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Assessing hydrological sensitivity of grassland basins in the Canadian Prairies to climate using a basin classification–based virtual modelling approach

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Abstract

Significant challenges from changes in climate and land-use face sustainable water use in the Canadian Prairies ecozone. The region has experienced significant warming since the mid 20th Century, and continued warming of an additional 2°C by 2050 is expected. This paper aims to enhance understanding of climate controls on Prairie basin hydrology through numerical model experiments. It approaches this by developing a basin classification–based virtual modeling framework for a portion of the Prairie region, and applying the modelling framework to investigate the hydrological sensitivity of one Prairie basin class (High Elevation Grasslands) to changes in climate. High Elevation Grasslands dominate much of central and southern Alberta and parts of southwestern Saskatchewan with outliers in eastern Saskatchewan and western Manitoba. The experiments revealed that High Elevation Grasslands snowpacks are highly sensitive to changes in climate, but that this varies geographically. Spring maximum snow water equivalent in grasslands decreases 8% per degree °C of warming. Climate scenario simulations indicated a 2°C increase in temperature requires at least an increase of 20% in mean annual precipitation for there to be enough additional snowfall to compensate for enhanced melt losses. The sensitivity in runoff is less linear and varies substantially across the study domain; simulations using 6°C of warming and a 30% increase in mean annual precipitation yields simulated decreases in annual runoff of 40% in climates of the western Prairie but 55% increases in climates of eastern portions. These results can be used to identify those areas of the region that are most sensitive to climate change, and highlight focus areas for monitoring and adaptation. The results also demonstrate how a basin classification–based virtual modeling framework can be applied to evaluate regional scale impacts of climate change with relatively high spatial resolution, in a robust, effective and efficient manner.

Key words: Prairie, basin classification, virtual experiments, climate change, snow, runoff

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Introduction

Hydrological models are essential tools to understand hydrological processes and function at the basin scale, and can also be used to diagnose how specific hydrological processes control catchment responses to change (Rasouli et al., 2014). Modelling a specific basin to evaluate processes or to simulate the effects of change entails large computational and labour costs and requires observations of the basin response with sufficient spatial and temporal coverage. Modelling of many individual basins is not efficient when attempting to predict regional responses to changes in climate and/or land-use. Basin classification can regionalize hydrological model outputs, based on the assumption that basins can be classified by their characteristics and that basins of the same class respond similarly to changes in climate inputs or their landscapes (e.g., McDonnell and Woods, 2004; Wagener et al., 2007). Parameterizing a model based upon a representative or stylized basin of a given class allows the output to be considered representative of all basins of that class. This assumption facilitates regionalization as it does not necessarily require simulating the distinctive characteristics of every basin, reducing cost and time required for large domain studies. Such a regionalization approach can be used to assess the sensitivity of large diverse areas to stressors, such as land-use and climate change.

One such region is the Canadian Prairie ecozone, that portion of the Great Plains of North America that includes southern parts of the provinces of Alberta, Saskatchewan, and Manitoba and Treaties 1, 2, 4, 6 and 7 in Western Canada (Spence et al., 2019), as mapped in Figure 2. This region has a cold sub-humid to semi-arid climate and was covered by grassland and sparse woodlands until the widespread adoption of cultivated agriculture in the late 19th and early 20th

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centuries. The region's geomorphology was formed by glacial and post-glacial processes which left numerous internally drained depressions and poorly defined drainage networks. Most of the Canadian Prairies is in the Saskatchewan-Nelson River Basin, but relatively little runoff is provided to the major rivers that traverse the region downstream of their mountain headwaters. Local streams and prairie-derived rivers often have intermittent and highly variable streamflow. These streams are important local sources of freshwater and are often managed to provide farm, agricultural and municipal water supply and support natural lakes and reservoirs (Pomeroy et al., 2005). Because they connect to larger systems only intermittently, a small headwater–basin scale approach is necessary to generate information about how their behaviour might be impacted by the aforementioned stressors.

Western Canada, including the Canadian Prairies, has been subject to substantial climate warming since the mid 20th century (DeBeer et al., 2016; Bush and Lemmen, 2019). Prairie precipitation trends indicate more rain and less snow in the spring and fall (Shook and Pomeroy, 2012) and runoff generation has been shown to be shifting from snowmelt- to rainfall-driven in eastern Saskatchewan (Dumanski et al., 2015). Recent analysis of hydrometric stations across the region identified sub-regional trends in streamflow associated with drying in the west and south and wetting in the east and north, associated with physical landscape characteristics and climate (Whitfield et al. 2020). However, it is difficult to attribute streamflow response solely to climate change because of impoundment of streams, widespread changes in agricultural practices and wetland drainage since the 1950s (Ehsanzadeh, 2016). Wetland drainage has become widespread in portions of the region (van Meter and Basu, 2015) and the loss of depressional storage capacity associated with drainage enhances streamflow volumes (Tiner, 2003; Fang et

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al., 2010; Wilson et al., 2019) and may alter the frequency, timing, and duration of regional streamflow (Ehsanzadeh et al., 2012; Spence and Mengistu, 2019). Extrapolating intensive studies of wetland drainage impact in individual basins (Wilson et al., 2019) can be challenging, because basin response is a function of wetland distributions that control contributing area dynamics (Stichling and Blackwell, 1957; Shaw et al., 2012; Shook and Pomeroy, 2011; Haque et al. 2017, Spence and Mengistu, 2019). It is uncertain how hydrological fluxes and states in Canadian Prairie basins will respond to continued climate change and wetland drainage. The statistical modelling and small basin modelling studies cited here have provided an excellent foundation, but an improved approach is needed to evaluate how changes in climate and agricultural practices impact hydrological regimes more broadly across the region.

Here, a classification-based virtual modeling framework is proposed as a means to examine hydrological sensitivity to different climate, land-use and wetland drainage. In this approach, each basin class is modelled in a virtual manner (Weiler and McDonnell, 2004; Armstrong et al., 2015); as a synthetic or generic basin with characteristics defined by the average or typical condition of all basins from the same class. In this way, the basin characteristics can be manipulated to determine how a typical basin may respond to change. There is evidence that such an approach is viable, as virtual experiments have been used to evaluate hydrological response to different conditions (Di Giammarco et al., 1996; Horn et al., 2005; Dunn et al., 2007; Mallard et al., 2014; Seo and Schmidt, 2013, Lopez-Moreno et al., 2020), identify factors influencing hydrological processes (e.g., Weiler and McDonnell, 2004), and study hydrological controls on water chemistry (Weiler and McDonnell, 2006). This paper aims to demonstrate the utility of a basin classification–based virtual modelling approach for assessing the sensitivity of

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Canadian Prairie catchments to climate. Two steps were taken to achieve this objective: (1) development of a robust class-based virtual basin model for a portion of the Canadian Prairie and; (2) exploration of virtual basin sensitivity of hydrological response to climate. This work provides a foundation to extend the virtual basin modelling approach more broadly across the Canadian Prairie to assess response to climate and land management scenarios.

Methodology

Framework of classification-based virtual basin modeling

A basin classification–based virtual modelling platform has three main components: (1) a classification analysis to derive virtual basin characteristics; (2) parameterization and evaluation of a hydrological model of the virtual basin and (3) application of the model to evaluate response to multiple scenarios (Figure 1).

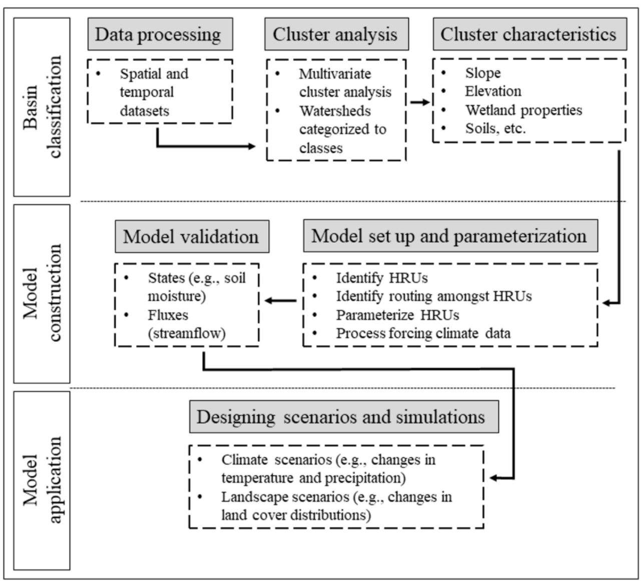

Figure 1: Components of the classification-based virtual basin modeling platform.

