Recent changes in patterns of western Canadian river flow and association with climatic drivers

Allison J. Bawden, Donald H. Burn and Terry D. Prowse

ABSTRACT

Climatic variability and change can have profound impacts on the hydrologic regime of a watershed, especially in regions that are sensitive to changes in climate, such as the northern latitudes and alpine-fed regions of western Canada. Quantifying historical spatial and temporal changes in hydrological data can provide useful information as to how water resources are affected by climatic and atmospheric forcings, as well as create an understanding of potential future variability. Trends in western Canadian runoff are examined for the period of 1976–2010. Regional patterns of spatial variability are quantified using a principal component analysis (PCA) that results in the identification of three hydrological regions. Both watershed-scale and PCA trend results show increased runoff in the northern-most watersheds, while decreased water availability has generally affected the mid-latitude basins. The southern watersheds show increases and decreases in runoff with no significant trends. Runoff is shown to be positively correlated with precipitation. Runoff in some regions of western Canada is shown to be influenced by the Pacific Decadal Oscillation and Pacific North American (PNA) modes of atmospheric variability. The results of this analysis provide water managers with an indication of the direction and magnitude of changing water availability in western Canada.

Key words | climate change, hydrology, Mann–Kendall, runoff, western Canada

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INTRODUCTION

Global climate has experienced a great deal of variability over the past century, but changes have differed widely from region to region. A number of studies (e.g., Zhang *et al.* 2007; Min *et al.* 2008) have documented significantly greater warming in the high latitudes of the northern hemisphere, in addition to contrasting increases and decreases in precipitation at higher versus more southerly latitudes, respectively, over the past 50 years. The implications of climate change, however, stretch beyond the scope of meteorological variability. In particular, a recent report of the Intergovernmental Panel on Climate Change (Bates *et al.* 2008) stressed that future climate is likely to intensify the hydrologic cycle and affect water security in certain locations. Rawlins *et al.* (2010) specifically looked at the intensification of the freshwater cycle in the Arctic. For some regions, this will mean enhanced access to water resources, but because the effects will not be spatially uniform, other locations will suffer reduced access (Prowse 2008). Given the nature of recent climate change – notably, the north–south contrasts in northern hemisphere precipitation patterns – it is likely that some large regions will contain zones of diametrically opposed responses, where neighboring areas may become 'water-rich' and 'water-poor', triggering a greater need for effective water management. One region where there is potential for this to occur is western Canada. An area of highly contrasting topographies and hydroclimatic regimes, western Canada spans the mid- to high-latitudes of the northern hemisphere, stretching from south of 50°N to the Arctic Coast. Coupled with the fact that the area is home to some of the world's largest rivers – a combination of both heavily used and pristine aquatic environments – western Canada is a critical region

in which the impacts of climate change and variability on water supply need to be assessed.

Water availability over the majority of western Canada is largely controlled by snowmelt, especially from alpine areas in the headwaters of many of the basins. Spring snowmelt is the dominant hydrological event of the year in snow-dominated regions, triggering the onset of the spring freshet, hence changes in both temperature and precipitation can drastically affect runoff and access to water resources. Winter and spring temperatures, for example, have been shown to affect the rate and timing of spring snowmelt, while changes in precipitation tend to affect snowfall and late-winter snow accumulation, directly influencing spring runoff volumes (Barnett *et al.* 2005).

A number of recent studies have documented changes in both the amount and timing of streamflow in western Canada. In northern British Columbia (BC) and the Rocky Mountains, Whitfield & Cannon (2000) identified a trend toward earlier timing of spring peak flows, as well as increased winter and decreased summer discharge, and related these changes to increased early-winter precipitation and warmer year-round temperatures. Stewart *et al.* (2004) similarly found widespread and regionally coherent trends toward earlier onset of spring snowmelt over most of western North America and attributed this observation to a combination of effects from the Pacific Decadal Oscillation (PDO), a major control of streamflow in the northern Rockies, and a long-term springtime warming trend spanning both phases of the PDO. Shifts toward earlier onset of the spring freshet were likewise identified for the greater Mackenzie River basin (Abdul Aziz & Burn 2006; Burn 2008) and its alpine-fed Liard and Athabasca River sub-basins (Burn *et al.* 2004a), as well as in both interior BC (Whitfield 2001; Zhang *et al.* 2001) and southern BC (Whitfield & Cannon 2000) watersheds.

In the snow-dominated high latitudes, Whitfield (2001) detected overall increased streamflow throughout the majority of the year, particularly during the winter months, due to a warming of winter temperatures and consequential release of stored water from glaciers, aufeis, permafrost, and snow deposits. Whitfield & Cannon (2000) similarly identified year-round increases in discharge caused by warmer and wetter conditions in the Canadian Arctic. St. Jacques & Sauchyn (2009) found increasing baseflow and mean annual flow for 23 hydrometric stations in the Canadian north. They postulate that the increased flow may be a result of permafrost thawing as well as an intensification of the hydrologic cycle. Déry & Wood (2005), on the other hand, found generally decreasing annual discharge in a collection of Arctic-draining Canadian rivers, and related these trends to changes in precipitation rather than evapotranspiration, as well as to teleconnections with various large-scale atmospheric phenomena.

In southern BC, Whitfield (2001) found reduced overall streamflow, especially during the winter months, as a result of extended warm summer temperatures and reduced fall precipitation. Lengthening of the summer dry season, typically mid-June through the end of September, and associated reductions in year-round discharge were likewise noted among the Pacific coast basins, despite the region not experiencing enough snowfall to be snowmelt-dominated. Whitfield & Cannon (2000) similarly identified generally lower summer flows in rivers flowing to the Pacific Ocean, but also detected higher winter flows and a delayed spring peak that they attributed to higher winter precipitation.

