ADAPTING TO CHANGING WATER IN ALBERTA

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Executive Summary

Water has underpinned Alberta's development and resolving the challenges related to water: its availability, its use by the irrigation, municipal, and industrial sectors, and its role in sustaining healthy ecosystems and environments are compelling factors in almost all political decisions in the province. This project aimed to 1) develop an integrated groundwater-surface water (GW-SW) model to simulate the regional hydrogeological conditions for Alberta; 2) quantify the future changes in the evapotranspiration, soil moisture, deep aquifer recharge, and water yield for the agricultural region of Alberta; 3) assess the impacts of climate change on future flooding in Alberta; 4) determine the contribution of Alberta's hydrologic model parameterization and regionalization to the overall climate-impact uncertainty chain and use this method to determine how spatial and temporal variation of hydro-climate conditions affect the uncertainty decomposition results; 5) predict changes in crop production and yield variabilities under both rainfed and irrigated agriculture and to explore risks and opportunities to export potentials of the province and to discuss trade-offs with environmental and water issues; and 6) develop a conceptual model that represents the competition for water between the three major water users namely irrigation, municipalities, and industries and identify the potential adaptation strategies at the river basin scale that can provide adaptation potential for the basin.

The conclusions of the project can be summarized as follows:

- The climate in the agricultural region of Alberta has become warmer and drier, especially in southern latitudes, and is expected to change in future periods. Seasonal and annual precipitation is expected to increase by 1% and 3% in the near future (NF: 2015-2040) while it is projected to increase by 5% and 7% in the far futures (FF: 2040-2064). The mean seasonal and annual temperature is likely to increase by 1.21 and 1.33 ◦C in the NF while they will increase by 2.14 and 2.32 ◦C in the FF, respectively. These climatic changes will impact hydrologic water balance components such as soil moisture, actual evapotranspiration, and water yields in the province.
- Floods in the selected 29 catchments of Alberta, Canada are generally intensifying with changes in the climate in the mid-21st century (except in a small number of catchments). About 2/3 of the catchments are expected to experience higher 50-year floods with projected increases of 2–104% (mean = 29%, median = 20%) for RCP 2.6 and 7– 86% (mean = 32%, median = 25%) for RCP 8.5. Most of the studied catchments have consistently shown exacerbated changes in the rate of occurrence of floods, shifts to earlier occurrences, increased variability of the events about the mean date of occurrence, whereas no significant change in the duration of floods was projected.
- Uncertainty analysis showed that climate models and hydrological model parameterization and regionalization are the dominant sources of uncertainty with results showing that there is a slightly higher agreement among climate model projections in near future scenarios compared to the far future. The results showed that uncertainty prediction varies over time and space.
- Our results for the historical 1985-2009 and future 2040-2064 periods revealed that: i) Future climate change leads to an overall increase in cereal crop yields and a decrease in virtual water consumption (VWC); ii) VWC varied substantially in time and space and for different crop production conditions (rainfed and irrigated); iii) The area-based weighted average VWC of both rainfed and irrigated crops at provincial level revealed that the VW flow of wheat grain from Alberta to more than a hundred countries in the world has led to global annual water savings of 4.897 billion m^3 during 1996-2005; iv) Future climate change may provide opportunities for increases in the export of virtual water through the export of cereal crops. However, it may exceed

hydrologic water balance and will be affected by local water resource availability. Our simulated results indicate that total VWF through the export of cereal crops would outweigh the total historical water yield and will account for about 47% of total precipitation and 61% of total ET due to ET from all vegetation and crop types; and v) For a sustainable VWT strategy and sustainable production-export management the future water renewals, as well as water quality and environmental impacts, should be predicted using locally adapted modeling tools.

- The South Saskatchewan River Basin (SSRB) was taken as a case study to test risks and opportunities to various water use sectors under uncertain climate and sector-specific development plans in the future. Initial Causal Loop Diagram (CLD) models were developed to connect the three key water use sectors of the SSRB with the available water supply. When fully developed, they provide a decision support tool allowing collaborative stakeholders framework - making to view consequence scenarios of various adaption measures needed to better sustain the future socio-economic developments in SSRB.

Introduction

The economy of the Province of Alberta depends on an adequate supply of water for the future. Water dependent activities, including irrigation, municipalities, and industries including power generation and the oil and gas industries, require predictable water for a sustainable future. Climate change and climate variability, however, are expected to alter the spatial and temporal water supplies for the province. Understanding the dynamics of the different water flows and endowments in space and time is needed to facilitate strategic decisions and better-targeted investments in efficient water infrastructures and management facilities. Moreover, events such as the 2013 flood in Calgary and the summer drought in the Edmonton region in 2015 necessitate that proper mitigation measures be adapted to accommodate future climate variability and future climate change scenarios. The socio-environmental and socioeconomic consequences of decisions for adaptation cannot be ignored. This project aimed to convey to decisionmakers the risks and opportunities for future growth scenarios as a result of changes in future water availabilities and socioeconomic developments. Long-term integrated water management requires all sectors of the economy: agriculture, ecosystem services, municipal, industrial, and energy (both oil and gas and power generation) to collaborate to ensure there is enough water, when is needed, to ensure a strong economy.

In parallel with the expected future changes in the water supply, Alberta is witnessing considerable expansions in its three key water sectors: irrigation, municipal, and, industrial (e.g., livestock, food processing, unconventional oil and gas among others) that will collectively increase the provincial water demands in the future. These pressures, together with the potential changes in climate, suggest higher water demands and less reliable water supplies in the future. More specifically, in southern Alberta, the South Saskatchewan River Basin (SSRB) is an area of high-water use, significant population growth, and development, and is in a semi-arid environment that is prone to both flood and drought events. To further complicate the matter, portions of the SSRB were recently closed to further allocations of water. With increased demand and uncertainties in future water supply, there are increased social, economic, and environmental risks to the growth potential of the SSRB. Therefore, it is necessary to quantify both future water supply and water demand and to understand the risks and opportunities of possible impacts of climate change. Additionally, adaptation strategies and management options must also be identified and assessed in terms of their near- and longer-term impacts on society, the economy, and the environment that can eventually increase the impacts on global export of food and energy commodities to overseas.

Global climate warming is undoubtedly happening due to anthropogenic influences, which include burning fossil fuels, deforestation, and rapid urbanization. It modifies the intensity and frequency of precipitation, in turn, changes the hydrological cycle. This change is likely to increase in the future and will continue to pose a threat to the water availability for agriculture. Soil water availability in an agricultural region is one of the primary inputs to raise agricultural production to feed a growing world population. Precipitation is a crucial driver controlling soil water in most of the rainfed croplands, whereas temperature is particularly important in most snow-dominated and semi-arid areas as in Canada. The sensitivity of semi-arid regions to changes in precipitation and temperature increases regional vulnerability to the potential effects of climate change on water resources and agriculture. Therefore, it is essential to investigate the changing properties of agro-hydrological variables, including precipitation, temperature, evapotranspiration, soil water, deep aquifer recharge, and water yield due to climate change.

Furthermore, studying extreme hydrologic events such as floods is of great interest because of their significant and widespread impacts on societies, ecosystems, and economies. Detrimental impacts of floods typically include fatalities, loss of property, and damage to critical infrastructure. Floods are the most frequent natural hazard (Buttle et al., 2016) and costliest disaster (Sandink, 2010) in Canada, and in particular, Alberta has witnessed several historic devastating and costly floods resulting in many deaths and disruptions from evacuations, such as the Alberta 2013 flood (Environment and Climate Change Canada, 2017; Milrad et al., 2015; Pomeroy et al., 2016; Teufel et al., 2017), making the province prone to increased future flooding risks. Further, concerns are growing that future flooding events will become more frequent and severe (Huang et al., 2014; Kay and Jones, 2012). In particular, climate change is expected to alter the statistical properties of several climatic variables, including seasonal and extreme precipitation, which are likely to increase in the future (Gizaw and Gan, 2016; Riahi et al., 2017). Also, there has been no other study conducted on the potential impacts of climate change on future floods in Alberta, both in terms of seasonality and design discharges. Therefore, it is imperative to study potential changes in flood severity in the future in terms of magnitude and seasonality, since they can significantly impact socioeconomic decisions. Here, the future changes in the 20-year and the 50-year floods were investigated and quantified. Besides, changes in the rate of occurrence, regularity, timing, and duration of floods in the future were also investigated.

Moreover, wetlands are critical elements of our natural ecosystems in Alberta for their social, economic, and environmental functions. They attract a wide range of recreational activities, reduce the detrimental impacts of floods through storage, retain sediments and sequestrate carbon, replenish groundwater resources, and help conserve biodiversity by providing a unique habitat for fish and wildlife. Therefore, understanding their short- and long-term functions, more specifically the dynamics of their water changes, is essential for managing our watersheds sustainably (Golden et al., 2016; Wang et al., 2008; Wester et al., 2018). Wetlands have been negatively affected and lost by anthropogenic activities (Junk et al., 2013; Marton et al., 2015). Compounded with climate change, it is expected that the loss of water in wetlands will continue, and it will likely worsen in the future. While the literature lacks formal assessments of wetland loss both globally and regionally and with little provision of supporting evidence and data sources, it is estimated that the global rate of wetland conversion and loss during the last century was at least 3.7 faster than before (Davidson, 2014). It is estimated that Alberta has lost two-thirds of its wetlands since the 1800s (Weber et al., 2017). Therefore, understanding the influences on stored volume in wetlands is imperative for projecting future changes on the stored water volume of geographically isolated wetlands in Alberta.

Climate change as a significant international environmental challenge is altering water resources; however, uncertainty is an inescapable characteristic of climate projections (Moss et al., 2010). It results from a lack of knowledge, lack of accurate input data, uncertain understanding of natural processes, and disagreement among experts. More specifically, climate-impact projections are subject to uncertainty arising from climate models, greenhouse gas emissions scenarios, bias correction and downscaling methods (BCDS), and the impact models. Therefore, the effects of hydrological model parameterization and regionalization (HM-P and HM-R) on the cascade of uncertainty were studied and quantified. In this study, a new, widely applicable approach was developed that improves the understanding of how HM-P and HM-R, along with other uncertainty drivers, contribute to the overall uncertainty in climate-impact projections.

Finally, given the above-mentioned challenges and the competition on the water between the different water sectors, including irrigated agricultural, municipalities, hydropower, ecosystems, and industries including oil and gas, an integrated water resources management approach is a necessity. Integrating both future water supply and demand scenarios with their social, economic, and environmental factors will allow us to represent the dynamic "feedbacks" between different variables of the water system. Such integration will result in an improved understanding of the water problem boundaries and potential risks and opportunities.

Project description

Within the context of adaptive supply-demand management in the face of future climate change and future socioeconomic developments, the overall objectives for the study were:

- To integrate tools, datasets, developed models, and contributions of stakeholders for adaptive management of the water systems in Alberta. This integration allows the development of the required water management responses to changing both surface water and groundwater resources to ensure the sustainability of our watersheds.
- To inform stakeholder groups about uncertainty in water supply-demand management resulting from climate change and the corresponding risks and opportunities to various stakeholders as a result of testing various adaptation strategies by implementing an integrated water management approach.
- To project and examine the future water supply and water demands for Alberta under several plausible and potential climate change and socio-economic development scenarios.

In order to accomplish these overall objectives, the ACWA project, more specifically, aimed to

- Develop an integrated groundwater-surface water (GW-SW) model to simulate the regional hydrogeological conditions for Alberta and the potential impacts of climate change and water withdrawal on GW-SW interactions.
- Quantify the future changes in the evapotranspiration, soil moisture, deep aquifer recharge, and water yield for the agricultural region of Alberta concerning the historical changes and the impacts on the water availability for dryland agriculture
- Investigate the impacts of climate change on future flooding in Alberta and more specifically for watersheds with minimum anthropogenic changes
- Investigate the changes in the storage volume of geographically isolated wetlands of Alberta under climate change and anthropogenic changes
- Devise a method to determine the contribution of hydrologic model parameter (HM-P) and regionalization effects (HM-R) to the overall climate-impact uncertainty chain and use this method to determine how spatial and temporal variation of hydroclimate conditions affect the uncertainty decomposition results.
- Predict changes in main crop yields, including of barley, wheat, and canola, in agriculture sector, as agriculture is known to be the most water-dependent sector among others in Alberta and elsewhere in the world.
- Identify the potential adaptation strategies at the river basin scale that can provide adaptation potential for the basin, building on those adaptation strategies that are identified in the SSRB Roadmap, and 2) quantify the impacts of changes in climate on future water supplies of the SSRB

and the anticipated developments and climate change on water demands of the three major water users of the SSRB namely, the irrigation, municipal, and industrial water sectors (i.e., livestock, food processing, oil and gas), and quantify their economic, environmental, and social consequences.

The project also aimed to advance the knowledge of water availability forecasting for Alberta and engage stakeholders through a series of direct interactive workshops to identify imbalances in demand and supply scenarios. Bringing the stakeholders together to examine future supply and demand scenarios, builds the necessary consensus to implement adaptation strategies to mitigate potential economic, environmental, and social consequences.

First, for the integrated GW-SW model for Alberta, the objective of this task was to apply SWAT–MODFLOW to simulate a vast region to study the regional hydrogeological conditions and the potential impacts of climate change and water withdrawal on GW–SW interactions. A case study for the Little Smoky River Watershed within the province of Alberta was selected. The specific objectives were: (1) to calibrate, validate, and provide uncertainty analyses for both model components, (2) to assess the effects of future climate change on the GW–SW exchange pattern, and (3) to examine the impacts of groundwater use scenarios on GW–SW interactions for the interval of 2010–2034. This was done to achieve the goal of further understanding of the use of SWAT–MODFLOW as a planning tool to predict the effect of natural and anthropogenic influences in Alberta in response to future climate change and variability.

