (a) present climate (2006-2015), (b) PGW conditions (2091-2100), and (c) changes between the present and PGW climates.

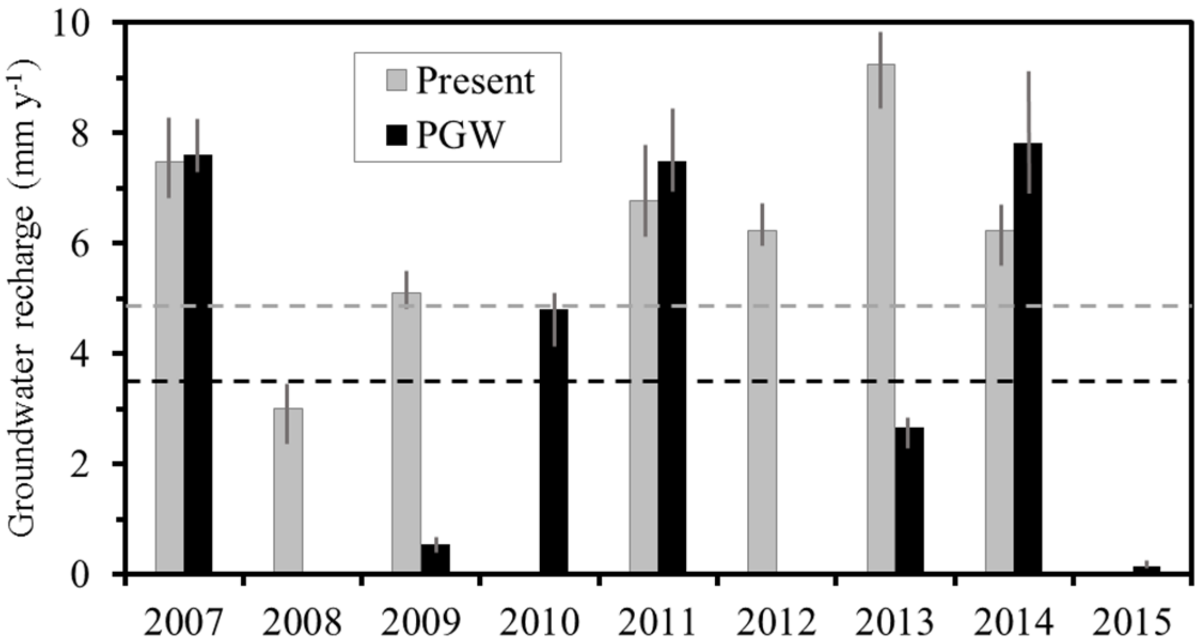

Figure 2 – Groundwater recharge estimated from four depressions at the Spyhill site under the present climate and the PGW scenario. Each bar indicates the average value of four depressions with a line showing the range of values. The dotted lines show the average value for the nine hydrological years (2007-2015 for the present and 2092-2100 for the PGW).

Additive Information

This work is one of the first attempts to understand how grasslands in the Canadian Prairies respond hydrologically to climate change, which can lead to build better decision-support tools for groundwater management, policies, and programs.

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