In the dry Canadian prairies, recent trends and future projections include lower summer streamflows, falling lake levels, retreating glaciers and increasing soil- and surface-water deficits (Sauchyn & Kulshreshtha 2008). In rivers feeding the western prairies, Schindler & Donahue (2006) found drastic reductions in summer discharge since the early twentieth century, ranging from 20% in rivers where human impact has been minimal to 84% in regions where damming and large water withdrawals have occurred. Rood *et al.* (2008) found generally declining summer flows for a collection of watersheds draining primarily undisturbed areas along the Continental Divide in southern Canada and northern United States. St. Jacques *et al.* (2010) examined streamflow for a collection of hydrometric gauging stations, primarily in southern Alberta, and found generally declining streamflow that they attributed to a combination of hydroclimatic trends and anthropogenic impacts. Their analysis corrects for the impacts of the PDO through a generalized least squares regression. For the South Saskatchewan River basin, Tanzeeba & Gan (2012) concluded that enhanced evaporation caused by rising temperatures will offset increases in future precipitation, contributing to reduced mean annual maximum

flows. Kienzle *et al.* (2011) simulated a range of climate change conditions for the upper North Saskatchewan River basin and found that a shift in the future hydrologic regime will include earlier spring runoff and peak flows, increases in both high and low flow magnitudes, and significantly greater discharge between October and June with correspondingly less between July and September. Barnett *et al.* (2005) indicated that increases in surface air temperatures in the Canadian prairies could lead to an increase in the frequency and severity of droughts (see also Bonsal *et al.* 2013). Wolfe *et al.* (2011) warned that regions dependent on high elevation runoff must prepare to cope with impending water scarcities, especially given that glaciers are smaller now than at any other time within the last 3,000 years.

It is clear that both climate and water resources in western Canada have changed to varying degrees over the recent historical record. Despite results from studies isolated to one or a few individual watersheds, knowledge of how water availability has changed over this region as a whole is still lacking. The CROCWR (Climatic Redistribution of Canada's Water Resources) project (Prowse *et al.* 2013) is concerned with quantifying these changes under past, present, and future climate through analyses of runoff and its driving climatic (Linton *et al.* 2013) and atmospheric forcings (Newton *et al.* 2014a, 2014b) for an area that encompasses most of northern and western Canada. This paper presents a spatio-temporal analysis of runoff in 25 conterminous western Canadian watersheds from 1976 to 2010. Relative to previous trend studies for this area, this research: (i) has a larger geographic scope; (ii) has a focus on relating runoff patterns to changes in the climatic drivers and atmospheric forcings; and (iii) involves a search for evidence in the streamflow records of climate-influenced changes in water availability.

DATA AND METHODOLOGY

Study area and hydrological data

Many of western Canada's largest rivers originate as snow and glacial meltwater from the Rocky Mountains. Tributaries to the Mackenzie River flow northward toward the Arctic Ocean, while streams feeding the Saskatchewan River run eastward toward Hudson Bay. The Pacific Coast of BC is also rich in water resources, with numerous rivers draining the Coast Mountains to the Pacific Ocean. The CROCWR study area covers nine major drainage regions stretching from Manitoba to the Pacific Ocean, and forming parts of the Mackenzie River basin, including the Liard, Peace, Athabasca, Peel, and Great Slave watersheds, and the Saskatchewan River basin, including the North and South Saskatchewan Rivers. The Fraser and Columbia Rivers and a number of Pacific Coast drainage basins are also represented. Basins were further divided into 'upper' and 'lower' contributing areas for the more alpine watersheds to quantify contributions from each.

The study region consists of 25 sub-basins as defined in Table 1 and shown in Figure 1. The sub-basins were delineated based on 37 WSC hydrometric gauging stations. Table 1 provides a summary of the WSC gauging stations used to define each watershed, as well as geographical characteristics of each basin. River basins were separated into upstream, downstream, and/or other contributing areas. Hence, some basins correspond to the contributing drainage area for a WSC gauging station (e.g., a headwater basin such as the Upper Athabasca) while other basins were defined based on subtracting upstream contributing streamflow for one or more gauging stations from a downstream streamflow station to represent the streamflow for a contributing area in the lower part of a watershed (e.g., the Lower Liard). The separate delineation of headwater and downstream areas was done to facilitate comparing the trend characteristics for different parts of the watersheds. For many of these watersheds, the majority of the runoff is generated in the headwater regions. The watersheds defined include a mix of regulated and unregulated regimes; regulation status is noted in Table 1. Much of the Mackenzie River system is unregulated, with the main exception being the upper part of the Peace River system, while much of the Saskatchewan River system is heavily affected by regulation and withdrawals. There is also regulation in the upper portion of the Fraser River on the Nechako River where the Kenney Dam results in a portion of the water being diverted from the Fraser River basin (Déry *et al.* 2012). The regulated portion of the Fraser River is less than 10% of the basin area. The regulation status of

Table 1 | Summary of the study region. Numbers correspond to basins identified in Figure 1

Watershed name	Definition (based on WSC stations)	Latitude (°)*	Longitude (°)*	Drainage area (km²)	Basin elevation (m.a.s.l.)[+]
Liard River Basin					
1 Upper Liard	10BE001	59.97	− 128.56	104,000	1,145
2 Fort Nelson	10CD001	58.16	− 123.65	20,300	970
3 Lower Liard	10ED002 – 10BE001 – 10CD001	60.09	− 123.76	150,700	674
Peace River Basin					
4 Upper Peace [R]	07FD002	56.17	− 123.91	101,000	1,187
5 Smoky River	07GJ001	54.66	− 118.56	50,300	863
6 Lower Peace	07KC001 – 07FD002 – 07GJ001	57.14	− 116.81	141,700	627
Athabasca River Basin					
7 Upper Athabasca	07AD002	52.88	− 117.97	9,770	1,960
8 Lower Athabasca	07DA001 – 07AD002	55.24	− 113.42	123,230	651
9 East Lake Athabasca	07LE002	58.88	− 105.47	50,700	426
10 West Lake Athabasca	07JD002	57.85	− 112.00	35,800	341
Great Slave Lake Basin					
11 Hay	07OB001	58.78	− 118.67	51,700	441
12 Great Slave	Fort Prov.[#] – 07OB001 – 07NB001	62.12	− 112.62	322,300	336
Mackenzie River Basin					
13 Upper Mackenzie	10GC001 – 10ED002 – Fort Prov.[#]	61.61	− 119.24	15,000	252
14 Mid-Mackenzie	10KA001 – 10GC001	64.61	− 122.12	324,500	320
15 Lower Mackenzie	10LC014 – 10KA001	66.00	− 129.81	84,600	245
Peel River Basin					
16 Peel	10MC002	65.44	− 135.50	70,600	855
Pacific Basins					
17 North Pacific	08BB005 + 08CE001 + 08CG001 + 08DB001 + 08EF001 + 08FF001	56.65	− 129.04	117,740	1,187
18 South Pacific	08FA002 + 08FB006 + 08FB007 + 08FC003 + 08GD004	51.95	− 125.47	19,550	1,432
Fraser-Columbia River Basins					
19 Fraser [R]	08MF005	52.56	− 122.40	217,000	1,107
20 Okanagan [R]	08NM085	49.85	− 119.50	7,590	1,185
21 Columbia [R]	08NE058	50.29	− 116.75	155,000	1,590
Saskatchewan River Basin					
22 Upper North Saskatchewan [R]	05DF001	52.55	− 115.78	28,100	1,337
23 Lower North Saskatchewan [R]	05GG001 – 05DF001	52.84	− 110.24	102,900	669
24 Upper South Saskatchewan [R]	05AJ001 + 05CK004	50.79	− 113.31	104,250	957
25 Lower South Saskatchewan [R]	05KJ001 – 05GG001 − 05HG001	53.66	− 104.00	117,000	398

