HYDROLOGICAL PROCESSES
Hydrol. Process. (2015)
DOI: 10.1002/hyp.10567

Hydrological regime changes in a Canadian Prairie basin

Stacey Dumanski, John W. Pomeroy* and Cherie J. Westbrook

Centre for Hydrology, University of Saskatchewan, 117 Science Place, Saskatoon, Saskatchewan, S7N 5C8, Canada

Abstract:

To illustrate the hydrological impact of climate and land use change on an unregulated basin, the agriculture- and wetland-dominated Smith Creek Research Basin (SCRB) was examined in detail. Streamflows (1975–1994) show behaviour typical of the Canadian Prairies – generation primarily by snowmelt and cessation in May due to lack of runoff or groundwater contributions. Depressional storage has been drained for decades, reducing the extent of ponds by 58% and increasing drainage channel length 780%. Climate has also changed; increasing temperatures since 1942 have brought on a gradual increase in the rainfall fraction of precipitation (no trends in total precipitation) and an earlier snowmelt by 2 weeks. The number of multiple-day rainfall events has increased by half, which may make rainfall-runoff generation mechanisms more efficient. Annual streamflow volume and runoff ratio have increased 14-fold and 12-fold, respectively, since 1975, with dramatically increasing contributions from rainfall and mixed runoff regimes. Snowmelt runoff has declined from 86% in the 1970s to 47% recently while rainfall runoff has increased from 7% to 34% of discharge. Peak discharge has tripled since 1975, with a major shift in 1994. Recent flood volumes in SCRB have been abnormally large, and high flows in June 2012 and flooding in June 2014 were caused solely by rainfall, something never before recorded at the basin. Changes to the observed character of precipitation, runoff generation mechanisms and depressional storage are substantial, but it is unlikely that any single change can explain the dramatic shift in SCRB surface hydrology. Further diagnostic investigation using process hydrology simulations is needed to explain the observed regime changes. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS Canadian Prairies; climate change; streamflow; wetland drainage; snowmelt; rainfall runoff; non-stationarity; geographically isolated wetlands

Received 30 October 2014; Accepted 4 June 2015

INTRODUCTION

The hydrology of the Canadian Prairies has been described as a semi-arid, cold regions system where snowmelt runoff over frozen soils dominates streamflow generation, substantial runoff is stored in depressions restricting basin contributing areas and summer rainfall primarily supplies crop evapotranspiration (Gray, 1970; Gray *et al.*, 1986; Granger and Gray, 1989; Pomeroy *et al.*, 2007; Fang *et al.*, 2010). But since early assessments, the region has undergone changes in climate (Akinremi *et al.*, 1999; Millet *et al.*, 2009; Bonsal *et al.*, 2012; Shook and Pomeroy, 2012) and land use (e.g. Rashford *et al.*, 2011) – both impact streamflow generating processes (e.g. Burn *et al.*, 2010). The Canadian Prairies are part of North America's Prairie Pothole Region (PPR), which typically receives less than 500 mm per year of precipitation (Burn *et al.*, 2008). Although snowfall accounts for only one-third of the total precipitation, over 80% of the streamflow is derived from snowmelt over frozen soils (Gray and Landine, 1988). The millions of isolated depressions in the PPR capture most of the runoff generated owing to their unusually high storage capacity (Hayashi *et al.*, 2003) but can connect to each other or streams during times of high runoff through the fill and spill process (Spence, 2007; van der Kamp and Hayashi, 2009). Connectivity among depressions changes with depressional storage, producing intermittent streamflow (Spence, 2007) and resulting in dynamic contributing area for runoff to streams (Shaw *et al.*, 2012). The relationship between contributing area and storage is hysteretic with a sharp decrease in contributing area as depressional storage evaporates or percolates into the subsurface (Shook *et al.*, 2013). Spring streamflow is controlled by the hydrological processes that transform snowfall into streamflow, including blowing snow redistribution, sublimation, snowmelt, infiltration into frozen soils and runoff over a variable contributing area connected to the stream channel via the fill and spill dynamics of depressional storage (Shook *et al.*, 2015).

Considerable research indicates that prairie hydrology is highly sensitive to changes in climate and land use

---

*Correspondence to: John Pomeroy, Centre for Hydrology, University of Saskatchewan, 117 Science Place, Saskatoon, Saskatchewan S7N 5C8, Canada.
E-mail: john.pomeroy@usask.ca

given its domination by cold regions hydrological processes and high evapotranspiration to precipitation ratio (Conly and van der Kamp, 2001; Fang and Pomeroy, 2007). In general, precipitation has increased (Millet *et al*., 2009) primarily due to an increase in rainfall (Vincent *et al*., 2007; Mekis and Vincent, 2011). The persistence of rainfall events has also changed. From 1951 to 2000, the number of multi-day storms increased at many sites in the Canadian Prairies while the number of single-day events decreased (Shook and Pomeroy, 2012). Future climate projections presented in Töyrä *et al.* (2005) using 11 global climate models over the Canadian Prairies were highly variable, yet the median of the results suggests increased temperature and precipitation by 2050 and 2080 when compared with that of 1961–1990 climatology. Annual temperatures are projected to increase 2.0 and 3.8 °C with increases in annual precipitation of 9.5% and 14.2% by 2050 and 2080, respectively.

Eradication of the plains bison and cessation of aboriginal grassland management by fire by the 1870s created substantial but poorly documented changes to the landscape. Since European settlement in the early 1900s, native grasslands and wetlands (Heagle *et al*., 2013) have been converted to cropland or pastureland (Hanuta, 2001; Upper Assiniboine River Basin Study, 2000). Although studies have shown that the conversion of grassland to cropland on the upland slopes of the wetlands increases the amount of runoff that enters the wetland (van der Kamp *et al*., 2003; Voldseth *et al*., 2007), the impact of such changes on streamflow under 100% conversion to cropland at a basin scale using a modelling approach was found to decrease streamflow by 2% due to a loss of winter snowfall accumulation caused by increased blowing snow sublimation (Pomeroy *et al*., 2010). Water levels in wetlands are also vulnerable to changes in climate (Johnson *et al*., 2005; Johnson *et al*., 2010; Werner *et al*., 2013) and other agricultural practices, such as tillage practices (eg. Elliott *et al.* 2001). About 70% of Canadian Prairie wetlands have been filled or drained since settlement (DUC, 2008). Because of recent intensification of agriculture (Rashford *et al*., 2011), efforts have been renewed to drain wetlands (Watmough and Schmoll, 2007) using drainage channels, which form permanent surface water connections between isolated wetlands, ditches or streams (Brunet and Westbrook, 2012). The reduced ability for depressions to store surface water permanently increases the contributing area and the volume of runoff (Brannen *et al*., in press; Upper Assiniboine River Basin Study, 2000).

Attention has also been focused on linking changes in land use and climate to watershed hydrological response. In terms of land use, better understanding the impacts of wetland drainage on streamflows has been of recent interest. Modelling research has shown wetland drainage increases annual and peak daily flows as well as the magnitude and frequency of flooding (Gleason *et al*., 2007; Pomeroy *et al*., 2010, 2014; Yang *et al*., 2010). The few observational studies across the PPR that have examined meteorological, land use and streamflow data have mixed conclusions. For example, Miller and Nudds (1996) examined 12 unregulated rivers from Canada and the USA and found that landscape alteration, not changes in precipitation, caused an increase in runoff. In contrast, Ehsanzadeh *et al*. (2012a, 2014) could not find a detectable impact of climate change, wetland drainage or farming practices on streamflow frequency distributions in the Canadian Prairies from a range of rivers that included regulated systems. Similarly, Ehsanzadeh *et al.* (2014) concluded that wetland drainage has not had a detectable effect on streamflows across the Canadian Prairies, with the exception of one site, Smith Creek, Saskatchewan. In this study, a mixture of regulated and unregulated basins was used for the analysis, which may have had an effect on the results.

