Climate Change and Hydrology at the Prairie Margin: Historic and Prospective Future Flows of Canada's Red Deer and other Rocky Mountain Rivers

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Abstract

The South Saskatchewan River Basin of southern Alberta drains the transboundary central Rocky Mountains region and provides the focus for irrigation agriculture in Canada. Following extensive development, two tributaries, the Oldman and Bow Rivers, were closed for further water allocations, while the Red Deer River (RDR) remains open. The RDR basin is at the northern limit of the North American Great Plains and may be suitable for agricultural expansion with a warming climate. To consider irrigation development and ecological impacts, it is important to understand the regional hydrologic consequences of climate change. To analyze historic trends that could extend into the future, we developed century-long discharge records for the RDR, by coordinating data across hydrometric gauges, estimating annual flows from seasonal records, and undertaking flow naturalization to compensate for river regulation. Analyses indicated some coordination with the Pacific Decadal Oscillation and slight decline in summer and annual flows from 1912 to 2016 (-0.13%/year, Sen's slope). Another forecasting approach involved regional downscaling from the global circulation models (GCMs), CGCMI-A, ECHAM4, HadCM3, and NCAR-CCM3. These projected slight flow decreases from the mountain headwaters versus increases from the foothills and boreal regions, resulting in a slight increase in overall river flows (+0.1%/year). Prior projections from these and other GCMs ranged from slight decrease to slight increase and the average projection of -0.05%/year approached the empirical trend. Assessments of other rivers draining the central and northern Rocky Mountains revealed a geographic transition in flow patterns over the past century. Flows from the rivers in Southern Alberta declined (around -0.15%/year), in contrast to increasing flows in northeastern British Columbia and the Yukon. The RDR watershed approaches this transition and this study thus revealed regional differentiation in the hydrological consequences from climate change.

Keywords: climate change; empirical trend analysis; hydroclimatic modeling; river discharge

Introduction

With fertile soils, abundant sunshine and warm summers, the North American Great Plains provides a global centre for agricultural crop production (Cunfer, 2005). This vast region of ~1.3 million km^2 supports prairie grasslands where local precipitation is insufficient for trees and forests. With this semiarid climate, there has been extensive irrigation development to increase crop diversity and yields, and the water distribution is efficient due the commonly flat terrain. With global warming, it is likely that this prairie ecoregion will expand northward and there would likely be a corresponding northward expansion of crop production and agricultural irrigation (Rosenberg et al., 2003).

The northern region of the Great Plains is situated in Canada, primarily within the South Saskatchewan River Basin (SSRB) of southern Alberta and southwestern Saskatchewan. The SSRB watershed supports around 70% of Canada's irrigated lands (Statistics Canada, 2011) and includes three major tributaries. Of these, the Oldman and Bow Rivers have been extensively developed for agricultural irrigation and were assessed as fully allocated by the year 2000, prompting their closure for further water licenses, and a water market system was established to allow continuing regional development (Pentney & Ohrn, 2008).

The northern tributary, the Red Deer River, remains open for further water allocation and this sub-basin is at the northern margin, or limit of the Great Plains. Prospective impacts of climate change on the flows of this river system are consequently of particular regional interest relative to the northward expansion of specialty crop production and agricultural irrigation. There is also broader interest since this zone provides the transition from the prairie grassland to the aspen parkland ecoregions, and this transition is likely to migrate northward with global warming (Schneider et al., 2009). Climate change is likely to have substantial influence on this transition since the warming climate is predicted to the have the greatest impact on the hydrological cycle in snow-dominated watersheds at higher latitudes (Barnett et al., 2005; Huntington & Niswonger, 2012; Nogués-Bravo et al., 2007).

While increasing temperatures with climate change are more universal, regional changes in the quantity and seasonality of precipitation are much more variable, and projections of impacts of climate change on river flows are correspondingly less certain (Stephens et al., 2010; Stevens & Bony, 2013). Winter warming alters the distributions of rain versus snow-fall, increasing winter flows and decreasing snow pack accumulations (Lapp et al., 2005). With spring warming, snowmelt and the commencement of the spring river flow peak have often advanced (Cayan et al., 2001; Mote et al., 2005; Rood et al., 2008). Overall precipitation has increased in some regions but due to increased evaporation (Tanzeeba & Gan, 2012), river flows in mid- to late summer have gradually declined from some rivers draining the Rocky Mountains. This has involved the central Rocky Mountain region, which straddles the international border and provides the headwaters for the SSRB tributaries which flow northeastward to Hudson Bay, (Rood et al., 2005; 2008; St. Jacques et al., 2010; 2013).

However, the hydroclimatic changes may vary considerably across geographic regions and current research efforts seek to better understand localized responses within and across watershed-scales. With this objective, this study was undertaken to analyze the historic and prospective future hydrology of the Red Deer River and its headwater tributaries. Based on prior studies, we expected that:

(1) air temperatures would have increased over the past century, particularly in the winter, while precipitation may have slightly increased;

(2) river flows would have progressively declined, especially summer and autumn flows;

(3) projections of river flows from hydroclimatic modeling following global circulation model (GCM) downscaling could provide similar outcomes as empirical trend projections; and

(4) there would be generally similar patterns of river flow change for the rivers that drain the central Rocky Mountains towards Hudson Bay, but there could be differences for more northerly drainages that flow to the Arctic Ocean.

Methods

The Red Deer River Basin

The Red Deer River (RDR) Basin is the most northern, and by area the largest sub-basin in the South Saskatchewan River Basin, but contributes only ~20% of the South Saskatchewan River flow (Clipperton et al., 2003). The RDR headwaters are in the Rocky Mountains of Banff National Park and the river flows eastward through foothills, boreal, and parkland natural regions, through the City of Red Deer and then the semi-arid badlands before joining the South Saskatchewan River near the Saskatchewan border (Figure 1). While mountain and foothills include about 20% of the RDR Basin area, these regions upstream of Red Deer provide ~85% of the total river flow (Gill et al., 2008).

1. Historical Temperatures and Precipitation in the Red Deer River Basin

To assess historical patterns in temperatures and precipitation, which could influence river flow patterns, we chose regional weather stations with the most complete records across the upper watershed, and avoided the City of Red Deer station due to possible influence from urban development. Subsequently, monthly and annual temperatures for stations at Banff, Rocky Mountain House, Olds and Lacombe were obtained from Environment and Climate Change Canada's Second Generation Homogenized Surface Air Temperature Database (Vincent et al., 2012), and generally extended from 1912 to 2016. These time series were infilled for occasional missing temperatures, through linear regression with values from adjacent stations that provided tight correspondences ($r^2 = 0.97$; Philipsen, 2017).

For precipitation, daily rainfall gauge and snowfall ruler data were extracted from the National Climate Data Archive of Environment Canada (https://www.ec.gc.ca/dccha-ahccd/default.asp?lang=en&n=2E5F8A39-1), following measurements that commenced in 1917. These data follow corrections for rain and snow measurements, as well as some merging of data from neighboring stations (Vincent et al., 2012). The record still includes occasional data gaps and we investigated trends in the monthly precipitation records without any data infilling. Annual precipitation records are more affected by the data gaps since a missing record for any month excludes a total for that year. Since regional precipitation is heaviest in summer, for gaps in other seasons, the average monthly values from the full record provided estimates for the data gaps and this allowed an estimation of annual precipitation for that year. However, because this data extension introduced errors, our statistical analyses emphasized the measured monthly values, rather than the infilled annual precipitation series.

2. Historical River Flows in the Red Deer River Basin

Streamflow data were obtained from HYDAT, the Water Survey of Canada's Hydrological Database (http://wateroffice.ec.gc.ca/). Trends in mean annual discharge (Q_a) and mean monthly discharge (Q_m) were analyzed for the available gauging locations (Figure 1, Table

1). Discharge records for the upper tributaries were limited since gauging only commenced around 1970. Longer records existed for the RDR at Red Deer but the upstream Dickson Dam and Gleniffer Reservoir were implemented around 1983. The dam was operated to capture and store water in the summer, for subsequent flow augmentation through the winter, partly to ensure sufficient dissolved oxygen for the aquatic ecosystem when the river was ice-covered. Subsequently, the monthly *Q* have been altered but annual flows are relatively unchanged due to the proportionally small size of Gleniffer Reservoir, and limited carry-over across years.