* Latitude and longitude are for the centroid of the watershed area.
[+] Median basin elevation (meters above sea level).
[#] Fort Providence station formed through combination of WSC stations 10GC001, 10ED002, 10FB002, and 10FA002, accounting for travel time.
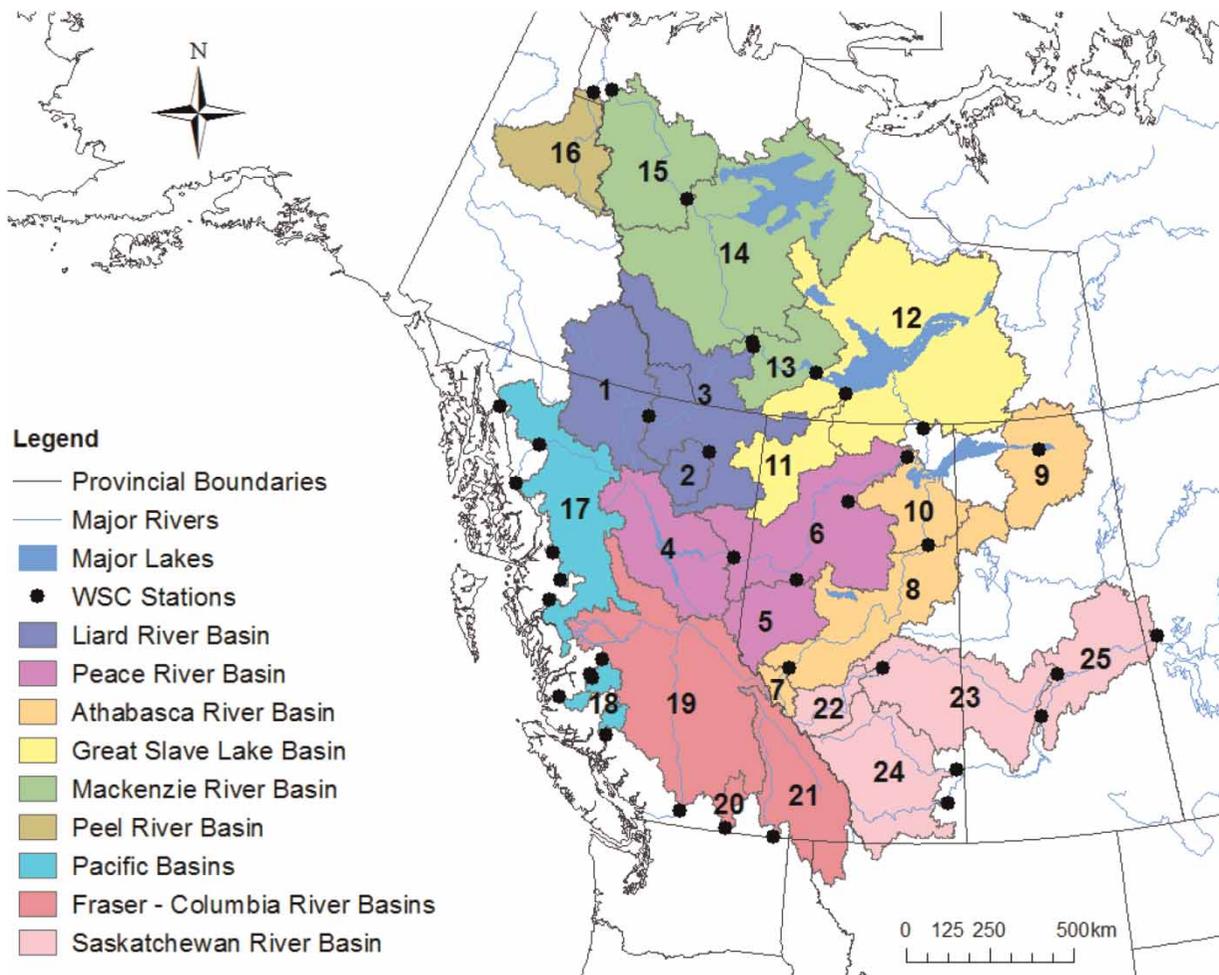[R] Watershed contributing area is affected by regulation.

Figure 1 | Map of the study area showing delineation of the watersheds.

some of the watersheds considered complicates the interpretation of the results of the analysis conducted herein. However, the impacts of the regulation status on the analysis is somewhat mitigated by the analysis of incremental flow contributions between upstream and downstream gauging stations, as outlined in Table 1. While most of the regulation noted above has been in place for the duration of the study period, some of the regulation is more recent, such as the Oldman River Dam in the headwaters of the South Saskatchewan River basin.

The spatial scale of the study area, the diversity of watershed characteristics, and the different hydrologic processes leading to runoff generation mean that interpreting the results of the analysis can be challenging. To address these challenges, individual watersheds are aggregated to better

describe the characteristic responses for different portions of this complex study area.