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Basin Classification

The classification of Canadian Prairie basins was based on the analyses of Wolfe et al. (2019), which divided over 4000 basins, each approximately 100 km^2 in area, into seven broad classes, based on a suite of physio-geographic characteristics (Figure 2). The basin delineations used in the study were taken from the HydroSHEDs dataset (Lehner and Grill, 2013), which provides geographically contiguous delineations of basins for the world including the Prairie ecozone. Physio-geographic characteristics, including climate, geology, topography, wetland distribution, and land cover, among others, were compiled and used to classify basins that would be expected to respond in a hydrologically coherent manner (Wolfe et al. 2019). Urban areas and large lakes were excluded from the analysis. A revised classification that excluded climate parameters was conducted and is used herein, following the same Hierarchical Classification of Principal Components (HCPC) approach. This was done because climate is introduced through the long meteorological time series used to drive the virtual basin model and in order to study climate sensitivity any classification that included historical climates could introduce bias. Exclusion of climate had a limited impact on the basin classification, with the seven classes of basins identified (Figure 2) closely following the original classification.

The High Elevation Grasslands (HEG) class (Figure 2) was selected for the development of the virtual basin model. This class featured 751 basins with an average size of ~100 km^2. Median basin characteristics, including land cover fractions, basin slope and elevation, and soil type, were determined and used for virtual basin model parameterization. Wetland areas derived from the Global Surface Water maximum water extent dataset (https://global-surface-water.appspot.com/download) were used to determine the shape and scale parameters of a

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generalized Pareto distribution (Shook et al. 2013, Table 1). These parameters were used to characterize the wetland complex within the virtual model, where the wetland complex is represented by multiple individual wetlands of varying sizes.

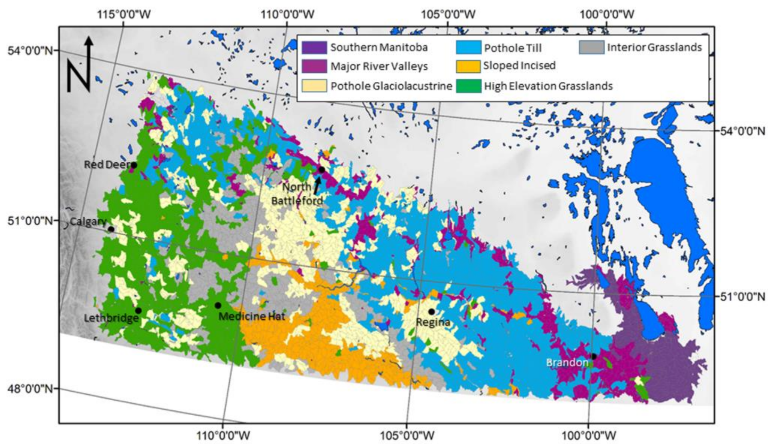

Figure 2: Basin classification map for the Prairie ecozone in western Canada. Colours represent the seven basin classes and excluded areas (lakes and urban areas) are shown in white. The focus of this paper is on the High Elevation Grasslands, shown in green. Climate data from the cities noted in this figure were used to drive the virtual model. Boundaries of the basins used in the classification are shown in grey

Table 1: CRHM parameters for the High Elevation Grassland virtual basin model. The suffix "-w" in the HRU name indicates HRUs in the wetland catena. LAI denotes leaf area index.

HRU	**Fraction of basin**	**LAI**	**Fetch (m)**	**Vegetation height (m)**	**Stalk density (/m^2)**	**Stalk diameter (m)**	**Manning's n**
Channel (CH)	0.01	0.001	300	0.50	1	0.003	0.07
Cultivated (CL)	0.32	0.001	1000	0.20	320	0.003	0.17
Cultivated (CL-w)	0.13	0.001	1000	0.20	320	0.003	0.17
Fallow (FL)	0.004	0.001	1000	0.01	320	0.003	0.05
Fallow (FL-w)	0.002	0.001	1000	0.01	320	0.003	0.05
Grassland (GL)	0.30	0.001	500	0.40	320	0.003	0.2
Grassland (GL-w)	0.12	0.001	500	0.40	320	0.003	0.2
Shrubland (SL)	0.02	0.001	300	1.50	100	0.01	0.2
Shrubland (SL-w)	0.006	0.001	300	1.50	100	0.01	0.2

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Woodland (WL)	0.02	0.4	300	6.00	100	0.1	0.4
Woodland (WL-w)	0.006	0.4	300	6.00	100	0.1	0.4
Wetland (WT)	0.07	0.001	300	1.50	1	0.01	0.2
Albedo							
Bare ground	0.17						
Snow (fresh)	0.85						
Wetland area Generalized Pareto Distribution parameters							
Shape (ξ)	1.152						
Scale (β)	2070.62						

Model set-up and parameterization

The Cold Regions Hydrological Modelling platform (CRHM) was selected to develop the virtual basin model, as CRHM is particularly suited for simulating the hydrology of the Canadian Prairies. CRHM is a modular, process-based, spatially semi-distributed hydrological model, which includes the key cold regions and warm season hydrological processes that operate in western Canada and elsewhere (Pomeroy et al., 2007). With the correct suite of modules, each representing a key hydrological process, CRHM has proven very capable of representing prairie hydrological processes and accurately emulating water fluxes in this landscape (Fang and Pomeroy, 2009; Fang et al., 2010). Most of the process modules in CRHM, particularly the surface processes, are strongly physically-based, and hence CRHM does not require model calibration, making it suitable for simulations under nonstationary conditions. As a virtual basin has no specific location, it cannot be calibrated to field observations from a particular basin, so setting parameters based on regional hydrological studies rather than calibration is advantageous.

The virtual basin area was set to 100 km^2, which aligns with the average basin size used in the classification. The virtual basin was divided into hydrological response units (HRUs), each of which has a single set of parameter values and for which water budgets are calculated. The HRU

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sequence by which runoff is routed follows a catena of land cover from cultivated fields at the highest elevation, followed by grasslands, shrublands, woodlands, and wetlands at successively lower elevations. Areas were set according to the median for that land cover observed across all HEG basins. Summer-fallow fields, whilst also included, cover a very small area (<1%; Table 1).

The virtual basin was separated into non-wetland, and wetland catenas (Figure 3) according to effective and non-effective fractions of HEG basins, respectively. The first, 'non-wetland' catena portion (i.e., cultivated, grassland, shrubland, woodland HRUs) of the basin (~67% of area) is considered to contribute flows directly to the HRU outlet (stream channel). Runoff from the 'wetland' catena portion of the virtual basin (~33% of area) features a wetland complex HRU within a landscape catena following a sequence from cultivated, to grassland, shrubland, and woodland HRUs (Figure 3). Runoff is routed through a wetland complex comprised of 46 individual wetlands; their areas follow a generalized Pareto distribution (Shook et al. 2013). This approach has been shown to effectively represent how wetlands dictate transmission of runoff from Prairie basins, by representing the dynamic area contributing flow downstream (Pomeroy et al., 2014).

