

## Research papers

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

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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

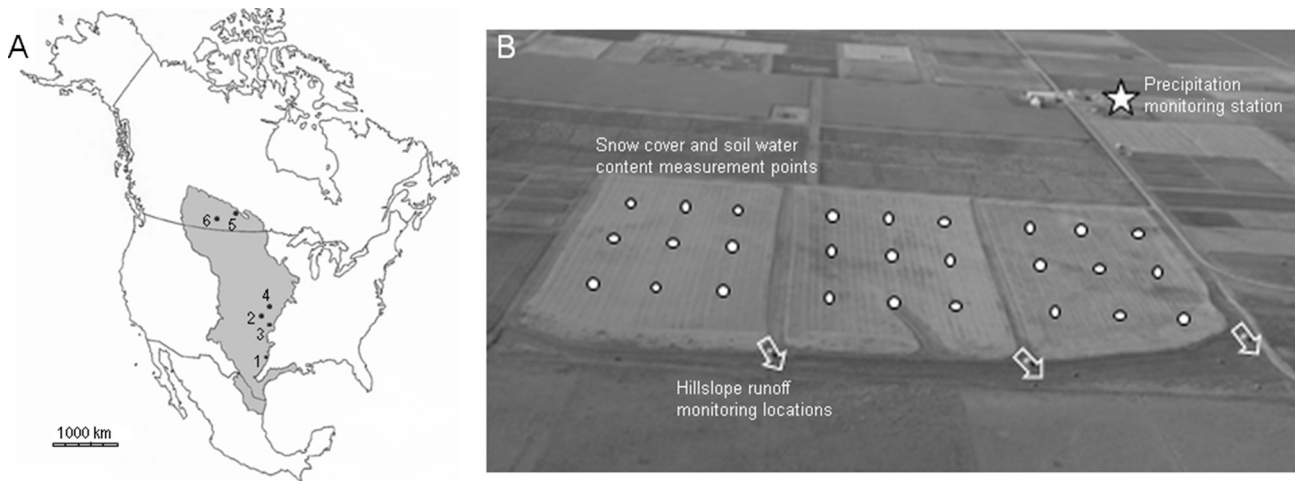
Climate impacts on the hydrology of the Great Plains of North America are poorly understood. Any such impact may have enormous consequences for agriculture on the Great Plains, where 80% of the region is under agricultural management, has a crop market value of approximately \$92 billion USD (Hatfield 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

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**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

are frozen from the soil surface to a depth of typically > 1 m (Ireson et al., 2013). At the Swift Current hillslopes, the ground freezes typically in late October, and begins to thaw in March during the snowmelt freshet, shown by soil temperature data from the meteorological station and observations on the hillslopes.

### 3. Dataset and methods

The data used in this study are summarized in Table 1. We use daily precipitation amounts and phase (rainfall or snowfall, where snow is given as snow water equivalent – SWE) from 1962 to 2013, measured at the Environment and Climate Change Canada meteorological station (Fig. 1b) using a total Geonor weighing gauge, tipping bucket, and Belfort weighing gauge. From this, we determined annual and seasonal totals of precipitation, rainfall, and snowfall, as well as annual and seasonal occurrences, durations, and sizes of one-day and multi-day rain events. Each season was defined as follows: winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). One-day rain events are defined as days with rainfall that are preceded and followed by days with no rainfall, while multi-day rain events are defined as two or more continuous rain days.

Snow cover for each hillslope was measured by manual snow surveys each year from 1965 to 2013. Snow depth and density were measured, and SWE calculated, at nine points on each hillslope (Fig. 1b), and means of each were calculated to give three hillslope-averages. These snow surveys were repeated several times from January to March, including one snow survey that was intended to capture the maximum snowpack before the onset of spring snowmelt. To explore the transformation of seasonal snowfall amounts into the amount of snow cover accumulated on the ground before the onset of spring snowmelt, we used data for air temperature and wind speed (daily maximum, minimum and mean) measured at 10 m above the ground surface. From this we determined the occurrence of above-freezing winter days, and the likely occurrence of over-winter melt events and blowing snow ablation or sublimation.

Gravimetric soil water content (water fraction by volume of soil) was measured twice per year (once in October, prior to freeze-up, and once in April, following spring snowmelt) from 1971 to 2013 on a permanent nine-point grid on each hillslope (Fig. 1b). These were converted to volumetric soil water contents using constant soil bulk densities. For each biannual soil water content measurement campaign, the soil water content was measured at five depth intervals in the soil profile (0–15 cm, 15–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm), where the soil water content was measured from a subsample of the entire mixed interval. The soil water contents were reported for the mid-point of the interval: 7.5, 22.5, 45, 75, and 105 cm, respectively. Hillslope-averaged soil water content at each depth was calculated from

the data at the nine points. Both hillslope-averaged and point-scale data were recorded from 1980 to 2013. From 1971 to 1979 only hillslope-averaged data were recorded.

Any runoff during the period 1962–2013 was routed through a heated H-flume at the outflow of each hillslope (Fig. 1b). Runoff was measured using a Stevens water level chart recorder in the stilling well of each flume. Rating curves for each flume were used to calculate daily runoff depths ( $\text{mm d}^{-1}$ ). No runoff was measured during 1970. Flow rates exceeded the flume capacity during heavy rainfall on June 14, 1964, and runoff during that event was estimated by McConkey et al. (1997). Rainfall-runoff events were identified as occurring when rainfall and runoff occurred on the same day. We calculated the runoff amounts derived from snowmelt and rainfall, distinguishing between one-day and multi-day rainfall-runoff amounts. No runoff from any rain-on-snow events was observed.

For all annual calculations and analyses, we used the hydrological year, October 1–September 30. For all variables of interest, we used the Mann-Kendall test, a common statistical test used for the analysis of trends in climatological and hydrological time series (Burn and Hag Elnur, 2002). We determined a trend to be significant if the computed  $p$ -value was <0.05. We used linear regression to determine the direction, gradient, and percentage change over time, of the trend.