Second, to quantify the future changes in the evapotranspiration, soil moisture, deep aquifer recharge, and water yield for the agricultural region of Alberta, this task aimed to investigate the variability and trend of hydrological variables, i.e., precipitation, temperature, evapotranspiration, soil moisture, deep aquifer recharge and water yield under the impacts of climate change in Alberta. The province of Alberta was considered as a primarily agricultural region in Canada and food supplier for the world. The province encompasses 17 primary river basins with each including diverse agro-hydrologic and hydro-climatic conditions. Besides, the careful calibration and validation of the developed hydrologic model of Alberta is available (Faramarzi et al., 2017, 2015), allowing simulation of agro-hydrologic variables for this study.

Third, the study incorporated the possible impacts of climate change on floods in much of Alberta. This allows predicting the future changes in the flood characteristics for Alberta to minimize potential risks of future flood events and for future development in terms of designing safe infrastructures such as storage reservoirs and their potential impacts as adaptation measures on both water availability and water demand for other water sectors studied in ACWA project. The specific objectives of this task of the project included (1) quantifying the changes in the future flood attributes during the future period of 2040-2064 in comparison to 1983-2014 and (2) quantifying the future changes in flood magnitudes in 29 unregulated watersheds in Alberta. The analyzed flood attributes included (i) the annual rate of occurrence of independent exceedances above a flooding threshold; (ii) the annual mean date of occurrence of exceedances; (iii) the duration of each flood event; and (iv) the variation about the mean date of occurrence referred to as the flood regularity. Two flood magnitudes that correspond to the 20- and 50-year return periods were chosen for the analysis.

Fourth, the changes in the storage volume of geographically isolated wetlands of Alberta under climate change and anthropogenic changes, the lack of quality and well-distributed data (i.e., surveyed geometry and bathymetry data) and the resulting conflicting spatial scales between modeling efforts and interests of policymakers led to estimate the status-quo regional WSV of GIWs in Alberta using easy access geographical information features via Machine Learning (ML) models when water depth measurements do not exist.

Fifth, for the contribution of HM-P and HM-R to the overall climate-impact uncertainty chain, we hypothesized that parameterization and regionalization of a hydrologic model might have a significant contribution in the cascade of uncertainty and its magnitude may outweigh other significant sources of uncertainty in climate impact projections. Therefore the specific objectives of this task were to (1) determine the share of different uncertainty sources in the overall uncertainty in the projection of blue and green water resources in Alberta using ANOVA-SUFI-2 coupled approach, allowed quantification of uncertainty resulting from hydrologic model parameterization and regionalization, along with other sources including climate models, greenhouse gas emission scenarios, bias correction and downscaling methods, evapotranspiration calculation methods, and their interactions, and (2) quantify the share of uncertainty caused by HM-P and HM-R in future impact assessments for Alberta.

Sixth, we contributed to: (1) providing high-resolution information where none exists about the future patterns of water availability (WA) for beef industry depicting its various sources (i.e., blue and green water). The blue water is defined as the sum of water yield and ground water recharge, and green water defined as the volume of soil moisture (green water storage) and actual evapotranspiration (green water flow); (2) providing spatio-temporal dynamics of water demand (WD) of different feed crops. The WD is defined as the quantity of freshwater consumptively used throughout the beef production chain (feed to meat) and it varies over time and space. This includes the demand of growing field crops (including annual and perennial field crops) and the water consumed by animals through on-farm services; (3) providing locally representative data and information on WA and WD of the beef industry. The data available in literature from global studies or from other jurisdictions in Canada have not been rigorous enough to allow for informed and transparent policy and planning for decision-makers and producers in Alberta. The WD of field crops varies substantially for rainfed and irrigated production conditions and future climate change leads to a considerable spatiotemporal changes in WD of crop production. Given the changes in WD pattern of crops the virtual water exports in the form of cereals and processed foods to other countries may outweigh the total water renewals and historical water yields.

Finally, this project aimed to integrate i) a hydrological model that represents the future water supply in the SSRB and ii) a conceptual System Dynamics (SD) model that characterizes future water demands under several development scenarios and policy measures as well as the outputs from the different phases of the project that included floods, and changes in the agro-hydrological variables in the agricultural region of Alberta., and the environmental demands for wetlands. The specific objectives of this phase included:

- Develop a conceptual model for water resources management for Alberta and, more specifically, for the SSRB that characterizes the competition for water between irrigated agriculture, municipalities, and industries (livestock, food processing, oil and gas, and power generation).
- Identify and rank potential strategies at the basin-scale that might provide adaptation potential for the SSRB based on participatory modeling approaching that employs involvement of key water stakeholders in the SSRB.
- Set the stage for a numerical System Dynamics simulation model (i.e., Alberta Water Policy Simulator: AWPS) that simulates and predicts the future water demands for Alberta for three key water users (i.e., irrigation, municipalities, and industries). This model will quantify the

impacts of changes in climate and the anticipated developments on the water demands of the three sectors of the SSRB. The model will allow testing the strategies for adaptation when the development of the AWPS is complete under both climate change and future developments.

2. Methodology

The project employed several methods to achieve its objectives and integrate the available knowledge on both the water supply and the water demand of Alberta and its uncertainties.

2.1 Coupling of groundwater-surface water interactions

For this task, a coupled groundwater-surface water (GW-SW) model, SWAT–MODFLOW, was developed and applied to study the hydrogeological conditions and the potential impacts of climate change and groundwater withdrawals on GW-SW interactions at a regional scale in Alberta. ArcSWAT 2012 was used to build a SWAT surface hydrologic model of the study area by delineating the Little Smoky watershed into 28 sub-basins (Figure 1) and to replicate the water network of the study area (primarily the Little Smoky River). For this study, the primary outlet of the watershed is located at the northernmost point of the modeled region. Historical weather data, including precipitation, temperature, relative humidity, wind speed, and solar radiation, were collected from different sources (Chunn et al., 2019), and were incorporated into the model for the time period of 1983–2007 (25 total run years). In the SWAT model, snowfall is simulated based on total precipitation and temperature data. The MODFLOW model was constructed using the Visual MODFLOW Classic Interface. The model area for this component was 44,955 km^2, with a length of 195 km in the x-direction and 230 km in the y-direction. Discretization for this model was intentionally kept coarse to ease the computational burden once coupled with SWAT. A 100 × 100 grid was used, with each grid cell having dimensions of 1.95 km × 2.30 km. While this does result in relatively low spatial resolution in the x–y directions, the MODFLOW component remains relatively complicated compared to those used in the previous SWAT–MODFLOW models by its seven layers, and the heterogeneous hydraulic conductivity found within these layers (thus maintaining variability in soil hydraulic conductivity (K) in all three dimensions). The integration of the SWAT model and the MODFLOW model is presented in Chunn et al. (2019).

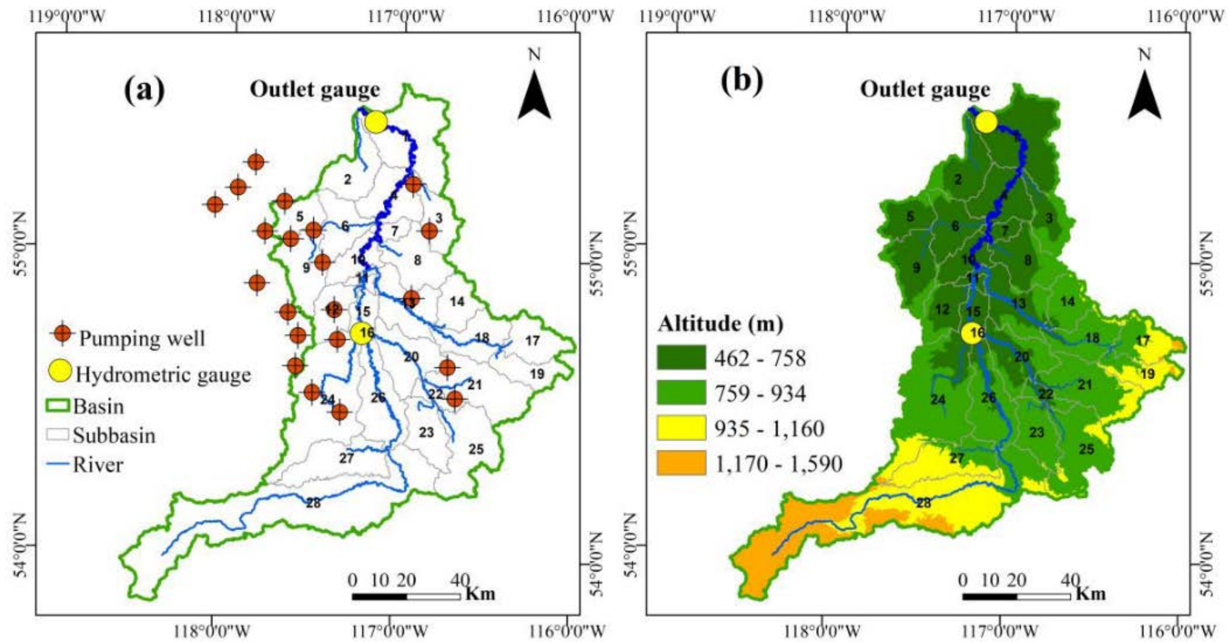

Figure 1. Little Smoky River watershed: (a) displaying the delineated sub-basins, hydrometric stations, and simulated pumping well locations (based on water well trends in the study area) included. Each well is proximal to or within the study area, with 16 of the 21 pumping wells located in the downstream portion of the modeled area; (b) displays the topographic classes and varying elevation (adapted from Chunn et al., 2019).

A key objective of this study was to evaluate the ability of SWAT–MODFLOW to simulate a watershed under the effects of both natural and anthropogenic influences. Three scenarios and a base scenario were analyzed, with the first focusing solely on the effects of pumping 21 simulated wells in the MODFLOW component. These wells were proximal to or within the study area (found along with the same trends as the water wells used for calibration), pumping at a rate of 468 m^3/d for six months of each simulation year. Although the durations of single energy operations are generally short-lived relative to the simulation period, the volumetric rate used here is consistent with one provided by an Albertan energy company with hydraulic stimulation operations near the study area. The second coupled scenario included climate change and no pumping, averaging the results for five distinct GCMs (Can_ESM2, CCSM4, CNRM_CM5, CSIRO-MK3, and MIROC5) from the Pacific Climate Impacts Consortium (PCIC, https://www.pacificclimate.org/data) under the RCP 8.5 (high carbon emissions) scenario. The third applies both the climate change scenario described above and increased the pumping rate of the wells used in the first scenario by order of magnitude to 4680 m3/d. The ten-fold increase in the pumping rate at the existing wells is meant to act as a way of simulating the installation of 10× as many wells because the wells are well-distributed in the geographic region of the model where groundwater withdrawals for the industry are most likely to occur. Although this scenario is unlikely to play out in the future (to this extent), it was included to maximize the stress on the hydrologic system to determine which extreme (climate change or heavy pumping) would have a more significant influence on the system. These GCM models (Table 2) were downscaled to match the observed interval of the reference period (1983–2007) to establish an empirical relationship between them and the model. This relationship is then used to project data for future scenarios, resulting in a simulation period of 25 years (2010–2034), similar to the historical model.

2.2 Projected changes in agro-hydrological variables in the agricultural region of Alberta

The province has 17 river basins and 19 census divisions (CD) of agriculture with 43,234 agricultural farms. The agricultural region of Alberta is spread out in 11 out of 17 river basins (Figure 2) that are chosen to assess the spatial variability of hydrological parameters in this task. A total of seven counties from seven agricultural CDs were selected based on the number of farms for trend analysis. First, the CD with the total number of farms in the division of more than 2000 was selected. Next, the county in each CD with a total number of farms >900 was selected for trend analysis. No county had been selected having less than 900 farms, even if the CD had more than 2000 farms. The name of these counties are: (a) Grande Prairie from Grande Prairie CD, (b) Lac St. Anne from Barrhead/Athabasca CD, (c) Leduc from Edmonton CD, (d) Lethbridge from Lethbridge CD, (e) Mountain View from Calgary CD, (f) Red Deer from Red Deer CD, and (g) Vermilion from Camrose/Vermilion CD. The selected counties represent various hydroclimate, geospatial, and management conditions in the province's agricultural lands. The study period was divided into three different time horizons (a) historical (His: 1983 to 2007), (b) near future (NF: 2010 to 2034), and (c) far future (FF: 2040 to 2064) under two climate scenarios (i.e., RCP 2.6 and RCP 8.5). The calibrated SWAT hydrological model was used to simulate hydrologic water balance variables for each climate model and scenario. Simulated daily records of agro-hydrological variables (temperature, precipitation, evapotranspiration, soil moisture, deep aquifer recharge, and water yield) were aggregated into seasonal (April–September), and annual (January–December) means. Long-term monthly mean also used to examine monthly changes in hydrological variables. More details about the method is presented in Masud et al. (2018).