The baseline hydrology is well documented in this region, but it has recently undergone rapid changes in climate and land use. Recent studies have examined changes in climate and streamflow separately, or integrated them for statistical analysis at the basin scale with mixed results. There is a need for detailed and comprehensive analysis of changing hydrometeorology, drainage and runoff processes in order to better understand the dimensions of hydrological change in the region. There exist very few basins with datasets where this can be accomplished, which precludes a detailed regional approach. The objective of this paper is thus to describe the historical variability of detailed hydrometeorological, runoff process and wetland drainage variables for what is possibly the best-documented wetland-dominated headwater basin in the Canadian Prairies, Smith Creek Research Basin. The data will be assessed for trends and change points and will be used to identify associations between changes in wetland drainage and climate to the changes in the hydrological regime.

STUDY SITE AND METHODS

Study site

Smith Creek Research Basin (SCRB) is located within the Assiniboine River Basin and is approximately 60 km southeast of the city of Yorkton, Saskatchewan, Canada (Figure 1). SCRB has a gross drainage area of 393 km^2 and is relatively flat with slopes of 2–5% and elevations of 490–548 m a.s.l. The dominant land use is agriculture (primarily cereals and canola) and the remainder is comprised of native grassland, deciduous woodland and natural wetlands (Fang *et al*., 2010). The dominant soil texture is loam (Saskatchewan Soil Survey, 1991). The

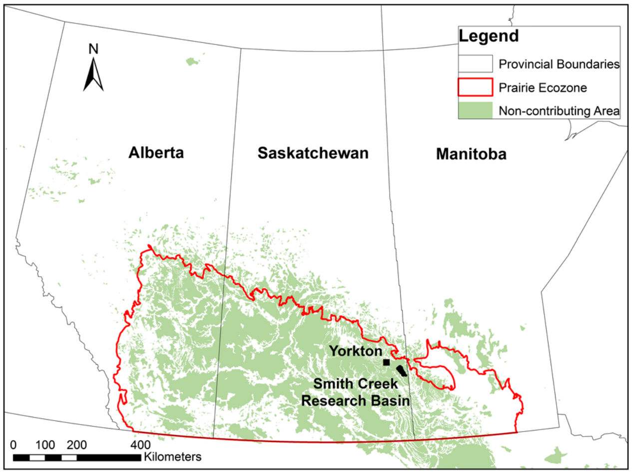

Figure 1. Location of Smith Creek Research Basin in the Canadian Prairie agricultural zone (outlined by the black outline). Shaded areas are non-contributing areas in 1 : 2 year flows as estimated by the Prairie Farm Rehabilitation Administration following Godwin and Martin (1975)

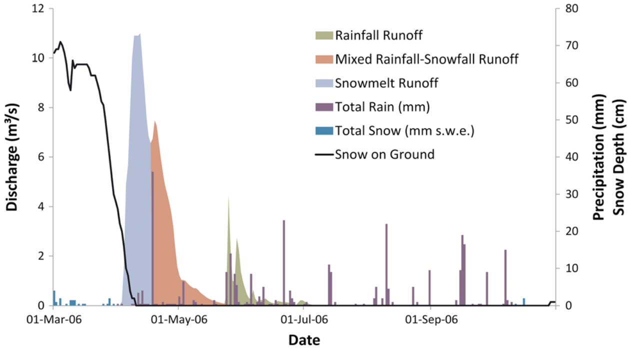

Figure 2. Example of streamflow contribution separation into snowmelt runoff, mixed snowmelt–rainfall runoff and rainfall runoff for 2006 at Smith Creek Research Basin

basin lies within the Prairie Pothole Region (PPR) where large portions of drainage basins do not normally contribute runoff to streamflow. The 1 : 2 year flow non-contributing area has been estimated by Agriculture and Agrifood Canada and is mapped along with the prairie agricultural zone and SCRB in Figure 1. The non-contributing area calculation is based on data from before the 1980s, and since then, depressions in the basin have been extensively drained. Flows in some depressions drains in SCRB are managed by the rural municipalities (RM) of Churchbridge and Langenburg through the use of culvert gates that are normally left open but are closed during periods of high spring runoff, resulting in the temporary restoration of the drained ponds in recent years. Hydrometeorological instrumentation at SCRB includes a streamflow gauge at the outlet operated by Water Survey of Canada, as well as two meteorological stations nearby each other in the southern part of the basin: one run by the University of Saskatchewan (U of S MET) and the other run by Environment Canada (station name: Langenburg, climate ID: 4014145).

Similar to the rest of the Canadian Prairies, peak discharge within SCRB has been typically caused by spring snowmelt that peaks in mid-April and ceases in May (see Figure 2 for example). Intense rainfall events have caused intermittent streamflow throughout the summer, but these events tended to be rare, small in volume and of short duration. From 2010 to 2014, streamflow within SCRB exhibited characteristics that are unlike the prairie hydrology that has been previously described (e.g. Gray, 1970). Mixed snowmelt and rainfall runoff in the spring of 2011 caused massive flooding, while high flows in 2012 and flooding in 2014 (including the all-time peak streamflow in 2014) were caused solely by rainfall, something that has never been recorded at the basin before 2012.

METHODS

Land use change

Ponded area and drainage channel length were manually measured from early summer aerial photographs obtained from 1958, 2000 and 2009 by Lyle Boychuck of Ducks Unlimited Canada as part of their wetland monitoring programme (Boychuk *et al.*, 2014). Ponds in the original analysis were divided into those with vegetation and those with open water, but for hydrological purposes, all shallow/open water and marshes were grouped together as ponds. Surface drainage channels are constructed to facilitate the flow of water from fields to the Smith Creek channel by enhancing natural spillways, create outlets for isolated depressions, or improving roadside ditches to handle increased flow from upstream drainage. Drainage channel features appear straight with uniform channel bottoms, and show evidence of excavation such as exposed clay or soil piles (Boychuk *et al.*, 2014).

Historical agricultural land use data were obtained from the Census of Agriculture conducted by Statistics Canada (1961 to 2011) every 5 years through a nationwide survey. Information for the RMs of Langenburg (No. 181) and Churchbridge (No. 211) were used to document changes in land use for the RMs adjoining and including the SCRB, and involved changes in crop land, summer fallow, pasture land, woodland and wetlands (unimproved land), and tillage practices (only available since 1991).

Precipitation and snowcover

Daily precipitation data (rainfall and snowfall) were compiled for the period between 1 November 1941 and 31 October 2014 following a hydrological year of November to October. Because of the short-term records from the U of S MET (2007–2013) and the missing data from the Langenburg Station (1960 to present), data from Yorkton, Saskatchewan (Environment Canada station ID: 4019080; 1942 to present), 60 km to the northwest, was used to both extend the records back to 1942 and infill missing data. Yorkton and Langenburg precipitation data were adjusted to the U of S MET based on the double mass curve method (Searcy and Hardison, 1960). Adjusted Langenburg data were used to infill missing U of S MET data, as well as backfill to 1960. Missing Langenburg data was replaced with adjusted Yorkton data, which were also used to backfill to 1942. Rainfall and snowfall data were adjusted separately as the relationship between sites changed with precipitation phase. Precipitation records from the Adjusted Homogenized Canadian Climate Database (AHCCD) were not used for this study due to limitations discovered at the nearest site, Tonkin, Saskatchewan. Data for AHCCD Tonkin site were compiled from two different stations with no corrections applied to account for site differences and were therefore deemed to be unsuitable for this study.

Daily rainfall in the SCRB from May to September was separated into single-day and multiple-day rainfall events. Single-day rainfall events are defined as daily rainfall values that are preceded and followed by days with zero rainfall. Single-day rainfalls are characteristically caused by convective storms that can be intense with great local depth but cover small areas and are hydrologically ineffective because the volume of rainfall at a basin scale is small. Multiple-day rainfall events have two or more consecutive days of rainfall. These are typically due to frontal storms, which may have embedded convection but that are generally of lower intensity and much large area than single-day storms. Because of their duration and areal extent, multiple-day storms can cause saturation overland flow and streamflow at a basin scale (Shook and Pomeroy, 2012). To consider the changes in convective storms during the period in which they normally occur, the time period of May to September was used.