Definition of variables

Daily streamflow data were downloaded from HYDAT and used to derive monthly streamflow for each watershed based on input and output stations representing upstream and downstream river segments, as defined in Table 1 and explained above. Missing data were not infilled. To remove the effect of watershed size on calculated statistics, monthly runoff values were computed by dividing streamflow by watershed area (Déry *et al.* 2009). Annual and 6-month seasonal runoff records were generated from the monthly runoff series: annual data series were created based on the hydrologic year (October

through September), while seasons were defined as cold (November through April) and warm (May through October). The same definition of warm and cold season was used throughout the study area to facilitate comparison of the results. It is recognized that for the more northerly parts of the study area, portions of the 'warm' season are likely to be rather cold. The time period selected for analysis was 1976 to 2010. While the length of this period (35 years) is shorter than desired for trend analysis, it represents a compromise between the enhanced spatial coverage available for this time period versus reduced data availability, especially for the more northerly stations, associated with longer time periods. This time period is similar to, but slightly longer than, that used by St. Jacques & Sauchyn (2009) in their analysis of trends in northern Canada for 1978 to 2007.

Trend detection

Runoff data were analyzed for trend using the Mann–Kendall (MK) non-parametric test (Mann 1945; Kendall 1975). The MK test is a rank-based statistical tool frequently applied in hydrologic studies for identification of significant trends in data that may be affected by seasonal climatic variability, missing values or extremes (Hirsch & Slack 1984). Following the method of Burn *et al.* (2004b), the trend analysis accounts for serial correlation via the trend free pre-whitening approach developed by Yue *et al.* (2002). The magnitude and direction of MK trends were estimated using the Theil–Sen robust slope estimator (Theil 1950; Sen 1968). Significant trends are reported at both the 5 and 10% significance levels. Field significance (Douglas *et al.* 2000) determines whether the trend behavior for a collection of results is unusual. Field significance is evaluated herein using Walker's test (Wilks 2006). In Walker's test, if there are K sites for which the (local) trend significance has been evaluated, then the smallest of the K *p*-values that have been determined is compared to a critical value that depends on the field significance level selected and the number of tests, K. Field significance is evaluated at both the 5 and 10% significance levels.

Hydrological regionalization

Principal component analysis (PCA) was used to classify distinct areas of runoff variability within the study region. PCA was

applied to the correlation matrix of the annual runoff for the 25 watersheds described in Table 1. PCA produces a new dataset of mutually orthogonal eigenvectors or principal components (PCs) with corresponding eigenvalues listed in decreasing order of importance. The time series related to the first few eigenvectors represent a large fraction of variability of the original dataset. The eigenvectors illustrate how geographical areas of runoff vary together. Spatial patterns often become more easily interpretable and physically meaningful when the eigenvectors are subjected to a rotation; this results in redistribution of the variances among the rotated modes (Jonsdottir & Uvo 2009). The orthogonal Varimax rotation, commonly used in PCA on hydroclimatic data, was applied in this study.

Influence of climate

The relationship between climate and water availability was explored using two methods. First, a correlation analysis was performed between surface climate variables and runoff data to identify the influence of regional temperature and precipitation on water availability in each basin. Data from a newly available Canadian climate dataset, ANUSPLIN, with $10 \text{ km} \times 10 \text{ km}$ spatial resolution (Hutchinson *et al.* 2009; McKenney *et al.* 2011) were used. Eum *et al.* (2014) conducted an extensive comparison of ANUSPLIN and the North American Regional Reanalysis (NARR), with a spatial resolution of $\approx 32 \text{ km}$ (Mesinger *et al.* 2006), for the Athabasca River basin, a subset of the current study area. Eum *et al.* (2014) found ANUSPLIN to have better agreement with adjusted station data (Mekis & Vincent 2011; Vincent *et al.* 2002) and also found that when ANUSPLIN was used as input to the variable infiltration capacity hydrologic model, the modeled streamflow generally provided better agreement with observed streamflow than when NARR data were used to drive the hydrologic model. Both datasets were found to provide comparatively poorer estimates of precipitation and temperature for the alpine headwater areas, as could be expected given the lack of observational data from mountainous areas for input to these datasets. ANUSPLIN was used to derive maximum, mean, and minimum air temperature and total precipitation data spatially averaged over each of the 25 watersheds to create basin-specific, 35-year time series for each climate variable. In addition to annual and 6-month warm- and cold-season series, temperature and precipitation data

were averaged into monthly time series to determine when the climate signal was strongest. Direct correlations between climate variables and runoff were computed for each watershed by measure of Pearson's *R*.

Climate indices were used to explore relationships between runoff and five predominant atmospheric circulation patterns known to describe climate variability in the North Pacific (NP) and Arctic regions. Indices for the Arctic Oscillation (AO), El Nino-Southern Oscillation (ENSO), PDO, and Pacific North American (PNA) modes of variability were obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center (http://www.esrl.noaa.gov/psd/data/climateindices/list). Data for the NP pattern were acquired from the National Center for Atmospheric Research Climate Data Guide (http://climatedataguide.ucar.edu/category/data-set-variables/climate-indices). The interested reader is referred to Bonsal *et al.* (2006) and Burn (2008) for a detailed description of these climate signals. Similar to runoff and surface climate data, climate index values were averaged into annual and 6-month series.

Since climate signals can exhibit strong connections with runoff in one phase, but weak teleconnections in the other, a direct linear correlation could fail to detect important signals; thus, a composite analysis approach was taken. Following the method of Maurer *et al.* (2004) and Burn (2008), the eight largest and eight smallest values in the series for each climate index were selected and runoff values for each watershed were examined for the years associated with each of the selected climate index values. A *t*-test was performed on the eight selected runoff values to determine whether runoff during these high (positive phase) and/or low (negative phase) climate index years differed significantly from the series mean. Normal probability plots were constructed to assess whether the runoff series followed a normal distribution; a loss of power for the *t*-test may have resulted in the few instances where a series deviated from the normal.

RESULTS

Trend analysis

The results of MK trend detection for 1976–2010 annual runoff are presented in Figure 2. The annual runoff trends are not field significant at the 10% significance level. A general tendency towards higher runoff in the most northern basins is apparent, while the band of watersheds stretching across the mid-latitudes of the study region has clearly experienced a shift toward decreased runoff (with the exception of the NP basin on the west coast). There are some clear exceptions to this pattern, however; namely, the Peel and Mid-Mackenzie basins exhibited slight decreasing tendencies on an annual basis, distinguishing them from the pattern observed for the other watersheds north of 60°N. No consistent trend direction was noted for the southernmost basins in the study region, however, it was interesting and unexpected to have slight increasing trends for the South Saskatchewan River basin, especially given the results of previous research. This may be attributable to the large degree of regulation this basin has undergone, and to the relatively short period of record studied.