## 4. Results

### 4.1. Precipitation

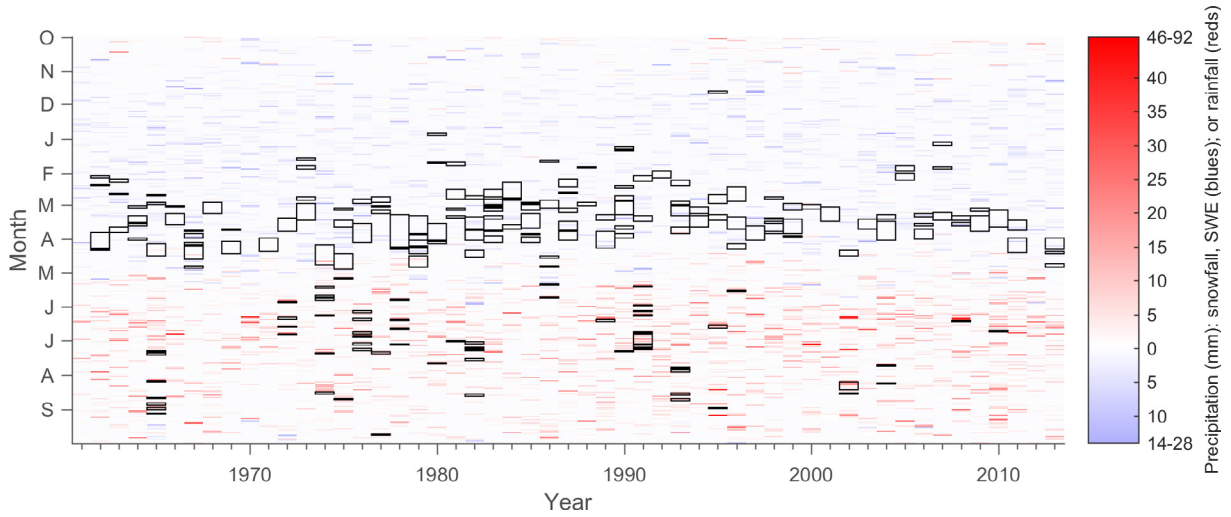
The long-term (1962–2013) average annual precipitation was 360 mm, of which 76% fell as rain and 24% as snow (Fig. 2). Over this period, total annual precipitation increased by 90 mm (a 28% increase) (Fig. 3a); total annual rainfall increased by 87 mm (a 51% increase) (Fig. 3b); and total annual snowfall decreased by 22 mm (an 18% decrease) (Fig. 3c). These latter two trends are due to shifts in precipitation phase and timing: more precipitation fell as rain and less as snow in winter and spring (no similar trend for fall) over the study period. For non-winter months over the period 1962–2013, we observed significant shifts in the delivery of rainfall from multi-day rain events (Fig. 4a). The number of multi-day rain events, volume of rain that fell during each event, and proportion of summer rainfall delivered by each event (as opposed to one-day storms), all increased ( $p < 0.05$ ). There were no equivalent trends in the delivery of rainfall from one-day rain events (Fig. 5a).

### 4.2. Snow accumulation and melt

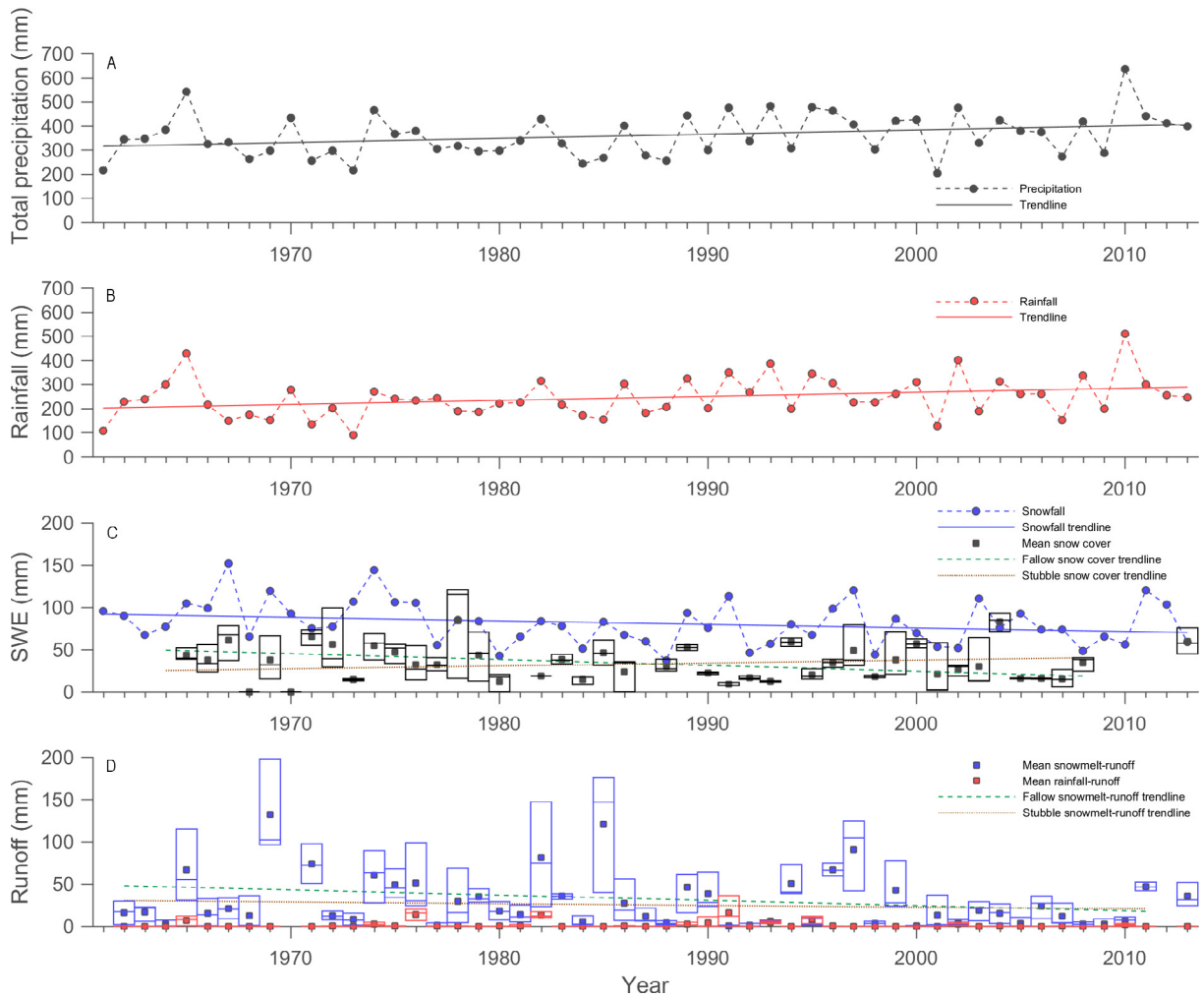
The SWE of the snow cover before spring snowmelt was, on average,  $43 \pm 31\%$  of total snowfall. This suggests that, on average,  $57 \pm 31\%$  of snowfall ablated through the winter via a combination of evaporation, sublimation, wind redistribution, and mid-winter