Snow on ground data were obtained from the Environment Canada Yorkton station from 1956 to 2012 (missing 2007) and were used to identify the maximum snow depth, duration of continuous snowcover days and first snow-free date on an annual basis. The maximum snow depth was identified as being the greatest depth of snow, even if it was only for a single day. The duration of continuous snowcover is defined as the longest length of time within one snow season where snow depth is ≥ 1 cm. Trace amounts of snow on the ground were assumed to be 0 cm of depth and were not classified as a continuous snowcover. The first snow-free date is the first day when snow depth is 0 cm (the day after the continuous snowcover is depleted).

Temperature

Temperature data were obtained from AHCCD (http://www.ec.gc.ca/dccha-ahccd/) Tonkin site from 1942 to 2012. Tonkin, Saskatchewan, is 40 km northwest of the University of Saskatchewan meteorological station and 20 km east of Yorkton. To include 2013 and 2014 in the analysis, data from Environment Canada Tonkin station were used. Missing data accounted for ~0.7%.

Streamflow and runoff mechanism

Streamflow data were obtained from Environment Canada's Water Survey of Canada (WSC) archived hydrometric database online (http://www.wsc.ec.gc.ca). The stream gauge has been operated by the WSC (station 05ME007) since 1975. Available from WSC were daily, monthly and annual streamflow discharge. Streamflow data from 2014 are provisional as flow data have not undergone quality control by WSC. Because of the station being inundated during the flood of 2014, 22 missing days of daily discharge data were linearly interpolated using manual measurements.

In order to separate the streamflow into various runoff mechanisms such as snowmelt, rainfall and mixed snowmelt and rainfall, observed daily temperature, rainfall, snowfall, discharge and snow on ground were used in a runoff estimation technique (Figure 2). It was assumed that no groundwater contributes to streamflow due to the lack of baseflow – the stream typically dries out after snowmelt runoff is complete. Streamflow is classified as being derived from snowmelt at the beginning of the spring freshet, which corresponds with rapid snowmelt. It remains classified as such until a daily rainfall of >5 mm occurs concomitantly with increasing discharge. If the discharge is $>0.1\,\text{m}^3/\text{s}$ prior to the rainfall event or snow depth >0 cm, the streamflow is classified as a mixed snowmelt and rainfall runoff regime. If the stream is dry or discharge is $<0.1\,\text{m}^3/\text{s}$ prior to the rainfall event and there is no recorded snow on the ground, the streamflow is classified as a rainfall runoff regime.

Statistical analysis

Trend tests. All observed variables were examined for the existence of trends at daily, monthly and annual time scales. Because of differing data characteristics, two different statistical methods were used for to test for trends: the nonparametric Mann–Kendall statistical test along with linear regression was used for continuous data (e.g. precipitation amounts) while logistic regression was used for discrete data (e.g. number of events). All data were tested for serial correlation at 95% confidence levels prior to the trend test as serial correlation can influence test results (Yue *et al.*, 2002). All tests were conducted in

R, a statistical computing environment and language. The packages used for these tests were Kendall (McLeod, 2011) and R Stats (R Core Team, 2012). Trend tests were considered statistically significant at 5% level.

Change point analysis. In order to identify shifts or changes in the direction of trends, change point analyses were conducted in R using the 'changepoint' package (Killick and Eckley, 2013). In this package, the Segment Neighbourhood was implemented to identify change points in the mean and variance. A detailed description of the Segment Neighbourhood method used can be found in Auger and Lawrence (1989). If change point lengths were less than 3 years, the maximum number of change points was reduced by one unit until all change point lengths were greater than 2 years to avoid spurious change points.

Teleconnections. Climate teleconnections such as the El Nino Southern Oscillation, Pacific Decadal Oscilation (PDO) and others have been shown to influence some annual streamflows in the Canadian Prairies; the influence is more frequently observed in the western portion of the region (St. Jacques *et al*., 2014). The influence of teleconnections on streamflow was conducted following the methodology of St. Jacques *et al.* (2010), which uses generalized least squares regression to model the impacts of climate oscillations. For this study, the average annual streamflow (based on daily flow values) is examined for the influence of the Southern Oscillation Index and PDO. R, an open-sourced statistical programming software and language, was used (R Core Team, 2012).

RESULTS

Land use change

Smith Creek Research Basin has been partially drained, with the extent of ponded area decreasing dramatically from 24% in 1958 to 12% in 2000 and then 10% in 2009, resulting in a 58% loss in ponded area (Figure 3, Table I). Drainage channel length increased fourfold from 1958 to 2000 and almost eightfold from 1958 to 2009, suggesting an increased rate of drainage in the 21st Century. Local farmers report that the rate of drainage (typically occurring in fall) increases following wetter spring conditions, which have commonly occurred in the last 20 years.

Substantial changes in agricultural land use and tillage practices have occurred between 1961 (Statistics Canada, 1961) and 2011 (Statistics Canada[1]). Crop land has become the dominant agricultural land use, increasing from 33% of total farm area to 60%. Pasture land slightly increased from 2% to 9%, while summer fallow decreased from 20% to 5% of total farm area. Woodland and

Table I. Changes in wetland area and drainage channel length measured by aerial photograph analysis from 1958 to 2009 in Smith Creek Research Basin

	1958	2000	2009
Ponded area (km^2)	96.0	47.0	40.3
Ponded area (%)	24	12	10
Drainage channel length (m)	119 348	503 722	931 312

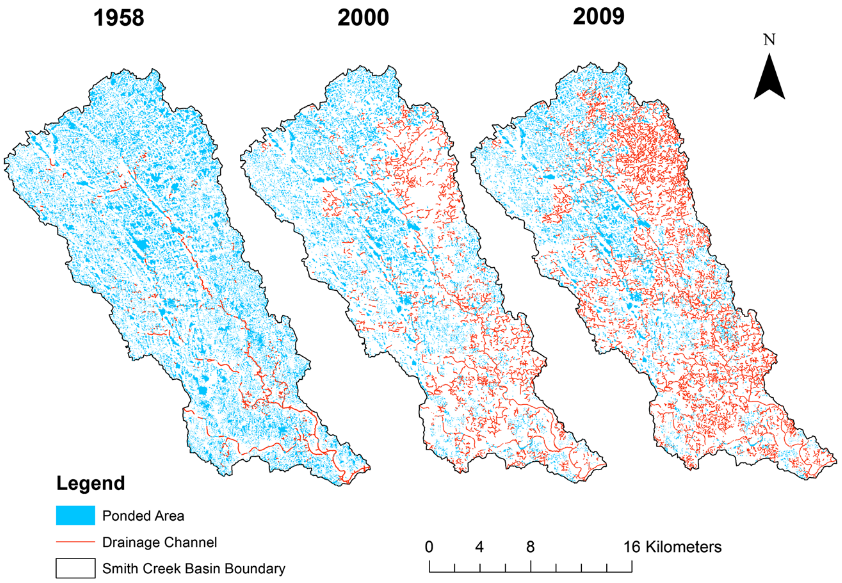

Figure 3. Wetland areas and drainage network in Smith Creek Research Basin in 1958, 2000 and 2009. Data provided by Lyle Boychuck, Ducks Unlimited Canada, from aerial photograph analysis and mapped for the basin area determined by Fang *et al.* (2010)

wetlands (unimproved land) decreased substantially from 46% to 27%. Between 1991 (Statistics Canada, 1991) and 2011 (Statistics Canada[2]), the adoption of zero till practices has been considerable, increasing from less than 2% of seeded land to 34%. Conservation tillage (tillage retaining most of the residue on the surface) also increased from 25% to 47% whereas conventional tillage (tillage incorporating most crop residue into the soil) decreased substantially from 73% of seeded land to 19%.

Temperature

Changes in meteorological variables observed in SCRB are indicative of a changing climate. The average maximum, minimum and mean temperatures in SCRB for 1942 to 2014 are 7.3, −3.9 and 1.7 °C, respectively. Temperatures have increased significantly over this period (Figure 4, Table II), with the basin maximum increasing by 1.2 °C. At a monthly scale, significant increases in temperatures ($p < 0.05$) were found for January, March, June and September. The range of monthly increases is from 1.1 to 4.0 °C, with large increases in March of 3.5 °C. In contrast, October minimum temperatures have decreased significantly ($p < 0.05$).