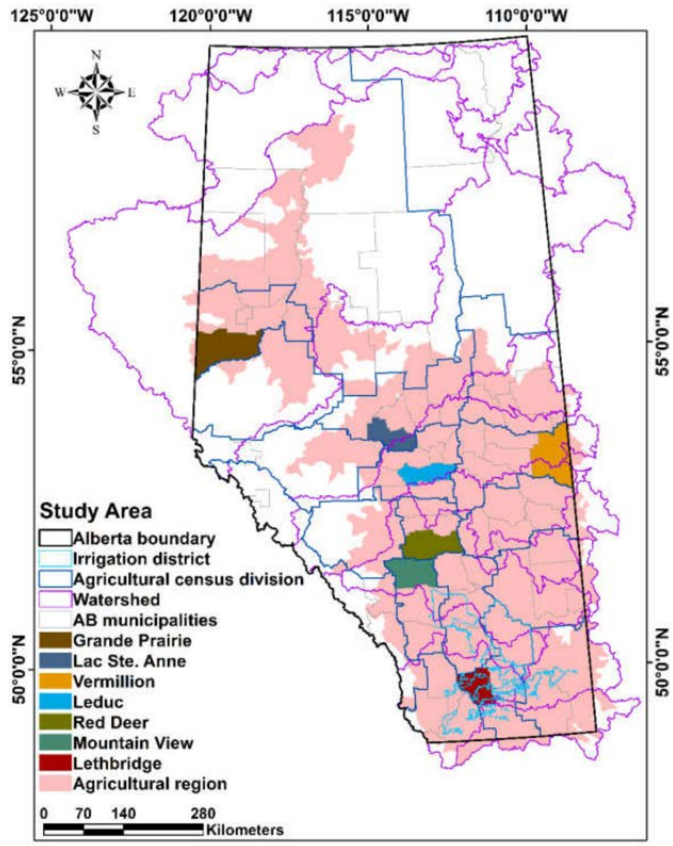

Figure 2. Map of the study area (agricultural region) overlaid with the Alberta boundary, watersheds, agricultural census divisions, Alberta municipalities and irrigation districts of Alberta. The seven shaded areas are the location of the case study for trend analysis (adapted from Masud et al., 2018).

A variety of statistical methods can detect the trends of hydrological variables at different temporal scales. Both non-parametric (Mann–Kendall test) and parametric (linear regression analysis) procedures are used to identify annual and seasonal trends. The Modified Mann–Kendall (MMK) statistical test was used to detect the trends in precipitation, temperature, and relative humidity. The trend of seasonal and annual precipitation and temperature were analyzed for the current and future periods. The magnitude of the trend and its significance in the time series were determined using the Sen's slope estimator and the MMK test. The trend analysis was performed separately for RCP 2.6 and 8.5 in seven selected counties in the Alberta agricultural region for His, NF, and FF. The ET was simulated by the developed SWAT hydrologic model for dominant land use (ET_DLU) and barley crop (ET_barley) for the historic period. These two ET were used for comparison of the water demand differences in a county for two land-use types. We intended to study how significant the water demand of the current dominant land-use type is in a county as compared to the water demand of a potential crop type.

2.3 Future changes in floods in Alberta

This task included eight of the 17 river basins in the province: Athabasca, Battle, Beaver, Bow, North Saskatchewan, Oldman, Peace, and Red Deer, as shown in Figure 3, covering almost 60% of Alberta. Several gauging stations in the eight river basins were selected at the main rivers and their large tributaries from the gauging database and flow records of the Water Survey of Canada. We selected streamflow gauging locations with at least 50 years of data over the province of Alberta. The SWAT hydrological model was used to derive the hydrologic projections of the selected watersheds in Alberta for the historical period (1983-2014) and the future period (2040-2064). Flood peaks data were extracted from the daily simulated streamflow series for the historical period and the projected data for the future period under each climate model and scenario using peaks-over-threshold (POT) (Ammar et al., 2020). Once the optimal thresholds are defined, and independency is ensured, one needs to fit a suitable probabilistic model to the POT series to estimate the design discharges. For that, the generalized Pareto distribution (GPD) was used to model the independent peak flow extremes statistically. Additionally, to account for the uncertainty in the flood peaks projections resulting from the variability of outputs from different climate models, an ensemble approach was employed. Two climate scenarios in an ensemble of five GCMs (i.e., CanESM2, CCSM4, CNRM-CM5.1, CSIRO-MK3.6.0, and MIROC5) were incorporated. Four flood attributes were identified and derived from each POT series under the different model-scenario projections: (i) the annual rate of occurrence of independent exceedances above the threshold; (ii) the annual mean date of occurrence of exceedances; (iii) the duration of each flood event; and (iv) the variation about the mean date of the occurrence referred to as the flood regularity. Two flood quantiles were derived from the fitted GPD that corresponds to the 20- and 50-year return periods, and the future changes were estimated. More details about the method is presented in Ammar et al. (2019).

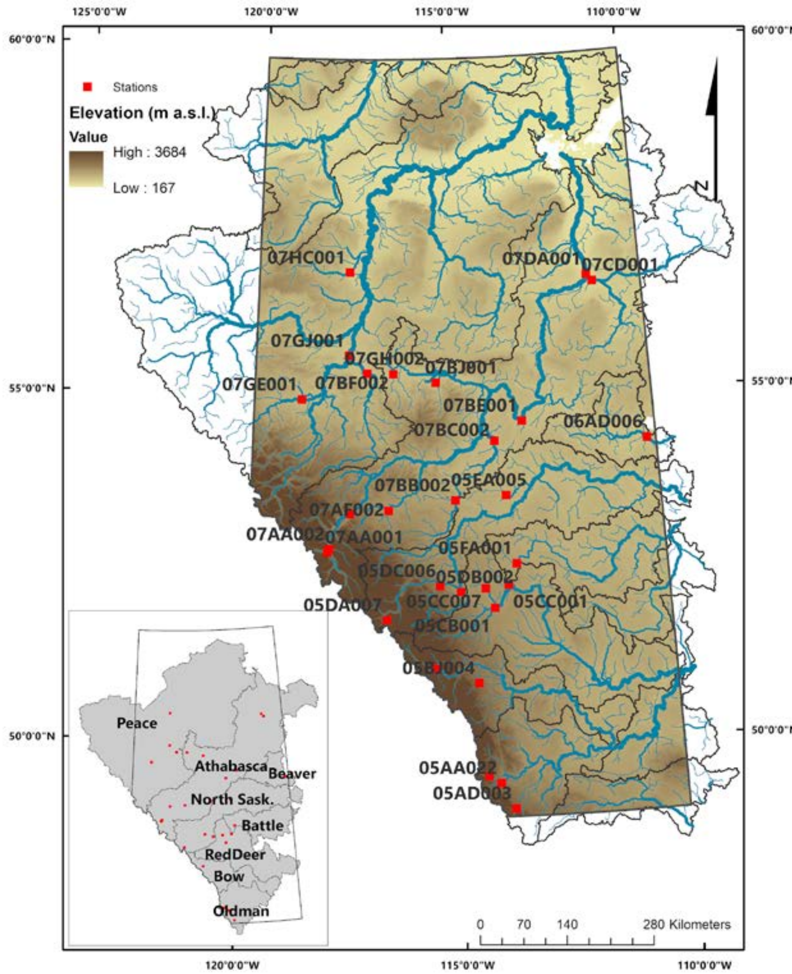

Figure 3. Map of Alberta showing the 29 streamflow gauges and their corresponding eight major river basins in grey (adapted from Ammar et al., 2019).

2.4 Change in the stored water volume of geographically isolated wetlands in Alberta

The goal of this study was to develop an estimate of water storage volume in GIWs at the regional scale based on the data collected by the Alberta Biodiversity Monitoring Institute. Wetlands survey sites were chosen randomly from a pool of suitable wetlands located near the grid pattern developed by ABMI using 20 km spacing across Alberta (1656 National Forest Inventory grids) (ABMI, 2017). For the data used in this project, all chosen wetland sites are year-round permanent, have a surface water area between 1×103 m2 and 1×105 m2, and a minimum depth of 0.5 m at the deepest point during summer. According to ABMI provided information, each wetland-sampling site was visited once during 2007-2017 (ABMI, 2017). In total, 234 sites were identified as GIWs and their data used for building the model.

The volume for the sampling wetland sites was calculated by the Kriging method. For each site, 14 GIF indicators were generated using the polygon of wetlands and an Alberta Digital Elevation (DEM) layer (2m×2m) in the ESRI ArcGIS Version 10.5 (ESRI, 2017) platform. Indicators include area, perimeter, thickness (defined as the deepest point within the zone from the polygon edges), length of the major axis, length of minor axis, orientation (defined as the angle between the x-axis and the major axis), and maximum and mean slopes of 50m, 100m, 150m buffer zone of wetlands. We also calculated a shape index (Shape= Area/(pi*Thickness^2)) and the ratio of axis (AxialRatio= MajorAxis/ MinorAxis) as additional indicators. These 14 GIF indicators were put into a multi-PCA analysis to select the most contributive and independent indicators for the next modeling step. We then employed 21 machine-learning regression models and 2 neural network models. The 21 regression models have varied settings from 5 types of machine learning regression models, including linear regression, regression trees, support vector machine (SVM), ensemble trees, and Gaussian progress regression (GPR) models. Model performance criteria were based on R-Squared (R2), the root mean squared error (RMSE), and the mean absolute error (MAE).

Based on sufficient validation process and comprehensive comparison, the Linear- Exponential-GPR (LEGPR) model with linear basic function and Exponential Kernel function performed the best in both the White Area and the Green Area. Since our sampling dataset covers all possible data ranges for all the variables, LEGPR was found to be the most suitable model for WWSV and was chosen to estimate the WWSV of GIWs in Alberta.

2.5 Uncertainty analysis of climate-impact projections

The uncertainties arising from general circulation models (GCMs), representative concertation pathways, BCDS, evapotranspiration calculation methods, and specifically HM-P and HM-R were analyzed. The previously calibrated-validated SWAT model of Alberta, Canada (Faramarzi et al., 2017, 2015), with the detailed model parameterization and regionalization at the sub-basin level, was employed. This detailed model allowed us to evaluate the impacts of spatiotemporal hydro-climatic variability on the uncertainty decomposition results. The analyses were performed over two future periods, including the near future from 2010 to 2035, called S1, and the far future from 2040 to 2065, called S2. A compound approach was developed consisting of the ANOVA method for decomposition of uncertainty sources and the SUFI-2 method for capturing the uncertainty associated with HM-P and HM-R in the overall uncertainty cascade of projected hydro-climatic variables. In addition to the HM-P and HM-R, six other sources of uncertainty were considered in this study namely: GCMs, RCPs, RCMs, bias correction and downscaling (BCDS) of climate data, and two different potential evapotranspiration (ET) calculation methods, i.e., Penman-Monteith and Hargreaves, which are widely-used approaches in hydrological models. The share of each source of uncertainty and their interaction were further quantified in the overall uncertainty. For this purpose, hydro-climate components were quantified including blue water availability (water yield plus deep aquifer recharge), green water flux (actual evapotranspiration), green water storage (soil moisture), precipitation, and mean temperature for two future horizons (i.e., 2010–2035 and 2040–2065). Finally, the results were aggregated from the sub-basin level to the provincial level. More details about the method is presented in Vaghefi et al. (2019).

2.6 Uncertainty-based projection of crop yields, crop water demands, and potential crop virtual water export

To model water demand of feed crops, we used the agro-hydrologic model Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) in combination with the Sequential Uncertainty Fitting program (SUFI-2) (Abbaspour, 2015) to calibrate, validate, and perform uncertainty analysis based on the available measured crop yield data. The modeled agricultural region of Alberta is shown in Figure 13.

2.6.1 SWAT model

SWAT is a computationally efficient simulator of hydrology and crop growth at various scales. It is a mechanistic time-continuous model that can handle very large watershed in a data-efficient manner. The SWAT model divides each watershed into sub-basins based on topography and subsequently into Hydrologic Response Units (HRU) according to the soil, land use, and slope characteristics. The plant growth component of SWAT, which is a simplified version of the Erosion Productivity Impact Calculator (EPIC; ref Williams, 1995), is capable of simulating a wide range of crops, grassland, and pasture. In the SWAT model, crop biomass development (above- and- underground) is simulated on a daily time-step based on light interception and conversion of CO_2 to biomass. Actual crop yield is then calculated as a product of actual above-ground biomass and the actual harvest index. Actual harvest index was calculated on a daily basis as a fraction of the above-ground plant dry biomass removed as dry economic yield. A plant is assumed to start growing once the temperature exceeds its base temperature (T_b). The portion of the mean daily temperature exceeding T_b will contribute to growth over the growing period. If the temperature falls below T_b then the plant is assumed to enter dormancy. The actual crop water uptake is simulated in a daily time step. It is based on soil water dynamics in different soil layers and crop potential evapotranspiration (PET). There are three different methods (i.e. Penman-Monteith, Priestley-Taylor, and Hargreaves) available in the model to calculate PET, with the Penman-Monteith being the most comprehensive as it considers various climatic factors (Allen et al., 1989). The Penman-Monteith approach was considered in this research as the base to simulate crop water use (CWU).

In this research, four and five management practices were selected for rainfed and irrigated conditions, respectively. The practices were ploughing, fertilizer application, irrigation, planting operation and harvest and kill operations. Two options are available for application of irrigation water and timing of fertilizer application: user specified and automatic. In the automatic option, an irrigation event is triggered by water stress threshold and fertilizer is applied based on nutrient stress factors. The total amount of fertilizer applied during the growing season is specified by the user. More details are given by Neitsch et al. (2011).