We analyzed temporal trends in annual and monthly temperatures, precipitation and *Q* with three statistical correlation tests using SPSS v.19 (IBM, Armonk, NY): (1) Pearson product moment correlations (*r*) that are similar to linear regressions; and two non-parametric rank-order tests, the (2) Kendall's τ, and (3) Spearman ρ tests. For preliminary analyses of *Q* trends (Gill et al., 2008; Philipsen, 2017) we undertook pre-whitening (Yue & Wang, 2002), but final analyses assessed the original data since pre-whitening attenuates trends and autocorrelation is less problematic for century-long data series (Rood et al., 2008). The analyses provided very similar outcomes with and without pre-whitening.

3. Prospective Future Climate and River Flows - Empirical Trend Projection

Empirical trend projection anticipates that the near future will extend from the recent past and thus extends the regressions from the historic *Q* time series. We focused on the RDR at Red Deer and to compensate for flow regulation at Dickson Dam, naturalized weekly *Q* values were obtained from Alberta Environment's Natural Flow Database (Alberta Environment, 1998). That dataset had been extended to provide weekly discharge data for the period from 1912 to 2009 and monthly *Q* were subsequently calculated. We undertook a similar reconstruction to further extend the monthly *Q* to 2013, by combining the inflows from the upstream reach and tributaries (Figure 1), and undertaking a regression-based correction based on the pre-dam interval (Philipsen, 2017). Our naturalized *Q* and Alberta Environment's naturalized *Q* produced very similar results, with tight correspondences for annual and mean monthly *Q* (r^2 = 0.99 and r^2 = 0.98, respectively).

In the correlation analyses for the RDR at Red Deer, Pearson *r* (linear regression) outcomes differed substantially from those of the non-parametric rank-order tests, and this reflected the exceptionally high flow years of 1915 and 1916, near the commencement of the time series. This would inflate the slopes in linear regression analyses and to compensate for these early outliers, we assessed the Sen's slopes, as calculated with MAKESENS (Salmi et al., 2002), with modification to accommodate data series that exceeded 100 values. The Sen's slopes for the monthly and annual *Q* time series were determined and we then extended these patterns forward to 2062, a century from 1962, the mid-point of the 1912 to 2013 historic record that was analyzed.

4. Projections from Global Circulation Models, Regional Downscaling and River Flow Routing

The analysis applied a similar approach to that described by Shepherd et al. (2010), a modeling sequence that provided river flow projections that converged with empirical trend projections for the Oldman River, also in the SSRB. The approach applied lumped models, which aggregate processes throughout a basin with the application of statistical methods to characterize quantitative associations, an approach that was suitable for the available environmental records for the RDR Basin (Bingeman et al., 2006; Kouwen et al., 2002; Pietroniro et al., 2006). The emissions scenarios were from CMIP3 (Coupled Model

Intercomparison Project phase 3), which provided very similar spatial patterns of temperature and precipitation change as the subsequent CMIP5 scenarios (Knutti and Sedláček, 2013; Wuebbles et al., 2014).

We applied four global circulation models (GCMs), CGCMI-A, ECHAM4, HadCM3 and NCAR-CCM3, using a scenario with a balanced emphasis on energy sources, SRES A1B, and statistically downscaled the data using an inverse distance process (Shepherd & McGinn, 2003). These models produce moderate projections relative to the range provided by the numerous GCMs (St. Jacques et al., 2018). These models and variants have been commonly applied across western North America (Shepherd and McGinn, 2003; Coquard et al., 2004; Shepherd et al., 2010; Gray & Hamann, 2013), including for rivers in the SSRB (Table 2).

Regionalization involved hydroclimatic downscaling from the GCM projections with watershed modelling for the tributary sub-basins upstream of Red Deer (maps and further details are provided in Gill et al., 2008). This commenced with the Mountain Climate model (MTCLIM; Hungerford et al., 1989), which was used to transform temperature and precipitation from base locations to mountain sites throughout the RDR basin through regressions with physical parameters. Historical base weather station data from 1960 to 1989 were obtained from Agriculture & Agri-Food Canada and downscaled to a 50-×-50 km grid of Alberta through the inverse distance squared method developed by McGinn et al. (1999). Climate grid points were extracted and input with site parameters including elevation, slope and aspect, derived from digital elevation models, and physical parameters including latitude and regional adiabatic lapse rate (Berg et al., 2007). However, this free-air lapse rate may have slightly overestimated the surface lapse rate, and temperature inversions are common in the winter (Wood et al., 2018), further challenging the modeling. The precipitation module of

MTCLIM was modified to derive precipitation from base sites rather than from isohyet maps, which were unavailable for some locations. To verify the modified MTCLIM model, simulated temperature and precipitation outputs were compared with meteorological data at two sites, Ricinus and Cuthead Lake (51°27'N, 115°46'W; in the Rocky Mountain foothills).

Outputs from MTCLIM were input into a snowpack and snowmelt module, with a modification of the UBC model SNOPAC (Pipes & Quick, 1977; Wyman, 1995; Lapp et al., 2005). Areas of each watershed in the headwaters of the Red Deer River were categorized into 48 topoclimatic classes by combining elevation, slope and aspect, and temperature and precipitation values were derived (Shepherd et al., 2010). This simulated whether precipitation fell as rain, snow, or a combination, based on a minimum and maximum projected air temperatures. Above a threshold, snowmelt was determined based on temperature, a point melt factor and reference dew point. Throughout the winter, snowpack increased and decreased, reflecting the balance between rain, snowfall and melt, which was aggregated with rainfall to provide water yields for each position in the upper tributary watershed (presented by Gill et al., 2008), and subsequently for the whole RDR Basin.

Water yields were translated into stream discharge using the river flow routing module, RIVRQ developed by Shepherd et al. (2010). This assessed stream discharge with two major components: contributions from a relatively stable perennial baseflow, and a more dynamic component arising from large rain or snowmelt events. We defined baseflow for each tributary as the typical annual low flow rate during the ice-free period and when water yield exceeded baseflow, alluvial aquifer recharge was the second priority of RIVRQ. After this removal, further water yield increased the downstream river flows, with accumulation over the river basin incorporating transit lags.

To compensate for the limited evapotranspiration modeling and for model inaccuracies, the final step in the hydroclimatic modeling was the application of quadratic regression corrections based on the RIVRQ-simulated versus measured river discharges for the record interval. Changes in annual and mean monthly discharge were forecast from the thirty year period around 1975 (1960 to 1989) relative to the thirty year period around 2055 (2040 to 2069) with the modelled future compared to the modelled past to compensate for differences between the actual recorded and modelled historic datasets.

5. Historical Flows of Other Rocky Mountain Rivers

Extending from prior analyses for the eastern drainages from the central and northern Rocky Mountains (Rood et al., 2005; 2015; 2017), we pulled forward the times series for the mean annual discharges (Q_{annual}) of major rivers with longer-term hydrometric records (Table 1). These study rivers generally drain relatively pristine watersheds, including a number of parks and protected areas, and this would reduce the confounding impacts from changes in land use that alter infiltration and run-off. Some rivers were regulated, but there would generally be limited carry-over across years and this would have slight influence on the Q_{annual} pattern with century-long time series.

As previously described (Rood et al. 2005; 2017), some flow series were extended to earlier intervals through linear regressions to derive Q_{annual} from records that lacked winter monitoring. All of these rivers displayed nival, or snowmelt-dominated patterns, with very low natural winter flows, which enabled these data extensions. Similar to the analyses for the rivers of the RDR Basin, we undertook trend analyses with three correlations, including the Pearson r and non-parametric Kendall τ and Spearman's ρ. We again present only the Kendall τ results if the three statistical tests provided similar outcomes. We also applied linear regressions to the historic time series to estimate the change rates with the regression slopes represented as % of the mean Q (Table 1).

For tables and graphs, red indicates drying effects with declining water (precipitation of discharge) or increasing temperature, and blue indicates wetter conditions with increasing water or decreasing temperature.

