



## Research papers

# Climate change impacts on hillslope runoff on the northern Great Plains, 1962–2013

A.E. Coles<sup>a,\*</sup>, B.G. McConkey<sup>b</sup>, J.J. McDonnell<sup>a,c</sup><sup>a</sup> Global Institute for Water Security; School of Environment and Sustainability, University of Saskatchewan, 11 Innovation Boulevard, Saskatoon, SK S7N 3H5, Canada<sup>b</sup> Swift Current Research and Development Centre, Agriculture and Agri-Food Canada, PO Box 1030, Swift Current, SK S9H 3X2, Canada<sup>c</sup> School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE, United Kingdom

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## ABSTRACT

On the Great Plains of North America, water resources are being threatened by climatic shifts. However, a lack of hillslope-scale climate-runoff observations is limiting our ability to understand these impacts. Here, we present a 52-year (1962–2013) dataset (precipitation, temperature, snow cover, soil water content, and runoff) from three 5 ha hillslopes on the seasonally-frozen northern Great Plains. In this region, snowmelt-runoff drives c. 80% of annual runoff and is potentially vulnerable to warming temperatures and changes in precipitation amount and phase. We assessed trends in these climatological and hydrological variables using time series analysis. We found that spring snowmelt-runoff has decreased (on average by 59%) in response to a reduction in winter snowfall (by 18%), but that rainfall-runoff has shown no significant response to a 51% increase in rainfall or shifts to more multi-day rain events. In summer, unfrozen, deep, high-infiltrability soils act as a ‘shock absorber’ to rainfall, buffering the long-term runoff response to rainfall. Meanwhile, during winter and spring freshet, frozen ground limits soil infiltrability and results in runoff responses that more closely mirror the snowfall and snowmelt trends. These findings are counter to climate-runoff relationships observed at the catchment scale on the northern Great Plains where land drainage alterations dominate. At the hillslope scale, decreasing snowfall, snowmelt-runoff, and spring soil water content is causing agricultural productivity to be increasingly dependent on growing season precipitation, and will likely accentuate the impact of droughts.

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## 1. Introduction

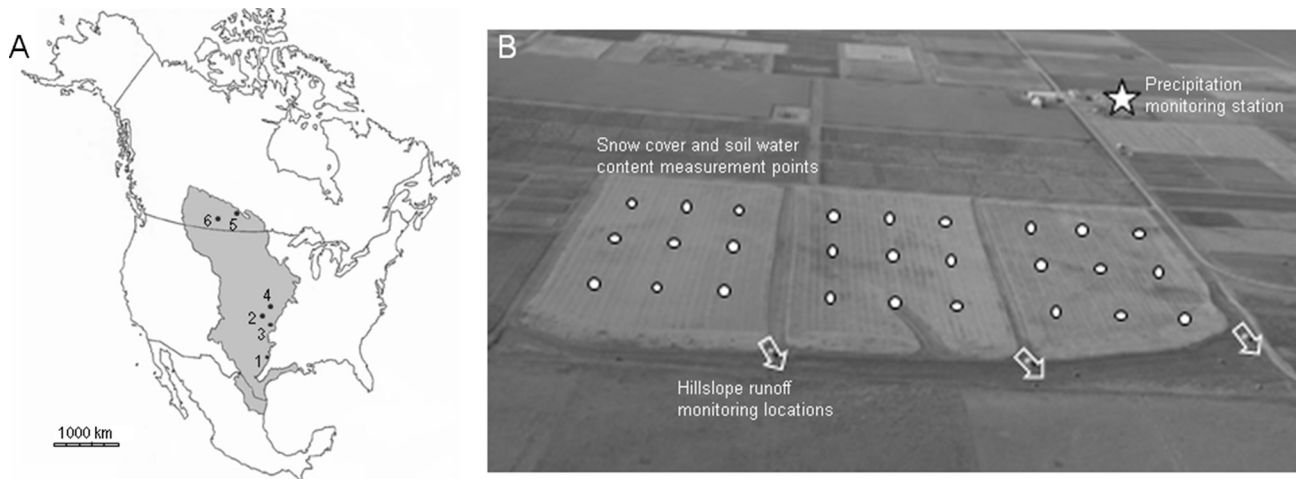
Climate impacts on the hydrology of the Great Plains of North America are poorly understood. Any such impact may have enormous consequences for agriculture on the Great Plains, where 80% of the region is under agricultural management, has a crop market value of approximately \$92 billion USD (Hatfield et al., 2014), and accounts for about half of the world's wheat production (Wishart, 2004). On the northern Great Plains, the focus of this study, the greatest source of water for agriculture comes from surface and near-surface sources; in the South Saskatchewan River Basin, agriculture accounts for 86.5% of surface water extraction and it is also reliant on shallow soil water storage (Pomeroy et al., 2009). However, in this northern, seasonally-frozen region, water regimes are being threatened by warming temperatures and changes in precipitation amount and phase. For future sustainable agricultural production, it is crucial to understand the