2.6.2 Input data, model development and parameterization

Historical climate data including daily precipitation, temperature, solar radiation, humidity, and wind speed were obtained from Faramarzi et al. (2015), who used a suite of four climate time series from local meteorological records, gridded products, and satellite data at a provincial coverage to reproduce historical streamflow records by using a calibrated SWAT hydrologic model. Other hydrological data include vegetation cover, soil characteristics, share of non-contributing areas due to the potholes, daily operation of large reservoirs and dams, and glacial maps to better represent natural and human-induced hydrological processes at sub-basin levels (Faramarzi et al., 2017). Agricultural management data such as the date of planting and harvesting, volume, and rate of fertilizer and irrigation application were obtained to develop the SWAT crop models. The crop-specific fertilizer application rate (N:P:K ratio), the maximum amount of annual fertilizer application (kg/ha/year), and the potential heat units required for crops were additionally obtained from the Government of Alberta and later adjusted through calibration scheme (Table 3). Yearly Y statistics for irrigated and rainfed crops were taken from Alberta Financial Service Corporation (AFSC) and Alberta Agriculture and Rural Development (AARD) over the period 1980–2009 for model calibration and validation. Here, Y data for irrigated and rainfed crops were collected at the county level from AFSC and at the Census Agricultural Region (CAR) level from AARD, respectively. For calibration and validation purposes, simulated data at sub-basin level and measured irrigated data at the county level were aggregated to CAR level to follow the same spatial resolution as the measured rainfed data, i.e., CAR level.

The climate projections of nine GCMs over the period 2040–2064 were obtained under two contrasting emission scenarios of RCP 2.6 and 8.5 (Representative Concentration Pathways) from the Pacific Climate Impacts Consortium (PCIC; Cannon, 2015) at a resolution of 5 arcmin (~10 km) (Table 2). The change factor approach (Chen et al., 2011) was used to downscale the data based on the local climate conditions of Alberta. Overall, an ensemble of eighteen climate projections (9 climate models by 2 scenarios) was downscaled and used in the calibrated SWAT model. We set the CO_2 concentration as 350, 450, and 750 ppm for the historical, RCP 2.6, and RCP 8.5, respectively. For each GCM and RCP combination, a total of 1000 SWAT simulations were performed on a daily basis using the calibrated parameter ranges. Although the model simulation was performed under each climate model-scenario combination, here we describe the results based on the ensemble average.

Changes in population size are important in determining the future demands for goods and services, particularly for food (Ercin and Hoekstra, 2014). We used the Government of Alberta population projection data for the historic (1985-2009) and future periods (2040-2064). Future population growth is based on historical trends of fertility, mortality, and migration, accounting for possible future patterns of change (Table 1). *Per capita* food consumption data were taken from FAOSTAT (FAOSTAT, 2018). The best available crop import and export data were collected for the 1996-2005 period from the Statistics and Data Development Section of Alberta Agriculture and Forestry (Alberta Agriculture and Forestry, 2018a). All input data are listed in supplementary Table 1.

2.6.3 Model set-up and performance indicators

In this study, a calibrated hydrological model of the province (Faramarzi et al., 2017, 2015) was utilized to develop a crop growth model using the ArcSWAT 2012 (Rev. 632). The SWAT crop growth model was built to simulate Y and crop ET (i.e., CWU) for both historical (1980-2009) and future (2040-2064) periods. In the hydrological model, a threshold drainage area of 200 km^2 was used to delineate the study area into a total of 2255 sub-basins, based on a 10 m Digital Elevation Model (DEM). The sub-basins were characterized based on soil, land use, slope, and associated physical parameters available from local sources, and further processed to meet the model requirements (Faramarzi et al., 2017). To simulate crop growth in this study, we developed and calibrated two separate models for each crop simulations (wheat, barley, and canola) to represent rainfed and irrigated conditions, respectively. In general, setting up a crop growth model based on a calibrated hydrological model has been recommended to improve soil-water dynamics in crop growth simulations (Faramarzi et al., 2010; Vaghefi et al., 2014). Heat unit requirements were optimized in the model through our calibration procedure to represent different varieties of crops that differ in growing degree-days across the province. Auto fertilizer and auto irrigation options of the SWAT model were used to represent the management calendar and were controlled by nutrient stress factor and plant-water-stress threshold, respectively. Planting and harvesting dates were obtained from available sources and communication with local experts. Since the cropping calendar did not fully cover the study domain, the suggested dates by local experts were further tuned through our calibration scheme over our study area.

For the model sensitivity, calibration, validation and uncertainty analysis, the SUFI-2 program of the SWAT-CUP software was used (Abbaspour, 2015). The SUFI-2 was used to calibrate the model for the 1995–2009 and to validate it for the 1983–1994 period. A three-year window was considered as a spinup period for both calibration and validation to mitigate the effect of initial conditions in the model. The inverse time periods were used for calibration and validation since better data were available in the later period. Based on an extensive literature review and author's judgment, a total of 14 to 30 physical and phenological parameters sensitive to water balance and crop growth was selected for each CAR under rainfed and irrigated conditions (Table 3). A global sensitivity analysis (GSA) was applied through the SWAT-CUP tool to screen the most sensitive parameters. The parameters were then sampled within a physically meaningful range using a Latin Hypercube Sampling (LHS) approach (Mckay et al., 1979) for 1000 model runs of each model simulation (under the historical period and 18 climate model-scenario combinations). The mean square error (MSE) was used as an objective function to compare simulated versus observed Y on a yearly basis for each CAR and parameter tuning for the next calibration iteration. In SUFI-2, the 95% prediction uncertainty (95PPU) of the output variables was considered to evaluate the model performance (Table 7). The 95PPU has been calculated at 2.5% and 97.5% levels of the cumulative distribution functions of an output variable that was generated through the propagation of the parameter uncertainties using LHS. Simulation results for Y and CWU are shown as of median of 1000 runs and indicated as M95PPU hereafter.

The p-factor and r-factor have been used to quantify the calibration performance of the model (Abbaspour et al., 2015; Faramarzi et al., 2017). The p-factor is the percentage of observed data covered by the 95PPU, and the r-factor is the thickness of the 95PPU, which is calculated as the ratio of the average width of the 95PPU to the standard deviation of the measured variable. A p-factor value of 1 (100%) and a r-factor value of zero is ideal. However, due to inherent uncertainties in input data, physical parameters, and model conceptualization in large-scale studies, the p-factor of above 0.5 (50%) and r-factor of around 1-2 and 3-5 is considered satisfactory in hydrologic and crop Y simulations, respectively (Abbaspour et al., 2015). Importantly, our calibration approach does not search for an optimal parameter set as a single solution to replicate historical data, rather an envelope of best solutions represented by the 95PPU. In other words, observed data for a specific year should fall within the 95PPU band (Table 6).

The crop ET is simulated based on crop biomass development, soil water dynamics in different soil layers, and potential crop ET on a daily basis. The Penman-Monteith approach is generally considered reliable and was used to estimate potential ET. Y and ET were simulated on a daily basis and aggregated for the growing season (planting to harvesting period; May to August). These output variables were simulated at sub-basin scale and then aggregated to CAR scale for calibration and validation purposes. More details about the method is presented in Masud et al. (2018, 2019).

2.7 System dynamics modeling for the SSRB

Additionally the project employed the System Dynamics (SD) modeling framework (Forrester, 1961; Mirchi et al., 2012; Sterman, 2000) as a unifying modeling approach to integrate the outcomes of the different phases of the project. SD is a system thinking method that is used to deal with dynamic, complex systems. It allowed to produce both conceptual and quantitative models to represent, simulate, and aid exploration of complex feedback and non-linear interactions among system components, management actions, and performance indicators. Models produced with SD demonstrate the behavior of a complex system and its responses to interventions over time. They are intended to increase understanding of the unpredictable effects of feedbacks, whose behavior would otherwise be assumed or ignored. Therefore, SD is well-suited for policy assessments in water resource systems where feedbacks are essential, as illustrated in Figure 4.

The causal loop diagrams consist of system variables linked by arrows denoting the causal relationship between the variables (e.g., Figure 4). Two variables linked by an arrow in a CLD are the independent and dependent variables, and a change in the independent variable causes a change in the dependent variable. Arrows are assigned polarities, either positive (+) or negative (-). For example, a negative link means that if the value of the independent variable increases (decreases), the value of the dependent variable decreases (increases), while a positive link means the variables increase (decrease) together. Connections between two variables can expand to form loops through a network of connections as shown in Figure 21, such loops are called "feedbacks", which have essentially two types: reinforcing (positive) loops and balancing (negative) loops. Reinforcing feedback loops are considered the drivers of a system, whose behavior is characterized by continuous trends of growth or decline. Balancing feedback loops have a target-oriented behavior, i.e., if some changes drive the system to shift away from its goal, the balancing feedback loop tries to *neutralize* the effects of that shift.

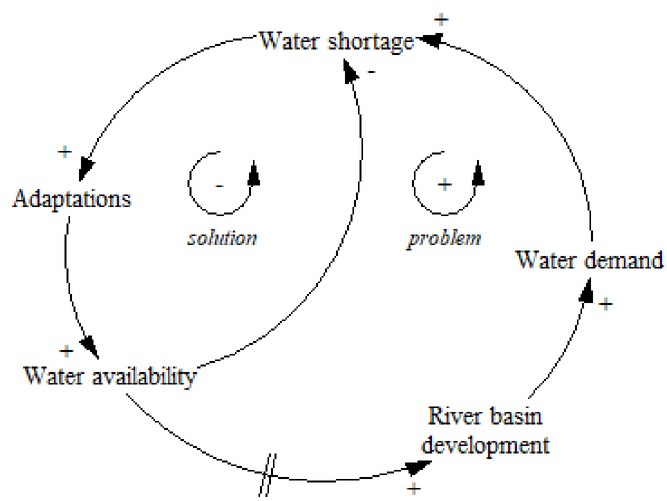

Figure 4. High-Level Feedbacks in water resources management in the SSRB

3. Project Results

3.1 GW-SW interaction

The results of this phase showed that the hydraulic heads in the regions with wells decrease, with a difference of up to 5 m of drawdown observed in comparison with the SWAT–MODFLOW model without pumping wells. On average, the aquifer discharge rate to the river decreased, with the simulated flow rate changing from −1294 m^3/d to −1261 m^3/d. The GW–SW interaction change observed is likely due to the fact that as water is extracted from the subsurface, less of the remaining water is available to provide baseflow to rivers. Depending on the rate and schedule of pumping (including the number of pumping wells), the results showed that the effects of pumping are immediately observable and may affect the discharge rates of associated rivers. However, at the tested pumping rate, the discharge decreases in terms of the overall discharge rates (approximately 150 m^3/s) of the Little Smoky River are relatively insignificant. This suggests that the bedrock aquifers within the study area could support water well pumping at rates like those tested.

A climate change run over the 2010–2034 period was the next scenario to be applied with the GW–SW exchange rates shown in Figure 5. Immediately noticeable in the figure is that the long-term average annual historical results for GW–SW interaction patterns look similar to the results of the climate change scenarios. This is indeed the case, as the overall average historical flow rate was −1294.04 m^3/d, while that of the averaged climate change scenarios was −1294.14 m^3/d, both indicating overall discharge into the river. These results indicated that the effects of climate change on this watershed over the 2010–2034 period are negligible. A possible reason for the lack of influence of the climate change scenario is that the simulation period was short, with little change occurring in the predicted CO_2 concentration over this timespan for the RCP 8.5. More detail description of the results is presented in Chunn et al. (2019).

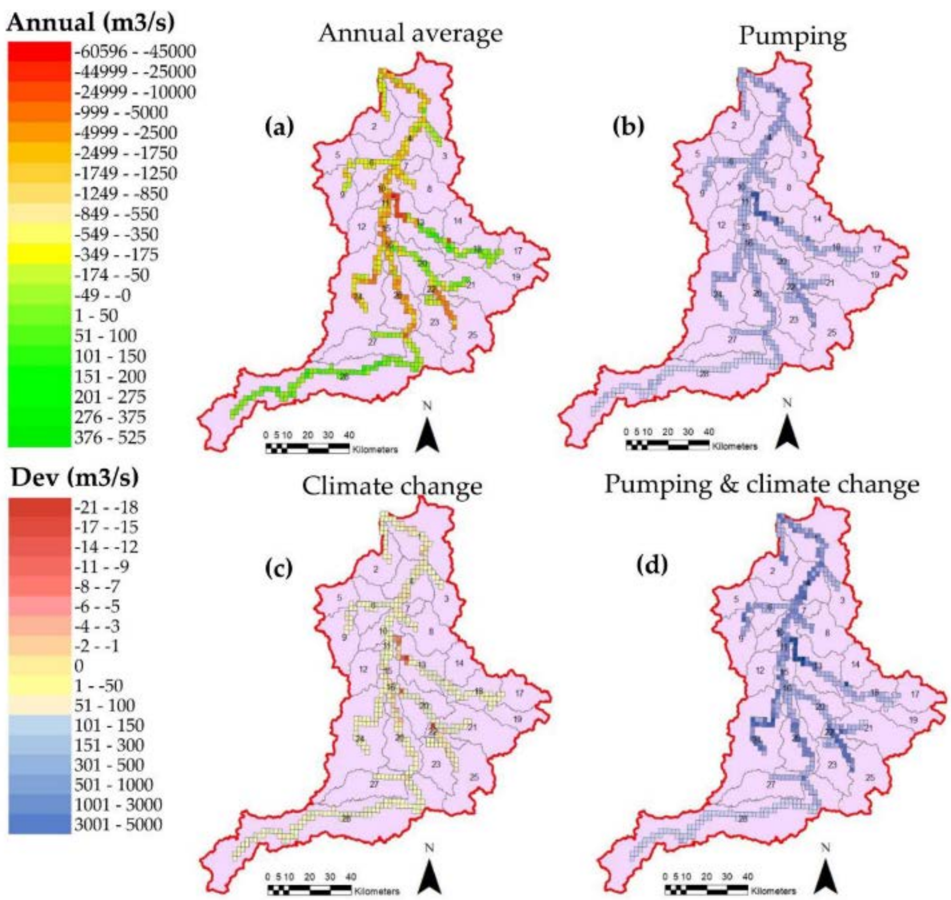

Figure 5. Long-term (1986–2007) average annual GW–SW exchange data (a), and differences from the average annual data for each MODFLOW river cell, with a pumping rate of 468 m^3/d (b), the averaged RCP8.5 (the heaviest greenhouse gas emission) scenario for 2010–2034 (c), and the averaged RCP8.5 scenario with a pumping rate of 4680 m^3/d (d). Dev (m^3/d) = monthly (m3/d) − yearly (m3/d) (adapted from Chunn et al., 2019).