Results

1. Historical Temperatures and Precipitation in the Red Deer River Basin

There has been substantial warming in the RDR Basin over the past century, with a progressive increase superimposed on substantial interannual variation (Figure 2). Warming was fairly similar across the four locations with about a 1.5°C rise in the annual mean over the past century (Table 3). Across the months, warming was significant in the winter interval of January, February and March, and also for September, with more localized warming in the summer months of June, July and August (Table 3). The annual and monthly temperature increases were similarly detected with the Pearson product correlation and the two non-parametric rank order tests, with results for the three tests displayed for Lacombe (Table 3). Test results were similarly consistent for the other stations. The correlation coefficients were quite similar for the Pearson product and Spearman ρ tests, while the Kendall τ test was slightly more conservative (Table 3).

Based on linear regressions, which provide the basis for the Pearson product correlation, monthly changes over the past century are displayed in Figure 3 for Rocky Mountain House and Lacombe. For each location, two plots are provided, with the mean monthly values over the historic record with the midpoint around 1964, and then projections a century later to around 2064, based on the historic warming rates. As shown, while the average annual temperatures rose around 1.5°C, warming in January, February and March was around two- or three-fold higher (4.6, 4.0, 3.1°C, respectively). Thus, in the RDR Basin there was substantial warming over the past century and this was greatest in winter. If this historic pattern continues, there will be further winter warming, along with more moderate warming in other seasons (Figure 3). The above freezing interval, which approximates the plant growth season, will commence earlier and consequently lengthen

Precipitation patterns were apparently more variable than temperatures over the past century (Figure 2). This variation confounded an annual pattern, but there were significant increases in the late spring to summer interval of May, June and July (Table 3, Figure 3). This represents the wettest interval for this region and thus the wet interval has gotten even wetter, while there was little change in precipitation through the other seasons. Thus, relative to the two primary weather components, temperatures have risen and this would increase sublimation and evaporation, while precipitation has increased, providing an opposing influence on regional water resources. However, the extended weather records only exist for lower elevations where towns and cities are located, while the major precipitation in the watershed falls in the higher mountain regions, which lack longer records.

2. Historical River Flows in the Red Deer River Basin

River flows integrate the hydrologic processes throughout the upstream watershed and will thus include climatic processes in the mountain regions. Within the RDR Basin, the only long-term hydrometric record exists for the RDR at Red Deer (since 1912; Table 1; Figure 4). There, annual mean flows have varied substantially over the past century but there has not been a major change (Figure 4 and Table 4). The record commenced in an exceptionally wet interval, with the two highest flow years in 1915 and 1916 (Figure 4). These high flows influence the linear regression and Pearson r, thus suggesting a decline in flows. Conversely, the outliers have less weighting in the rank-order tests and the Kendall τ test provides less support for a progressive pattern (Table 4).

Opposing the apparent decline in annual flows of the RDR at Red Deer over the past century, the shorter records for the other hydrometric gauges indicate increasing flows over the past half-century (Figure 4). For this recent interval, there may have been increase in the flows of the RDR at Red Deer but that pattern was uncertain (1960 to 2016: $Q_{annual} = 0.159 \times \text{year} - 272$; $r^2 = 0.031$). The possible increase in annual flows over the past half-century may represent a shorter-term pattern and the century-long record displayed some correspondence with the Pacific Decadal Oscillation (PDO; Mantua & Hare, 2002; Mote, 2006; St. Jacques et al., 2010), with a cool and wet phase early in the twentieth century when hydrometric gauging commenced (Figure 5). A change in the PDO to the warm and dry phase was associated with low river flows through the 1930s and 1940s, and a PDO change followed and was associated with the cool and wet, high flow interval through the 1950s. A subsequent return to the regional warm phase occurred in the mid- to late 1970s, leading to the warm and low flow interval in the 1980s. Some further correspondence with the PDO over the past four decades may have been associated with the apparent, short-term increases in RDR flows (Figure 5).

For the seasonal patterns, there were substantial changes in monthly flows at Red Deer over the past century (Table 4), but this largely reflects the deliberate flow regulation by Dickson Dam. This provided trapping of summer flows in Gleniffer Reservoir and later release to augment winter flows. This contributed to the observed decreases and increases in the summer and winter flows, respectively (Table 4).

For the naturalized record which represents monthly flows that would have occurred without the damming and flow regulation, the variable record was uncertain, with no significant monthly patterns detected by the non-parametric Kendall τ and Spearman ρ tests. The Pearson r indicated significant ($p < 0.05$) flow decline in August and statistical trends ($p < 0.1$) suggesting declines in September, October and November (Table 4).

For the upstream reach, or upper RDR, the record was much shorter and over the past half-century there were flow increases in February, March and June (Table 4). Some tributaries also displayed increased flows in June, but patterns for other months were slight or inconsistent (Table 4). Similar to the record for the annual flows, these changes in monthly flows would have represented temporary trends, since there weren't progressive flow increases for the longer record of the RDR at Red Deer (Table 4).

3. Prospective Future Flows - Empirical Trend Projection

To avoid trend inflation from the two early, exceptionally high flow years (Table 4) the non-parametric Sen's slope analysis was more appropriate than linear regression. The historic naturalized record extended from 1912 to 2013 with a mid-point around 1962, and the monthly Q Sen's slopes were extended forward to provide projections around 2062 (Figure 6).

As shown (Figure 6), the historic record displayed little change in river flows in the winter months of December, January and February. This was despite the substantial winter warming (Figure 3) that could increase the rain versus snow proportion and subsequent winter run-off. March flows apparently increased (0.038 m^3/s per year; 0.22%/year), and this would be consistent with an earlier commencement of snow melt. The greatest discharge changes over the past century involved declining flows in the high flow interval of May and June (Figure 6; 0.104 and 0.092 m^3/s per year; 0.10 and 0.09%/year, respectively), although the variability limited the confidence in this interpretation. Subsequently, August flows declined, and autumn flows probably declined over the past century.

The interannual flow variation challenged the analyses but the patterns indicate flow decline, with negative correlations for 10 or 11 of the months, and all four seasons (Table 4; 11/12 decline: $\chi^2 = 8.33$, $p = 0.004$). It is thus likely that the overall flow of the RDR at Red Deer has declined over the past century, and extending the Sen's slope, the decline could extend into the twenty-first century (Figure 6). An apparent annual decline rate of ~0.060 m^3/s (0.13%/year) would result in a flow reduction of about 10% from the mid-1970s to the mid-2050s, an interval that matches that of modeling projections from regionally down-scaled global circulation models (GCMs, Table 2).

4. Projections from Regional Downscaling of Global Circulation Models and River Flow Routing

The validation phase of the hydroclimatic modeling indicated high accuracies in the simulations of mean monthly maximum and minimum temperatures (T). The correspondences were very close for the Ricinus meteorological station for the period of June 1986 to October 1987 (r^2 =0.997 T_{max}, r^2 = 0.996 T_{min}) and for the Cuthead Lake meteorological station for the comparison period from January 1999 to January 2005 (r^2 = 0.958 T_{max}, r^2 = 0.934 T_{min}). The simulation of localized precipitation was much less accurate. There was reasonable correspondence between modeled and observed monthly precipitation at the Ricinus station values (r^2 = 0.789) but weaker correspondence at the higher elevation Cuthead Lake site (r^2 = 0.340).

The modeling errors were reduced with integration over the watersheds and following the flow routing with RIVQ, the simulated monthly discharges provided reasonable correspondences for the tributaries in the upper RDR Basin for the period from 1960 to 1989 (r^2 = 0.786), with the patterns for the upper RDR displayed in Figure 7. As displayed, the April and May discharges were underestimated as the modelling apparently delayed spring peak flows, the June flow was overestimated, and subsequent summer and autumn flows were closely associated in the modeled and observed time series (Figure 7). The correspondence between simulated and measured results was weaker for the high flow decade from 1960 to 1969, especially due to underestimation of peak flows in the flood year of 1964 (Gill et al., 2008). Conversely, the low flow decade from 1980 to 1989 provided the closest correspondence over the thirty year validation interval.