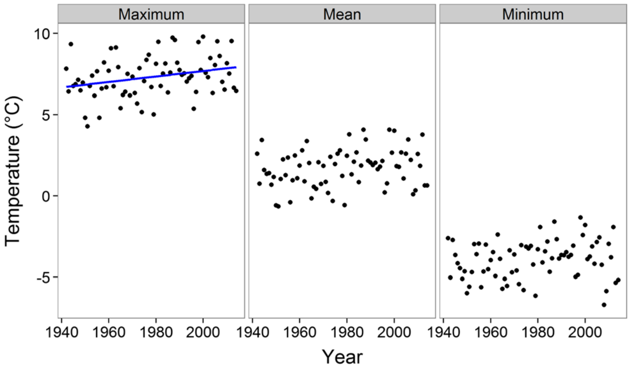

Figure 4. Maximum, mean and minimum temperatures from Tonkin, Saskatchewan, 40 km northwest of Smith Creek Research Basin from 1942 to 2014. Blue line represents significant linear trend

Table II. Changes in annual and monthly temperature (°C) in Smith Creek Research Basin

	Maximum	Minimum	Mean
Annual	+1.2	—	—
January	+4.0	—	—
March	+3.4	+3.5	+3.5
June	+1.2	+1.1	+1.1
September	+3.2	—	+2.1
October	—	−1.4	—

All results shown are significant at $p \leq 0.05$.

Precipitation and snowcover

Mean annual precipitation from 1942 to 2014 was found to be 442 mm, with rainfall accounting for 325 mm (73%) and snowfall 117 mm (27%; Figure 5). Although there are no significant trends ($p > 0.1$) or shifts in total annual precipitation, the increasing temperatures have led to a gradual phase change. Annual rainfall has significantly increased ($p = 0.013$) at a rate of 0.9 mm/year while annual snowfall has decreased ($p = 0.102$) by 0.5 mm/year. The result is a significant increase in the annual rainfall fraction of precipitation ($p = 0.043$; Figure 6) from 68% to 78% of annual precipitation between 1942 and 2014. Concurrently, snowfall fractions gradually decreased from 32% to 22%. On a monthly scale, rainfall fractions have significantly increasing in March ($p = 0.006$) with change points in 1963 and 1972 that ultimately quadrupled the mean rainfall fractions in March from 4.8% to 19.0%. Monthly rainfall fractions were only found to be changing in March, but there were significant increases in the amount of rainfall in March ($p = 0.010$), May ($p = 0.034$), June ($p = 0.048$) and October ($p = 0.051$). Mean monthly rainfall gradually became

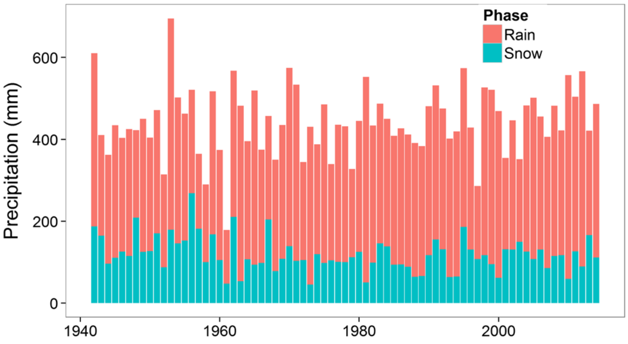

Figure 5. Annual rain and snow at Smith Creek Research Basin from 1942 to 2014 (partly interpolated from Yorkton and Tonkin, Saskatchewan). Although there are no trends in annual precipitation, rainfall has significantly increased while snowfall has significantly decreased

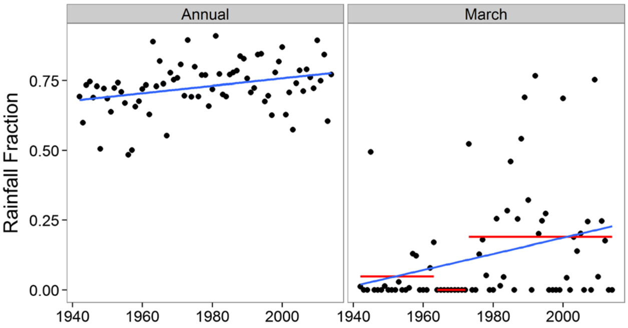

Figure 6. Rainfall fraction of annual precipitation on an annual basis and for the month of March, both of which are significantly increasing. For March, a change in the mean and variance was identified in 1971, with the mean more than quintupling from 0.035 to 0.19. Blue line represents significant linear trend; red lines represent the change points

more concentrated in the early summer between 1942 and 2014; increasing from 1 to 4 mm in March, from 31 to 59 mm in May, from 58 to 92 mm in June and from 14 to 23 mm in October.

The number of multiple-day events has increased significantly by 50% ($p = 0.029$, Figure 7), yet the number of single-day events have not significantly changed ($p > 0.1$), resulting in an increase in the total number of rainfall events of 14% ($p = 0.025$). From 1942 to 2014, the annual number of multiple-day rainfall events has increased by 5 whereas the total number of rainfall events has increased by 3.5.

Given the decreases in snowfall and increases in temperatures (particularly in January and March), the maximum snow depth has significantly decreased from 1956 to 2012 ($p < 0.001$) at a rate of 8 cm/decade (Figure 8). The duration of continuous snowcover has decreased ($p = 0.058$), resulting in a significantly earlier first snow-free date ($p = 0.042$). On average, the duration of continuous snowcover is 128 days (~4.25 months), with the first snow-free date gradually moving from April 9 to March 26. Subsequent snowfalls can occur after the first snow-free date, but they tend to be small (<5 cm) and coverage short-lived.

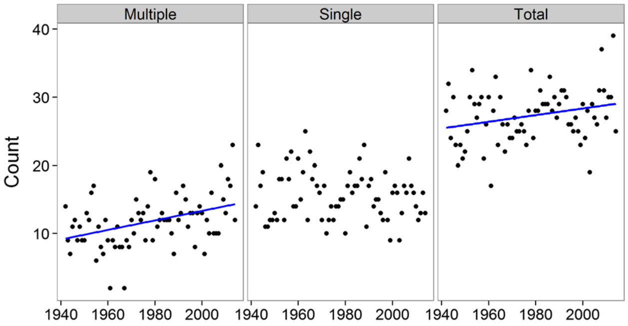

Figure 7. Total annual number of summer rainfall events as multiple-day, single-day and total from 1942 to 2014. Blue line represents a significant linear trend

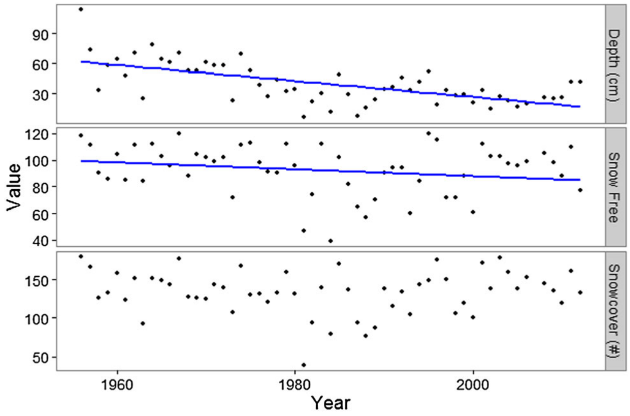

Figure 8. Maximum snow depth (cm), snow-free date (Julian date) and duration of continuous snow cover days (number of days) from 1956 to 2012. Blue line represents significant linear trend

Streamflow

Annual streamflow volume in the SCRB has increased by 14-fold (significant at $p < 0.001$) over the period of record (Figure 9). The average annual streamflow volume from 1975 to 2014 is 9715 dam^3, and change points were identified in 1994 and 2010 (Table III) that increased the mean annual volume. Streamflow volumes tripled between 1995 and 2010, a period that included the worst multi-year drought (1999–2004) on the Canadian Prairies (Bonsal and Wheaton, 2005). The second change point marked the beginning of one of the wettest years on record in the northern portion of the Canadian Prairies (Chun and Wheater, 2012) with 498.8 mm of rainfall in 2010 which ranked 2nd highest since streamflow records started. During the last changepoint, the Assiniboine Watershed (including the SCRB) experienced widespread flooding in 2011 and 2014. Annual average streamflows were not found to be correlated to the PDO ($R^2 = 0.329$) or Southern Oscillation Index ($R^2 = 0.281$), although the 40 years of available data mainly encompassed the positive phase of the PDO (1977 to 2007; St. Jacques *et al.*, 2014).