3.2 Projected changes in agro-hydrological variables in the agricultural region of Alberta

Results revealed that Alberta had become warmer and drier during the His period. The future projection showed an increase in precipitation and temperature and therefore changing spatiotemporal pattern of SM, DA, and WYLD in the agricultural lands of Alberta. Irrespective of RCPs and time periods, the regional precipitation and temperature were projected to increase between 1% (seasonal) to 7% (annual), and 1.21◦C (seasonal) to 2.32 ◦C (annual), respectively (Figure 6, and Figure 7). Seasonal precipitation showed a higher trend magnitude than that of annual precipitation. The temperature generally had an increasing trend in the future with a maximum in southern Alberta. Monthly average ET is likely to increase and decrease in the rising and falling limbs of the bell-shaped curve across the 12 months of the year with a peak in July. A comparison of water demand from two land-use types (dominant land use and barley) during the His period showed a water deficit occurred in July and August. Annual precipitation was projected to increase by 3% and 7% in most of the sub-basins during the NF and FF, respectively. Similarly, the seasonal precipitation could increase by 1% and 5% for NF and FF periods, respectively.

The projection suggested a larger increase (decrease) in ET (SM) in the sub-basins (Figure 8, Figure 9), where the temperature was also projected to increase with high precipitation. The spatial pattern of blue water components (the summation of water yield (WYLD) and deep aquifer recharge (DA)) was similar to that of precipitation. Out of the 440-mm mean annual precipitation in His period, about 64 mm was renewable blue water resources in the agricultural region. Based on the projected changes, the blue water resources were expected to marginally increase in most of the sub-basins.

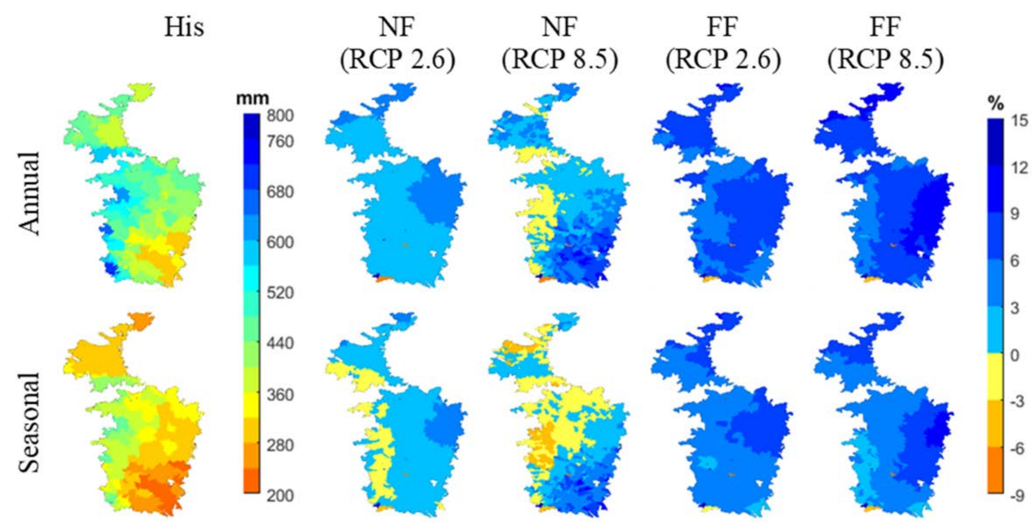

Figure 6. Spatial distribution of mean seasonal and annual precipitation and their projected changes (%) in the future under RCP 2.6 and 8.5, where His indicates historical period (1983–2007), NF indicates near future (2010–2034) and FF indicates far future (2040–2064) (adapted from Masud et al., 2018).

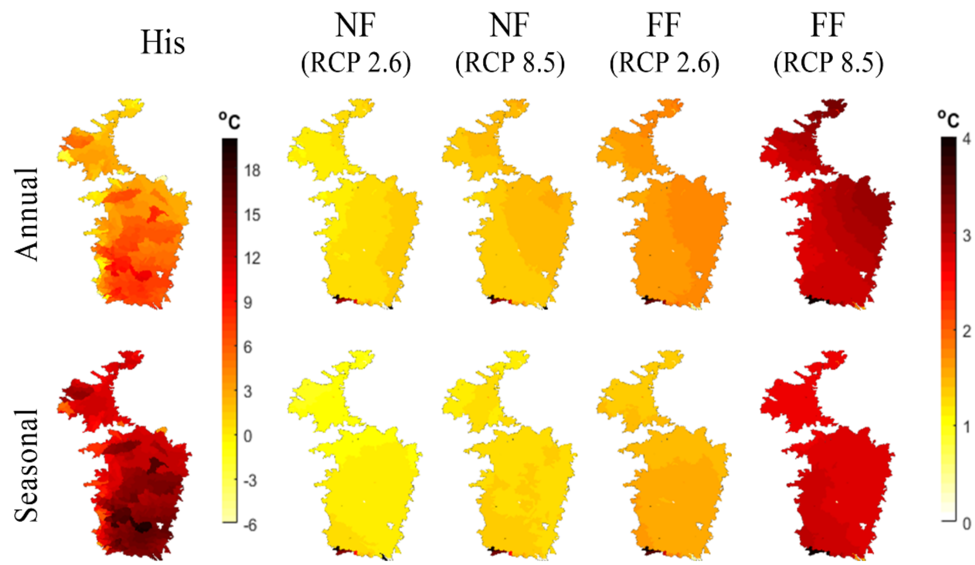

Figure 7. Spatial distribution of mean seasonal and annual temperature and their projected changes (°C) in the future under RCP 2.6 and 8.5, where His indicates historical period (1983–2007), NF indicates near future (2010–2034) and FF indicates far future (2040–2064) (adapted from Masud et al., 2018).

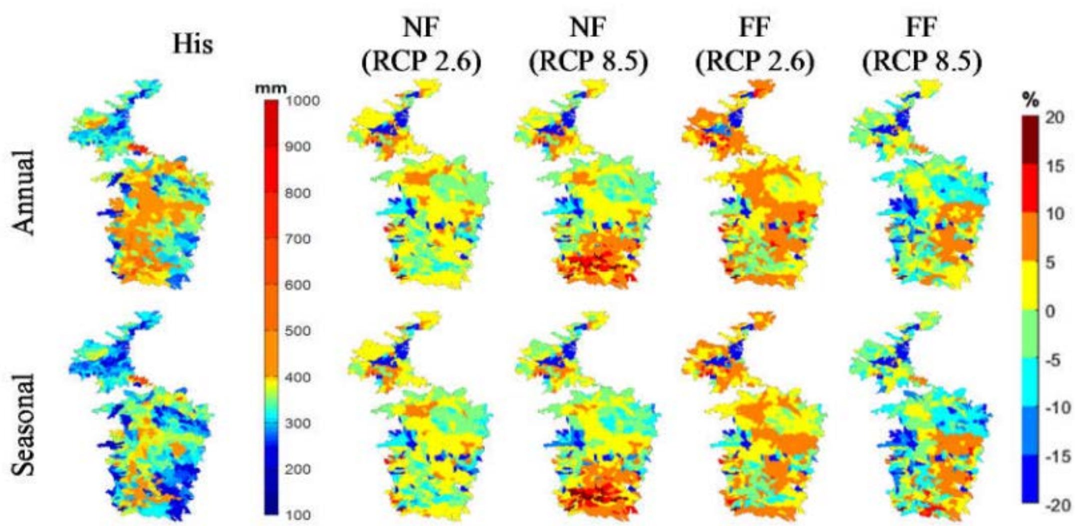

Figure 8. Spatial distribution of ET for RCP 2.6 and RCP 8.5, where His indicates historical period (1983–2007), NF indicates near future (2010–2034), and FF indicates far future (2040–2064). For historical period simulated ET is shown in the map, and for the NF and FF percentage change is shown in the map. The effects of irrigation are not accounted in these maps (adapted from Masud et al., 2018).

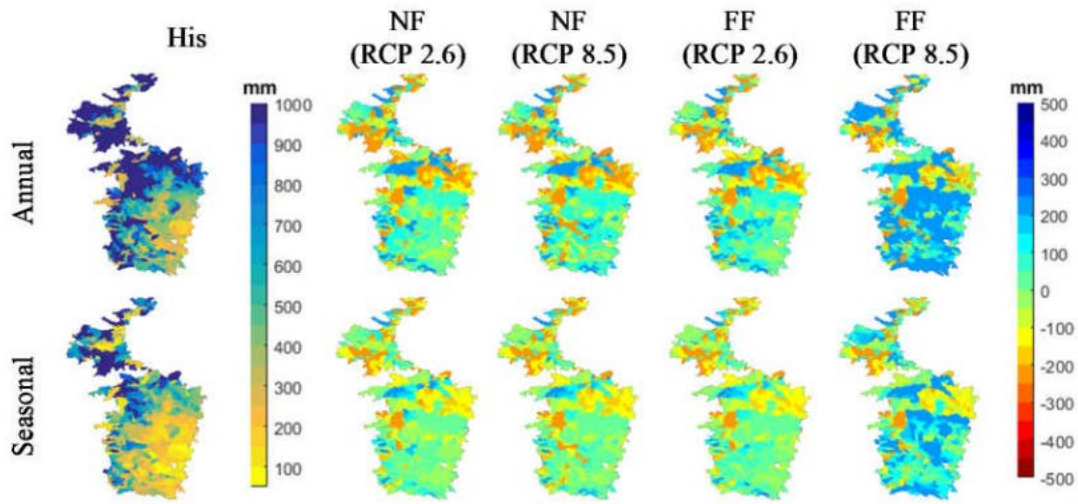

Figure 9. Spatial distribution of soil moisture by RCP 2.6 and 8.5, where His indicates historical period (1983–2007), NF indicates near future (2010–2034), and FF indicates far future (2040–2064). For the historical period, simulated soil moisture is shown in the map (adapted from Masud et al., 2018).

Additionally, the results showed that ET had a non-significant decreasing trend in all counties during His period, and this trend continued in the future. However, there was a positive trend for annual ET in Grande Prairie county. Similar to the temperature, the trend magnitude of annual ET was higher than that of seasonal magnitudes during the His, NF, and FF. The annual SM during His period showed a decreasing trend in most of the counties except Leduc and Red Deer. For seasonal SM in the His period, most of the counties showed a positive trend except Grande Prairie and Mountain View, where the trend was negative. In the future, the annual SM showed a negative trend for both RCPs. In contrast, the seasonal trend in the future was found to be positive for most of the counties. There were some counties that observed a statistically significant trend in annual and seasonal SM for RCP 8.5 only, including Lethbridge (annual SM), Red Deer, and Vermilion (seasonal SM). The trend magnitude of DA was very mild. The slope was zero for some of the counties and time horizons. These results indicate a relatively constant level of DA with respect to other hydrological variables during the study periods. In all time periods (His, NF and FF), Grande Prairie showed a non-significant negative trend of DA. Seasonal and annual WYLD trends showed a positive magnitude in most of the counties during the His period. More details can be found in Masud et al. (2018).

3.3 Future changes in floods in Alberta

The results for this phase of the project showed that only five catchments of the 29 studied are expected to experience decreases ranging from 11% to 54% in the rate of occurrence of floods in the future period (2040-2064) relative to the historical period (1983-2007) (Figure 10) with one catchment in each of the Athabasca, Battle, Beaver, North Saskatchewan, and Peace river basins for RCP 2.6. The other 23 catchments showed increases ranging from 5% to 112%, and only one catchment (07AA002) in the Athabasca river basin showed no change. On the other hand, RCP 8.5 resulted in more intense changes than RCP 2.6 for the rate of occurrence. For RCP 8.5, only two catchments namely 07BF002 in the Athabasca river basin and 05FA001 in the Battle river basin are projected to experience decreases in the rate of occurrence of peak flows by 23% and 27%, respectively, whereas the other 27 catchments showed increases ranging from 6.6% to 143%. The results indicate that the majority of the catchments in the Peace river basin will likely experience considerable increases in the rate of floods occurrence with an average change of +41% and +57% in RCP 2.6 and RCP 8.5, respectively, followed by the catchments of the Red Deer (36% in RCP 2.6 and 46% in RCP 8.5), Oldman (15% in RCP 2.6 and 20% in RCP 8.5), Bow (14.9% in RCP 2.6 and 22% in RCP 8.5), Athabasca (9.4% in RCP 2.6 and 22% in RCP 8.5) and North Saskatchewan (5.8% in RCP 2.6 and 19% in RCP 8.5) river basins. Whereas, the studied catchment of the Battle river basin (05FA001), showed a decrease of 54% and 27% for RCP 2.6 and RCP 8.5 climate scenarios, respectively. The studied catchment of the Beaver river basin showed contrasting changes in the rate of floods occurrence for both climate scenarios with a change of -14% and +16% for RCP 2.6 and RCP 8.5.