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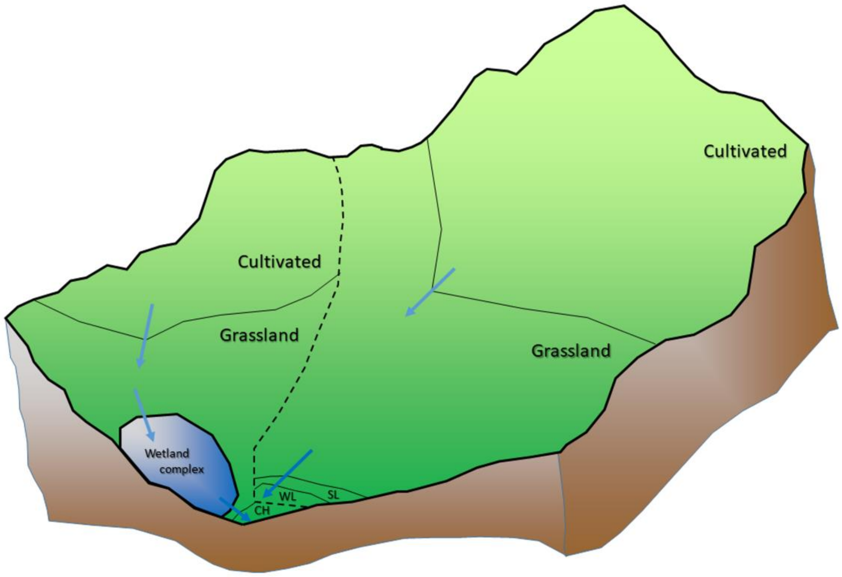

Figure 3: Illustration of HRU distribution in the virtual model of a typical High Elevation Grasslands basin. The illustration depicts two catenas, one with a wetland complex and one without, separated by the dashed line. Relative areas are meant to approximate those listed in Table 1. SL denotes shrublands; WL, woodlands; and CH a channel HRU (see Table 1). The fallow and shrubland and woodland HRU's directed through the wetland complex are too small to be shown at this scale.

The Prairie Hydrological Model (PHM), created using CRHM (Pomeroy et al., 2010, 2012), was used to simulate virtual basin hydrological response. PHM includes a specific set of physically-based modules linked sequentially to represent the dominant hydrological processes for the virtual basin. The Observation module reads in meteorological data and calculates the precipitation phase using a maximum temperature threshold of 0°C for snow and a minimum temperature threshold of +2°C and distributes these to each HRU along with lapse rates for temperature and precipitation and temporal interpolation to adjust observation time steps to hourly data. The Radiation module outputs incoming shortwave radiation to slopes, longwave radiation, and net radiation. The Canopy module (Sicart et al., 2004; Ellis et al., 2010) was used to adjust the effects of vegetation canopies on sub-canopy net radiation reaching underlying

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snow. The leaf area index was assigned a value of 0.4 for woodland HRUs, which is a typical value for aspen trees during winter (Pomeroy et al., 1999). For other HRUs, a minimum value of 0.001 was set to simulate the canopy effects of Prairie vegetation (crop residue, grass) on radiation for snowmelt. The values of the initial albedos for bare ground and fresh snow were set to 0.17 and 0.85, respectively (Table 1), based on suggested values by Armstrong et al. (2008) for summer conditions and Male and Gray (1981) for snow.

To simulate snow redistribution processes, the Prairie Blowing Snow Model (PBSM) (Pomeroy and Li, 2000), and Walmsley's windflow model (Walmsley et al., 1989) modules were used. Fetch distances were set using values recommended in Pomeroy et al. (2007). Fetch distance was set to 1000 m for exposed sites such as cultivated and fallow HRUs. A 500 m fetch was assigned for grassland HRUs. For other HRUs, a 300 m fetch was selected. The distribution factor parameterizes the allocation of blowing snow transport from aerodynamically smoother (or windier) HRU to aerodynamically rougher (or calmer) ones and was selected according to the prairie landscape aerodynamic sequencing of Fang and Pomeroy (2009). Vegetation height, stalk density, and stalk diameter were set to represent the values for the prairie environment during fall and winter (Table 1) (Pomeroy and Li, 2000).

The Energy-Budget Snowmelt Model (EBSM) (Gray and Landine, 1988) module includes algorithms applicable to the Canadian Prairies and was used to simulate snowmelt by calculating the balance of radiation, sensible heat, latent heat, ground heat, advection from rainfall, and change in internal energy. Infiltration to unfrozen and frozen soils was calculated by the Prairie Infiltration module with algorithms based on Ayers (1959) and Gray et al. (1985), respectively.

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Actual evapotranspiration was simulated using the Penman-Monteith equation (Monteith, 1965), and evaporation from typically saturated surfaces subject to advection, such as wetlands and stream channels, was calculated using the Priestley and Taylor equation (Priestley and Taylor, 1972).

The Soil module calculates the water balance for the soil column, which is divided into two layers: the top layer (called the recharge zone) and the lower layer. The depth of the recharge layer was set at 1.4 m as this is typically a zone of higher hydraulic conductivity in the glacial till derived soils of the region (Brannen et al., 2015). Wolfe et al. (2019) identified the predominant HEG soil texture as loam, which was then assigned as the soil type for all HRUs. The Muskingum routing method was used for the routing amongst HRUs. The routing length for each HRU was calculated using the modified Hack's Law length-area relationship, which was derived from a previous CRHM-PHM modeling study of Smith Creek in Saskatchewan (Fang et al., 2010; Pomeroy et al., 2010).

Model application

To ensure that the role of climate variability across HEG was captured in streamflow simulations the model was run over a 46-year baseline period (1960–2006) driven using data from seven locations. The locations were within and nearby the geographical extent of the HEG classification, and represented the variation in climate across the region (Figure 2; Table 2). The mean annual average temperature at these seven sites ranged from +2.1°C to +6.1°C and mean annual precipitation ranged from 323 to 487 mm (Table 2). The virtual basin model was run using daily precipitation data from the Adjusted and Homogenized Canadian Climate Data

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(AHCCD) (Mekis and Vincent, 2011; Vincent et al., 2012) collected at these seven locations. This dataset corrects shifts identified due to station relocation and changes in observing practices and automation. Other discontinuities are adjusted with multiple linear regression using a penalized maximal t-test and a quantile-matching algorithm. For precipitation, corrections are applied to account for wind undercatch, evaporation, and gauge-specific wetting losses. Snowfall density corrections are derived based on coincident ruler and Nipher measurements. Trace precipitation is added. The daily precipitation data were converted to hourly data required by CRHM using linear interpolation using the Observation module. The other hourly forcing variables (temperature, relative humidity and wind speed) were taken from Environment and Climate Change Canada observations for stations for the same seven locations. The data were quality controlled and infilled using nearby station data.

Table 2: Climate characteristics (1981–2010 climate normal) of the seven selected locations located in and near the High Elevation Grassland class. T_a is mean annual temperature and P denotes mean annual precipitation

Location	Latitude	Longitude	T_a (˚C)	P (mm)
Red Deer, Alberta	52° 16’ 22” N	113° 48’ 36” W	2.8	487
Calgary, Alberta	51° 02’ 37” N	114° 04’ 33” W	4.4	419
Medicine Hat, Alberta	50° 02’ 43” N	110° 40’ 05” W	6.1	323
Lethbridge, Alberta	49° 41’ 32” N	112° 51’ 07” W	5.9	380
North Battleford, Saskatchewan	52° 46’ 37” N	108° 17’ 43” W	2.1	374
Regina, Saskatchewan	50° 26’ 58” N	104° 37’ 10” W	3.1	390
Brandon, Manitoba	49° 50’ 51” N	99° 56’ 50” W	2.2	474

Outputs from the baseline simulations (1965–2006) were used to assess whether the virtual basin model captured typical behaviour of HEG basins. The first five years of simulations were excluded from the analysis to avoid the potential to misrepresent initial conditions due to lag effects associated with antecedent conditions. Because the virtual basin is designed to represent

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typical behaviour of a basin class, it does not reproduce the hydrology of any specific basin and there is no direct physical analogue for which observations can be used to completely assess performance. Previous studies have described the application of CRHM to Canadian Prairie basins, and its ability to represent the region's predominant hydrological processes is well established (Fang et al., 2010). These findings lend confidence that the virtual basin model, informed by these other CRHM applications, can be applied for the diagnostic purposes of this study. Furthermore, the aim of the simulations was not to simulate specific basins in the region, but to assess the sensitivity of the hydrological regime to changes in climate forcings. For this reason, spring snow water equivalent (SWE) values from snow courses and mean annual hydrographs from hydrometric gauges at multiple sites within the HEG class were compared to virtual basin model outputs to establish that the virtual basin model was capturing the correct timing and magnitudes of important states and fluxes. Runoff ratios were also compared to establish if the virtual model was dividing the water budget in a reasonable manner.