Extending downstream, the model underestimated the spring snow melt contributions from the boreal and foothills tributaries and this provided lower projections of April, May and June flows of the RDR at Red Deer (Figure 7). The modeling process provided improved reconstructions for the Rocky Mountain headwaters (upper RDR, Figure 7), progressively weaker correspondences for the James River near Sundre (r^2 = 0.480), the Medicine River near Eckville (r^2 = 0.416), the Little Red Deer near the mouth (r^2 = 0.395), and the weakest association for the smallest tributary, the Raven River near Raven (r^2 = 0.113). Thus, the topoclimatic modelling and flow routing were most accurate for the higher elevation mountain zones and were progressively less accurate for the descending foothills, boreal and parkland zones. Those lower zones provide proportionally minor contributions to the RDR flows but the modeling errors weakened the seasonal projections for the overall RDR at Red Deer (Figure 7; and Philipsen, 2017). The modeling errors were partially absorbed with the final bias corrections through quadratic regressions and importantly, the future projections are compared to the modeled historic flows. With this, the reconstructions and projections would be similarly distorted, allowing comparisons across the climate scenarios.

With the implementation of the climate projections, the seasonal RDR flows were similarly estimated with the different GCMs for the various rivers and reaches. Figure 8 provides the monthly *Q* projections with the different GCMs for the upper RDR, and these forecast changes in flow seasonality but slight change in the annual *Q*. Thus, winter flows could slightly increase, with some variations in magnitude across the four GCMs (Figure 8). With spring warming, the major interval of snow melt commences earlier, increasing river flows in April and May. The four models similarly project the greatest change being declining flows in May (Figure 8), consistent with the empirical trend projection (Figure 6). The GCM projections anticipate little change in flow over the summers from the headwaters (Figure 8) due to opposing impacts from warming weather versus increasing precipitation. The overall outcome from these modest projected changes in monthly flows is minimal change in the overall annual discharge from the mountain headwaters. The outcomes from the four GCMs were very consistent with net flow changes of only around 0.1 m^3/s, substantially lower than the modelling precision.

Extending downstream along the RDR, the hydroclimatic modeling anticipated increasing precipitation and consequently slight increases in the tributary flow contributions from the lower foothills and boreal regions. Subsequently, the RDR at Red Deer was projected to display flow increases for most months other than April and May (Figure 8). Increased summer rains were forecast to increase water contributions and this would extend into autumn. The net outcome would be slight increases in the annual discharge, with similar values of ~5 m^3/s from all four GCMs, over an 80 year interval to around 2055 (Figure 8). This would be about 8% of the reconstructed annual mean discharge of ~60 m^3/s, or an annual flow increase of ~0.1%.

Thus, the flow projections from hydroclimatic modeling from four commonly applied GCMs indicated minimal change in river flows from the Rocky Mountain headwater and slight increase in flows of the overall RDR due to increased precipitation and runoff from the foothills and boreal regions.

5. Historic Flows of other Rocky Mountain Rivers

The assessments of modest changes in RDR flows over the past century were compared with historic discharge patterns for other rivers draining the central and northern Rocky Mountains. This study component extended data series that we and others have previously analyzed (Rood et al. 2005; 2008; 2017; St. Jacques et al., 2013). The historic records were extended from a decade to 15 years and the patterns previously detected were generally confirmed (Table 1, Figure 9).

The most confident change was with substantially increasing annual flows of the Liard River (Table 1 (7), +0.29%/year; Figures 9 and 10). This is a major tributary of the Mackenzie River and the most northerly Rocky Mountain drainage in this study. Moving southward, the Hay River (18) involves substantial boreal drainage and its annual flows have not displayed a significant pattern over its record (Figure 10, Rood et al., 2017). The Peace River (8) has the massive W.A.C. Bennett Dam and associated Williston Reservoir, which can substantially alter seasonal flows. Annual flows have been increasing over the past century (Table 1, +0.18%/year; Figure 9) and infilling for the data gap is provided in Rood et al. (2017), supporting this conclusion.

In contrast to those rivers that drain the northern Rocky Mountains, the upper reaches of the rivers that drain the central Rocky Mountains have displayed declining flows over the past century (Table 1; Figure 10). The Smoky River (9) flow record extended from 1916 to 2013 but has an extensive gap from 1922 through 1954. Recognizing this weakness, the record indicates declining flows (Q_{annual} = -0.822 × year + 1969; r^2 = 0.056; -0.24%/year). The Athabasca River has been extensively studied since it flows through the oil sands region downstream from Fort McMurray (reviewed in Rood et al., 2015). Long-term records exist for the Rocky Mountain headwater zone (10), which displayed declining flows over the past century (Figure 10 and Rood et al., 2015). Conversely, with apparently slightly increasing tributary inflows from foothills and boreal regions (19; Rood et al., 2015), the Athabasca River at Athabasca (11) and downstream, has displayed substantial interannual variation and some correspondence with the PDO, but no significant long-term pattern over the past century (Table 1, Figure 9).

The North Saskatchewan River (12) includes substantial drainage in the Rocky Mountain headwaters in Banff and Jasper National Parks and has displayed declining flows over the past century (Table 1, Figure 9). Also draining Banff, the Bow River has displayed declining flows in the headwater regions (13) and the decline persists downstream to Calgary (14; Table 1, Figures 9 and 10). Damming and the relocation of hydrometric gauges challenges analyses for the Oldman River (15) but the composite records are consistent with declining flows over the past century. Its tributary, the Waterton River (16) has displayed declining flows (Table 1, Figure 9) and close correspondence with the Pacific Decadal Oscillation (Foster and Rood, 2017).

Those prior rivers drain the Rocky Mountains while the final river that was studied, the Milk River, is a transboundary river that drains foothills and grassland ecoregions (17, Figure 10). It drains regions south of the Milk River Ridge, or Hudson Bay Divide, and provides the most northerly drainage into the Missouri and Mississippi River system that flows into the Gulf of Mexico. Its flows were very variable over the past century, with no progressive trend (1910-2016 ice-free season only: $r = 0.02$).

Discussion

With the study commencement, our first prediction was based on prior analyses (Cutforth et al., 1999; Barnett et al., 2005; Millett et al., 2009), and anticipated that the climate at the northern limit of the Great Plains would have progressively changed over the past century, with seasonal warming and slightly increasing precipitation. The weather data sets now extend for a century and confirm these prior interpretations. Average winter temperatures have increased significantly in January through March but somewhat surprisingly, not in November or December. Slight temperature increases occurred in the summer and in early autumn. The warming temperatures would increase regional evaporation and extend the growth season for regional vegetation, increasing the annual transpiration (Xia et al., 2015). The combination would increase the regional evapotranspiration (ET), the net water loss from the prairie and woodland ecosystems.

Countering the increased water vapor loss, regional precipitation has increased over the past century, and particularly in the wet months of May, June and July. Increasing rain during the wet interval, when the watershed is more saturated, should increase run-off contributions to river flows. Relative to these weather changes there was an inversion in the seasonality, with the greatest warming in the winter, while precipitation primarily increased in the summer.

Following from the patterns of other rivers in the SSRB (Rood et al., 2005; Shepherd et al., 2010; St. Jacques et al., 2013; Sauchyn et al., 2016), we expected that the historic climate changes would have resulted in the progressive decline in Red Deer River flows, providing our second prediction. This was supported as there was apparently decline in May, and June flows, and annual flows over the past century. Due to the exceptionally high flows after the commencement of gauging, the non-parametric Sen's slope was applied, indicating an annual flow decline rate of ~0.13%. The same decline rate was determined for both Bow River locations and for the Waterton River (Table 1), but with a different estimation method, the parametric, linear regression approach. This finding of declining flows in the SSRB is consistent with prior studies (Rood et al., 2005; Shepherd et al., 2010; St. Jacques et al., 2010; 2013; Sauchyn et al., 2016), but with the longer hydrometric records, the typical river flow decline rate for this region has dropped from ~0.2%/year to ~0.15%/year.

Our third prediction was that hydroclimatic modeling with GCMs would provide converging projections with those from empirical trend projection (Shepherd et al., 2010; St. Jacques et al., 2013) but this correspondence was less clear. The modelling projected minimal change from the Rocky Mountain headwaters and with increasing precipitation in the spatially larger foothills and boreal regions, the modeling estimated an increase of ~8% for the overall Red Deer River flows from around 1975 to around 2055. The four GCMs that we applied provided consistent projections that were also fairly similar to the average 14% increase from ten regional circulation models (RCM) applied for this river system by St. Jacques et al. (2018) (Table 2). Those RCMs were selected to represent a broader range of modelling approaches and scenarios and of those, six indicated minimal change, while four projected higher flow increases than our estimates.