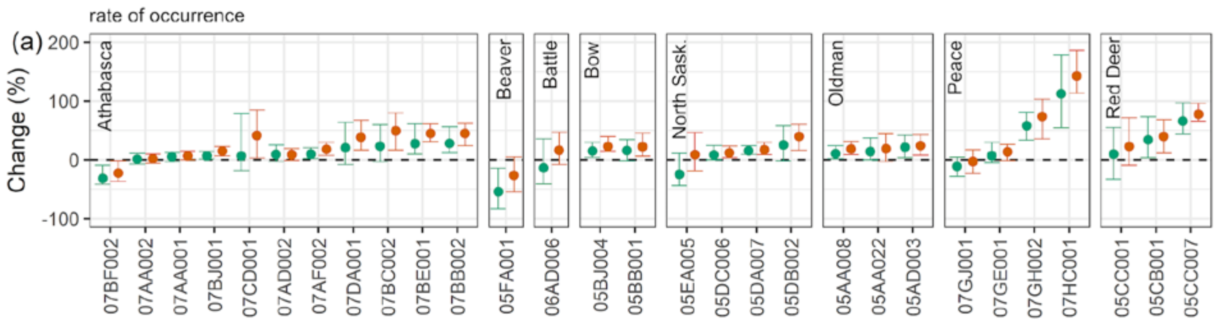

Figure 10. Changes in the rate of occurrence of flood in the studied catchments (adapted from Ammar et al., 2019).

For the means of the ensemble simulations, event magnitudes corresponding to 20- or 50-year return periods for the mid-century are becoming more intense in both climate scenarios except for a few cases, as shown in Figure 11. On the one hand, in RCP 2.6, 17 catchments are projected to experience increases in Q20 in the range of 4% to 52%, and only one catchment remained unchanged, while 20 catchments are expected to increase in Q50 with a range of 2% to 104% as shown in Figure 11. The catchments of the Bow river basin had the highest average increase in Q20 of 10% and in Q50 of 12% followed by the catchments of Red Deer (9% in Q20 and 5% in Q50), Beaver (9% in Q20 and 2% in Q50), Oldman (7% in Q20 and no change in Q50), and Athabasca river basin (3% in Q20 and no change in Q50). The studied catchments of the Peace River basin showed both decreases and increases in Q20 and Q50. Catchments of both North Saskatchewan and Battle river basins showed interesting results with contrasting change direction in Q20 that in Q50, indicating a decrease of 2% and 12% in Q20 and an increase of 17% and 104% in Q50, respectively. On the other hand, for RCP 8.5, of the 29 catchments, 10 showed decreases in Q20 ranging from 15% to 62%, while 18 catchments showed increases ranging between 3% to 55%, as presented in Figure 11. For Q50, nine catchments showed decreases ranging from 7% to 82%, while increases dominated 17 of the catchments with a range of 7% to 86%, and one showed no change. The studied catchment of the Beaver river basin (05FA001) showed notable increases in both Q20 and Q50 with changes of +26% and +49%, respectively, followed by the catchments of Red Deer, Oldman, Bow, and Athabasca river basins with an average change of 17%, 10%, 6%, and 4% in Q20, and 11%, 8%, 9%, and no change in Q50, respectively. The results also indicate that the studied catchments of the Peace river basin are expecting both decreases and increases in the future ranging from -62% to 44% for Q20 and from -82% to 52% for Q50. The catchments of the North Saskatchewan river basin showed mostly decreases in both Q20 and Q50 except for one catchment (05DB002), where increases of 55% and 86% are predicted, respectively.

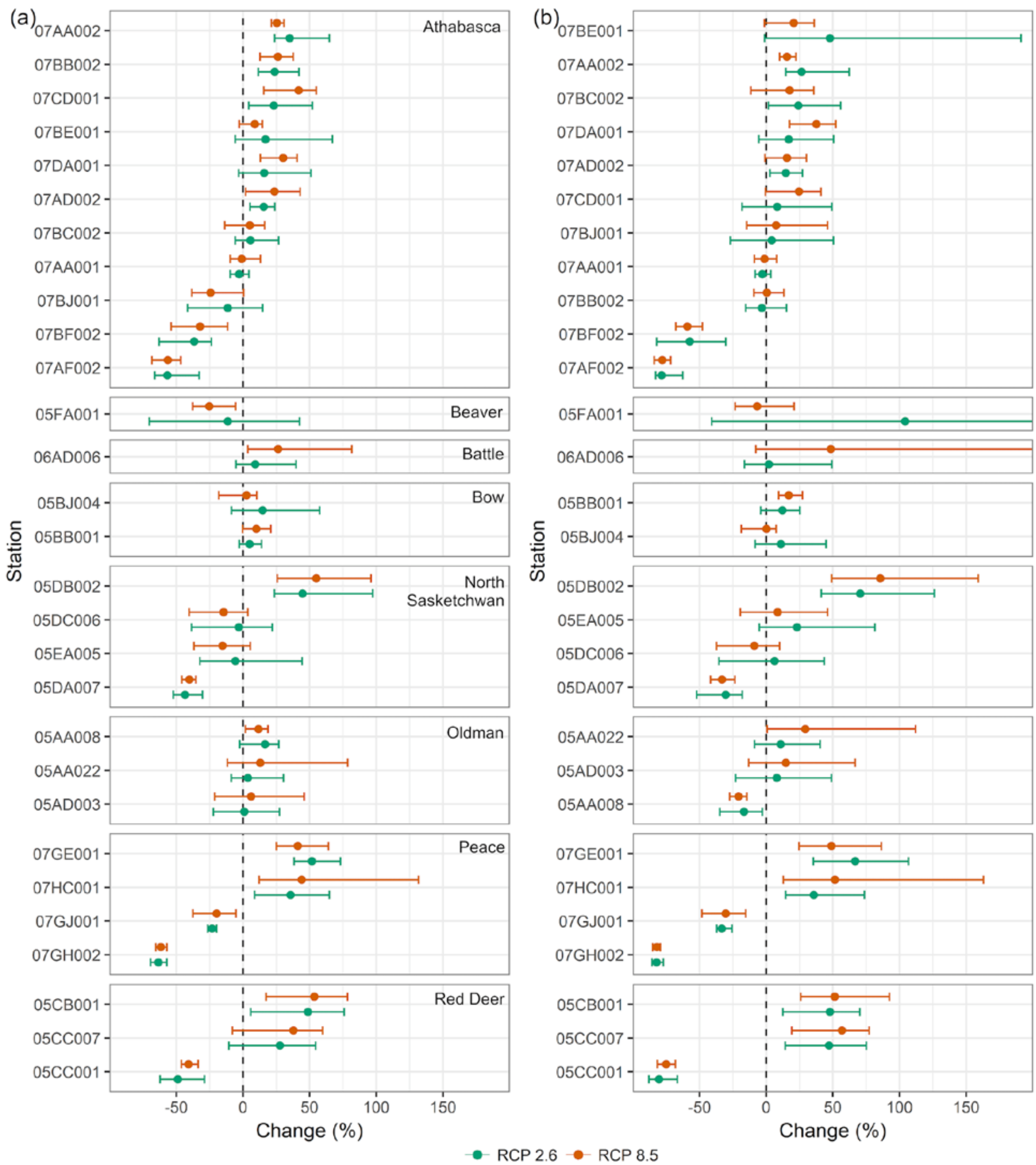

Figure 11. Changes in the (a) 20-year and (b) 50-year return levels for the 29 streamflow gauges under RCP 2.6 and RCP 8.5 using POT approach with generalized Pareto distributions. Different shapes denote the eight river basins and represent the mean of the multi-model ensemble change. Lines represent the uncertainty range arising from the different climate models used. Stations arranged by descending order of the mean change value for RCP 2.6 from top to bottom for each river basin. Note that the figure does not report changes of more than 200% (adapted from Ammar et al., 2019).

3.4 Changes in the stored water volume in isolated wetlands in Alberta

We estimated WWSV of GIWs in Alberta based on the geospatial dataset Alberta Merged Wetland Inventory (AMWI) generated by Alberta Environment and Parks (2017). The GIW layer including GIWs in Alberta are open water polygons with an area between 1×103 m^2 and 1×105 m^2. The mountain zones, National Parks, and cities were excluded to refine the scope of the model.

In this research, our historical time scale was defined based on the time span of the ABMI data that were collected between 2007 and 2017. The chosen LEGPR models were used to estimate WWSV for the Agricultural (White) and Boreal (Green) areas, independently. The WWSV results were then aggregated to a sub-basin level (Figure 12). A total of 2255 sub-basins are delineated in Alberta to serve as the minimum spatial units for simulation and projection of hydrologic cycle in SWAT model (Faramarzi et al., 2015, 2017). We aggregated our WWSV to sub-basin spatial scale to further use SWAT simulated water balance data for future projections. A total number of 99892 geographically isolated wetland sites were identified in Alberta, of which 31.76% were located in the Green Area, and 68.24% were located in the White Area. We calculated that the total surface area of GIWs is 9.77×108 m^2, accounting for 20.54% of the total water surface area of all waterbodies across Alberta (including lakes, rivers, ponds etc.). Using the 'temporal variability of the GIWs' dataset as provided by ABMI, we estimated permanent GIWs have a surface water area of ~5.02×108 m^2 and ephemeral GIWs have a surface water area of ~4.75 ×108 m^2. Permanent GIWs usually have a larger surface area (accounting for 17.27% of all GIWs) while ephemeral GIWs are generally smaller in size (accounting for 82.73% of all GIWs). This signifies that the ephemeral GIWs are likely to be more vulnerable to alterations in the hydrological cycle resulting from a changing climate.

For volume, we found that the overall WSV for GIWs in Alberta is 5.51×108 m^3. This does not include lakes that have a surface area of larger than 1×105 m^2 (10ha), wetlands that have open water area smaller than 1×102 m2, and the wetlands that are connected to stream networks. Although the Athabasca and Peace watersheds hold the greatest volume of WWSV in GIWs, the density-volume of GIWs is larger in other watersheds in Alberta. For example, the watersheds which have WWSV of >1000 m^3/km^2 are Great Slave Lake, Battle, Slave, Red Deer, and North Saskatchewan river basins. The density-number of GIWs, expressed as the number of GIWs per unit of area in each watershed, averages between 0.1-0.3 GIW/km^2, but can be as high as 0.5 to 0.7 GIW/km^2 in Lake Athabasca and Battle river basins. The results of this study established the basis for regional assessment of future WWSV of GIWs in Alberta.

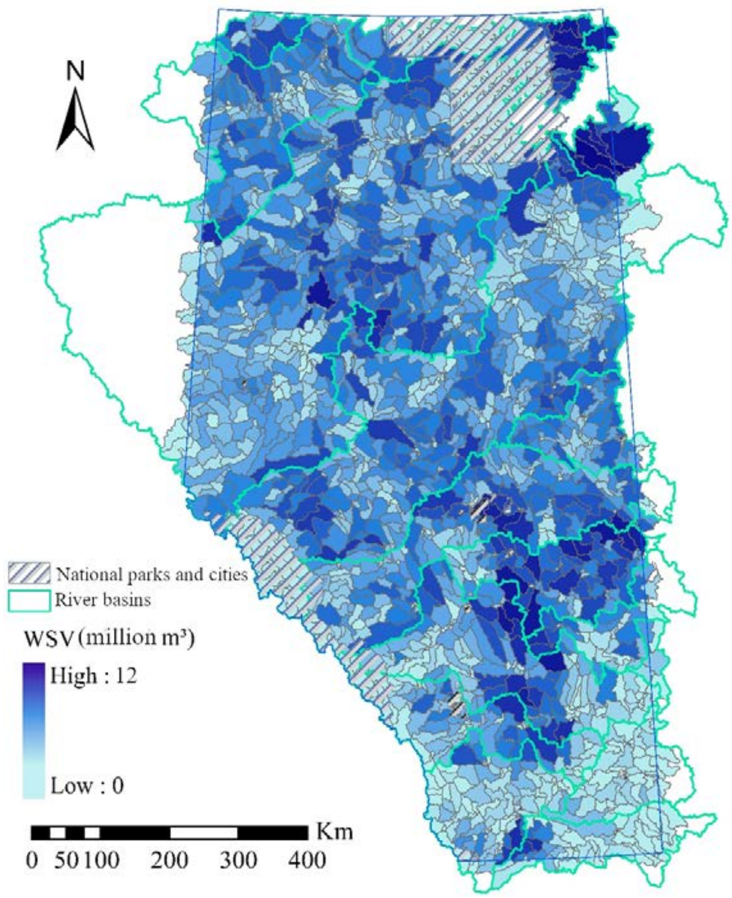

Figure 12. Spatial distribution of the baseline WSV of GIWs within the 17 river basins in Alberta computed using the best performing ML approach. Data shown are WSV of GIWs that are aggregated to SWAT delineated subbasin level (i.e., 2255 subbasins across the study area).

3.5 Uncertainty in Climate Projection

Using ANOVA-SUFI-2 method, the aggregated results from subbasin to a provincial scale showed that climate models were found to be the dominant sources of the uncertainty along with the hydrological model parameterization and regionalization among other sources. The share of uncertainty varied over different seasons. We found that during spring and summer seasons the climate models are the largest contributors to the overall uncertainty. For the winter and spring, the contribution of HM-P and HM-R decreased, while other sources shared more uncertainty in overall cascade. In general, our results showed a higher discrepancy between RCMs results (from NARCCAP) compared to GCMs results (Figure 13 and Figure 14). This is likely because of the inconsistency in the biases due to representation of physical processes in RCM and GCMs. Our results showed that there is a slightly higher agreement among climate model projections in near future scenarios compared to the far future. The monthly analyses of projected water resources showed that HM-P and HM-R contribute 21–51% and 15–55% to the blue water, and 20–48% and 15–50% to the green water overall uncertainty in near future and far future, respectively. Overall, we found that in spring and summer seasons uncertainty arising from HM-P and HM-R dominates other uncertainty sources, e.g. GCMs. We also found that global climate models are overall dominant source of uncertainty in future impact projections along with HM-P and HR-P. However, this share of uncertainty may vary across the province and the results may differ depending on the accuracy of initial hydrologic model setup and the input data quantity and quality used in the initial model setup.