To evaluate spring snow accumulation, measured SWE at the Alberta Environment and Parks Wetaskiwin, Kneehill Valley and Innisfail East snow courses (Table 3) were compared against modelled SWE values for the cultivated HRU on the same day measurements were taken, using climate data from the nearest station (Red Deer) (Table 2), for the period during which there was data overlap (1987–2006). It is recognized that snow accumulation in this region is not continuous throughout the winter as there can be significant ablation events, however, measurements are not taken earlier than late February. Mean monthly discharge depths from basins 100% within the HEG class were generated using climate data from four nearby meteorological stations (Table 2) and were plotted and visually compared to the 14 Water Survey

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of Canada hydrometric stations gauging a stream within 100 km of one of the meteorological stations (Table 3). The selected basins and meteorological stations used for these evaluations were all in Alberta as this was where the class was most common and contiguous. These tests were to discern if the virtual basin model was capturing streamflow seasonality, variability and annual runoff ratios.

Table 3: Sources of observed data for model evaluation. Water Survey of Canada's (WSC) hydrometric data were obtained from the HYDAT database, available at https://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/. Effective drainage area is defined by Godwin and Martin (1975) as the drainage area that contributes streamflow to the gauged location during the median annual flood was also obtained from HYDAT. The snow water equivalent data were obtained from Alberta Environment and Parks snow courses.

Station name	*Period of record used for validation*	*Associated climate location(s)*	*Gross drainage area (km^2)*	*Effective drainage area (km^2)*
Hydrometric				
Battle River near Ponoka (05FA001)	1976 - 2006	Red Deer	1820	1550
Maskwa Creek No. 1 above Bearhills Lake (05FA014)	1976 - 2006	Red Deer / Calgary	79.1	61.2
Renwick Creek near Three Hills (05CE011)	1976 - 2006	Red Deer / Calgary	58.9	58.1
Ray Creek near Innisfail (05CE010)	1976 - 2006	Red Deer	44.4	44.4
Blindman River near Blackfalds (05CC001)	1976 - 2006	Red Deer	1796	1460
Battle Creek at Alberta Boundary (11AB117)	1976 - 2006	Medicine Hat	111	111
Gros Ventre Creek near Dunmore (05AH037)	1976 - 2006	Medicine Hat	215	206
Beaver Creek near Brocket (05AB013)	1976 - 2006	Lethbridge	257	257
Prairie Blood Coulee near Lethbridge (05AD035)	1976 – 2006	Lethbridge	214	214
Pothole Creek near Magrath (05AE011)	1976 – 2006	Lethbridge	372	351
Snake Creek near Vulcan (05AC030)	1976 – 2006	Lethbridge	350	346

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Trout Creek near Granum (05AB005)	1976 – 2006	Lethbridge	441	441
West Arrowwood Creek near Ensign (05BM018)	1976 – 2006	Calgary	30	30
Snow Course				
Innisfail East (05CE801)	1987 - 2006	Red Deer		
Wetaskiwin (05FA801)	1987 - 2006	Red Deer		
Kneehill Valley	1987 - 2006	Red Deer		

After evaluation, the virtual basin model was used to explore (1) the role of climate variability within the HEG class, and (2) how hydrological patterns may change in response to potential future shifts in climate. Future climate scenarios were investigated using the delta method, which applies uniform changes to historic daily air temperature and total precipitation records (Lopez-Moreno et al., 2012; Rasouli et al., 2014). This method has the advantages of being computationally inexpensive, while avoiding bias, and preserving the covariances among variables, which are important in modeling cold-regions processes (Shook and Pomeroy, 2010). It has the disadvantage of not assessing sensitivity to changing extreme events, and does not account for seasonal differences associated with climate change. Temperature increases of up to +6°C and precipitation decreases of 20% and increases of up to 30%, based on model projections for southern Alberta by 2050 (Zhang et al. 2018) were investigated. Within these ranges, multiple scenarios were run using increments of 1°C (temperature) and 10% (precipitation), totalling 35 scenarios for each of the seven climate locations. These scenarios were used with the model to quantify sensitivity of snow accumulation and annual runoff to climate change. The spatial distributions of the sensitivities were mapped by extrapolating the values for these seven model locations (Table 2, Figure 2) in ArcGIS using ordinary kriging, assuming a spherical semivariogram and a lag value of 0.01964.

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Results

The HEG class occupies much of the western portion of the Canadian Prairies, and includes the majority of southern Alberta and several isolated patches in both Saskatchewan and Manitoba (Figure 2). Basins in this class tend to have a high fraction of native grasslands (40% of the basin area). The elevations of these basins are amongst the highest in the Canadian Prairies. The mean wetland density of 0.8 km^{-2} is amongst the smallest of the virtual basin classes (Wolfe et al., 2019). Relatively dense drainage networks, coupled with the small wetland densities, result in 67% of the gross drainage area of a typical HEG basin contributing to runoff to the outlet in a median flow year. This is a relatively high percentage for a Canadian Prairie basin.

Virtual basin model performance

Spring snow water equivalent

The virtual model captured the intra- and inter- annual variability in snow water equivalent (SWE) quite well as indicated by comparison of CRHM HEG model simulated SWE (Red Deer forcing data) and snow survey course data (Figure 4). The simulated values were calculated on the same days as the snow surveys with dates varying between February and April. The agreement is quite good considering that a) the forcing meteorological data were collected up to 60 km from the snow survey site, and b) that a virtual model, not tuned to the specific traits of the snow survey location (e.g., vegetation height), was used. Simulated and observed means and standard deviations were similar, but in two instances the model simulated SWE values notably larger than observed during the comparison period (Figure 4). A best fit line with a slope of 1.1 and r^2 of 0.53 can be drawn among the simulated and observed data.

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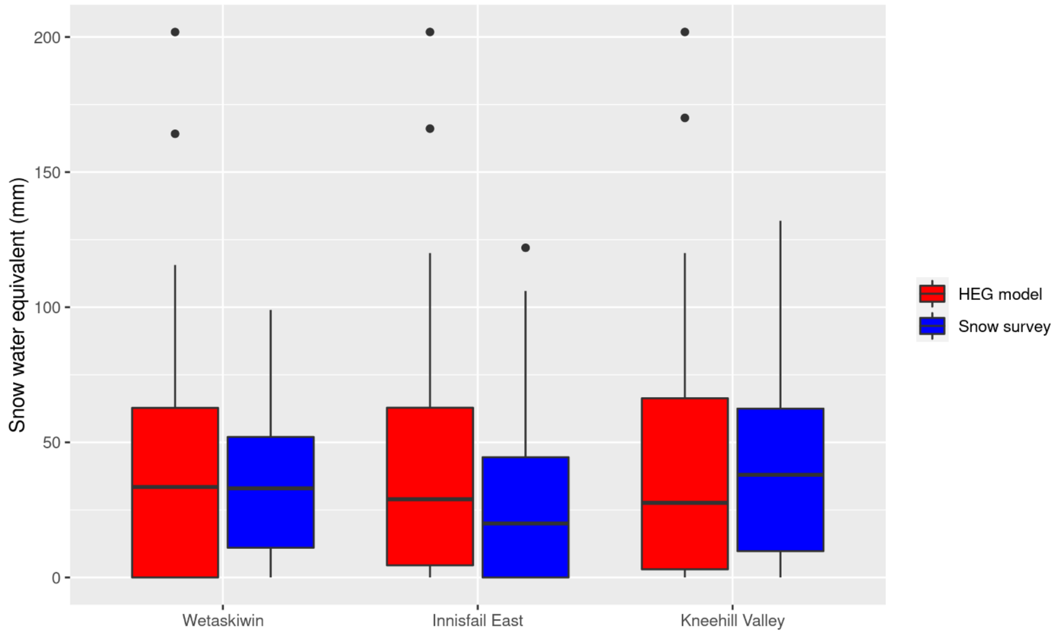

Figure 4: Comparison of 1987–2006 simulated SWE using the Red Deer climate forcings and SWE observed at the three Alberta Environment and Parks (AEP) snow courses near Red Deer.