**Table 1**  
Summary of all variables used in this paper.

Variable	Period of record	Time step of measurement	Notes
Precipitation (mm) (rainfall and snowfall, SWE)	1962–2013 1995–2013	Daily Hourly	We used daily data to calculate annual and seasonal totals. We used hourly data to determine rainfall intensities necessary to generate rainfall-runoff
Snow cover (mm SWE)	1965–2013	Several times per winter	Snow surveys throughout the winter measured depth and density, and SWE was calculated, at nine points on each hillslope. We used the snow survey data measured as soon as possible before the onset of snowmelt to determine hillslope-averaged snow cover water equivalent
Soil water content (vwc)	1971–2013	Biannually (fall and spring)	Soil water content was measured at five depths (7.5, 22.5, 45, 75, and 105 cm) in the soil profile, at nine points on each hillslope. Hillslope-averages were calculated for each depth using the nine points. We used point-scale data for when it was available (190–2013) and hillslope-averaged data for the whole time period (1971–2013)
Runoff (mm)	1962–2013 (except 1970)	Daily	We calculated total runoff (mm) for each hillslope for each event ( <i>i.e.</i> from each snowmelt season and from each rainfall-runoff event)

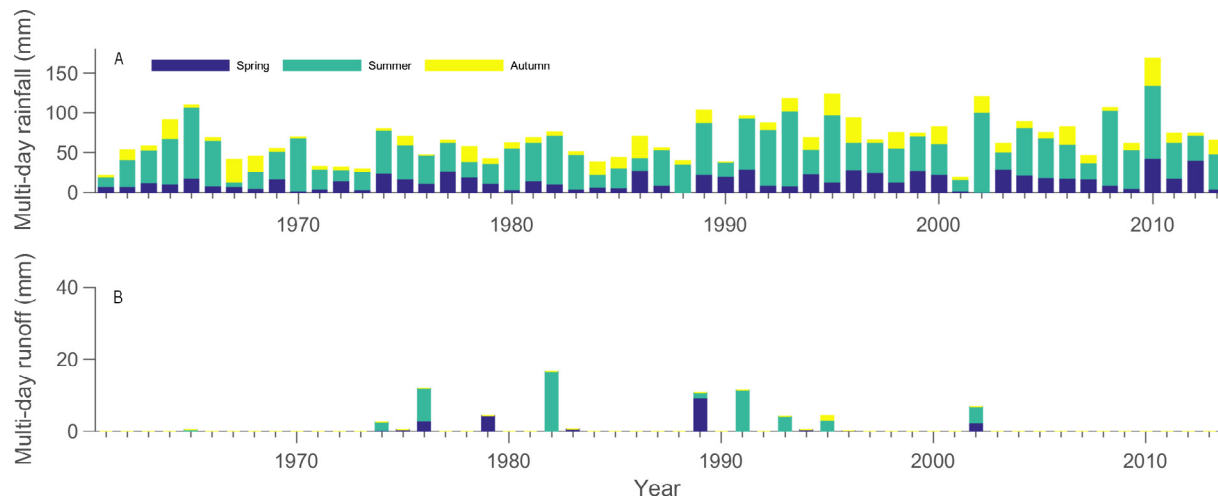


**Fig. 2.** Daily precipitation and runoff at the Swift Current hillslopes, 1961–2013. Daily snowfall as SWE (blues) and rainfall (reds) at the site, with colour shade corresponding to daily volumes. Occurrences of snowmelt- and rainfall-runoff from the three hillslopes (combined) are indicated by black rectangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 3.** Annual (hydrological year) precipitation and runoff at the Swift Current hillslopes, 1961–2013. A) Total precipitation depths (rainfall and snowfall combined), with trendline. B) Rainfall depths, with trendline. C) Snowfall depths as SWE (blue circles), with trendline. Also shown is snow cover depth (as SWE) on the hillslopes, measured from snow surveys on the hillslopes just prior to springtime snowmelt. The boxes indicate the maximum, median and minimum hillslope snow cover SWE (one value for each of the three hillslopes), with the mean seasonal snow cover amount indicated with black squares. Trendlines for snow cover depth under different land cover types are given. D) Annual snowmelt-runoff amounts (blue) and rainfall-runoff amounts (red). The boxes indicate the maximum, median and minimum runoff amounts (one value for each of the three hillslopes). Trendlines for snowmelt-runoff amount under different land cover types are given. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)





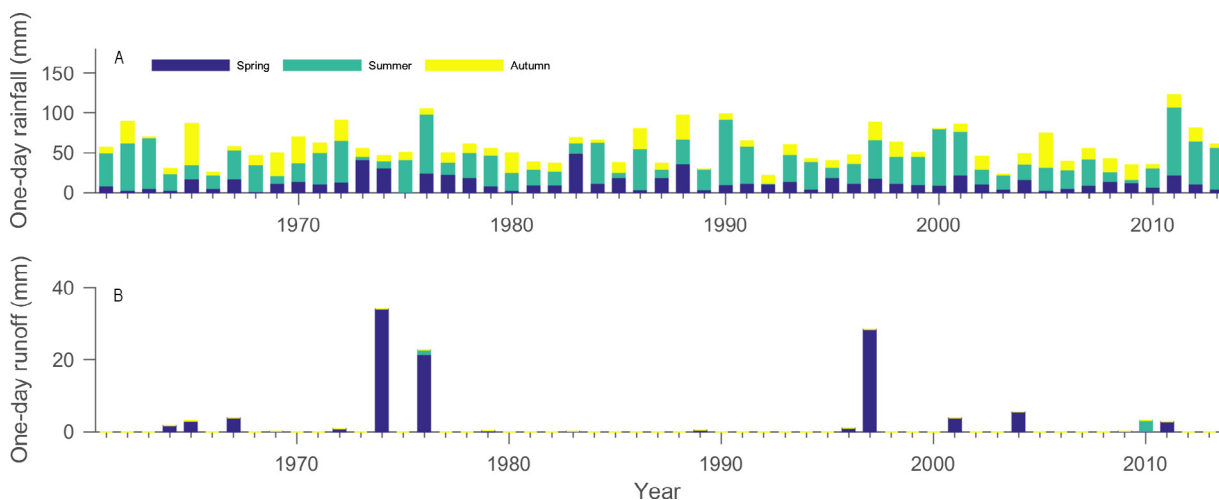
**Fig. 4.** A) Total rainfall from multi-day rain events for spring (blue), summer (green), and autumn (yellow). Trendlines indicated for spring (dashed line), summer (dotted line), and autumn (solid line). B) Total runoff from those multi-day rain events, following the same seasonal colour scheme. No significant trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