One of the key drivers of uncertainty in southern Alberta is likely the Pacific Decadal Oscillation (PDO). To account for the effects of PDO, integration of algorithms into existing models is necessary and it helps better characterization of natural/decadal variability. Improving the representation of the PDO would require a better representation of the relevant physics and dynamics in climate models. Overall, a large share of HM-P and HM-R in the cascade of uncertainty in climate-impact projections, may raise an argument that physical and process based models such as SWAT could be subjective in climate change impact studies. However, application of such models could be limited if the initial SWAT model of a watershed was not set up cautiously and accurately by providing adequate input data, and if the uncertainty range of initial model parameters was wide. This hypothesis could apply to other physical process based models.

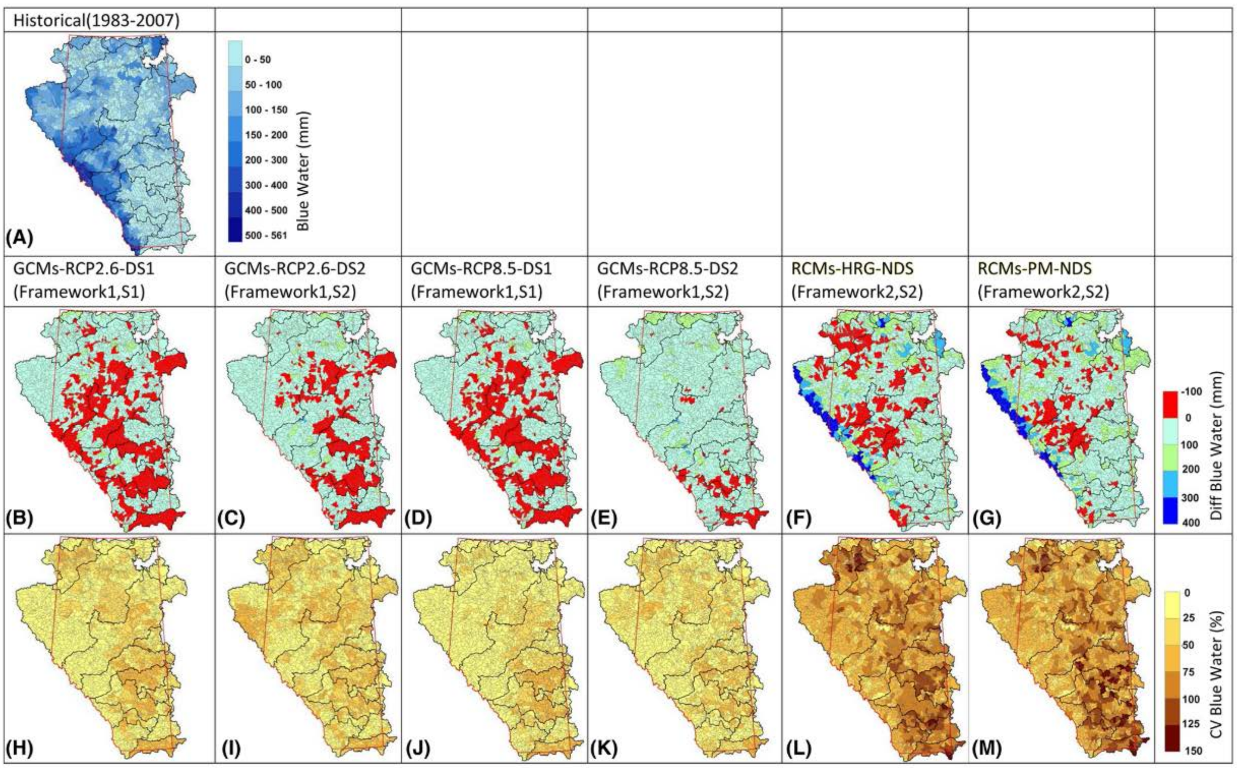

Figure 13. Spatial distribution of annual blue water for historical period (1983–2007) (a), its changes (Changes = [[future values − historical values]/historical values] × 100) between near future (2010–2035) and historical period (b, d), and between far future (2040–2065) and historical period (c, e) calculated using ensemble of GCMs-bias corrected data under RCP 2.6 and RCP 8.5 scenarios, respectively. f, g The spatial distribution of changes between 2040 and 2065 and historical period calculated using ensemble of RCMs using Hargreaves and Penman Monteith evapotranspiration calculation methods, respectively. The coefficient of variation, indicating inter-model variation, for the near future (h, j), far future (i, k) under the RCP 2.6 and RCP 8.5 scenarios, respectively. l, m The coefficient of variation for RCM models projections using Hargreaves and Penman–Monteith evapotranspiration calculation methods, respectively (adapted from Vaghefi et al., 2019).

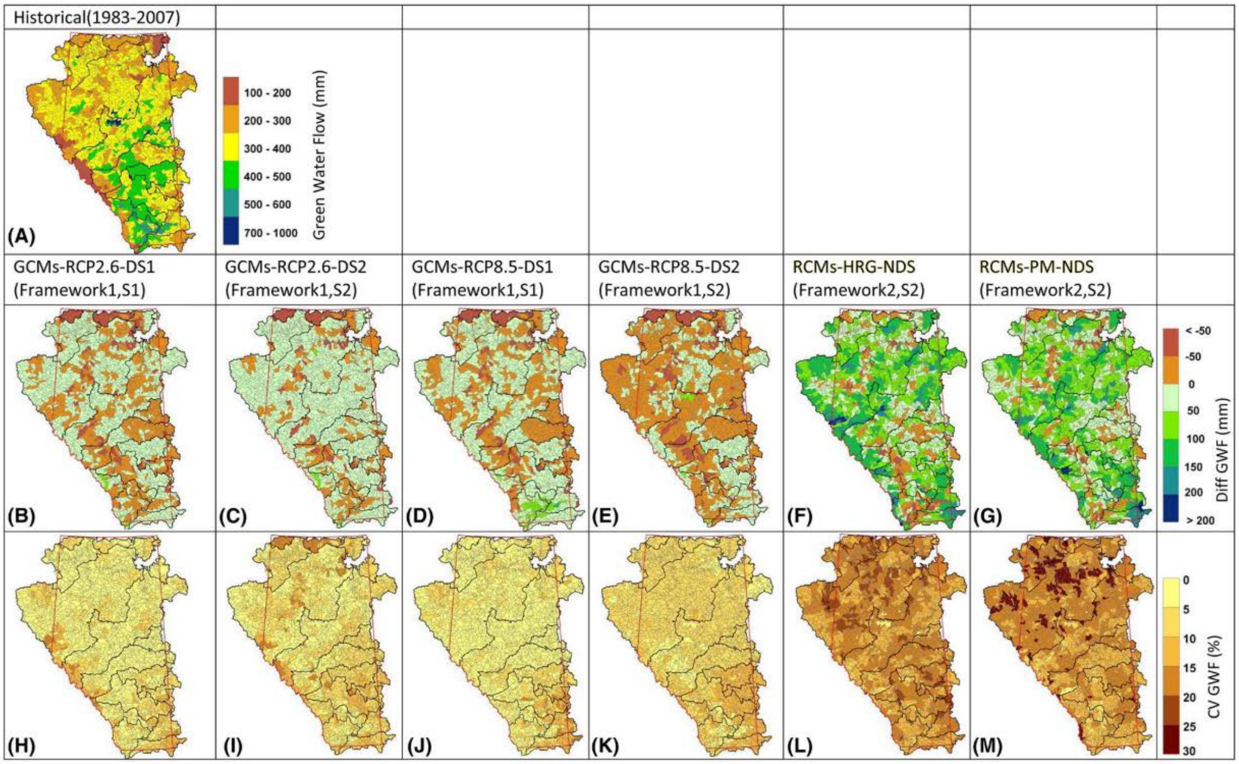

Figure 14. Spatial distribution of annual green water flow for historical period (1983–2007) (a), its changes (Changes = [[future values − historical values]/historical values] × 100) between the near future (2010–2035) and historical period (b, d), and between far future (2040–2065) and historical period (c, e) calculated using ensemble of GCMs-bias corrected data under RCP 2.6 and RCP 8.5 scenarios, respectively. f, g The spatial distribution of changes between 2040 and 2065 and historical period calculated using an ensemble of RCMs using Hargreaves and Penman–Monteith evapotranspiration calculation methods respectively. The coefficient of variation, indicating inter-model variation, for the near future (h, j), far future (i, k) under the RCP 2.6 and RCP 8.5 scenarios, respectively. l, m The coefficient of variation for RCM models projections using Har- greaves and Penman–Monteith evapotranspiration calculation methods, respectively (adapted from Vaghefi et al., 2019).

3.6 Changes in future crop yields, crop water demand, and potential virtual water export

3.6.1 Spatially explicit distribution of Y and virtual water content (VWC)

Historical and future Y, and their projected changes for rainfed wheat, barley, and canola in Alberta are shown in Figure 15. Overall, simulated average canola Y was lower (1.68 tonnes/ha) for the historic period, followed by barley (2.93 tonnes/ha) and wheat (3.15 tonnes/ha), although there were some sub-basins where barley Y is projected to be more than 5 tonnes/ha in the future period. Simulated Y of all rainfed crops for the historic period was higher in the central and northern parts of Alberta followed by low Y in the south-eastern province. Rainfed Y is projected to substantially increase for both RCP scenarios (2.6 and 8.5) by up to 80% in many sub-basins with some others decreasing by up to 20%. On average, wheat, barley, and canola Y are projected to increase by 11, 25 and 33% for RCP 2.6 and 31, 65 and 69% for RCP 8.5, respectively. The spatial pattern showed that wheat Y is expected to increase more uniformly over the study domain than other crops, and such results are in agreement with other global scale studies on wheat production (e.g., Iizumi et al., 2017). Canola Y was projected to increase less than the other two crops, however, the projected Y differences were noticeable between RCP 2.6 and 8.5 having significantly higher magnitudes for the latter scenario.

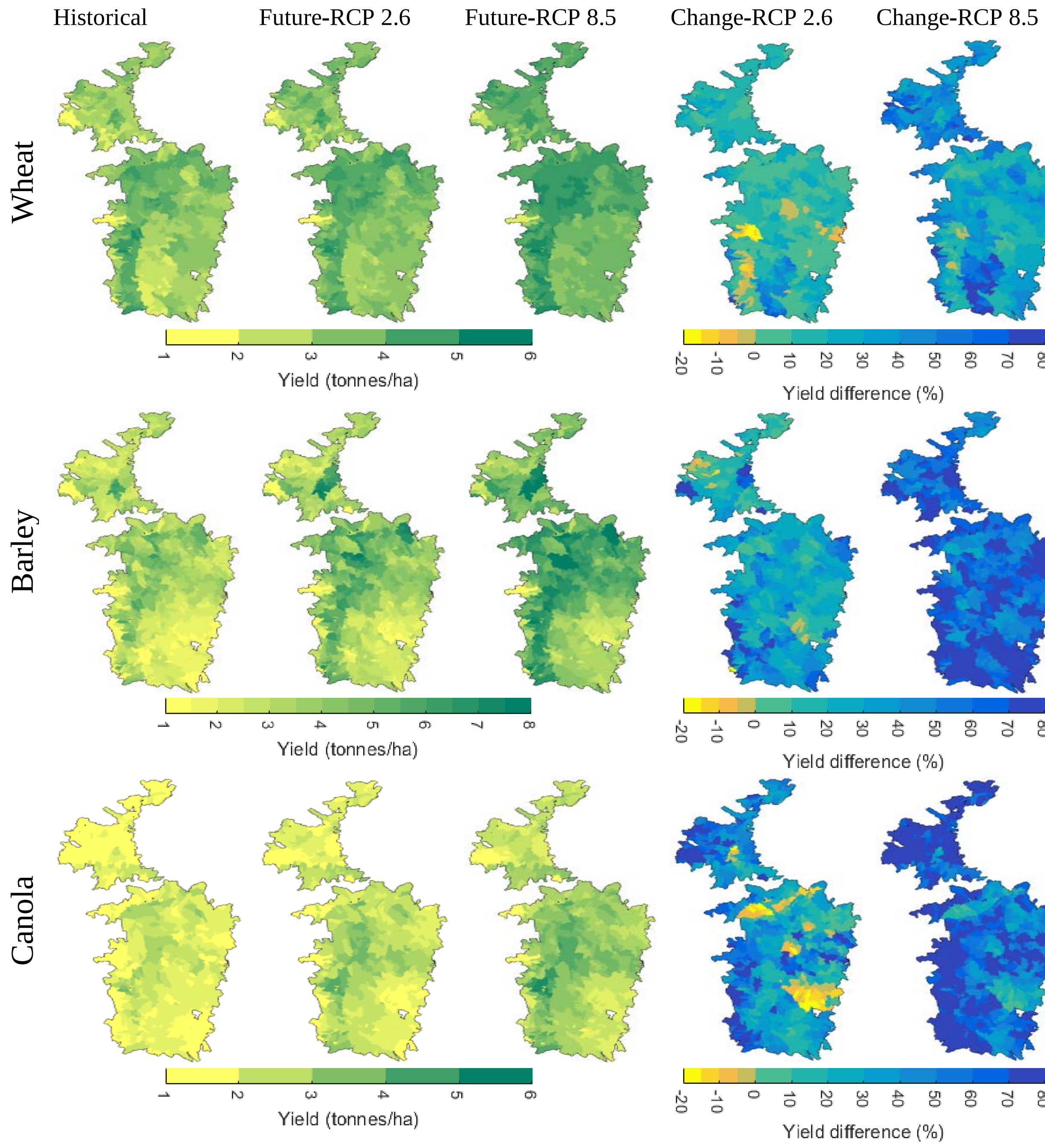

Figure 15. Simulated long-term average rainfed yield (Y) (tonnes/ha) for historical (1985-2009) and future (2040-2064) periods and their projected changes (%) (adapted from Masud et al., 2019).