365 *Mean annual hydrographs and runoff ratios*

As with SWE, the CRHM HEG model produces reasonable simulations of streamflow. Monthly discharge depths for the HEG model driven by climate forcings from the four Albertan climate locations were in good agreement with WSC gauged streams in the HEG classification (Figure 5). The monthly means were computed only from those years for which data were available for the HEG virtual model and for all gauging sites. As would be expected, the largest median monthly discharges are found in March through May, due to the spring melt of the accumulated snowpacks. The HEG virtual model did a good job of reproducing the timing and magnitudes of monthly discharge depths, particularly for March and April. This is impressive considering that the meteorological data were collected up to 60 km away from the stream gauging sites. The

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agreement between the simulated and gauged discharge depths was poorer in the summer, particularly in June and July. Mean conditions are well simulated, but there are numerous instances of outliers in the observed time series, especially in May and June (e.g., Lethbridge – Figure 5) not captured by the simulations. These events are undoubtedly the result of small, fast-moving, short duration and intense convective storms rainfall events. The use of daily precipitation reduces rainfall intensities in the meteorological forcings, and appear less in the simulated time series.

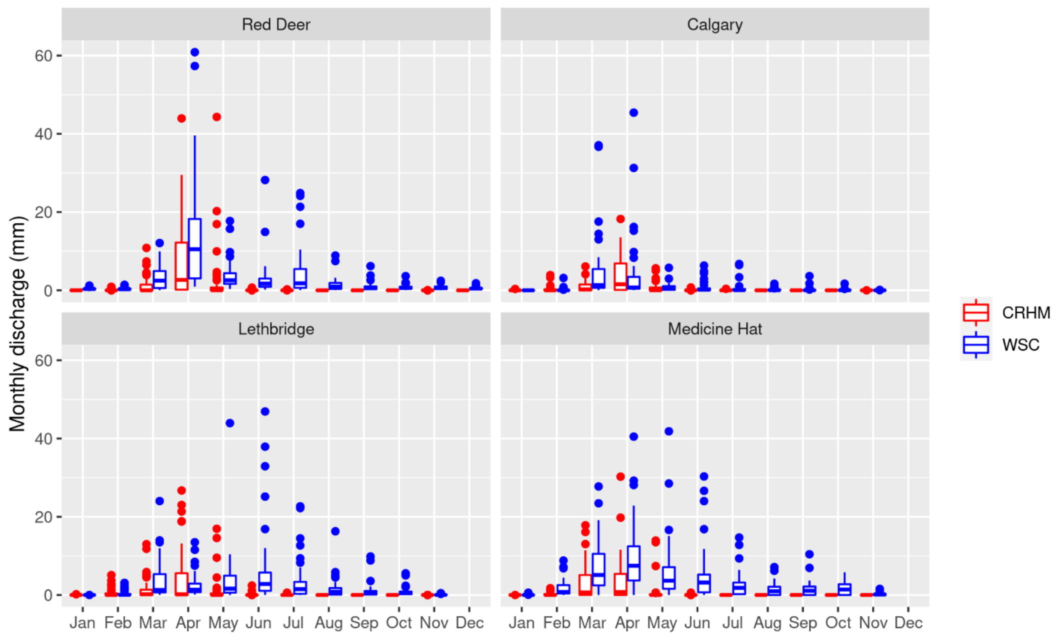

Figure 5: Simulated (CRHM) monthly simulated discharge depths (red) using forcing from four of the climate locations compared with those from WSC gauged streams (blue). The horizontal line in the middle of the box denotes the mean, and the top and bottom of the box denote plus or minus one standard deviation. The whiskers denote 10% and 90% percentiles. Circles represent values beyond these percentiles.

Runoff ratios were evaluated to determine if the virtual model was dividing the water budget correctly and producing a reasonable amount of annual runoff. The mean simulated annual

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runoff ratios for HEG basins during 1965-2006 were 0.08 ± 0.11. These values are slightly lower than those from the literature. Most documented values of runoff ratios from this landscape are from hillslope and agricultural field scales. Woo and Rowsell (1993) estimated the mean value of annual runoff ratios from a grassland slope in Saskatchewan to be 0.13, which is within the range estimated by the model. Rainfall runoff ratios never exceeded 0.11 from grassland slopes observed by Neath and Chanasyk (1996) in the fescue grasslands of southern Alberta, which aligns well with the lower streamflows simulated by the model after spring melt (Figure 5). Pavlovskii et al. (2019) observed hillslope scale runoff ratios for snowmelt events that have a wide range of values, with lower values experienced in mid-winter (~0.3) (i.e., January and February) versus those in spring (~0.5). Higher runoff is often documented when using Water Survey of Canada gauge data than from the virtual basin model (Whitfield et al., 2020), partly because most basins gauged by the Water Survey of Canada have median contributing area fractions that approach 1.0, higher than the typical value for HEG basins, and are more efficient at producing streamflow.

Hydrological sensitivity to climate

Snow cover

According to Li et al. (2019) and Zhang et al. (2018) future climates at the end of the 21st century for the region could be as much as 30% wetter and 6°C warmer than the mid 20th century. The effects of these changes on snow cover differ among HRUs (Figure 6; Table 4). The virtual basin model results support the well-documented cold regions phenomenon in that the annual peak SWE declines with warming (Najafi et al., 2017; Fang and Pomeroy, 2008). Source HRUs for redistribution of snow (e.g., cultivated HRUs) experience small absolute changes. This may

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be because blowing snow is affected by vegetation height, and a 6°C temperature rise does not reduce the depth of accumulated snow below this threshold. HRUs receiving blowing snow, such as wetlands, are more sensitive to warming (Figure 6). Warming of 6°C with no change in mean annual precipitation decreased the simulated annual peak SWE by 27% in the cultivated HRU and 51% in the wetland HRU in a climate comparable to Medicine Hat's– this is similar to the sensitivity of snowdrift SWE to warming found by Fang and Pomeroy (2007; 2009) and is due to the temperature sensitivity of the occurrence of blowing snow (Li and Pomeroy, 1997).

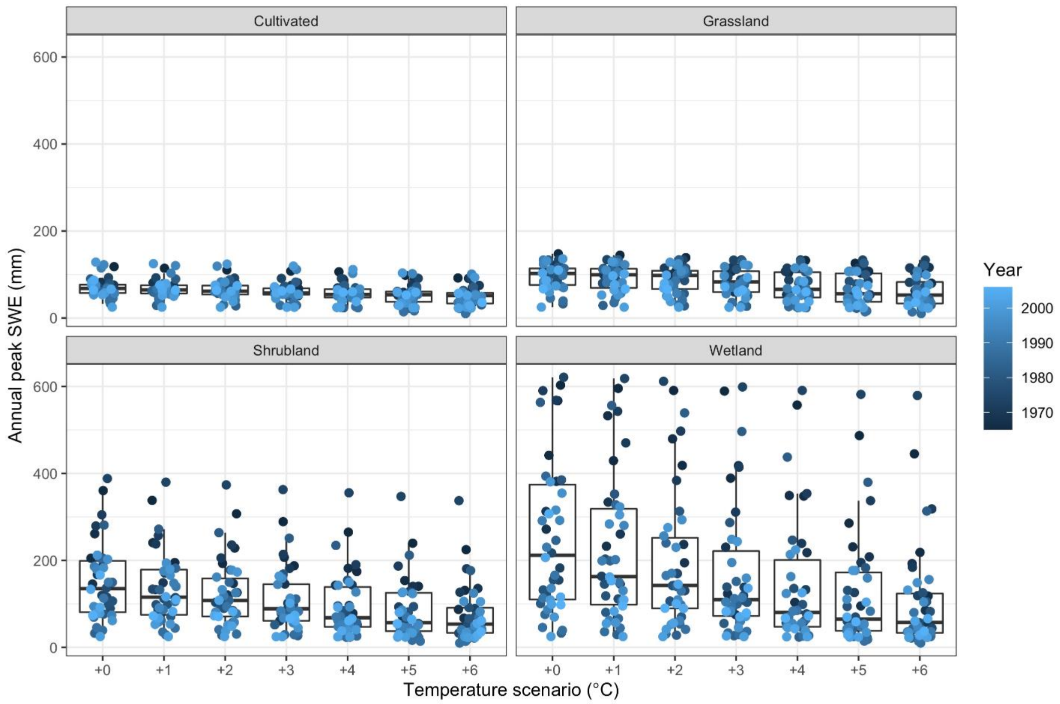

Figure 6: Peak virtual model simulated annual snow accumulation (SWE) for cultivated, grassland, shrubland, and wetland HRUs for Medicine Hat climate under baseline conditions (1965–2006: 0°C) and warming of air temperature up to 6°C.