Not only has the volume of runoff increased within the SCRB, but the runoff mechanisms that produce streamflow have shifted throughout the study period as evidenced from increased contributions from snowmelt, mixed and rainfall runoff since 1975 (Table III and

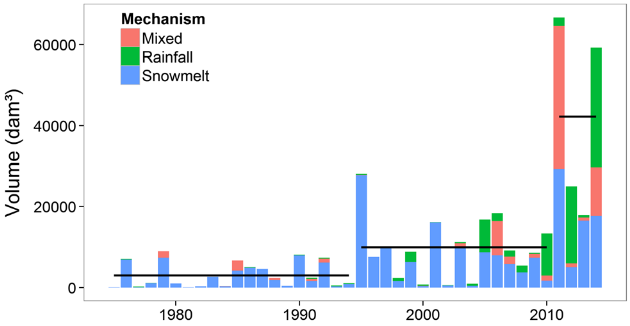

Figure 9. Annual streamflow volumes separated into varying runoff mechanisms (Figure 2) for Smith Creek Research Basin from 1975 to 2014. Change points in the mean and variance were identified in 1994 and 2010 (black lines)

Table III. Volume of streamflow derived from the various runoff mechanisms (snowmelt, mixed and rainfall runoff) from Smith Creek Research Basin from 1975 to 2014

	1975–1994	1995–2010	2011–2014
Annual runoff	3000	9900	42 700
Snowmelt runoff	2600	7210	17 880
Mixed runoff	300	860	11 500
Rainfall runoff	80	1800	13 350

Figure 9). Despite observed decreases in snowfall amounts, annual streamflow volume derived from snowmelt runoff has increased fivefold. Annual mixed snowmelt–rainfall runoff volumes have increased 34-fold and rainfall runoff volumes have increased 150-fold. The substantial increase in rainfall runoff may in part be due to the timing of the increased rainfall amounts since 1942 primarily in May and June (28 and 34 mm, respectively) mainly in the form of multiple-day rainfall events. The timing of such events is occurring shortly after the snowmelt season when basin conditions are still relatively wet.

Although streamflow volume derived from all forms of runoff increased and contributed to extensive flooding after the second change point, the increases were not the same for all forms and favoured rainfall-runoff mechanisms; for instance, snowmelt and mixed runoff volumes increased threefold, and rainfall runoff volume increased 23-fold after the first change point and before the second change point. Prior to the first change point in 1994, snowmelt runoff accounted for 86% of the annual streamflow within SCRB, a value consistent with Gray and Landine's (1988) estimate for the Canadian Prairies of >80%. Since then, the fraction of streamflow derived from snowmelt runoff have declined to 71% and then 47%, while mixed and rainfall runoff have increased to 29% and then 53%, suggesting a reversal of the basin from being snowmelt dominated to rainfall-runoff dominated (Table IV, Figure 9). After the first change point, decreases in the fraction of streamflow derived from snowmelt runoff were offset by increases in the fraction of rainfall runoff. These changes were further amplified after the second change point, with the additional increase in the fraction of streamflow derived from mixed runoff. The substantial changes in runoff mechanisms after the second change point are primarily due to rain-induced high flows in 2012 and flooding in 2014. These floods account for a majority of the runoff in those years. Further, streamflow during the 2011 flood was dominated by mixed runoff as there was high rainfall shortly following snowmelt. This event marked a change point in the fraction of streamflow derived from mixed snowmelt and rainfall runoff.

Table IV. Fraction of streamflow derived from the various runoff mechanisms (snowmelt, mixed and rainfall runoff) from Smith Creek Research Basin from 1975 to 2014

	1975–1994 (%)	1995–2010 (%)	2010–2014 (%)
Snowmelt runoff	86	71	47
Mixed runoff	7	6	19
Rainfall runoff	7	23	34

2014 data are preliminary.

Runoff ratios were evaluated in order to gain greater insight into runoff generation processes within the SCRB. Runoff ratio is the fraction of precipitation that falls within the basin that becomes streamflow. From 1975 to 2014, runoff ratios increased significantly ($p < 0.001$; Figure 10), and the period was marked by two change points occurring in 1994 and 2010. The change points shifted the mean annual runoff ratios from 0.019 prior to 1994 to 0.057 in 1995–2010, and then to 0.22 after 2011. The shifts in runoff ratios were coincident with shifts in annual streamflow volume and amount to a 12-fold increase in runoff ratio over the period of record.

Figure 11 depicts the maximum, minimum and mean hydrographs of the three change point time periods to facilitate further discussion of the dramatic changes in SCRB hydrological regime. It should be noted that each time period has a different length. From 1975 to 1994, streamflow in SCRB was dominated by snowmelt runoff and typically receded back to zero flow after the completion of snowmelt in spring. Negligible runoff

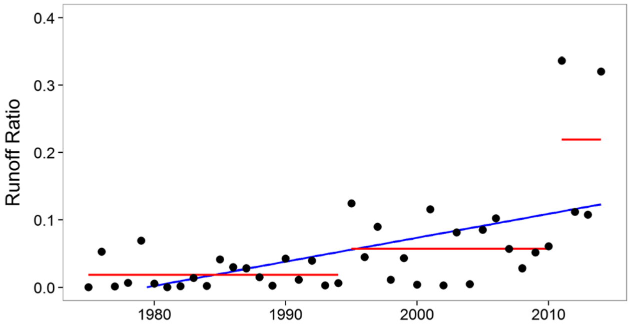

Figure 10. Runoff ratios calculated for Smith Creek Research Basin from 1975 to 2014. Red lines represent change points while the blue line represents the linear trend (p < 0.05)

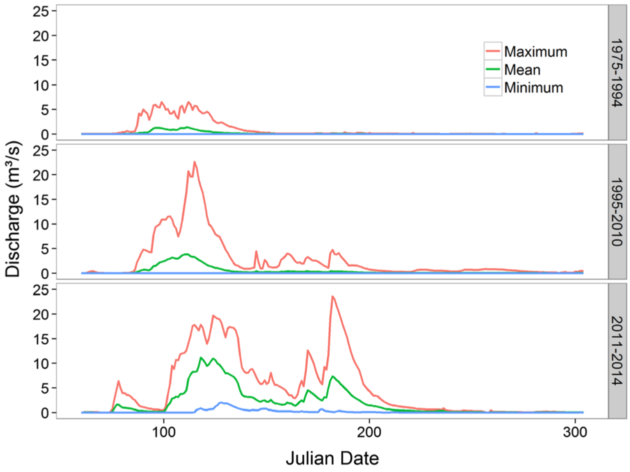

Figure 11. Smith Creek Research Basin maximum, minimum and mean daily discharges for the three time periods identified with change point analysis

occurred during the summer months. From 1995 to 2010, streamflow duration expanded into the summer months due to rainfall-runoff mechanisms and rain-on-snow contributed to generating higher runoff peaks in the spring period. The largest peak flow during this 1995 to 2010 period (1995) was caused by widespread spring flooding resulting from snowmelt satisfying depressional storage. Streamflow was first sustained throughout much of the summer in 2010. Hydrograph shapes are substantially different from other years in the 2011–2014 changepoint period. During this period, streamflow still peaked in spring because of snowmelt and mixed runoff, but there were second peaks that occurred in the summer months, not driven by snowmelt. Double peaks occurred in 2012 and 2014, with the rainfall driven peak being larger than the snowmelt peak in both years.