Warm- and cold-season trends generally resembled those for the annual results, but some discrepancies are worth noting. For the warm season, decreasing trend slopes in the mid-latitudes were generally stronger in magnitude, indicating that a large portion of the 'drying' in these basins occurred during the summer months. The warm season runoff trends are field significant at the 5% significance level. For the cold season, a greater number of basins in the upper latitudes exhibited increasing trends, including the Peel River basin, while the Mid-Mackenzie River basin showed no overall trend and the Upper Mackenzie basin experienced a slight decreasing tendency ($p > 0.1$). Decreasing trend slopes in the mid- and lower latitude basins tended to be weaker in magnitude during the cold season than was noted for both the warm-season and annual runoff variables. This is likely attributable to the fact that overall runoff is substantially lower during the winter months and therefore changes are likely to be smaller. The cold season runoff trends are not field significant at the 10% significance level.

As noted earlier, the study area consists of a mix of regulated and unregulated watersheds (see Table 1). The southern portion of the study area is heavily impacted by regulation. As described above, the southern portion of the study area did not exhibit strong trend behavior and experienced a mix of increasing and decreasing trends at the watershed level. Some of the observed trends, while not
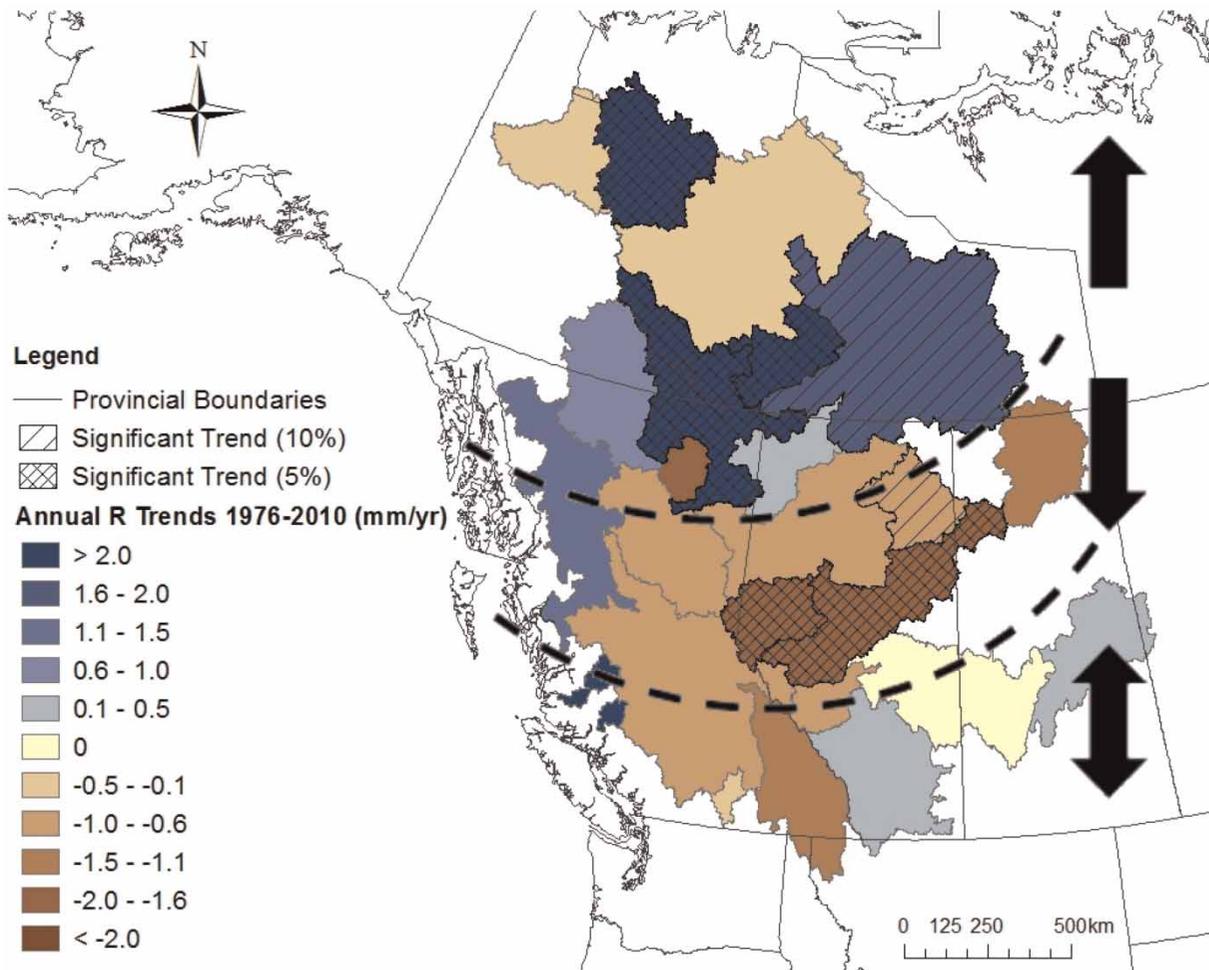
Figure 2 | Annual runoff trend magnitudes.

strong, are contrary to expectations based on previous work, especially in the South Saskatchewan River basin. It is possible that the regulation status of this watershed has had an impact on the observed trends. The other regulated sub-watershed is the Upper Peace, which is affected by the W.A.C. Bennett Dam. This sub-watershed exhibits similar trend behavior to other nearby watersheds, suggesting that the regulation status of this sub-watershed has not had an appreciable effect on the trend behavior. Areas downstream of the Upper Peace will be affected by the regulation of the Upper Peace; however, since watersheds are defined in this work based on the contributing areas between gauging stations, the subtraction of upstream flows from downstream flows should mitigate the possible impacts of regulation on the downstream contributing areas.