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Table 4: Simulated annual peak SWE and runoff under different climate scenarios (temperature and precipitation expressed as °C or % change from reference scenario) with a climate similar to that at Medicine Hat.

Variable	**HRU**	**Temperature: 0 °C Precipitation (%)**					**Temperature: 2 °C Precipitation (%)**					**Temperature: 6 °C Precipitation (%)**				
		0	–20	+10	+20	+30	0	–20	+10	+20	+30	0	–20	+10	+20	+30
Annual peak SWE (mm)	Cultivated	60	46	68	77	84	48	38	52	59	65	44	34	49	54	59
	Grassland	67	50	74	84	92	50	40	56	64	70	46	35	51	57	62
	Shrubland	71	52	80	92	101	51	40	58	67	75	46	35	52	59	65
	Wetland	133	93	154	178	197	82	54	98	120	138	65	44	77	94	111
Annual runoff (mm)		9	4	12	15	19	6	3	8	11	15	5	2	6	9	12

The date of annual peak SWE advances as annual air temperature warms (Figure 7). The maximum advance in the date of the annual SWE peak (with no change in precipitation) is about 40 days. The date of peak SWE is more sensitive for climates typical of western Alberta (e.g. Calgary) than those further east (e.g. Regina, Brandon). For example, an increase of 2°C is needed to advance peak SWE date by 20 days near Calgary while a similar change requires 4°C in Saskatchewan or Manitoba. This could be due to the colder initial temperatures further east and north (Table 2). The nearly horizontal isochrones in Figure 7 suggest that the peak SWE date is less a function of potential changes in precipitation amount and more a function of anticipated temperature increases.

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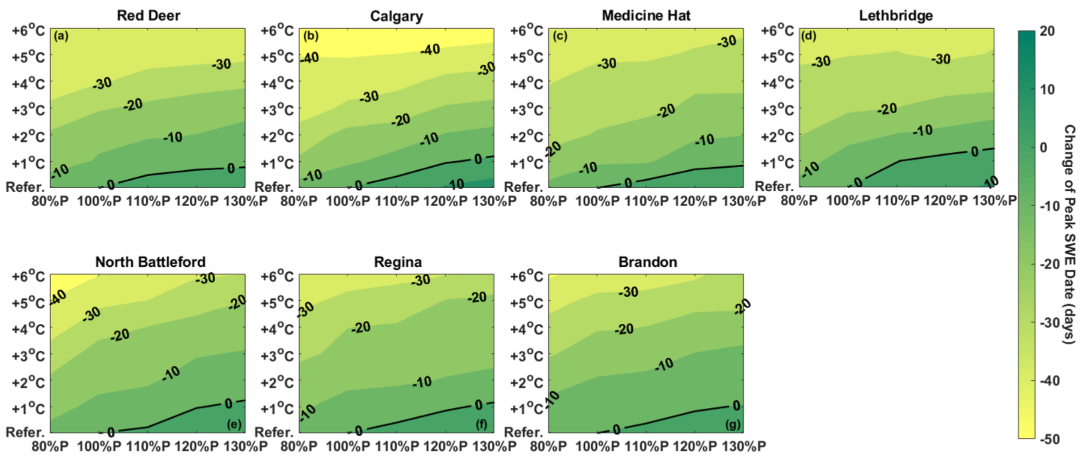

Figure 7: Change in peak annual snow water equivalent date at the wetland HRU under warming and changes in precipitation for simulations using the perturbed 30 year climate data. Negative signs in peak SWE date plot represent advance in time and positive signs denote delay in date of peak SWE accumulation.

Warming is associated with an unequivocal decrease in the amount of snowfall, as the ratio of rain to annual precipitation can increase by more than 10% with warming of 6°C (Figure 8). Greater absolute decreases in wetland HRU SWE with warming were simulated using climate from the eastern and northern edges of the class (i.e., Brandon, North Battleford and Regina) (Figure 8). Under warming of 6°C annual peak SWE in the wetland HRU decreased by 100 mm in a climate such as Medicine Hat's and as much as 220 mm in a climate such as Brandon's. The absolute differences are due to the drier climates of the western locations (Table 2) that produce smaller baseline annual peak SWE (157 mm at Medicine Hat vs. 409 mm at Brandon). The dry climates also tended to be warmer, with a rain ratio more sensitive to warming (e.g., Lethbridge vs. North Battleford, Figure 8). This results in a higher rate of loss in SWE in a climate such as southern Alberta's (11% loss in annual peak SWE per °C) compared to climates from the eastern portions (5% loss in annual peak SWE per °C) (Figure 9).

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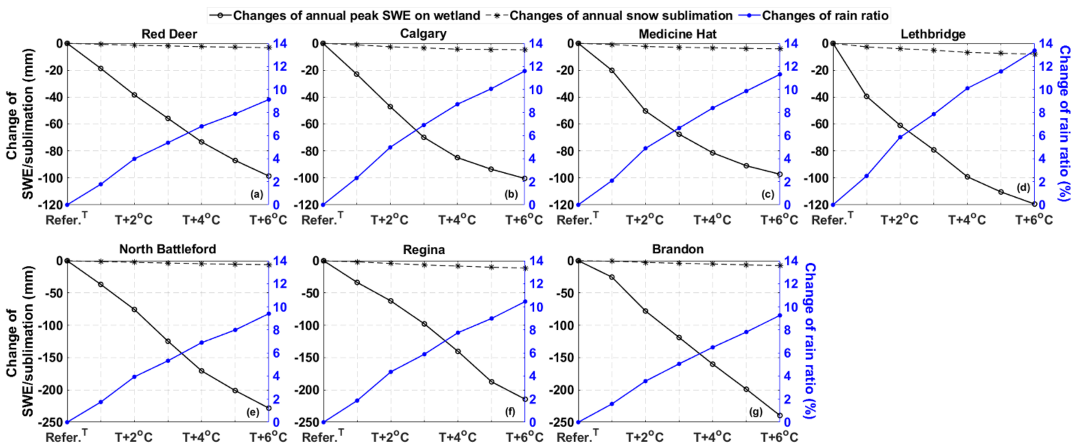

Figure 8: Changes in mean annual peak snow water equivalent (mm) in a wetland HRU, annual blowing snow sublimation (mm) and the change in the mean ratio of rain in annual precipitation (%). Change of rain ratio was calculated by rain ratio of scenario (%) minus the rain ratio of reference (%).

The changes in rainfall ratio illustrated in Figure 8 are evident when model simulations are extrapolated across the HEG class (Figure 9). In much of the class, the annual maximum spring SWE declines by more than 7% for each °C of warming. The most sensitive regions are in western Alberta. When temperature change is held constant in the model, annual maximum SWE changes almost proportionally with precipitation (Table 4). When the effects of temperature and increasing precipitation are combined, there is a trend from east to west of larger decreases in annual maximum SWE (Figure 9) with a warming and wetting climate. The predicted increase of 30% in annual precipitation does not offset the impact of increases in temperature on SWE, but the maximum annual SWE reductions per degree slow and range from 8% to 1%. The most sensitive regions become concentrated in western Alberta as these become relatively drier.