long-term climate-induced shifts in water availability. For this, we need long-term records of climate and runoff.

While many long-term climate records exist on the Great Plains, there are relatively few sites with long-term combined climate-runoff records for this region (Fig. 1a). Most of these are in the southern Great Plains (Garbrecht, 2008; Harmel et al., 2006; Heppner and Loague, 2008; Wine and Zou, 2012). The only long-term climate-runoff record pertaining to the seasonally frozen northern Great Plains is the 40-year dataset from an agriculture- and wetland-dominated catchment, Smith Creek Research Basin, on the Prairies of Canada (Dumanski et al., 2015). All are catchment-scale streamflow observations. The catchment-scale studies on the Great Plains, like many catchment-scale studies in other regions (Woo et al., 2006), demonstrate that catchments can act as nonlinear filters of climatic signals to either possibly damp or enhance the resultant runoff signal. Harmel et al. (2006) and Wine and Zou (2012) found statistically significant trends in precipitation, but no resultant shifts in streamflow. Meanwhile, Dumanski et al. (2015) and Garbrecht (2008) both showed much

\* Corresponding author.

E-mail address: [anna.coles@usask.ca](mailto:anna.coles@usask.ca) (A.E. Coles).



**Fig. 1.** A) The Great Plains of North America, indicating the locations of study sites with existing climate-runoff datasets. 1: A 69-year dataset from the USDA-ARS Grassland Soil and Water Research Laboratory experimental watershed in the Texas Blacklands Prairies near Riesel, Texas, USA (Harmel et al., 2006). 2: A 65-year dataset from crop- and pasture-land of the Fort Cobb Reservoir watershed in central Oklahoma, USA (Garbrecht, 2008). 3: An 8-year dataset from the R-5 rangeland catchment in the USDA-ARS Washita River Experimental Watershed in central Oklahoma, USA (Heppner and Loague, 2008). 4: A c. 54-year dataset from Council Creek watershed in the tallgrass prairie of north-central Oklahoma, USA (Wine and Zou, 2012). 5: A 40-year dataset from an agriculture- and wetland-dominated catchment, Smith Creek Research Basin, on the prairies of Canada (Dumanski et al., 2015). 6: This paper's study site, the Swift Current hillslopes, at South Farm, Swift Current, SK, Canada with a 52-year dataset. B) Aerial photograph (facing south) of the Swift Current hillslopes (from right to left: Hillslope 1, Hillslope 2, Hillslope 3), taken in a year when wheat was grown. Precipitation, snow cover, soil water content, and runoff measurement locations are indicated. Photograph reproduced, with permission, from Cessna et al. (2013).

more amplified streamflow trends than their corresponding precipitation trends.