melt and infiltration. Over the 1962–2013 period, the hillslopes exhibited decreasing trends in snow cover depth (SWE; measured prior to spring snowmelt) (Fig. 3c). In years where the hillslopes were left fallow, snow cover SWE decreased by 88% over the 1962–2013 period (Fig. 3c). The decrease in snow cover was over four times greater than the decrease in snowfall (a 21% decrease). No significant trends in snow cover were found over the same period when the fields were covered in stubble (Fig. 3c).

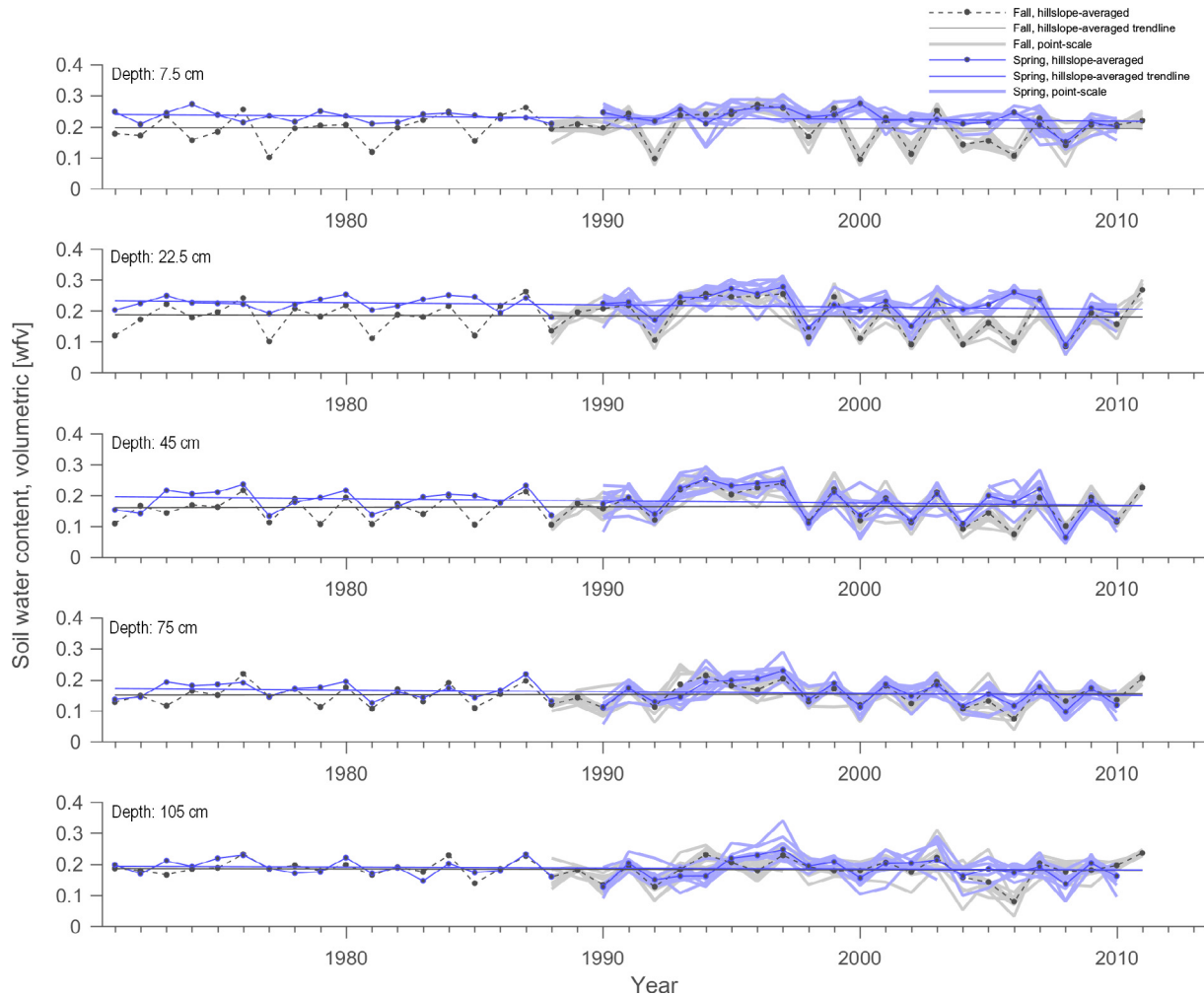
#### 4.3. Soil water content

Over the period 1971–2013, mean volumetric soil water content measured in the spring was 0.22 at the surface (wettest depth) and 0.18 at 105 cm depth (driest and deepest measuring depth). The hillslopes were typically drier in the fall, when mean volumetric water content of the soil was 0.19 at the surface, and 0.17 at 105 cm depth. Between 1971 and 2013, the hillslope-averaged spring soil water content decreased for all hillslopes and at all depths; however, this trend was only significant ( $p < 0.05$ ) at the soil surface (there, soil water content decreased by between 8.7%

(Hillslope 1) and 9.5% (Hillslope 3) over the 43-year study period). There were no consistent trends in the equivalent, hillslope-averaged fall soil water content. Soil water content time series on Hillslope 3 (Fig. 6), which had a consistent wheat-fallow rotation, is perhaps most reliable for climate-runoff analysis since any changes do not reflect the effects of land management. On Hillslope 3, between 1971 and 2013, hillslope-averaged spring soil water content showed a decreasing trend for all depths (although only significant at the soil surface), but there were no apparent changes in the fall. At the point scale, however, for which we have data from 1980 to 2013, there were significant trends at some points, depths, and hillslopes, for both spring and fall wetness conditions. Spring data showed decreasing soil water content at all depths, while fall data showed decreasing soil water content at the surface and increasing soil water content at the lowermost depths (75 cm and 105 cm). We also examined the difference in soil water content from the fall to the spring for all hillslopes and at all depths over the period 1970–2011. We found a decreasing trend in the amount of soil water that was added to the soil profile following snowmelt.