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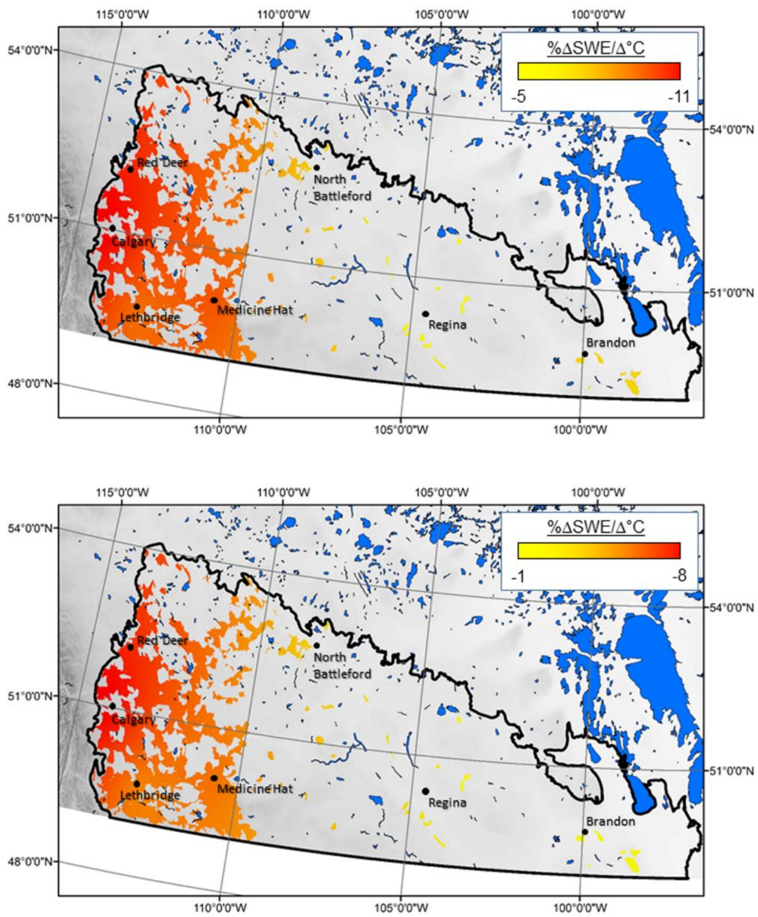

Figure 9: Sensitivity of annual maximum snow water equivalent (SWE) in the grassland HRU to warming, assuming no change in precipitation (top), and a 30% increase in mean annual precipitation (bottom).

Streamflow

Absolute decreases in runoff in the climates of Red Deer, Calgary and Lethbridge are all similar under a warmer climate (Figure 10). Similar, but larger absolute decreases were simulated for the colder climates of Brandon, Regina and North Battleford. These colder sites do not see as large an increase in the rainfall ratio. (Figure 10). The smallest absolute change in annual runoff (7

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mm) was found for areas with a Medicine Hat climate; however, this represents a 78% decrease in runoff, as baseline runoff (9 mm; Table 4) was the smallest of the seven climates investigated. Two reference conditions can result in lower relative change in runoff with warming, either a dry or cold climate. This is evident in Figure 10. For each °C of warming, streamflow from HEG basins with western Alberta climates decrease 15%, but in those with climates from the east and north, this impact diminishes to 7% per °C of warming. Under a warmer and wetter climate (6°C warming and 30% increase in annual precipitation) runoff in western portions still experience decreases, but runoff in climates such as Brandon's increase and remain the same in climates such as Saskatchewan's (Figure 11).

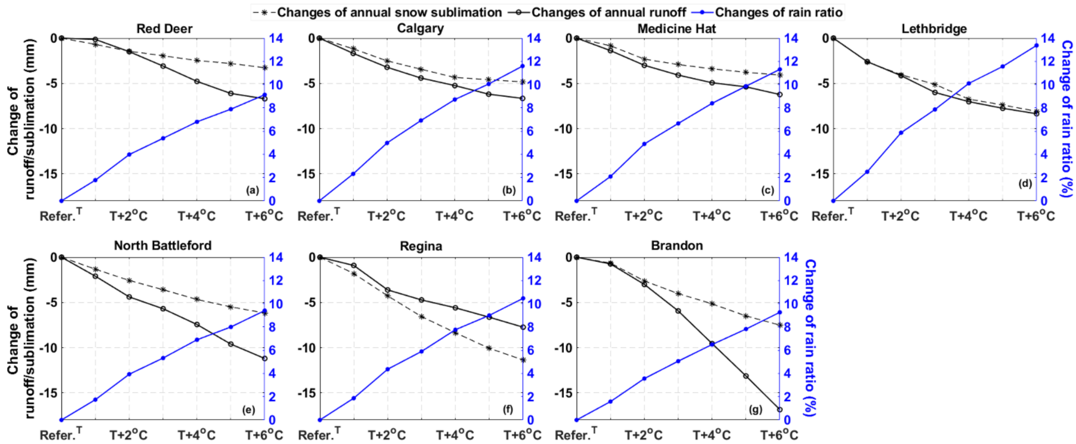

Figure 10: Change in runoff (mm), annual blowing snow sublimation (mm) and change in the ratio of rain in annual precipitation (%) for each climate (annual blowing snow sublimation and ratio of rain as in Figure 8).

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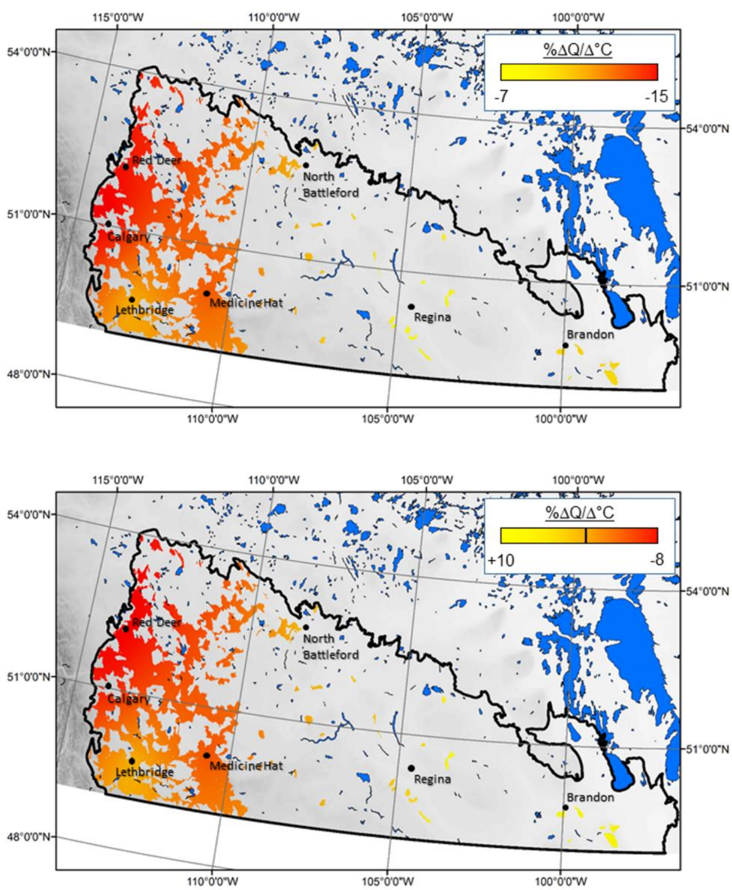

Figure 11: Sensitivity of annual runoff from HEG basins to warming assuming no change in precipitation (top), and a 30% increase in mean annual precipitation (bottom). Note that the black bar on the legend for the bottom panel denotes the colour at which there is no change.

Discussion

It is difficult to glean from observations alone how Canadian Prairie basins respond to change (Ehsanzadeh, 2016), because neither climate nor land-use have remained stationary over the last half century. The value of using a virtual basin model is the ability to isolate the influence of individual drivers such as climate on hydrological responses. The model results imply that the

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effects of temperature and precipitation changes will differ amongst HRUs. Increases in precipitation may also cancel the direction and slow the magnitude of changes in streamflow caused by increased temperatures, and these patterns vary across the region.