Opposing these projections of increasing flows, a decrease of ~ 12% was projected by Lapp et al. (2009) by combining different GCM estimates of future temperature and precipitation with the WATFLOOD hydrologic model. Those projections were somewhat consistent with analyses by Tanzeeba and Gan (2012), who applied a landscape hydrologic model, MISBA, Modified Interactions Soil-Biosphere-Atmosphere. That modelling indicated that the increased evaporation with climate warming would result in substantial water loss, resulting in regional river flow declines of ~10 to 20% through the non-winter seasons. That modelling was still incomplete relative to transpirational water use by woodlands including riparian cottonwood forests, and that hydrologic component is advancing, following the regional applications of newer research tools including eddy covariance flux measurements (Flanagan et al., 2017).

Substantial variation in river flow projections from downscaled GCMs or RCMs is common since precipitation modeling and forecasts are inherently variable and much less confident than temperature estimations (Coquard et al., 2004; Stephens et al., 2010; Knutti and Sedláček, 2013). The important snow accumulation and melt processes are especially challenging for modelling in the SSRB due to the common temperature inversions in the central Rocky Mountains in the winter, and extensive sublimation and redistribution due to the frequent warm and dry Chinook winds (Shepherd et al., 2010; Wood et al., 2018).

Different hydroclimatic modeling with a range of GCMs and RCMs has thus been applied to the RDR system and the outcomes are consistent in projecting that changes in river flows would be slight with anticipated future climate conditions. However, the projections are variable in the outcomes, ranging from slight increase, through no change and to slight decrease, and there was also variation relative to the seasonality of the changes. The blending of these projections could indicate little change or a slight decrease, with the latter outcome being consistent with the empirical trend projection. From these different approaches, the magnitude of change may be ~ 0.1%/year, a change rate within the imprecision of the hydroclimatic models and the statistical trend projection. Consequently, the composite conclusion would be that changes in RDR flows over the next half century will likely be slight and might involve gradual decline superimposed on interannual variation that is partly coordinated with the PDO (Rood et al., 2005; St. Jacques et al., 2013).

Alberta WaterSMART (2015) researchers affiliated with the study by St. Jacques (2018) had previously recognized substantial uncertainty in model projections for the RDR. They proposed that part of this uncertainty reflected a geographic transition between the southern Canadian prairies that are becoming dryer with declining river flows, versus the wetter, more northerly boreal regions that are apparently becoming wetter. We have similarly observed regional differences in the hydrologic consequences of climate change, with declining flows of the rivers that drain the central Rocky Mountains toward Hudson Bay, little change in river flows in a transition zone, and increasing flows of the rivers that drain the Northern Rocky Mountains towards the Arctic Ocean (Rood et al., 2005; 2015; 2017).

This relates to our fourth prediction, and we explored flow patterns for the major rivers that drain a north-south transect along the Canadian Rocky Mountains (Figure 10). As anticipated, there was an apparent transition, with declining flows of rivers draining the central Rocky Mountains of southern Alberta and this pattern extended northward to the Arctic Ocean/Hudson Bay watershed divide. Extending northward into British Columbia (BC), annual flows of the Peace River increased over the past century and from northern BC and the Yukon, more substantial flow increase was displayed for the most northern drainage, the Liard River.

There was also a second regional pattern, with differentiation between the Rocky Mountain headwaters and the lower elevation foothills and boreal regions. In contrast to the mountain zones, those easterly areas displayed minimal change in river flow contributions over the past century (Figure 10). This pattern apparently extended over an extensive north to south corridor, from the Hay River near the 60th parallel (Rood et al., 2017), southwards possibly to a foothills zone near the American border (49^{o}N), which provided run-off to the Milk River.

Our study thus supports the prediction of regional differentiation in the impacts of climate change on hydrologic patterns and river flows.

This study characterized the changes in temperatures, precipitation and river flows for the Red Deer River system, which occurs at the northern limit of the North American Great Plains. With these regional hydroclimatic changes, it is likely that the treeless prairie region will expand northward, while the aspen parkland will also shift northward (Schneider et al., 2009). The future conditions may favor increased agriculture in some areas of the RDR Basin,, with a lengthening frost-free growth season. Increased summer precipitation could alsoenable regional crop diversification (McGinn et al., 1999; Bryant et al., 2000).

The projection of slight decline in RDR flows is important relative to establishing limits for water withdrawal from this river for irrigation and other uses (Alberta WaterSMART, 2015). As well, water budgeting for the RDR Basin is important for water management in the overall South Saskatchewan River Basin since the southern tributaries, the Oldman and Bow Rivers, are fully or over-allocated, and this has imposed stress on the aquatic and riparian ecosystems (Golder, 2003; World Wildlife Fund-Canada, 2009). In addition, the combined flows from the three tributaries are assessed for the requirement to pass on sufficient flows downstream, in accordance with the Agreement on Apportionment for the Canadian Prairie Provinces. Water management of the transboundary SSRB also has international obligations in accordance with Boundary Waters Treaty between Canada and the United States (Pentny & Ohrn, 2008), further emphasizing the need to better understand how climate change is altering river flows from the different Rocky Mountain regions of western North America.

This study reveals the complexity and uncertainty in analyzing hydrological consequences of climate changeat the river basin scale, which often provides the basis for water resource management. We undertook somewhat independent approaches, by assessing: (1) historic weather patterns, (2) historic river flows, and (3) hydroclimatic modeling after GCM downscaling, and while there was some convergence, there was also some differentiation in the outcomes. For other river systems, we would recommend a similar approach that blends trend analyses of historic weather and discharge data with the longest records possible, along with hydroclimatic modeling with different GCMs, different regional downscaling methods, and alternate river routing approaches, to strengthen the confidence in the outcomes and interpretations.

However, even with these multiple approaches, some uncertainty may remain and this diminishes the confidence relative to future flow projections, which are essential for water resource managers to assess water budgets and consider aspects such as applications for additional water withdrawals to enable irrigation expansion (Bryant et al., 2000; Rosenberg et al., 2003; Elliott et al., 2014; Alberta WaterSMART, 2015). For the RDR system and for other regulated rivers in which the future flow projections are uncertain, it would be appropriate to apply the precautionary principle (Pentney & Ohrn, 2008; Lapp et al., 2009). This would encourage limiting further water allocations until the hydrometric record is lengthened to better characterize the natural variability, advancements in hydroclimate modeling provide outcomes that converge with the actual empirical patterns, and the superimposed influences of anthropogenic climate change are more fully understood (Barnett et al., 2005; St. Jacques et al., 2010; Knutti & Sedláček, 2013; Sauchyn et al., 2016).

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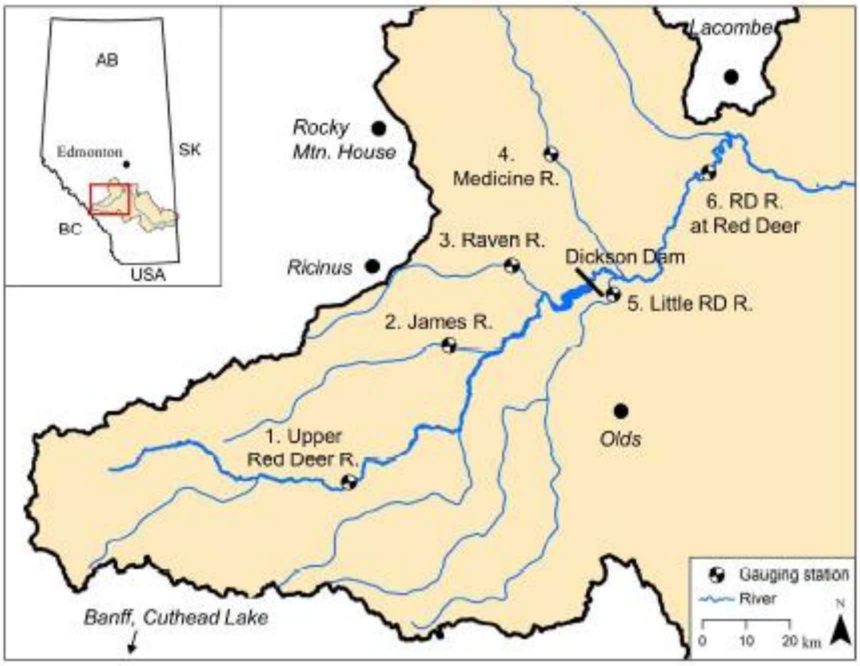

Figure 1. Map of the Red Deer River Basin in Alberta, Canada. The locations of weather stations are displayed and Banff is in the adjacent Bow River watershed, ~ 175 km SSW from Red Deer.