Not only has the volume of runoff and streamflow increased within the SCRB but the peak discharge has also increased substantially (Figure 12). There is greater uncertainty in peak discharge values than lower discharges because the culvert at the gauging station was inundated during peak flow in 1995, 2011 and 2014. There are also differences in natural unimpeded flows and those at the gauging station due to impoundment of flows and the formation of a temporary lake upstream of the gauge due to restricted flow through the culvert and the damming effect of a road above the culvert. There are several roads and culverts in the basin that act to funnel and obstruct streamflow during extremely high flows. From 1975 to 2014, mean annual peak discharge at Smith Creek significantly increased ($p = 0.006$), with a change point occurring in 1994. Prior to the change point, mean annual peak discharge was $3\ m^3$/s, which tripled to $9.2\ m^3$/s afterwards. The size of the culvert at the outlet of the SCRB has not changed since the WSC gauging station was installed at the inlet to the culvert in 1975. However, the roadway above the culvert was built up to prevent being washed out after the 1995 flood, allowing for a higher head, which can increase the flow rate (Smith, 1985) through the outlet culvert. Impacts of this alteration are only likely during extremely high flows wherein the culvert is overtopped and upstream ponding occurs. In these cases, a whirlpool forms over the inlet – whirlpools were observed in 2011 and 2014. Changes in culvert size thus cannot fully explain the tripling of peak discharge after 1994.

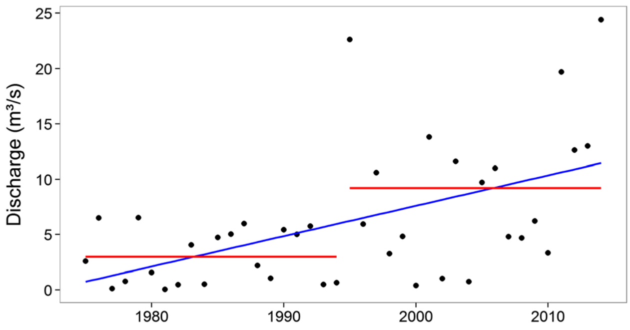

Figure 12. Annual peak discharge from the outlet at Smith Creek Research Basin from 1975 to 2014. Red lines represent change points while the blue line represents the trend

DISCUSSION

The climate, land use and hydrological regime of SCRB have changed dramatically in the last half-century. As compared with changes in streamflow, changes to the climate are modest, but changes in drainage are similarly dramatic. The annual amount of precipitation to the basin has not significantly changed over time, which differed from the average increase of 9% across the PPR presented in Millet *et al.* (2009). Tremendous changes were observed in the way precipitation is delivered, which may be a factor impacting streamflow. Despite decreases in snowfall amounts, the absolute volume of streamflow derived from snowmelt runoff has increased. The maximum depth of snow has gradually decreased, and the timing of snowcover depletion is occurring 2 weeks earlier (March 26). The increase in March rainfall may have increased the frequency or spatial extent of ice layers at the base of the snowpack. Ice layers restrict the infiltration of snowmelt water into frozen soils (Gray *et al.*, 2001) and can cause almost all snowmelt to form runoff. Increases in rainfall amounts (predominantly in May and June) combined with the increased frequency of multiple-day rainfall events in the summer months have almost certainly contributed to the increase in the amount of mixed and rainfall runoff observed at the basin scale.

Gradual changes to the character of precipitation cannot fully explain the 14-fold increase in streamflow volumes, 12-fold increase in runoff ratio and tripling of peak discharge over the period of record. The last change point (2011 to 2014) is short in duration because of the availability of data at the time of the study. Future analysis on subsequent years as they become available will determine the length and the following shift direction. Although flow frequency analysis was not conducted, it is clear that the hydrological regime of Smith Creek is non-stationary. Research in the prairie region has shown that not only do changes in precipitation influence streamflow but so do anthropogenic changes (St. Jacques *et al.*, 2010; Miller and Nudds, 1996). In the SCRB, over 58% of the ponded area has been lost due to drainage. The drainage channels that have been created are generally well-engineered, allowing for little to no residual depressional storage. Farmers in the basin have openly stated that they amplify their drainage efforts in flood years to reduce the amount of water sitting on the landscape and associated economic losses.

Modelling studies have concluded that wetland drainage increases annual and peak daily flows, as well as the magnitude and frequency of flooding (Gleason *et al.*, 2007; Yang *et al.*, 2010; Pomeroy *et al.*, 2014). Streamflow generation from runoff is mainly controlled by depressional storage (Shook *et al.*, 2015), and draining depressions increases the contributing area to streamflow (Brannen *et al.*, in press). Comparable results were presented in Miller and Nudds (1996) who concluded that landscape alteration caused an increase in runoff in unregulated rivers, as there were no changes to the amount of precipitation. Ponded area in SCRB was reduced by 14% and drainage channel lengths increased by 185% from 2000 to 2009. The 12-fold increase in runoff ratios from the 1970s to the current decade reflects factors such as changing precipitation delivery, infiltration capacity, contributing area and depressional storage of the basin, all of which are affected by changes in climate and land use. While spring infiltration rates may have dropped due to March rainfall increases and the greater number of summer multiple-day rainfall events in May and June can increase summer runoff, the marked increase in late spring and summer flows due primarily to increasing mixed and rainfall runoff is disproportionate to these climate change impacts. Given that over half the ponded area was drained and drainage channel length increased eightfold in the last 56 years, both the depressional storage capacity was decreased and contributing area was increased. It is therefore highly likely that the increase in runoff ratios, along with annual streamflow volumes and peak discharge, is partly driven by enhanced drainage.

Primary changes in agricultural land use in the SCRB include substantial increases in crop land and the extensive adoption of zero and conservation tillage practices. On the Canadian Prairies, the conversion of land use to cropland decreases infiltration in the spring (van der Kamp *et al.*, 2003; Pomeroy *et al.*, 2010) due to the destruction of macropores (van der Kamp *et al.*, 2003), yet the shorter plant height results in decreased snow accumulation due to increased blowing snow sublimation (Pomeroy *et al.*, 2010). Results from a modelling study in the SCRB found that spring streamflows were relatively unaffected (−2%) under complete conversion to cropland (Pomeroy *et al.*, 2010). Runoff differences under conservation and zero tillage practices have been shown to have little effect during the snowmelt period yet can effectively reduce runoff during the growing season (Elliott *et al*, 2001; Tiessen *et al.*, 2010). As a result, it is likely that such changes have had little effect on the streamflow in the SCRB and may even act to reduce runoff during the summer months when the largest changes in streamflow have been observed. Further diagnostic hydrological process studies are needed to gain a better understanding of how land use change, including drainage, influences streamflow in this and similar basins.

The results from this study confirm and help explain many findings of recent research conducted on the Canadian Prairies. Ehsanzadeh *et al.* (2012a, 2014) suggested that changes in precipitation inputs would result in sudden changes to streamflow, which appears to be supported here in that a dramatic increase in streamflow volume occurred with changes in the delivery but not the annual volume of precipitation. The disproportionate response of streamflow to such changes may in part be due to the dynamic nature of the contributing area (Ehsanzadeh *et al.*, 2012a). Many studies have shown the importance of depressional storage effects on streamflow generation (Gleason *et al.*, 2007; Yang *et al.*, 2010; Shook *et al.*, 2015), which affects the shape and slope of the flow frequency curve (Ehsanzadeh *et al.*, 2012b), and such non-stationary effects may be becoming apparent in SCRB as depressional storage declines with drainage. Increased streamflow and runoff ratios for the SCRB were also presented in Ehsanzadeh *et al.* (2014), yet the lack of long-term trends in the Assiniboine River and across the Canadian Prairies in Ehsanzadeh *et al.* (2012a, 2014) is not supported by the data and detailed analysis for SCRB shown here, where there are strong and statistically significant trends for increasing discharge. It may be that the impact of river regulation on the statistical analysis employed by Ehsanzadeh *et al.* (2012a, 2014) masked the ability to detect increased runoff from the many creeks. Unfortunately, as most unregulated creeks and rivers in the region are ungauged, it is not possible to assess at larger scales whether the unregulated flows show non-stationarity due to changes in basin hydrology in the same manner as this study has shown for SCRB.