Hydrological sensitivity to climate change

The climate of the Canadian Prairie has been warming since the mid 20th century, with more variable and greater precipitation (DeBeer et al., 2016; Gan 1998; Millett et al. 2009), which has altered water availability and flood characteristics (Pomeroy et al., 2009) which are of interest to water managers and others. The uncertainty in future climate change projections, particularly in precipitation (Bush and Lemmen, 2019), can be partially mitigated by the type of sensitivity analysis conducted here, which can provide some information on how hydrological states and fluxes may respond to alternate future climate conditions and to identify potential thresholds in hydrological response. On the Canadian Prairie, the sensitivity to climate varies among landscape components. There is confidence that annual warming of 6°C coupled with increases in precipitation of 30% for HEG basins will induce detectable changes in spring snow condition, with snowpacks in cultivated fields being less sensitive than wetlands. This type of change could happen by the late 21st century. The sensitivity analysis implies that a 6°C warming alone could result in a 27% decline in annual maximum SWE in cultivated areas and a 51% decline in depressions (Table 4). Blowing snow redistribution to depressions is particularly sensitive to warming temperatures (Figure 8). The increase in temperature reduces snow accumulation and, in turn, the redistribution of blowing snow to sink areas such as depressions. Rasouli et al. (2014) also documented a non-linear response in annual peak SWE to changes in temperature and precipitation, albeit in a mountain basin, where even a 30% increase in precipitation could

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not compensate for the impacts of a 6°C warming on peak annual SWE. The reduction in depression SWE has important implications for groundwater recharge as depressions provide recharge at volumes disproportionate to their area on the landscape (Hayashi and van der Kamp, 2005). Given that wetland depressions of the region are well known as biodiversity hotspots (Mantyka-Pringle et al. 2019), these changes could have cascading effects for biophysical systems.

Warming in the spring and reduced winter snow accumulation advance the timing of annual peak SWE. With an increase of 6°C, the timing of annual peak SWE advances by nearly six weeks. This lengthening of the snow free season enhances the opportunity for evaporative losses. The consequence for streamflow is a 44% decline in annual volume in a drier HEG climate such as Medicine Hat's (Table 4). Year-to-year variation may be more extreme than suggested by the model because streamflow variability in the virtual basin model simulations is less sensitive to inter-annual variation in climate than streamflow records for gauged basins within the classification indicate. The results imply that changes in streamflow due to warming can be offset by rising precipitation. Warming of this magnitude has occurred in the last 60 years in southern Alberta (DeBeer et al., 2016) and the influence can be seen in the smallest simulated SWE values typically appearing later in the simulation period (Figure 6). Whitfield et al. (2020) found that basins that align with the HEG class are already responding to this kind of climate change, exhibiting earlier and smaller runoffs, implying the area is becoming drier. This is expected to continue with a further 2°C increase from current conditions (i.e., ~4 - 5°C from the mid 20th century) predicted by 2040 (Zhang et al., 2019). The value in understanding the dynamics of combined impacts of temperature and precipitation changes on SWE and

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streamflow is that it can highlight conditions that require more attention for mitigation. The diversity in streamflow response across the class, with greater decreases in streamflow simulated in the west and possibly increases in the east (Figure 11) may require a variety of regionally specific policies and practices to be implemented across the region. This information could be helpful to water managers and policymakers in the region, including informing how small dams are operated (Muzik, 2001), and wetlands are managed (Wilson et al., 2019).

The sensitivity of hydrological regimes documented here is similar to those of other studies conducted in the HEG classification and other nearby Prairie basins. Fang and Pomeroy (2007) and Pomeroy et al. (2007) attempted to determine the sensitivities of snow accumulation and runoff to drought at Bad Lake, Saskatchewan. They adjusted initial soil moistures, vegetation heights and winter temperature and precipitation in ways that were informed by previous droughts and by the Global Climate Model predictions of the time. In their work, simulated snow cover duration decreased by 40 days given a 1°C winter warming and a 15% increase in winter precipitation, which may suggest greater sensitivity to changing winter climate than our results under similar climate perturbations (single digit advancement of timing and modest decreases in amount of peak annual SWE; Figure 8). Muzik (2001) altered precipitation in a simulation of the Little Red Deer River, Alberta, and also found disproportionate changes in streamflow. Using downscaled values from Providing Regional Climates for Impacts Studies (PRECIS) and the Canadian Regional Climate Model (CRCM) and stochastic weather generator data to force an application of the Soil Water Assessment Tool (SWAT) Model to a Prairie Pothole basin in Saskatchewan, Zhang et al. (2011) found winter runoff increases to be a function of how frequently the air temperature exceeds 0°C. Simulations of Beaver Creek,

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Alberta to quantify climate change impacts on snow accumulation and streamflow indicated that changes in precipitation of more than 10% are needed to alter annual runoff (Forbes et al., 2011). Rasouli et al. (2014) suggest that in mountainous areas of Alberta, runoff is more sensitive to changes in precipitation than temperature, however our results in the Canadian Prairies imply a more dynamic system. When there is warming and drying, runoff is sensitive to both precipitation and temperature, but as conditions become wetter, the Prairie system becomes less sensitive to temperature. This is not necessarily due to changes in the snowpack, which responds in a more linear manner (Figure 9), but perhaps due to higher amounts of rainfall relative to the storage capacity of the landscape.

Conclusions

Virtual experiments have proven to be suitable to diagnose the hydrological response of basins in this landscape. This work introduces a modelling approach that can be used to generate new knowledge of hydrological behaviours at a regional scale under different boundary conditions. Where previous studies have focussed on the sensitivity of individual basins in cold regions, and conclusions about wider applicability were made by assuming the basins to be representative, this approach is meant to provide a methodology to assess how regional hydrology may respond to change by modelling a prototypical virtual basin that represents one type of basin in a region. The results of this study can be used, in part, to address demands for regional-scale information. Such information is required to develop informed policies for climate change mitigation, but also more broadly for water resources management in this landscape where land use is predominantly for intensive agriculture. However, there are some limitations as the model assumes a homogenous basin with an area of 100 km^2. It also does not account for second order changes

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such as how agricultural practices will adapt in response to a warmer and wetter environment over time and the role these landscape changes play in influencing hydrological processes. Outputs of virtual experiments are less useful in predicting exact future system states than in specifying how alternative climate possibilities would alter hydrological behaviour. Therefore, the model output should be interpreted with some caution as the approach is less useful in predicting exact future system states than in specifying how alternative choices could alter the tendency to move towards each of those conditions.

The simulations provide novel insights into the interactions that influence the Prairie hydrological response to different climates. The experimental design was successful in simulating the sensitivity of a basin class in the Canadian Prairie to expected climate change. The scenario results show that the hydrology of HEG basins in the Canadian Prairies is highly sensitive to changes in climate. What should be considered is that the changes simulated by the virtual basin model are already underway. For instance, the mean annual temperature at Medicine Hat for the baseline simulation period (1960 – 2006) was 5.5°C. The region is expected to warm 2°C above the 1976 – 2005 climate normal (6.1°C) to 8.1°C by 2040 (Zhang et al., 2019). It is reasonable to expect that the 2°C (i.e., 7.5°C) warming scenario presented here will be the normal by the end of this decade. Water managers should expect 38% less snow in depressions and 20% less snow in cultivated fields in the spring, and 33% less annual runoff. Of course, this depends on how wet the next ten years are. Simulations imply that a 10-20% increase in average annual precipitation would be needed to offset the warming. These are profound differences in the response of the hydrological regime of the region to a warmer and

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wetter climate. Water managers and agricultural producers need to consider carefully how they can adapt their practices in light of such changes.

Data Availability: All model forcing datasets used in this research are publicly available and can be accessed via the references and links provided. The virtual basin model outputs are available from the authors by request.

Author contributions: CS and CJW conceived the study. ZH, BM and KRS lead the modelling effort and data analysis. JDW lead the catchment classification. All authors contributed to writing.

Competing interests: The authors declare that they have no conflict of interest.

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