The hydrology of the uplands at the sub-catchment-scale is most important for agriculture. For instance, dugouts (small excavated storage reservoirs), which collect water from adjacent hillslopes, are an important source of water for livestock watering and farm household use on the Canadian Prairies. These dugouts are purposefully not located on or within significant watercourses, so all inflow is determined from local hillslope hydrology. The hillslope scale is also the scale at which we observe runoff generation processes that ultimately deliver water to soil water recharge, groundwater recharge, and streamflow. To date, there have been no published long-term climate-runoff observations at the hillslope scale on the Great Plains. Further, it is very difficult to relate catchment-scale observations back to hillslope-scale water trends and resources when sloughs (water-filled depressions), riparian zones with possible groundwater contribution, and other geomorphic zones in the landscape influence the catchment-scale integrated streamflow signal (McGuire and McDonnell, 2010). As a result, we do not know how, if at all, runoff generation processes and hillslope-scale water availability have responded to changes in, for example, temperature and precipitation, and whether or not hillslope-scale runoff generation is coupled or decoupled from climate variations. Therefore, for understanding water availability for dryland agriculture in this region, we need observations of hillslope-scale runoff.

In the seasonally-frozen northern Great Plains, snowmelt in the spring freshet drives c. 80% of the annual runoff, when a rapid release of water from the snowpacks during a 1–3 week snowmelt season occurs over frozen ground of limited infiltration capacity (Granger et al., 1984; Fang et al., 2007). However, cold regions are losing their cold (Tetzlaff et al., 2013): decreased winter snowfall has been observed on the northern Great Plains (e.g. Akinremi et al., 1999; Cutforth et al., 1999; Mekis and Vincent, 2011), as has increased spring and fall rainfall fractions (e.g. Mekis and Vincent, 2011; Shook and Pomeroy, 2012). One might hypothesize that climate-related changes will yield cascading effects on hydrological regimes, runoff generation, and ultimately water resources available for agriculture and other uses. In the summer months, hillslope-runoff occurs occasionally during intense, one-day con-

vective rainstorms that may generate infiltration-excess overland flow. But recent observations show decreasing one-day rain events, and an increase in less-intense, multi-day frontal rain events with greater overall magnitude (Shook and Pomeroy, 2012). As yet, for both snowmelt- and rainfall-driven runoff events, the effects of these precipitation trends on hillslope-scale runoff generation and water availability are unknown.

Here, we use a 52-year hillslope-scale dataset of climate and runoff data from three 5 ha agricultural hillslopes on the northern Great Plains to quantify changes in precipitation amount, phase, and timing, and identify if/how they relate to changes in runoff and water availability. Specifically, we ask the following questions:

1. How have hillslope-scale snowmelt- and rainfall-runoff events responded to changes in precipitation quantity, timing, and phase?
2. Do hillslope-scale snowmelt- and rainfall-runoff responses differ in their response to long-term trends in precipitation?

## 2. Study site

The study site (South Farm, Swift Current Research and Development Centre, Agriculture and Agri-Food Canada, Swift Current, Saskatchewan, Canada; 50°15'53"N 107°43'53"W; hereafter referred to as the Swift Current hillslopes) is situated on the northern Great Plains of North America (Fig. 1a). The Swift Current hillslopes are a set of three adjacent 5 ha agricultural hillslopes with undulating topography and 1–4% north-facing slopes. Grassed berms around the perimeters of the hillslopes prevent runoff from transferring between hillslopes. The soil is a Swinton silt loam (Cessna et al., 2013). The hillslopes are under an annual rotation of wheat (*Triticum aestivum*) and fallow, with some interspersions of grass (*Agropyron cristatum*) and pulses (lentils and peas; *Lens culinaris* and *Pisum sativum*, respectively). In addition, a nearby (c. 700 m to the south-southeast) Environment and Climate Change Canada standard meteorological station has recorded precipitation and temperature daily from 1886 to present and hourly from 1995 to present, as well as daily snow depth and wind speed (at 2 m and 10 m above the ground surface) from 1960 to present. During the 4–6 month winter season, the soils of the northern Great Plains

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