CONCLUSIONS

The hydrological regime of the SCRB has changed substantially. Drainage has increased in the basin over the last 56 years, reducing the ponded area extent by 58% and increasing drainage channel length 780% between 1958 and 2009. The climate change observed within the basin is indicative of warming, with air temperatures increasing substantially and the greatest increases occurring in early spring. In response, the rainfall fraction of total precipitation has gradually increased, with the greatest shift from snowfall to rainfall events in March. Snowfall amounts have decreased along with the maximum depth of snow, resulting in snowmelt occurring 2 weeks earlier. The frequency of multiple-day rainfall events has increased by 50% and this may reflect greater frontal precipitation rather than convective precipitation mechanism. Increased rainfall has predominately occurred in May and June, which is shortly after the snowmelt season ends and the basin is still relatively wet.

Streamflow volumes, runoff ratios and peak discharge have increased dramatically since 1975, with large shifts occurring in 1994 and 2010. Despite decreases in snowfall amounts, the volume of streamflow derived from snowmelt has increased. However, vastly increased discharge contributions from rainfall and mixed rainfall–snowmelt runoff processes have changed the fraction of streamflow derived from various runoff mechanisms; fraction of snowmelt runoff decreased and rainfall runoff increased. Mean annual peak discharge and runoff ratios tripled after 1994, and runoff ratios then almost quintupled after 2010.

It is unlikely that any single change is responsible for the dramatic shift in SCRB hydrology. The substantial but gradual changes to the character of precipitation cannot fully explain the 14-fold increase in streamflow volumes, 12-fold increase in runoff ratios, transformation from snowmelt dominated to rainfall dominated runoff and tripling of peak discharge. This rapid shift in hydrology is likely due to a non-linear or threshold-like response to combinations of a changing climate, exacerbated by changes in land use and recent increases in drainage. Therefore, it is critical to consider the influence that land use change, including drainage, exerts on prairie basin hydrology under a changing climate. Further diagnostic investigation using process hydrology simulations is needed to fully explain the mechanisms behind the observed regime changes.

ACKNOWLEDGEMENTS

This research was supported by funds were from the Canada Research Chairs Programme, Natural Sciences and Engineering Research Council of Canada (NSERC), Ducks Unlimited Canada, Environment Canada, Agriculture and Agrifood Canada, Manitoba Water Stewardship, Saskatchewan Water Security Agency and the University of Saskatchewan. The authors would like to thank Lyle Boychuk, Xing Fang, Kevin Shook, Phillip Harder, Michael Solohub, Adam Minke, Joni Onclin, Larisa Barber and Nicole Seitz for assistance in data analysis and field data collection.

REFERENCES

Akinremi OO, McGinn SM, Cutforth HW. 1999. Precipitation trends on the Canadian Prairies. *Journal of Climate* **12**: 2996–3003.

Auger IE, Lawrence CE. 1989. Algorithms for the optimal identification of segment neighborhoods. *Bulletin of Mathematical Biology* **51**: 39–54.

Bonsal BR, Wheaton EE. 2005. Atmospheric circulation comparisons between the 2001 and 2002 and the 1961 and 1988 Canadian prairie droughts. *Atmosphere-Ocean* **43**: 163–172. DOI:10.3137/ao.430204.

Bonsal B, Aider R, Gachon P, Lapp S. 2012. An assessment of Canadian prairie drought: past, present, and future. *Climate Dynamics* **41**: 501–516. DOI:10.1007/s00382-012-1422-0.

Boychuk L, Mayer E, Dunn S, Tulloch R. 2014. Canadian Wetland Inventory: Prairie Wetland Interpretation Guideline, Version 2. *Ducks Unlimited Canada Publication*. December 2014.

Brunet NN, Westbrook CJ. 2012. Wetland drainage in the Canadian prairies: nutrient, salt and bacteria characteristics. *Agriculture, Ecosystems and Environment* **146**: 1–12. DOI:10.1016/j.agee.2011.09.010.

Burn DH, Buttle JM, Cassie D, MacCulloch G, Spence C, Stahl K. 2008. The processes, patterns and impacts of low flows across Canada. *Canadian Water Resources Journal* **33**: 107–124.

Burn D, Sharif M, Zhang K. 2010. Detection of trends in hydrological extremes for Canadian watersheds. *Hydrological Processes* **24**: 1781–1790. DOI:10.1002/hyp.7625.

Chun KP, Wheater HS. 2012. An extreme analysis for the 2010 precipitation event at the south of Saskatchewan prairie. *Global NEST Journal* **14**: 311–324.

Conly FM, van der Kamp G. 2001. Monitoring the hydrology of Canadian Prairie wetlands to detect the effects of climate change and land use changes. *Environmental Monitoring and Assessment* **67**: 195–215.

DUC. 2008. The impacts of wetland loss. Information Sheet, Ducks Unlimited Canada, 4pp.

Ehsanzadeh E, van der Kamp G, Spence C. 2012a. The impact of climatic variability and change in the hydroclimatology of Lake Winnipeg watershed. *Hydrological Processes* **26**: 2802–2813. DOI:10.1002/hyp.8327.

Ehsanzadeh E, van der Kamp G, Spence C. 2014. On the changes in long term streamflow regimes in the Prairies. *Hydrological Sciences Journal* DOI:10.1080/0262667.2014.967249.

Ehsanzadeh E, Spence C, van der Kamp G, McConkey B. 2012b. On the behaviour of dynamic contributing areas and flood frequency curves in North American Prairie watersheds. *Journal of Hydrology* **414-415**: 364–373. DOI:10.1016/j.jhydrol.2011.11.007.

Elliot JA, Cessna AJ, Hilliard CR. 2001. Influence of tillage system on water quality and quantity in Prairie Pothole wetlands. *Canadian Water Resources Journal* **26**: 165–181. DOI:10.4296/cwrj2602165.

Fang X, Pomeroy J. 2007. Snowmelt runoff sensitivity analysis to drought on the Canadian Prairies. *Hydrological Processes* **21**: 2594–2609. DOI:10.1002/hyp.6796.

Fang X, Pomeroy JW, Westbrook CJ, Guo X, Minke AG, Brown T. 2010. Prediction of snowmelt derived streamflow in a wetland dominated prairie basin. *Hydrology and Earth System Sciences* **14**: 991–1006. DOI:10.5194/hess-14-991-2010.

Gleason RA, Tangen BA, Laubhan MK, Kermes KE, Euliss, Jr. NH. 2007. Estimating water storage capacity of existing and potentially restorable wetland depressions in a subbasin of the Red River of the North. *USGS Northern Prairie Wildlife Research Center* Paper 89.

Godwin RB, Martin FRJ. 1975. Calculation of gross and effective drainage areas for the Prairie provinces. In: *Canadian Hydrology Symposium - 1975 Proceedings*, *11–14 August 1975*, *Winnipeg*, *Manitoba*. Associate Committee on Hydrology, National Research Council of Canada, Ottawa: 219–223

Granger RJ, Gray DM. 1989. Evaporation from natural non-saturated surface. *Journal of Hydrology* **111**: 21–29.

Gray DM. 1970. *Handbook on the Principles of Hydrology: With Special Emphasis Directed to Canadian Conditions in the Discussion, Applications, and Presentation of Data*. Water Information Center: Huntingdon, New York. ISBN:0-912394-07-2.

Gray DM, Pomeroy JW, Granger RJ. 1986. Prairie snowmelt runoff. In: Proceedings, Water Research Themes, Conference Commemorating the Official Opening of the National Hydrology Research Centre. Canadian Water Resources Association, Saskatoon. 49–68.

Gray DM, Landine PG. 1988. An energy-budget snowmelt model for the Canadian Prairies. *Canadian Journal of Earth Sciences* **25**: 1292–1303. DOI:10.1139/e88-124.

Gray DM, Toth B, Zhao L, Pomeroy JW, Granger RJ. 2001. Estimating areal snowmelt infiltration into frozen soils. *Hydrological Processes* **15**: 3095–3111. DOI:10.1002/hyp.320.

Hayashi M, van der Kamp G, Schmidt R. 2003. Focused infiltration of snowmelt water in partially frozen soil under small depressions. *Journal of Hydrology* **270**: 214–229.

Hanuta I. 2001. A reconstruction of wetland information in pre-settlement southern Manitoba using a geographic information system. *Canadian Water Resources Journal* **26**: 183–194. DOI:10.4296/cwrj2602183.