**Fig. 5.** A) Total rainfall from one-day rain events for spring (blue), summer (green), and autumn (yellow). No significant trends. B) Total runoff from those one-day rain events, following the same seasonal colour scheme. No significant trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 6.** Seasonal soil water content (volumetric, wfv) measurements for Hillslope 3 for five depths (7.5, 22.5, 45, 75, 105 cm below the soil surface) for fall (gray) and spring (blue). Gray circles and dashed line indicates the hillslope-averaged fall soil water content amount, while blue circles and solid line indicates the equivalent for spring. These data are the mean of point-scale soil water content measurements (9 points on each hillslope, 27 points total), for which the data were only archived from 1988 onwards. The solid gray and blue lines (data only available from 1988) indicate those point-scale soil water content measurements for spring and fall, respectively. Trendlines are indicated for the hillslope-averaged fall and spring soil water content data; no hillslope-averaged trendlines are significant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

#### 4.4. Runoff

Over the period 1962–2013, mean snowmelt-derived spring runoff for each hillslope was 26 mm (Hillslope 1), 39 mm (Hillslope 2), and 22 mm (Hillslope 3). Over the same period, snowmelt-runoff decreased on each hillslope by 68%, 59%, and 51%, respectively (Fig. 3d), although the trend was only significant on Hillslope 1. Snowmelt-runoff ratios also decreased over the period 1962–2013, regardless if calculated based on total snowfall data or snow cover data. This implies that progressively less SWE was translated into runoff from the hillslopes with more going to a combination of infiltration, sublimation, evaporation, and blowing snow. We found no relationship between fall or spring rainfall fraction and the amount of snowmelt-runoff. We observed a significant relationship between snow cover SWE, snowfall SWE, and the amount of snowmelt-runoff in the snowmelt season, with all decreasing over the 1962–2013 period.

Rainfall-runoff events occurred in 28 years out of the 52-year study period. For those years in which rainfall-runoff events occurred, mean runoff generated was 5 mm (Fig. 3d). The majority of runoff (60% of the total volume) was generated by one-day rain events, and the remainder by multi-day rain events. A single one-

day rainfall-runoff event was on average 20% larger in volume than a single multi-day rainfall-runoff event. While multi-day rain events increased in occurrence over the period 1962–2013 (Fig. 4a), there was no corresponding increase in occurrence of runoff events generated by those multi-day rain events (Fig. 4b). Instead, there were shifts in rainfall-runoff timing and type: prior to 1976 and after 1996, rare runoff events were triggered predominantly by one-day rainfall events in March or April (Fig. 5b), while in the intervening years runoff events were triggered predominantly by multi-day rain events throughout the summer months (Fig. 4b).

#### 5. Discussion

Our 52 years of data on hillslope precipitation and runoff amounts from a research site on the northern Great Plains are the first such published data of their kind. For predicting and managing hillslope-scale water resources and sustainable agricultural production, it is essential to understand whether changing temperature and precipitation trends have induced changes in runoff and water availability at the hillslope scale. The observed cli-

mate trends over these 52 years of data are consistent with observations from elsewhere on the northern Great Plains (DeBeer et al., 2015; Dumanski et al., 2015; Mekis and Vincent, 2011; Shook and Pomeroy, 2012; Vincent et al., 2007; Vincent and Mekis, 2006; Zhang et al., 2000) and show: increased total precipitation, increased rainfall, increased winter and spring rainfall fraction, decreased snowfall and snow cover, and a shift towards more frontal multi-day rainfall events as opposed to convective one-day events. However, our observed runoff trends are much less clear and in many cases not related to climate trends as we discuss in further detail in the following sub-sections.

### 5.1. More rainfall, but not more rainfall-runoff at the hillslope-scale

Our findings show that the 51% increase in rainfall has not yielded any increase in rainfall-runoff events at the hillslope scale. Further, despite the increase in multi-day rainfall events as compared to one-day rainfall events, there has been no similar change in the proportion of hillslope-scale rainfall-runoff events generated by those types of rainfall events.

Deep soils with high unfrozen infiltration capacities are a feature of hillslopes on the northern Great Plains (Elliott and Efetha, 1999). At the Swift Current hillslopes, measured unfrozen surface infiltration capacities range from 0.4 to 63.5 mm h<sup>-1</sup>, with a median of 13.9 mm h<sup>-1</sup> (field observations on Hillslope 2 in July–August 2013; reported in Seifert, 2014). The unfrozen infiltration capacities are highly spatially variable, however, with the downslope portion of Hillslope 2 exhibiting the greatest infiltration capacities. This means that any rainfall-runoff generated over patches of low infiltration is likely to run-on to areas of higher infiltration downslope, and infiltrate.

Rare rainfall-runoff events at the hillslope scale are triggered by high intensity rains that exceed the soil's infiltration capacity along the full length of the flowpath. Rainfall events that have triggered runoff on the hillslopes since 1995 (from when we have rainfall data at an hourly timescale) had peak rainfall intensities ranging from 0.6 to 14.8 mm h<sup>-1</sup>. Since multi-day rain events tend to be frontal and of lower intensity than one-day convective rainstorms, an exceptional frontal system would be needed to generate rainfall intensities that can exceed the infiltration capacity of the soil on the Swift Current hillslopes. Consequently, although the nature and total amount of rainfall has changed, the frequency of high-intensity rainfall has remained similar, at least since 1995. We hypothesize that, over the full 52 years of study, the number of rain storms of sufficient magnitude to create rainfall-runoff has not changed, so the occurrence of rainfall-runoff has not responded to the increase in rainfall.