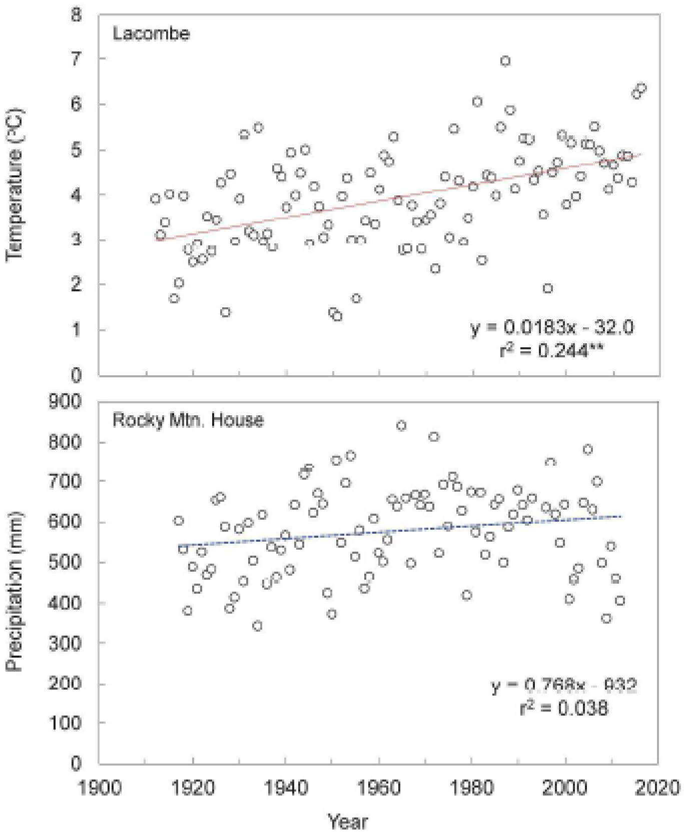

Figure 2. Mean annual temperature at Locombe (top) and annual precipitation at Rocky Mountain House (bottom) near the Red Deer River Basin, over the past century.

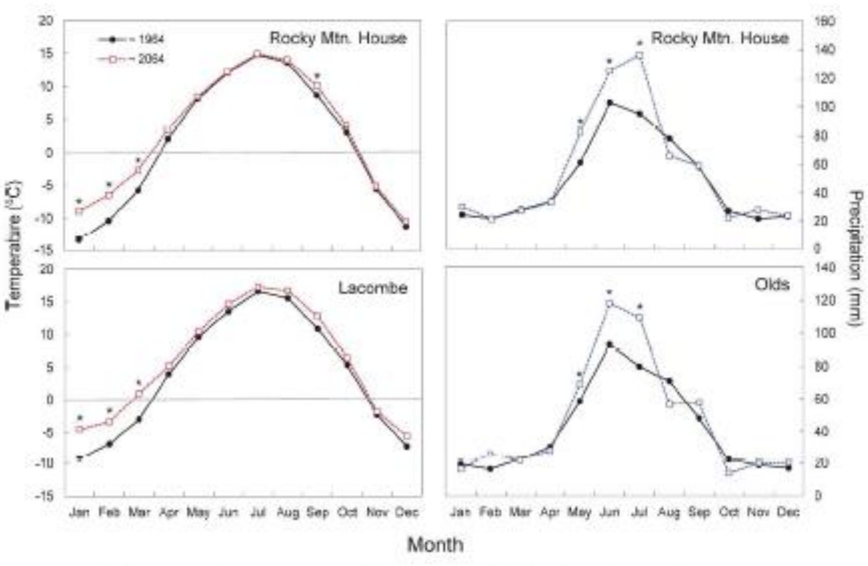

Figure 3. Average monthly temperatures (left) and precipitation (right) over the past century and with empirical trends projected to around 2055 for weather stations around the Red Deer River Basin, with significant monthly trends indicated (*, $p < 0.05$).

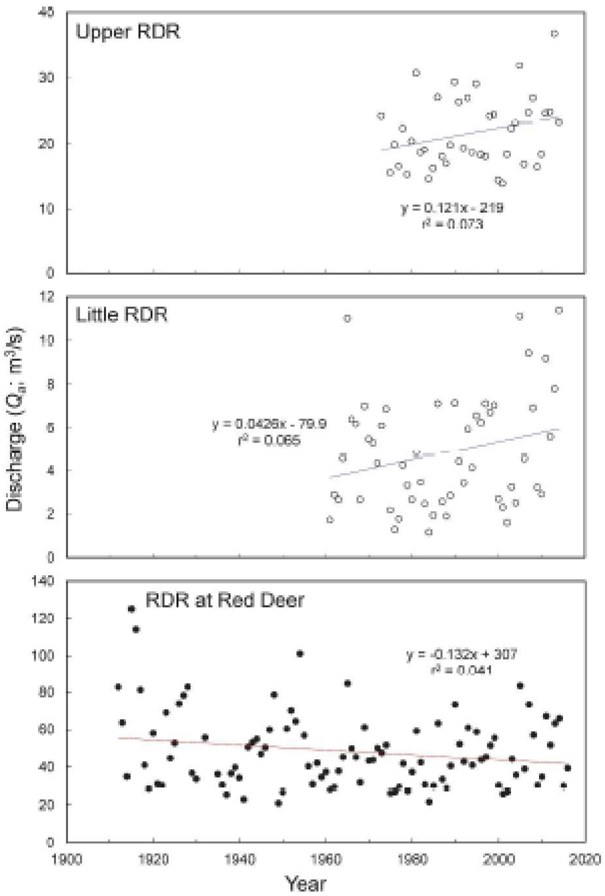

Figure 4. Mean annual discharges (Q_a) for locations along the Red Deer River system over the periods of record, with linear regression plotted.

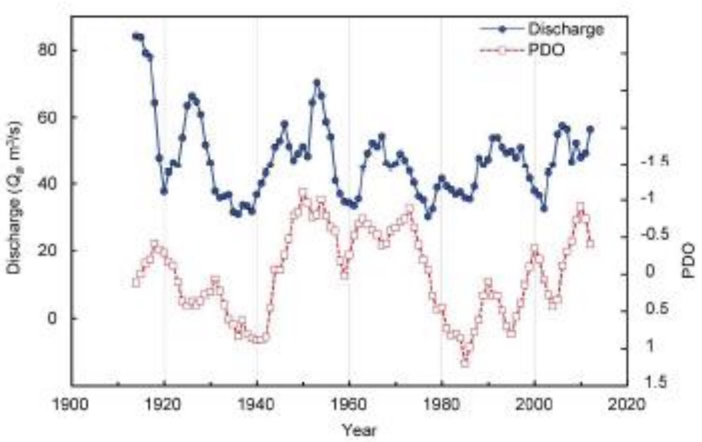

Figure 5. Moving 5-year average discharge of the Red Deer River and for the Pacific Decadal Oscillation (PDO) over the past century.

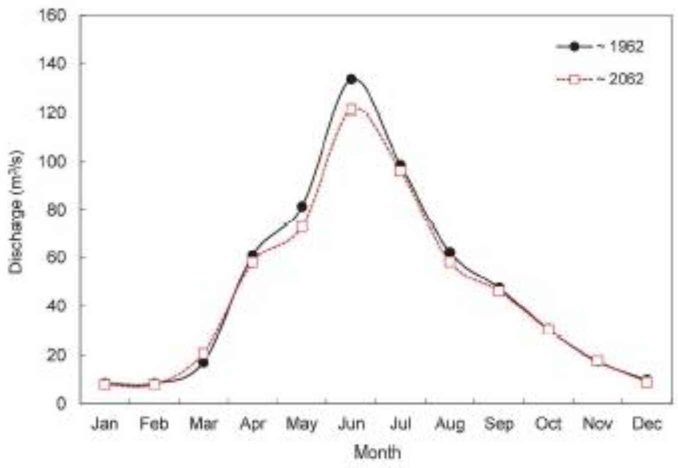

Figure 6. Averaged monthly discharges of the Red Deer River from 1912 to 2012 and flows around 2062 estimated by historic trend projections.