PC analysis

Rotated PCA of annual runoff revealed three regions of coherent hydrological variability: the high latitudes or 'northern region' (NR), the mid-latitudes or 'middle region' (MR), and the lower latitudes or 'southern region' (SR). These three regions were also prevalent for the warm season, however cold-season PCA showed a somewhat different outcome, most notably due to differences in basins loading to the MR PC. The first three PCs accounted for 53.9% of variance in annual runoff, 53.5% in warm-season runoff, and 49.0% in cold-season runoff. Figure 3 presents the first three PCs for annual runoff. Factor loadings with magnitudes of 0.32 to 0.55 were considered significant but weak; loadings of 0.55 to 0.78 were considered moderate; and loadings of 0.78 to 1.0 were considered strong.
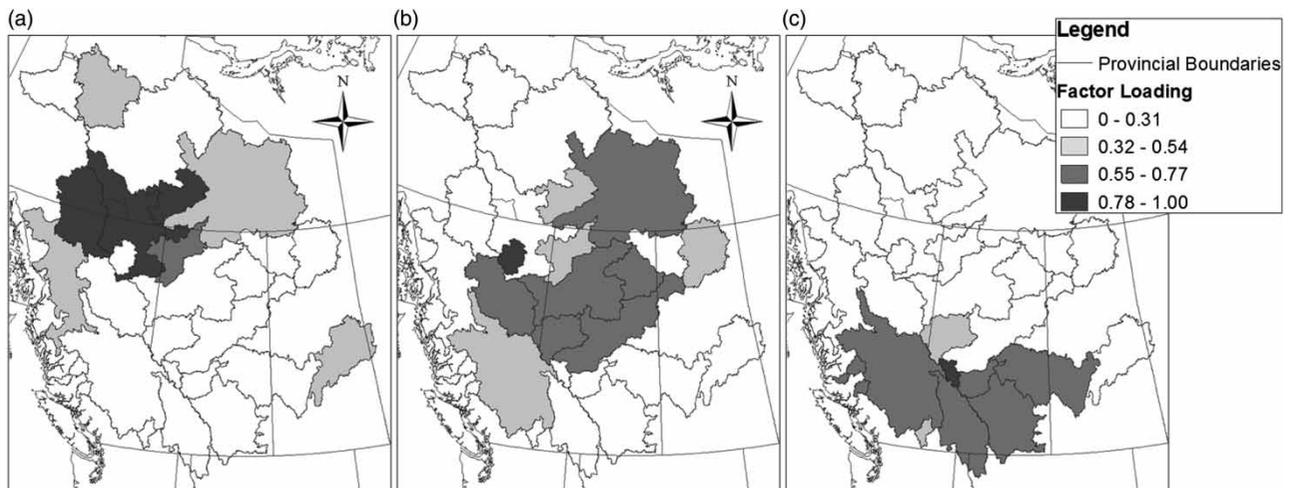
Figure 3 | Annual runoff PC loadings for each watershed for the PC defining the northern region (a), middle region (b), and southern region (c).

For annual and warm-season runoff, the NR included mainly watersheds that exhibited increasing trends or tendencies on both an annual and seasonal basis. The Mid-Mackenzie and Peel River basins again differed from surrounding watersheds by not loading significantly to the NR PC. The MR included mainly watersheds that displayed decreasing runoff trends and tendencies annually and seasonally, including the Peace–Athabasca River system. The MR included the largest number of basins during the warm season, extending both northward and southward; this region was least similar during the cold season, when significant loadings stretched as far northwest as the Liard River basin. For all three variables, the SR consisted of the lowest latitude basins, however the region also extended north for the cold season,

encompassing the NP and Athabasca River basins, as well as a portion of the Liard–Mackenzie River region.

For each variable, the runoff data matrix was projected onto the PC loadings matrix to obtain time series for each PC. The correlation matrix was specified in the PCA to avoid loadings being focused exclusively in regions of high runoff (Maurer *et al.* 2004), hence PC factor loadings represent patterns of spatially coherent runoff anomalies (Lins 1997). MK trend analysis was performed on the PC scores, providing a source of comparison between watershed-scale trend results. Figure 4 shows plots of the first three PC scores for annual runoff. Table 2 provides PC score trend results for each variable. Trend slopes are in units of runoff anomaly per year (or per 35 years).
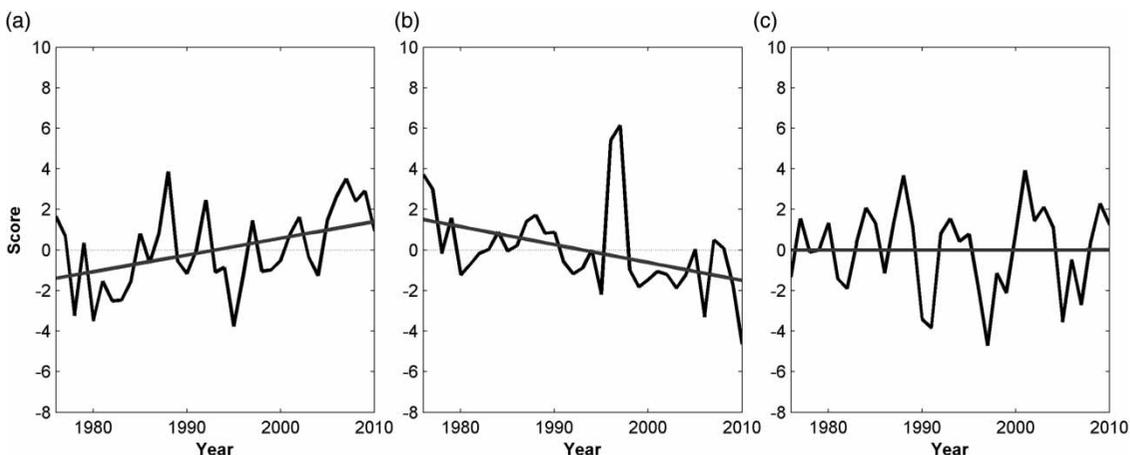

Figure 4 | Time series of annual runoff PC scores for the northern region (a), middle region (b), and southern region (c).