### 5.2. Less snowfall, and also less snowmelt-runoff at the hillslope scale

While summer rainfall-runoff events have shown no response to changing rainfall, spring snowmelt-runoff has shown a nonlinear decrease (on average by 59%) in response to an 18% reduction in snowfall. We hypothesize that these seasonal differences are a result of the frozen and reduced infiltrability of the soil profile in the winter. In the summer, the deep soils and their high infiltrabilities act to mute the runoff response to rainfall inputs but this feature disappears for the winter season and spring freshet when the ground is frozen. The long-term decreasing snowmelt-runoff is not occurring because of any increase in infiltration due to thawed spring soils, since, for the years where we have soil temperature data, the snowmelt-runoff period occurred always over ground that was still frozen at the soil surface (data not shown). There was little change in soil water content profiles over the winter months, from fall to the following spring (Fig. 7a): wet fall soil profiles remained wet in the following spring, and dry fall soil profiles tended to remain dry.

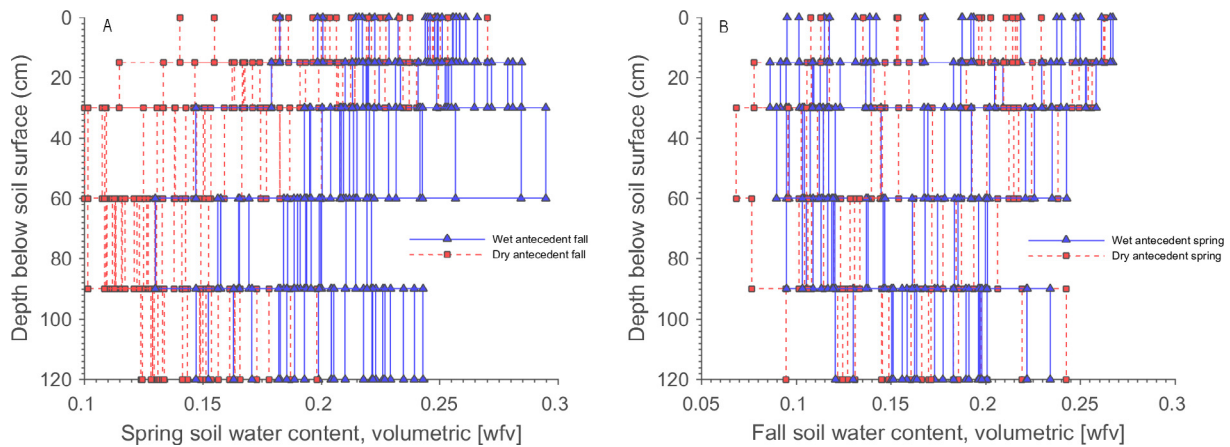
The reduced soil infiltrabilities means that the snowmelt season, despite seeing approximately a third of the annual precipitation melting onto the soil within a short, 1–2 week period, does not induce significant changes in the soil profile water contents.

This suggests minor vertical redistribution of water into the soil profile of over-winter precipitation or spring snowmelt water, consistent with the measured data shown in Fig. 7. By comparison, there is no distinction in fall soil water content profiles based on the previous spring's soil water content (Fig. 7b). Therefore, the non-winter months exhibit vertical redistribution of soil water of over-summer precipitation and evapotranspiration. At the onset of spring snowmelt, the soil is still frozen and its infiltration capacity is greatly reduced: measured frozen surface infiltration capacities range from 0.09 to 2.57 mm h<sup>-1</sup>, with a median of 0.33 mm h<sup>-1</sup> (laboratory observations in fall 2015 using intact soil cores extracted from the Swift Current hillslopes). When frozen, the soil lacks this shock absorber function for the snowmelt, where runoff at and over the soil surface is driven by and significantly related to the precipitation input. Of course, runoff amounts are always smaller than the corresponding snowmelt input amounts because of other factors acting at the surface, such as micro-surface depression storage, evaporation, sublimation, and some limited infiltration into the frozen soil surface.

### 5.3. Hillslope-scale runoff response counter to that of catchment-scale

Overall, our observed changes in hillslope-scale runoff were highly equivocal and largely at odds with existing nearby catchment-scale observations (that have been subject to increasing wetland drainage) on the northern Great Plains (Dumanski et al., 2015). Our decreasing snowmelt-runoff trends at the hillslope scale in response to decreasing snowfall are counter to Dumanski et al.'s (2015) catchment-scale findings, which showed a fivefold increase in snowmelt-runoff since 1975, despite decreasing snowfall. This long-term increase in snowmelt-runoff is also apparent across the northern Great Plains in regional-scale analyses (Novotny and Stefan, 2007; Ryberg et al., 2015). Further, the lack of a clear change in rainfall-runoff events at the hillslope scale, despite increasing rainfall, is inconsistent with catchment-scale findings, which show a 150-fold increase in rainfall-runoff since 1975, in response to increasing rainfall (Dumanski et al., 2015).

At the catchment scale, streamflow generation is strongly related to depressional storage (Shaw et al., 2012; Shook et al., 2015). When depressional storage is satisfied, the hydrological connectivity and contributing area of the catchment increases, resulting in much higher streamflow (Fang et al., 2010; Shook and Pomeroy, 2012). In Dumanski et al. (2015), alterations of the landscape affected the catchment results. Drainage channel length increased 8-fold and the surface area of sloughs decreased by one-half. The loss of sloughs and the drainage into lower sloughs would decrease the depressional storage in the catchment and enhance flows by the mechanism described above. In fact, Dumanski et al. (2015) noted that some of the largest runoff events were from rainfall falling shortly after the snowmelt season, when sloughs were still relatively full and catchment conditions wet. Although unsatisfied depressional storage will also decrease runoff, increasing artificial drainage minimized this effect over time. Our hillslope scale lacks either the enhancement or damping effect of depressional storage (other than the micro-topographic, 0–1 m relief in the soil surface). Other changes to the landscape made it difficult to discern the climate signal in runoff in the study of Dumanski et al. (2015). The area of unimproved land decreased from 46% to 27% of the catchment. The amount of tillage on the cropland decreased and the proportion of land in summer fallow also decreased dramatically. In contrast, in our hillslope study we were able to relate any hydrologic change to climatic change.