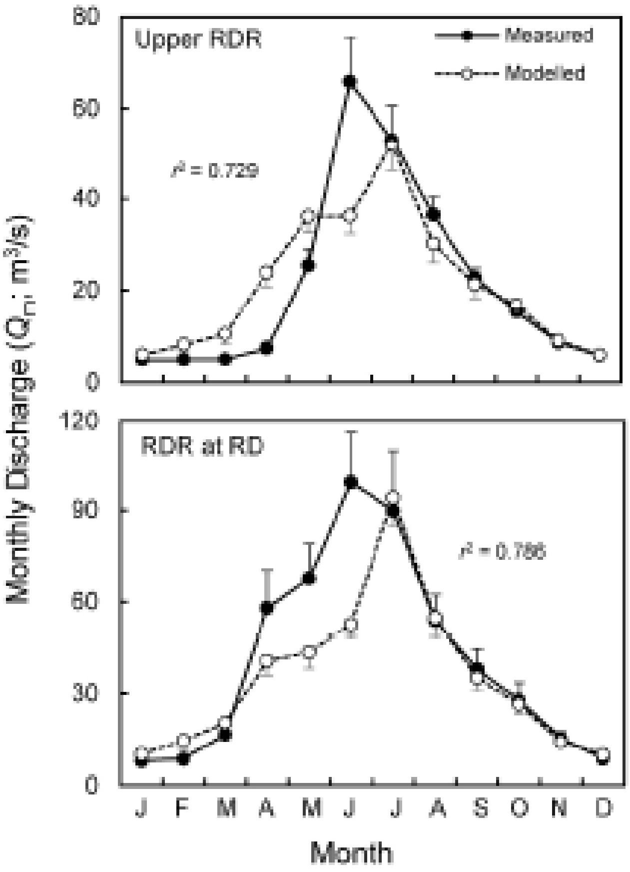

Figure 7. Measured and modelled monthly discharges of the Red Deer River (RDR) below Burnt Timber Creek ('Upper RDR') and at Red Deer.

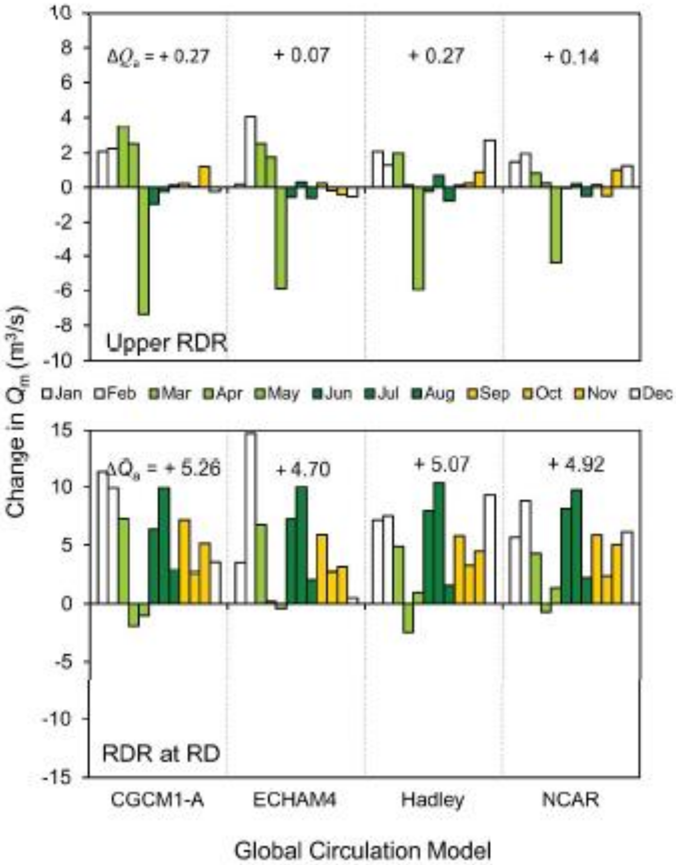

Figure 8. Projected changes in monthly river flows of the Red Deer River (RDR) below Burnt Timber Creek ('Upper') and at Red Deer, following GCM climate projections, followed by regional downscaling and river routing.

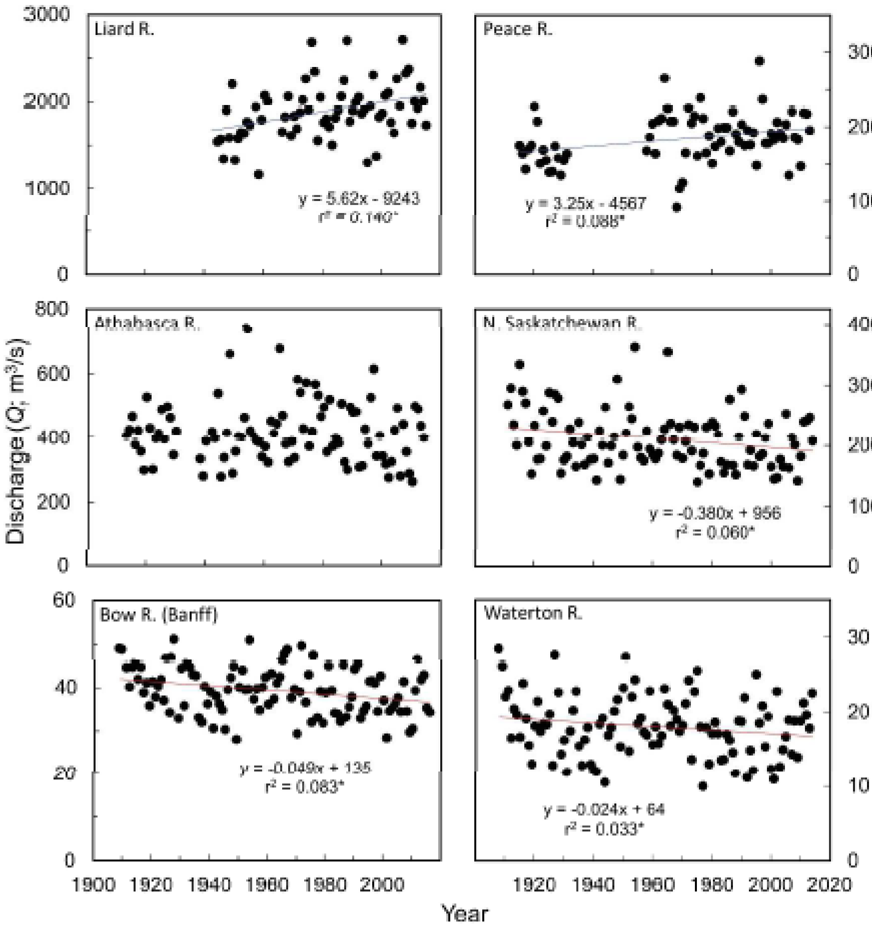

Figure 9. Mean annual discharges (Q_a) for rivers that drain the east-slope of the central Rocky Mountains of Canada, over the periods of record, with significant linear regression plotted (blue, increasing; red, decreasing).

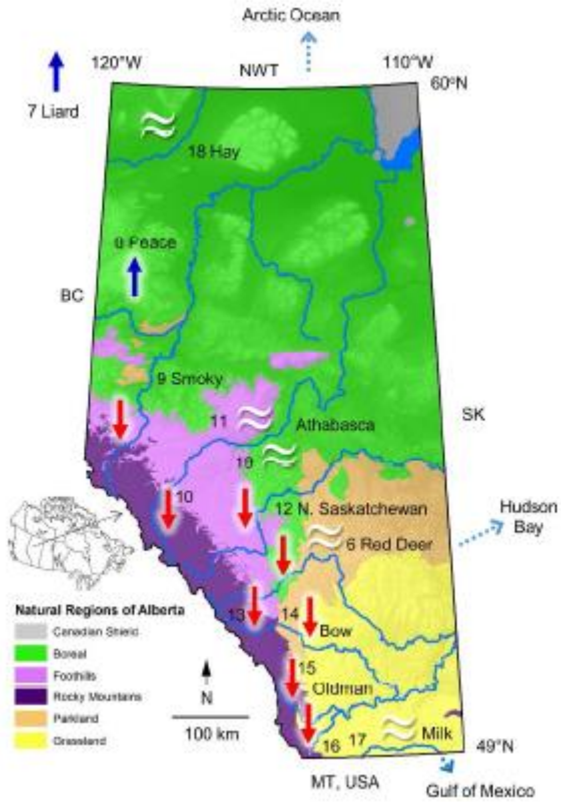

Figure 10. Map of Alberta with major rivers plotted and river and reach numbers in accordance with Table 1. Additionally, the Hay (18) and Athabasca tributaries (19) are included, based on analyses in Rood et al., 2017 and 2015, respectively.