Table 2 | Trend slopes (anomaly per year or per 35 years) for each PC region. Bold slopes are significant at the 5% significance level

	Northern region		Middle region		Southern region	
	/yr	/35 yr	/yr	/35 yr	/yr	/35 yr
Annual runoff	**0.1**	**3.2**	− 0.1	− 2.9	0	0.1
Warm-season runoff	**0.1**	**2.9**	− 0.1	− 3	0	− 0.5
Cold-season runoff	0.1	1.9	**0.1**	**4**	0	0.4

Regional trend analysis of PC scores confirmed observations that the higher latitudes have experienced significantly increased runoff, while the mid-latitudes have undergone reduced runoff both annually and during the warm season. For the cold season, only the MR displayed a significant trend in the positive direction; however, it is important to reiterate that the cold-season MR differed from both the annual and warm-season MR. The cold-season MR encompassed a number of northern basins, including the Liard and NP River basins, therefore it was not unexpected to see an increasing trend here. The annual and warm-season increases in high-latitude runoff and related drying of the mid-latitude subtropics reflect documented north–south contrasts in precipitation patterns (e.g., Serreze et al. 2000; Zhang et al. 2007; Min et al. 2008).

Correlation analysis

Annual, warm-season, and cold-season runoff series were correlated with maximum, mean, and minimum air temperatures and total precipitation data for the corresponding annual, warm season, and cold season, as well as for the preceding year, cold season, and warm season, respectively. The number of basins that showed a significant ($p < 0.05$) correlation between runoff and each climate metric is given in Table 3. Average Pearson R values (R_{avg}) for the basins that experienced significant correlations are also provided. Bold values indicate relationships in which more than half of the basins exhibited a significant correlation.

Table 3 shows that precipitation is a much stronger driver of runoff than is air temperature, at least during the warm season and annually. Eighty percent of the basins studied exhibited a significant correlation between annual runoff and annual precipitation of the same year, whereas less than half showed relationships between any measure of temperature and runoff. Antecedent temperature and precipitation from the preceding year were also shown to not have much influence on annual water availability.

Warm-season runoff was highly influenced by precipitation during both the warm season as well as the preceding cold season. A positive correlation for both relationships indicates that increased precipitation was related to increased runoff and decreased precipitation

Table 3 | Summary of correlation analysis between runoff and surface climate variables. The number of basins that exhibited a significant correlation between runoff and each measure of climate is given, as is the percent out of 25 watersheds. R_{avg} values indicate average Pearson R of correlations that were significant at the 5% significance level

	MaxT	MeanT	MinT	Precip	MaxT	MeanT	MinT	Precip
Annual runoff	**Same year climate**				**Preceding year climate**			
# of basins (%)	5 (20)	4 (16)	5 (20)	**20 (80)**	2 (8)	2 (8)	2 (8)	6 (24)
R_{avg}	− 0.39*	− 0.39*	0**	**0.62**	− 0.36	− 0.36	− 0.35	0.60
Warm-season runoff	**Warm-season climate**				**Preceding cold-season climate**			
# of basins (%)	8 (32)	3 (12)	1 (4)	**16 (64)**	6 (24)	6 (24)	6 (24)	**15 (60)**
R_{avg}	− 0.44	− 0.47	− 0.49	**0.60**	− 0.46*	− 0.48*	− 0.48*	**0.49**
Cold-season runoff	**Cold-season climate**				**Preceding warm-season climate**			
# of basins (%)	7 (28)	7 (28)	8 (32)	6 (24)	0 (0)	0 (0)	0 (0)	11 (44)
R_{avg}	0.47*	0.49*	0.46*	0.26**				0**

* R value for one basin was opposite in sign from all other basins exhibiting significant correlation and hence was excluded from R_{avg} calculation.
** Sign of R value was inconsistent among stations.
MaxT = maximum temperature, MeanT = minimum temperature, MinT = minimum temperature, Precip = precipitation.
Bold values indicate relationships in which more than half of the basins exhibit a significant correlation.

related to decreased runoff. The relationship between warm-season runoff and temperature was opposite, where generally increases in temperature (during both the warm and cold seasons) corresponded to decreases in warm-season runoff and vice versa. This relationship, however, was not as pronounced over the study region, indicating that evapotranspiration is not as strong a driver of runoff as is precipitation. Correlations were also calculated between warm-season runoff and temperature and precipitation data for the individual months of March through October. Overall, June climate was shown to have had the strongest influence on warm-season runoff, with 10 sub-basins exhibiting significant correlations between runoff and precipitation, and nine sub-basins displaying a significant relationship between maximum temperature and warm-season runoff. This result is likely because the largest increase in runoff occurs at the onset of the spring freshet, which begins in June for the majority of these basins, and hence even small changes in climatic conditions during this period can strongly affect runoff response.

Cold-season runoff was shown to be significantly correlated with precipitation from the preceding warm season in 11 of the 25 sub-basins. The sign of these correlations, however, were highly variable resulting in an average Pearson R value of 0 for this relationship. The relationship between cold-season runoff and temperature was shown to be opposite in sign to what was found for warm-season runoff; increases in temperature during the cold season resulted in increases in cold-season runoff for the majority of sub-basins that exhibited a significant correlation. This is likely due to the fact that increases in temperature have caused earlier spring melt (which now occurs during the cold season in some watersheds) (Linton et al. 2013) as well as later autumn freeze-up, meaning more open-water flows during the cold season. Cold-season runoff was also correlated with temperature and precipitation from the months of September through April; no strong relationship was apparent between runoff and any of the climate variables for any one month in particular.

Teleconnections

Significant relationships between runoff and large-scale atmospheric and oceanic processes are presented in

Table 4. A relationship was deemed noteworthy if four or more basins (at least 16% of the total) experienced runoff that differed significantly ($p < 0.05$) from the series mean for the 8 years of highest (positive phase) or lowest (negative phase) climate index values. Similar to correlation analysis with surface climate, teleconnections were investigated for runoff during the same year or season as the climate anomaly, as well as for runoff during the year or season following the climate anomaly.