**Fig. 7.** Hillslope-averaged volumetric soil water content measurements for five depth intervals in the soil profile for spring (A) and fall (B). The profiles are distinguished by whether, in the antecedent season, all measurement depths were drier (red, dashed line with square markers) or wetter (blue, solid line with triangle markers) than the long-term (1971–2013) mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Overall, these discrepancies between runoff responses at the catchment and hillslope scale are attributed to factors – such as drainage, depressional storage, changing areas of different land use and land covers, and influences of groundwater and wetland fringe riparian areas – that are important at the catchment scale, but which are relatively unimportant or absent at the hillslope scale. As a result, extrapolation of snowmelt-runoff or rainfall-runoff responses to long-term changes in precipitation from the catchment scale to the hillslope scale, or vice versa, are extremely challenging. We need to maintain hillslope monitoring systems to enable continued understanding and prediction of hillslope-scale water availability.

#### 5.4. Decrease in snowmelt-runoff ratios

Snowmelt-runoff ratio has decreased over time, as indicated by the much more pronounced reduction in snowmelt-runoff (on average, 59%) as compared with the reduction in snowfall (18%). In other words, the transformation of snowfall into snowmelt-runoff, via processes such as snow redistribution, mid-winter ablation, snowmelt, and frozen soil infiltration (Shook et al., 2015), has become less efficient. A part of this is the nonlinear relationship that we observed between a decreasing trend in the amount of snowfall and a more amplified decreasing trend in the amount of snow cover at the onset of spring snowmelt. This snowfall-snow cover transformation was described by Shook et al. (2015) as occurring via snow redistribution and mid-winter ablation. Here, we see that this transformation becomes less efficient – gradually smaller proportions of snowfall are being retained as snow cover. We attribute this to the effects that reduced snow depth and snow cover have in driving heightened over-winter snow ablation. For example, any over-winter melting period would be more likely to expose the soil surface, and energy advected from these snow-free areas of lower albedo cause accelerated melting of the surrounding snowpack. Further, when the overall snow cover is shallow, wind is more likely to cause losses of snow from sublimation and scouring than additions from deposition. The reason for this is that landscape features that trap snow, such as standing grass and other standing vegetation, small depressions, and fence-lines, will not be at capacity so less snow is moving across the landscape to deposit on the hillslopes in years with shallow snowpacks. There were neither trends in the mean, minimum, or maximum winter temperatures over this period, nor in the number of winter days where temperatures rose above freezing ( $0^{\circ}\text{C}$ ). There was, however, a trend towards longer periods of cumulative above-

freezing days: there were more frequent occurrences of five or more consecutive above-freezing days. There is therefore this feedback effect between reduced snowfall creating smaller snowpacks, which are then nonlinearly smaller because of the enhanced processes of blowing snow redistribution and over-winter snowpack melt for small snowpacks.

Also a contributor in the reduction of snowmelt-runoff ratio over time is the nonlinear relationship we observed between a decreasing trend in the amount of snow cover at the onset of snowmelt and the decreasing trend in snowmelt-runoff. In other words, runoff ratios have decreased over time even when we use the SWE of snow cover retained on the hillslopes (rather than the seasonal snowfall total) as the input parameter in the runoff ratio calculation. This is unusual since one might expect that over-winter ablation events (that increased significantly through the record), would create a lower-permeability ice lens at the soil-snow interface or within the snowpack (Gray et al., 2001), and thus also increase runoff ratios. Instead, the decrease in runoff ratios might be a result of reduced antecedent soil water content: we observed no increase in fall rainfall and a steady drying trend for fall soil conditions over the study period. Thus greater infiltration of spring snowmelt might be expected (which is supported by the soil water content change between fall and spring). This is equivalent to Shook et al.'s (2015) second transformation, of snowmelt to runoff, via infiltration processes. Increased sublimation and evaporation of the snowpack and snowmelt water during the spring snowmelt is also a potential reason for decreased runoff ratios. Overall, enhanced snow redistribution and over-winter ablation of smaller snowpacks, as well as drier antecedent soil water content driving enhanced infiltration, are competing with (and trumping) the restriction of infiltration by ice lenses and soil water content increases due to over-winter ablation, to cause reduced runoff ratios over time.

#### 5.5. Relationships between vegetation cover and snowmelt-runoff

Vegetation cover was important for snow accumulation, runoff ratio, and runoff signal in response to the 52-year precipitation signal. In any given year, fallow hillslopes showed reduced snow accumulation, compared to when the hillslopes had stubble residue over winter. On average, instances of stubble on the Swift Current hillslopes exhibited 1.6 times as much snow accumulation as instances of fallow. This is supported by previous studies that found that, on the Canadian Prairies, wheat stubble fields had much smaller losses to blowing snow than did fallow fields due



to variations that vegetation cover induces in wind speed near the snow surface (Cutforth and McConkey, 1997; Fang and Pomeroy, 2009; Pomeroy et al., 1990; Pomeroy and Gray, 1995). Fang et al. (2007) found that, on prairie sites, snow accumulation in stubble fields is approximately 1.1–2.1 times greater than snow accumulation in fallow fields.

In the previous section, we described the nonlinear relationship between a decreasing trend in the amount of snowfall and a more amplified decreasing trend in the amount of snow cover at the onset of spring snowmelt. We observed that this long-term trend towards decreasing snow accumulation was strongest for fallow years (an 88% reduction). Again, this can be explained by the typically smaller snowpacks that form during fallow conditions, compared to stubble conditions, and the positive feedback effect that a small snow cover has on over-winter ablation processes. For instances of standing stubble, a strong positive relationship existed between mean temperature of above-freezing winter days and the proportion of SWE that was ablated during that season. For instances of fallow, mean wind speed was strongly correlated with the proportion of ablated SWE during individual seasons, on days where mean wind speed exceeded  $7.5 \text{ m s}^{-1}$  (the wind speed threshold for transport of fresh snow blowing snow; Li and Pomeroy, 1997). Land covers therefore have different main drivers of ablation; standing wheat stubble reduces surface wind speed (Cutforth and McConkey, 1997) so ablation is more dependent on energy input as indicated by air temperature, compared to fallow, for which wind transport of mass and energy is relatively more important.