Table 1. Water Survey of Canada hydrometric stations included in the analyses. Significant ($p < 0.05$) flow trends are provided for mean annual discharge (Q), based on linear regression slopes, except for the RDR that was based on the Sen's slope (red = flow decline; blue = increase).

	Station Name	Number	Drainage area (km^2)	Start	Mean Discharge (Q; m^3/s)	Flow Trend (%/year)
Red Deer (RD) River (R) system						
1	RDR b Burnt Timber Ck.	05CA009	2,250	1973	21.6	
2	James R near Sundre	05CA002	821	1955	seasonal	
3	Raven R near Raven	05CB004	645	1971	2.29	
4	Medicine R near Eckville	05CC007	1,920	1962	4.21	
5	Little RDR near mouth	05CB001	2,580	1960	4.81	
6	RDR at RD[a]	05CC002	11,600	1912	48.0	-0.13
Other regional, Rocky Mountain rivers						
7	Liard R at Ft. Liard	10ED001	222,000	1942	1,960	+0.29
8	Peace R at Peace R[a]	07HA001	194,000	1915	1,850	+0.18
9	Smoky R at Watino	07GJ001	50,300	1915	342	decline[b]
10	Athabasca R near Jasper	07AA002	3,870	1913	87.1	decline[b]
11	Athabasca R at Athabasca	07BE001	74,600	1913	421	no change[b]
12	N. Sask. R at Edmonton[a]	05DF001	28,100	1911	210	-0.18
13	Bow R at Banff	05BB001	2,210	1909	39.1	-0.13
14	Bow R at Calgary[a]	05BH004	7,870	1911	90.1	-0.13
15	Oldman R - 05AA001 &	05AA023	1,940	1908	13.7	decline[b]
16	Waterton R - Waterton Pk.	05AD003	613	1908	18.0	-0.13
17	Milk R at western crossing	11AA025	1,050	1931	seasonal	no change[b]

[a]Regulated
[b]For rivers with data complications, analyses are presented in the Results text.

Table 2. Global circulation models (GCMs) and projected changes in Red Deer River flows by the mid-twenty-first century. The outcomes from different analyses have been adjusted to provide 80 year projections to ~2055 (red = increase, blue = decline). Each study included multiple GCMs, and mean or median outcomes are provided, as listed in those reports or calculated from the figures presented. Model abbreviation or nationality: CCSM, Community Climate System Model, USA; CGCM, Coupled General Circulation Model, Canada; CSIRO, Australia; ECHAM, Germany; GFDL, Geophysical Fluid Dynamics Laboratory, USA; HadCM, Hadley Coupled Model, UK; MIROC, Model for Interdisciplinary Research on Climate, Japan; NCAR, National Ctr. for Atmospheric Research, USA.

Source	Global Circulation Models	Change in flow	Comments
Pietroniro et al., 2006	10 GCMs screened, chose ECHAM4, HadCM3, NCAR-PCM	-12%	NCAR projected increase; other 2 models suggested spring and autumn decrease
Lapp et al., 2009	CGCM3, CSIRO- MK3, ECHAM5, GFDL2, HadCM3, MIROC3.2	-13%	Decrease in summer and autumn flows
Tanzeeba & Gan, 2012	CCSRNIES, CGCM2, ECHAM4, HadCM3	-15%	Decrease especially in summer flows
St. Jacques et al., 2018	CCSM, CGCM3, GFDL, HadCM3, coupled with RCMs	+14%	6 model combinations indicated little change, and 4 projected major increase in spring flows
This study	CGCMI-A, ECHAM4, HadCM3, NCAR-CCM3	+8%	General increase in flows
This study	Empirical Trend Projection (Sen's slope)	-10%	Decrease in summer flows

Table 3. Correlation coefficients revealing historical trends in monthly or mean annual temperatures or precipitation for weather stations in or near the Red Deer River basin (Figure 1), generally from 1912 to 2012. For temperatures, positive coefficients (red) indicate warming, and for precipitation, positive (blue) indicates increasing precipitation (t, $p < 0.1$; *, $p < 0.05$; **, $p < 0.01$).

	Temperature						Precipitation	
	Banff	Rocky Mtn. House	Olds	Lacombe			Rocky Mtn. House	Olds
	Kendall τ			Pearson *r*	Kendall τ	Spearman ρ	Kendall τ	
Jan	0.150*	0.186**	0.154*	0.269**	0.185**	0.282**	0.070	0.086
Feb	0.176**	0.185**	0.155*	0.267**	0.173**	0.256**	-0.009	-0.022
Mar	0.217**	0.197**	0.160*	0.316**	0.224**	0.313**	-0.030	-0.004
Apr	0.069	0.105	0.034	0.149	0.083	0.117	-0.005	-0.039
May	0.079	0.082	0.082	0.157	0.126t	0.181t	0.159*	0.078
Jun	0.099	0.054	0.136*	0.240*	0.137*	0.208*	0.115	0.148*
Jul	0.115t	-0.029	0.094	0.187t	0.134*	0.193*	0.147*	0.138*
Aug	0.156*	0.091	0.128t	0.243*	0.160*	0.244*	-0.320	-0.033
Sept	0.193**	0.172**	0.161*	0.285**	0.188**	0.278**	0.010	0.089
Oct	0.062	0.068	-0.013	0.153	0.085	0.127	0.001	-0.093
Nov	-0.025	0.024	-0.017	0.043	0.033	0.047	0.096	0.017
Dec	-0.005	0.038	0.016	0.112	0.072	0.099	0.041	0.057
Annual	0.296**	0.226**	0.239**	0.494**	0.347**	0.510**		
Warming (°C per century)	1.41	1.45	1.11	1.83				

Table 4. Correlation coefficients revealing historical trends for annual, monthly or seasonal discharge (Q) of the Red Deer River (RDR) or tributaries (start year indicated, analyses to 2013). Kendall's τ coefficients are shown, except for the Naturalized RDR at Red Deer, as indicated. Flow increases are in blue, declines in red; t , $p < 0.1$; *, $p < 0.05$; **, $p < 0.01$.

				RDR at Red Deer 1912		
	Upper RDR 1973	Little RDR 1960	Medicine R. 1962	Measured[a]	Naturalized Pearson *r*	Naturalized Kendall τ
Annual	0.176	0.164[t]	0.153	-0.007	-0.156	-0.038
Month						
Jan	0.207t	0.135	0.145	0.414**	-0.120	-0.032
Feb	0.222*	0.089	0.235*	0.476**	-0.066	-0.033
Mar	0.356**	-0.067	-0.008	0.298**	0.073	0.104
Apr	0.023	-0.039	0.072	-0.005	-0.058	-0.022
May	0.022	0.080	0.085	-0.154	-0.078	-0.050
June	0.295**	0.177t	0.226*	-0.136	-0.030	-0.045
July	0.095	0.073	0.113	-0.061	-0.110	-0.009
Aug	-0.058	0.164t	0.049	-0.112t	-.201*	-0.042
Sept	0.049	0.258	-0.031	-0.033	-0.177t	-0.018
Oct	0.190[t]	0.217*	-0.027	0.026	-0.189t	-0.003
Nov	0.096	0.150	0.008	0.148**	-0.187t	0.009
Dec	0.150	0.187*	0.167	0.312**	-0.142	-0.044
Seasonal (3 months, winter = DJF, etc.)						
Winter	0.257*	0.100	0.195t	0.394*[a]	-0.137	-0.051
Spring	0.062	-0.001	0.095	-0.064	-0.071	-0.039
Summer	0.197t	0.184*	0.144	-0.107	-0.113	-0.018
Autumn	0.095	0.240**	-0.008	0.040	-0.188	-0.010

[a]This is downstream from Dickson Dam which is operated to trap summer flows and augment winter flows (this analysis to 2016).