No significant relationship was observed between any runoff variable and a climate index corresponding to the same period of time. For the lag 1 analysis, however, the PDO and the PNA were shown to exhibit significant influences on runoff. The negative values of the PDO index from the preceding year were associated with reduced runoff in seven out of eight basins showing a significant relationship with this climate index. These basins were concentrated in the MR and SR of the study region, confirming that the PDO has an influence in the more southerly rivers, including those originating in the Rockies. Negative values of the preceding warm-season PDO index were also associated with decreased cold-season runoff, while positive values of the PDO index in the preceding cold-season were associated with decreased warm-season runoff; both observations were again concentrated among the mid- and lower-latitude watersheds. In addition, the positive phase of PNA from the preceding cold season was related to decreased warm-season runoff in basins originating in the

Table 4 | Summary of composite analysis between runoff and climate indices. The number of basins that exhibited a significant relationship between runoff and the climate index is given, as is the percent out of 25 watersheds

	Climate index (phase)	# of basins (%)	Climate index (phase)	# of basins (%)
Annual runoff	**Same year climate**		**Preceding year climate**	
	None	–	PDO (−)	8 (32)
Warm-season runoff	**Warm-season climate**		**Preceding cold-season climate**	
	None	–	PDO (+)	5 (20)
			PNA (+)	4 (16)
Cold-season runoff	**Cold-season climate**		**Preceding warm-season climate**	
	None	–	PDO (−)	7 (28)
			PNA (+)	4 (16)

The positive phase of a climate index is denoted by a '(+)', while the negative phase is denoted by a '(−)'.

Rocky Mountains, while the same index phase from the preceding warm season was associated with increased cold-season runoff in basins originating outside of the Rockies. The positive phase of the PNA is associated with above-average temperatures over western Canada. The AO, ENSO, and NP indices did not exhibit any significant relationships with runoff at the annual or seasonal time scale.

It should be noted that the PDO is considered to have been in a positive phase since 1976; hence the duration of the present study has been part of a positive PDO phase. However, there have been times during this positive PDO phase when the PDO index has had a negative value, most notably 3 or 4 years around 2000 and also towards the end of the current study period (2010). As such, while the relationships with negative PDO are not as meaningful as they would be if derived from a longer time frame incorporating a longer portion of the PDO cycle, they are nevertheless indicative of the impact that this climate index can have on hydrologic conditions within portions of the study domain. While Fleming *et al.* (2006) noted different responses to teleconnections for glaciated versus nival basins, differences were not noted in this work. This may be partly a reflection of the larger size of the headwater basins in this work relative to the size of basins examined in Fleming *et al.* (2006). The size of the headwater basins for our study will result in the basin response being a combination of a glacial response and a nival response, hence blurring any distinction in these behaviors.

DISCUSSION AND CONCLUSIONS

Trends in western Canadian runoff were analyzed for the period of 1976–2010. Overall, runoff was found to have increased in most watersheds north of 60°N, especially during the cold season, but with some notable exceptions – namely, the Peel and Mid-Mackenzie River basins, which displayed decreasing tendencies in both annual and warm-season runoff. The mid-latitude watersheds, with the exception of the NP basin, generally experienced decreased runoff for all variables, implying a northward shift in water availability from adjacent southerly basins. Watersheds bordering the continental United States (i.e., the lowest latitude basins) showed a mix of both increasing and decreasing

tendencies, suggesting the prediction that the 'lower latitudes are becoming drier' is not applicable in all cases. However, this result may also be due to the large degree of regulation that has occurred in a number of these basins (e.g., the Fraser and South Saskatchewan River basins) where increasing population has increased water demands. Hence, because of such regulation, it is difficult to discern the exact factors controlling these trends (e.g., natural variability, anthropogenic climate change or other).

PCA of runoff data revealed three regions of coherent runoff variability: the NR, MR, and SR. Consistent with the results of watershed-scale trend analysis, the NR experienced increased runoff for all variables, while the MR exhibited decreased runoff both annually and during the warm season; for the cold season, the formation of the MR was notably different, including some high-latitude basins, and consequently the region saw an overall increase in runoff anomaly. No trend was present in SR runoff for any variable due to a mix of both increasing and decreasing trends occurring within individual basins in this region.

While there have been a number of previous studies that have examined trends in streamflow for portions of the study area examined herein, direct comparison of the earlier results to the present results is challenging due to the inclusion of different gauging stations, different analysis methods, and different periods of analysis. Nevertheless, there are some notable similarities between the main outcomes of this work and previous work and also some cases where differences have been noted. The north–south contrast in trend results noted herein for the study area can also be seen in the results of Zhang *et al.* (2001), albeit for an earlier and shorter time period (1967–1996). Other studies have examined portions of the current study area. Whitfield (2001) found: increased flow in the coastal mountains, consistent with increasing annual flows in the North and South Pacific watersheds in this study; increased streamflow in northern BC and Yukon, consistent with increased annual flow in the northern region for this study, although this study does not include as much of the Yukon as was the case for Whitfield (2001); and decreases in the flow for the Okanagan, as was also found in this study. Burn *et al.* (2004a) noted a constrast between the Liard and Athabasca Rivers, with the latter displaying generally decreasing trends. In this

work, the Athabasca is part of the MR (decreasing trends) and the Liard is part of the northern region (increasing trends). St. Jacques & Sauchyn (2009) found increases in baseflow and, to a lesser extent, annual flow in the Northwest Territories which corresponds to increasing flows in the cold season and on an annual basis in the northern region for this study. An area of disagreement is the Saskatchewan River basin for which this study identified slightly increasing trends in contrast to other studies that have shown decreasing trends (Rood *et al.* 2008; St. Jacques *et al.* 2010). The short data record for the present study and the impacts of regulation in this watershed may partially explain this anomaly.

Correlation analysis with surface climate variables revealed that runoff in the majority of western Canadian watersheds is significantly and positively influenced by precipitation, but that the effect of temperature, and in effect evapotranspiration, varies seasonally and is not as strong or widespread. This has important implications for projecting future water availability within western Canada, as the quality and certainty of climate model projections for precipitation are weaker than those for air temperature. In addition, composite analysis with large-scale climatic processes revealed that, although runoff in some basins was significantly related to the PDO and PNA patterns, the runoff regimes for a vast majority of basins, especially in the north, were not influenced by any teleconnection. This suggests that changes in western Canadian runoff between 1976 and 2010 were likely caused by other factors, including more meso-scale climatic changes. If future changes in climate enhance the north–south contrasts in air temperature and precipitation regimes, this will likely be further reflected in similar runoff-regime patterns and will create a greater need for revised water management, including potential re-allocation.

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