For all hillslopes, runoff ratio was greater, but absolute runoff was smaller, under fallow conditions compared to vegetated conditions. Reduced infiltration under fallow conditions would explain these greater runoff ratios. Fang et al. (2007) found that the type of vegetation cover affects the soil water content at the time of freeze-up, with fallow fields generally being wetter than stubble fields due to less soil water extraction in the preceding growing season. Our data support this explanation for higher runoff ratios under fallow conditions. Fallow conditions also exhibited the strongest trend towards decreasing runoff ratios and decreasing runoff over time. Overall, the relative contributions of snowmelt-runoff from vegetated or fallow hillslopes was a combination (and sometimes trade-off) between the snow trapping qualities of stubble fields, and the typically higher soil water contents (albeit with some minor over-winter modifications; De Jong and Kachanoski, 1987; Gray et al., 1985) of fallow fields compared to cropped and/or stubble fields.

### 5.6. Crop type effects on soil water

Not only did the occurrence of fallow have a noticeable effect on soil water storage, but the crop type in non-fallow years also did. The crop type influenced the fall, and often following spring, soil water contents. Pea and lentil crops use less soil water than wheat (Angadi et al., 2008) and so soil water contents following summers when Hillslope 2 was cropped with pulses were greater than soil water contents following summers when wheat was the crop. This is true for soil water contents in both the fall (on average 30% higher) and the following spring (on average 4% higher), for all depths (data not shown). The increased stored soil water in spring following pulse crops compared with wheat is an important benefit of including pulse crops in crop rotations in this semi-arid climate (Gan et al., 2003). Similarly, soil water contents following summers when Hillslope 1 was cropped along with green manure were higher than soil water contents following summers when wheat was the crop: fall soil water contents were on average 32% higher, while spring soil water contents were on average 20% higher (data not shown). This is due to water stored in soil after green manure growth termination in early July. At Swift Current,

while soil water is typically high following legume green manure management, and higher than other crops, fallow conditions still are most efficient at storing soil water owing to the use of precipitation during the green manure crop growing period (Zentner et al., 2004).

### 5.7. Outlook for the future of the northern Great Plains

Few studies (Fang and Pomeroy, 2007; Pomeroy et al., 2009) have addressed the effects of future climate change on the hydrology, runoff generation processes, and agricultural productivity of the northern Great Plains. Climate change scenarios for the region project warming by between 0.5 and 3 °C for the 2020s, and between 2 and 6.5 °C for the 2080s, above baseline (1961–1999) temperatures (Barrow, 2009). The largest range of temperatures (and also the biggest rise in temperatures) are expected in the winter months (Barrow, 2009). Precipitation changes are uncertain: decreases by as much as 30% are projected by some scenarios into the 2080s, while increases are more likely to occur (Barrow, 2009). Further warming, therefore, will inevitably lower the influence of snow on hydrological systems, with cascading impacts on the streamflow regime and the magnitude and timing of runoff (Tetzlaff et al., 2013).

Our 52-year analysis shows that the partitioning between surface, near-surface and deeper water sources is shifting. Over the last half-century, decreases in snowfall and snowpack depth have driven decreases in spring soil water content and spring snowmelt-runoff. These decreases seem to be damped if the previous growing season was cropped with wheat and had vegetation residue (stubble) on the fields over winter. Whether trends will continue in the same direction and to the same magnitude as those observed here is unclear, and depends upon the balance between runoff-enhancing and runoff-damping factors (e.g. less snowfall vs. more fall rainfall and wetter soils).

The amount of stored soil water is an important determinant of crop yield in this semi-arid climate where growing season moisture deficit is a certainty. Stored soil water is as important as growing season precipitation for crop yield (Campbell et al., 1997) and the yield of crops grown on stubble is particularly sensitive to the amount of stored soil water (Kröbel et al., 2014). Therefore, the increasing reduction in soil water in the spring makes crop production, especially that grown on stubble, increasingly dependent on growing season precipitation. The trends towards increasing rainfall and increasing multi-day rain events are beneficial for crop production. However, in the semi-arid climate, drought is a continual risk. Multi-year droughts, such as that in 2000–2002, where multi-day rain events are in short supply, are a likely feature of future climate change in this region (Masud et al., 2016). Such events result typically in poor crop yields, such as was seen in 2001 (Masud et al., 2016). Decreasing soil water reserves in the spring will accentuate the impact of droughts. Minimum tillage to promote infiltration into frozen soils through macropores, and continuous cropping systems to reduce blowing snow sublimation may help promote higher post-melt soil water contents (Elliot et al., 2001). This might ameliorate the detrimental effects on agriculture from low rainfall in the growing season, and earlier spring runoff with greater evaporation losses before the growing season (Cutforth et al., 1999).

The reduction in spring freshet volumes has important ramifications for on-farm water supplies. Investments for additional water collection and storage and/or for transporting water will be needed to meet water demands at farmsteads. Such investments may not be warranted for pastures, so some pastures may have to be left ungrazed when there is insufficient volumes of water in dugouts to meet the needs of livestock. As a result, lower runoff increases the costs of agriculture.

## 6. Conclusion

Our analysis of a 52-year, hillslope-scale, climate-runoff record from the northern Great Plains shows that snowmelt-runoff and spring soil water amounts have decreased in response to winter snowfall decreases, but that rainfall-runoff has shown no response to increases in rainfall or shifts to more multi-day rain events. We attribute these seasonal differences to soil infiltrability and soil storage modulation. In the summer, thawed, deep, high-infiltrability soils act to buffer the long-term runoff response to rainfall. In the winter and spring freshet, frozen ground limits infiltration and removes the soil storage buffer, which means that trends in surface runoff responses more closely resemble the trends in snowfall and snowmelt (albeit with some nonlinear trend relationships between snowfall and runoff, which could be explained in part by enhanced over-winter ablation of smaller snowpacks). These findings are different from climate-runoff relationships observed at the catchment scale on the northern Great Plains. This is likely due to the confounding effect of landscape alteration, especially drainage. These long-term findings have clear implications for agriculture on the northern Great Plains. The hydrology of hillslopes is important for dryland crop production and for on-farm water supplies. Meeting water needs in a situation of declining runoff, declining spring soil water, and resultant accentuation of summer drought impacts will increase costs to agriculture.

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