Heagle D, Hayahsi M, van der Kamp G. 2013. Surface-subsurface salinity distribution and exchange in a closed-basin prairie wetland. *Journal of Hydrology* **478**: 1–14.

Johnson CW, Millet BV, Gilmanov T, Voldseth RA, Guntenspergen GR, Naugle DE. 2005. Vulnerability of northern prairie wetlands to climate change. *BioScience* **55**: 863–872.

Johnson CW, Werner B, Guntenspergen GR, Voldseth RA, Millet B, Naugle DE, Tulbure M, Carroll RWH, Tracy J, Olawsky C. 2010. Prairie wetland complexes as landscape functional units in a changing climate. *BioScience* **60**: 128–140. DOI:10.1525/bio.2010.60.2.7.

Killick R, Eckley I. 2013. Changepoint: an R package for changepoint analysis. R package version 1.0.5. http://CRAN.R-project.org/package=changepoint.

McLeod AI. 2011. Kendall: Kendall rank correlation and Mann–Kendall trend test. R package version 2.2. http://CRAN.R-project.org/package=Kendall.

Mekis É, Vincent LA. 2011. An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. *Atmosphere-Ocean* **49**: 163–177. DOI:10.1080/07055900.2011.583910.

Miller MW, Nudds TD. 1996. Prairie landscape change and flooding in the Mississippi River Valley. *Conservation Biology* **10**: 847–853.

Millet B, Johnson WC, Guntnspergen G. 2009. Climate trends of North American Prairie Pothole Region 1906–2000. *Climatic Change* **93**: 243–267. DOI:10.1007/s10584-008-9543-5.

Pomeroy JW, Gray DM, Brown T, Hedstrom NH, Quinton WL, Granger RJ, Carey SK. 2007. The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence. *Hydrological Processes* **21**: 2650–2667.

Pomeroy JW, Fang X, Westbrook C, Minke A, Guo G, Brown T. 2010. Prairie hydrological model study final report. *Centre for Hydrology Report #7*. January 2010.

Pomeroy JW, Shook K, Fang X, Dumanski S, Westbrook C, Brown T. 2014. Improving and testing the prairie hydrological model at Smith Creek Research Basin. *Centre for Hydrology Report No. 14*. May 2014.

R Core Team. 2012. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Rashford BS, Bastian CT, Cole JG. 2011. Agricultural land-use change in prairie Canada: implications for wetlands and waterfowl habitat conservation. *Canadian Journal of Agricultural Economics* **59**: 185–205. DOI:10.1111/j.1744-7976.2010.01212.x.

Saskatchewan Soil Survey. 1991. The soils of Langenburg (181) Fertile Belt (183) Churchbridge (211) Saltcoats (213) rural municipalities, Saskatchewan. Saskatchewan Institute of Pedology, Saskatoon, Saskatchewan. Publication S208.

Searcy JK, Hardison CH. 1960. Double-mass curves, manual of hydrology: part 1. *General Surface-Water Techniques*, *USGS Water-Supply Paper 1541-B*.

Shaw DA, van der Kamp G, Conly FM, Pietroniro A, Martz L. 2012. The fill-spill hydrology of prairie wetland complexes during drought and deluge. *Hydrological Processes* **26**: 3147–3156. DOI:10.1002/hyp.8390.

Shook KR, Pomeroy JW. 2012. Changes in the hydrological character of rainfall on the Canadian prairies. *Hydrological Processes* **26**: 1752–1766. DOI:10.1002/hyp.9383.

Shook K, Pomeroy JW, Spence C, Boychuk L. 2013. Storage dynamics simulations in prairie wetland hydrology models: evaluation and parameterization. *Hydrological Processes* **27**: 1875–1889. DOI:10.1002/hyp.9867.

Shook K, Pomeroy JW, van der Kamp G. 2015. The transformation of frequency distributions of winter precipitation to spring streamflow probabilities in cold regions; case studies from the Canadian Prairies. *Journal of Hydrology* **521**: 395–409. DOI:10.1016/j.jhydrol.2014.10.014.

Smith CD. 1985. *Hydraulic Structures*. University of Saskatchewan Printing Services: Saskatoon; 364.

Spence C. 2007. On the relation between dynamic storage and runoff: a discussion of thresholds, efficiency, and function. *Water Resources Research* **43**: W12416. DOI:10.1029/2006WR005645.

St. Jacques JM, Sauchyn DJ, Zhao Y. 2010. Northern Rocky Mountain streamflow records: global warming trends, human impacts or natural variability? *Geophysical Research Letters* **37**: L06407. DOI:10.1029/2009GL042045.

St. Jacques JM, Huang YA, Zhao Y, Lapp SL, Sauchyn DJ. 2014. Detection and attribution of variability and trends in streamflow records from the Canadian Prairie Provinces. *Canadian Water Resources Journal* **39**: 270–284.

Statistics Canada. 1961. Census of agriculture. Field crops seeded or to be seeded for harvest in 1961. Ottawa, Ontario: Statistics Canada. Accessed via ODESI. March 25, 2015. http://search1.odesi.ca/details/view.html?uri=/odesi/agcensus-95F0354-E-1961-xls.xml

Statistics Canada. 1991. Census of agriculture. Operating arrangements, land use and land management practices. Ottawa, Ontario: Statistics Canada. Accessed via ODESI. March 25, 2015. http://search1.odesi.ca/details/view.html?uri=/odesi/agcensus-95F0354-E-1991-xls.xml

Statistics Canada^1. No date. Table 004-0203 – Census of Agriculture, land use, every 5 years. *CANSIM* (*database*). Accessed: February 25, 2015.

Statistics Canada^2. No date. Table 004-0205 – census of agriculture, tillage practices used to prepare land for seeding, every 5 years. *CANSIM* (*database*). Accessed: February 27, 2015.

Tiessen KHD, Elliot JA, Yarotski J, Lobb DA, Flaten DN, Glozier NE. 2010. Conventional and conservation tillage: influence on seasonal runoff, sediment, and nutrient losses in the Canadian Prairies. *Journal of Environmental Quality* **39**: 964–980. DOI:10.2134/jeq2009.0219.

Töyrä J, Pietroniro A, Bonsal B. 2005. Evaluation of GCM simulated climate over the Canadian Prairie provinces. *Canadian Water Resources Journal* **30**: 245–262. DOI:10.4296/cwrj3003245.

Upper Assiniboine River Basin Study. 2000. Appendix A: drainage and flood control committee report. http://www.assiniboinewatershed.com/publications/reports-1/reports. Date accessed: October 20, 2014.

van der Kamp G, Hayashi M, Gallen D. 2003. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. *Hydrological Processes* **17**: 559–575. DOI:10.1002/hyp.1157.

van der Kamp G, Hayashi M. 2009. Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America. *Hydrogeology Journal* **17**: 203–214.

Vincent LA, van Wijngaarden WA, Hopkinson R. 2007. Surface temperature and humidity trends in Canada for 1953–2005. *Journal of Climate* **20**: 5100–5113. DOI:10.1175/JCLI4293.1.

Voldseth RA, Johnson WC, Gilmanov T, Guntenspergen GR, Millet BV. 2007. Model estimation of land-use effects on water levels of northern prairie wetlands. *Ecological Applications* **17**: 527–540.

Watmough MD, Schmoll MJ. 2007. Environment Canada's Prairie and Northern Habitat Monitoring Program Phase II: recent habitat trends in the PHJV. Environment Canada, Canadian Wildlife Service, Edmonton, AB.

Werner BA, Johnson WC, Guntenspergen GR. 2013. Evidence for 20th century climate warming and wetland drying in the North American Prairie Pothole Region. *Ecology and Evolution* **3**: 3471–3482. DOI:10.1002/ece3.731.

Yang W, Wang X, Liu Y, Gabor S, Boychuck L, Badiou P. 2010. Simulated environmental effects of wetland restoration scenarios in a typical Canadian prairie watershed. *Wetlands Ecological Management* **18**: 269–279. DOI:10.1007/s11273-009-9168-0.

Yue S, Pilon P, Phinney B, Cavadias G. 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes* **16**: 1807–1829.