Our results suggest a larger increase in wheat and canola yield under irrigated conditions as compared to rainfed Y. However, this is opposite for barley (Figure 16). A possible reason could be a larger Y gap in

Wheat and Canola under the irrigated condition that is the difference between actual and potential Y. The large historical Y gap can then be closed in the future due to more favorable conditions (Schierhorn et al., 2014). On the other hand, historical barley Y gap is already meager, therefore, more water or temperature may not help to boost up yield under irrigated conditions. Overall, the complex interaction of growing season precipitation, temperature, antecedent spring and winter soil moisture status influence the Y difference in the future (Kukal and Irmak, 2018). These results are consistent with Lu et al. (2018) who used empirical models to study crop Y response to climate variability.

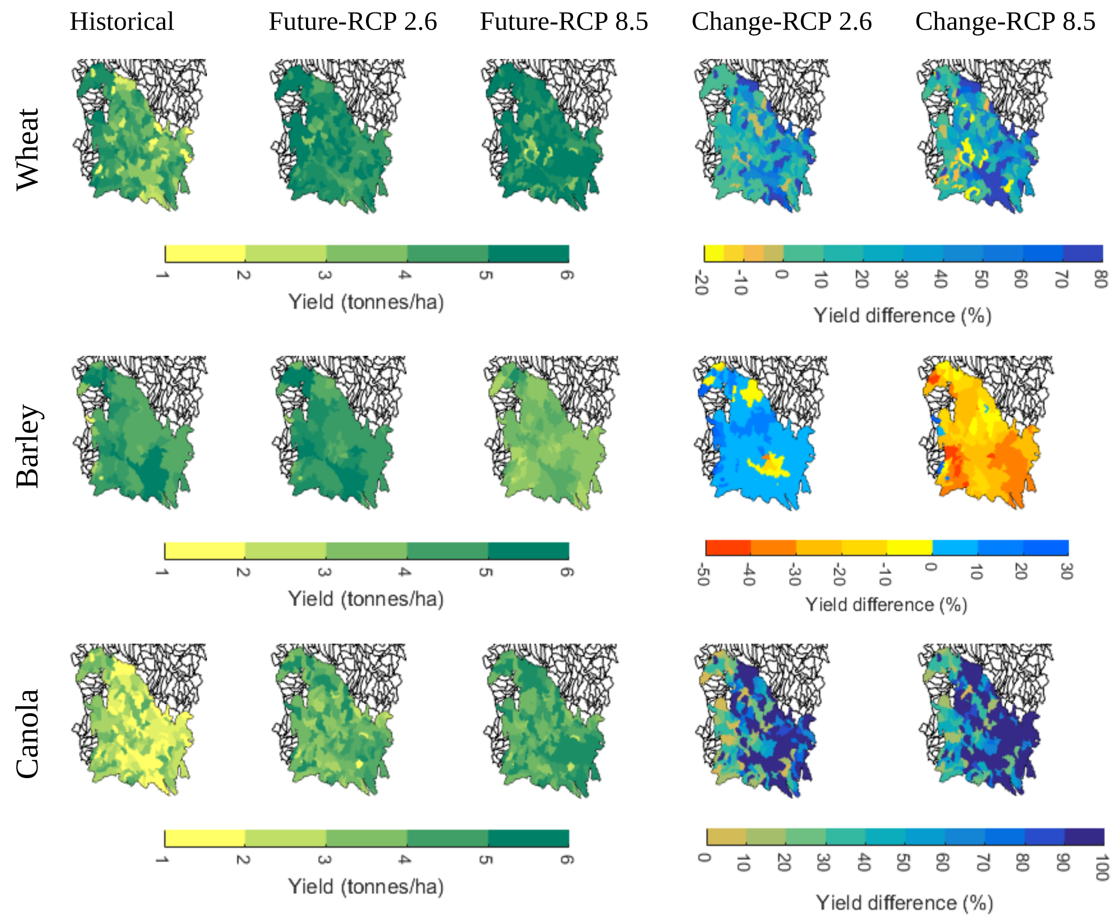

Figure 16. Model simulated irrigated yield (tonnes/ha) for historical and future period and their projected changes (%) (adapted from Masud et al., 2019).

Simulated VWC of rainfed crops for the historical period shows that canola has the highest VWC followed by wheat and barley (Figure 17), implying a higher volume of water to produce a unit of canola than the other two crops. In general, maximum VWC was found in southern parts of the province as this area experienced higher temperature inducing higher ET. Projected future VWC shows a decreasing trend from RCP 2.6 to RCP 8.5. One possible reason could be the lower ET under RCP 8.5 scenario, where a higher CO_2 concentration reduces crop stomatal closure, hence decreases actual crop ET by reducing plant transpiration (Deryng et al., 2016). Similar to rainfed crops, the VWC of irrigated crops is projected to decrease in the future (Figure 18). The magnitude of VWC in irrigated crops is more than rainfed crops in southern Alberta. This is due to a higher (atmospheric) evaporative demand in the southern part of the province that needs to be supplemented by irrigation. Overall, the magnitude of VWC and the projected changes (i.e., decrease) are highest for canola followed by barley and wheat.

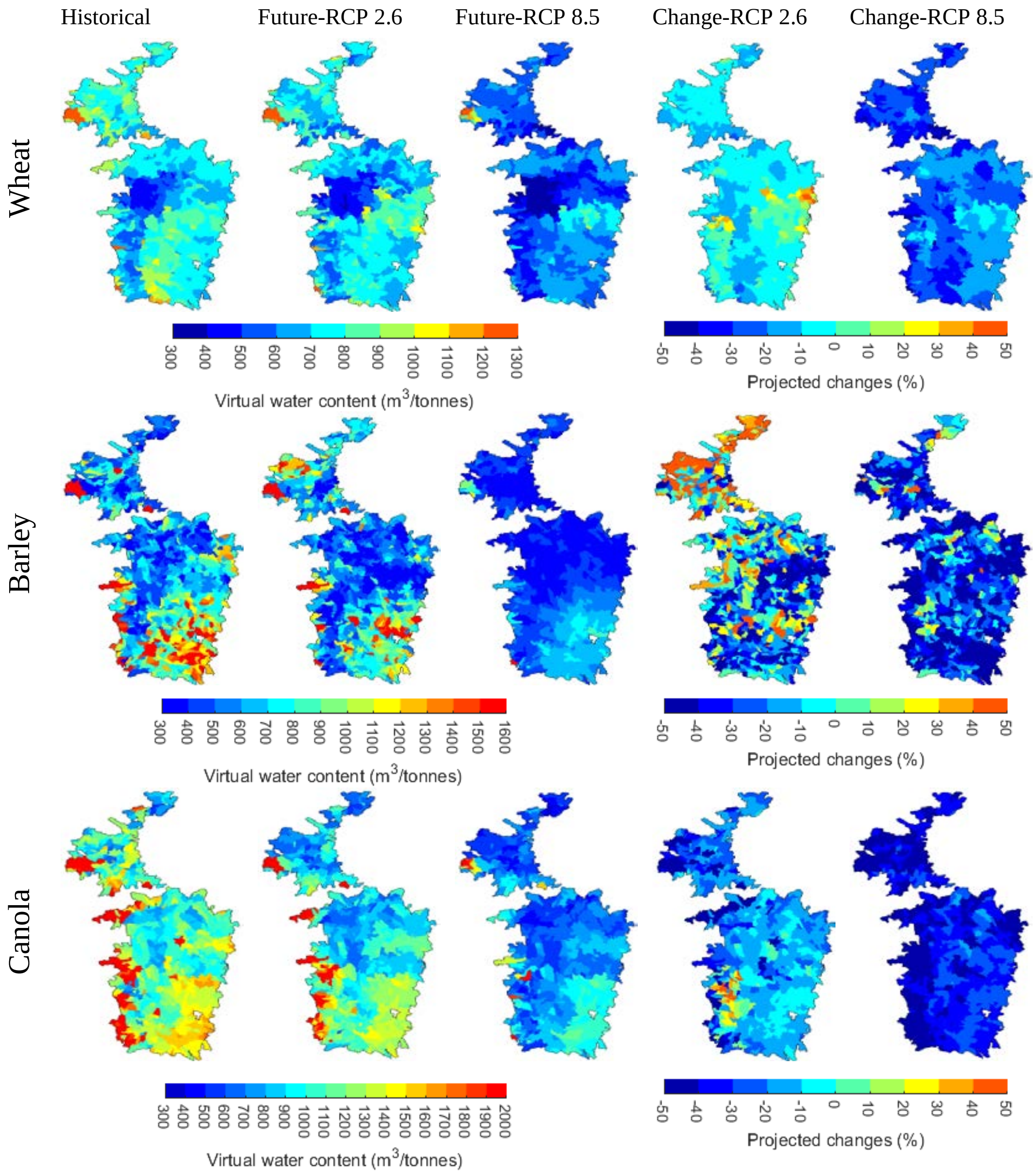

Figure 17. Simulated long-term average pattern of virtual water content (VWC) for historical (1985-2009) and future (2040-2064) periods for the rainfed crops (m3/tonnes) and their projected changes (%) (adapted from Masud et al., 2019).

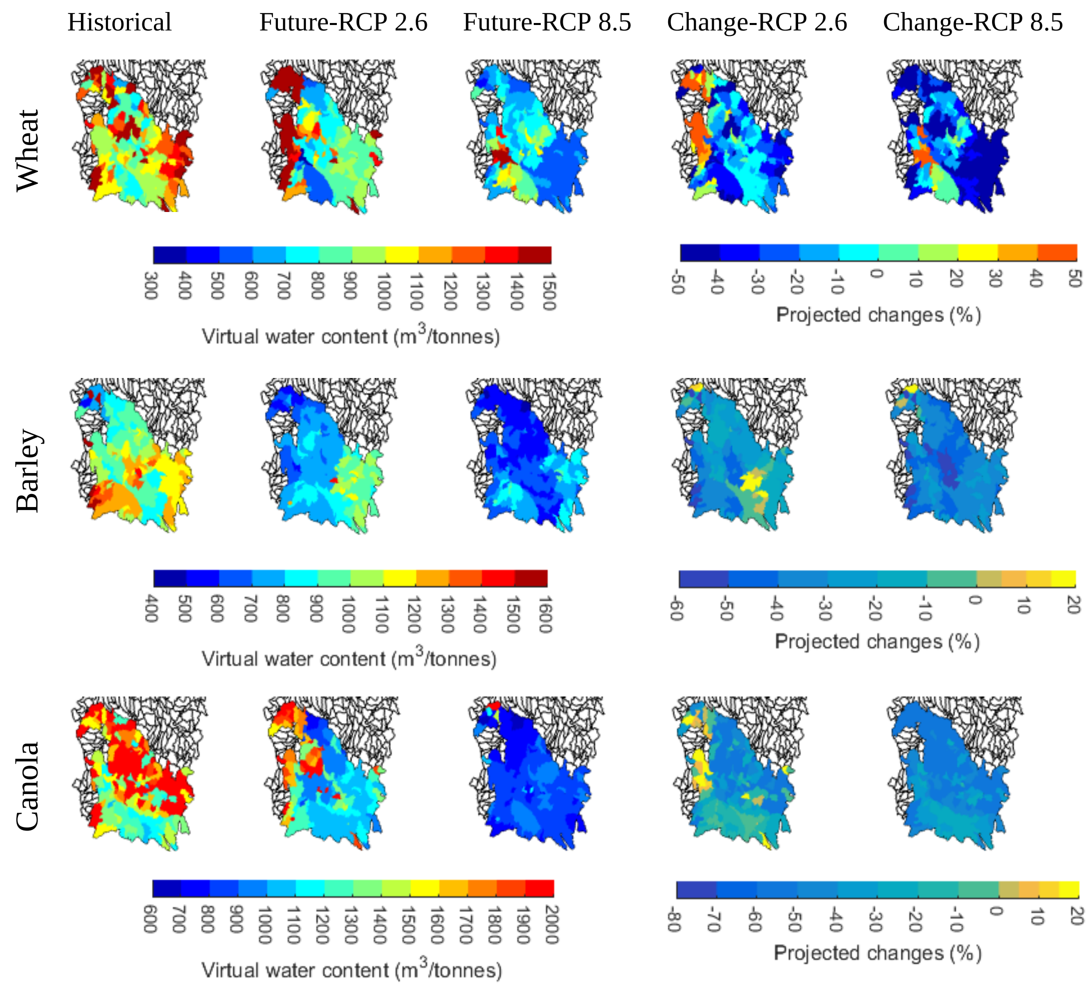

Figure 18. Spatial pattern of virtual water content (VWC) for the irrigated crops and their projected changes (adapted from Masud et al., 2019).

3.6.2 VWC at the provincial level

Temporal variation of simulated VWC at the provincial level is shown in Figure 19 for wheat, barley, and canola for the 1985-2009 period. VWC exhibits substantial temporal variation in the historical period. It is noticeable from Figures 19 and 20 that VWC varied for different crop types (wheat, barley, and canola), production conditions (rainfed vs. irrigated), and geographical locations in different parts of the province (north vs. south). Our models captured the temporal fluctuation of VWC due to interactive feedback between local agro-hydrologic, climate, and management factors. In global studies (e.g., Mekonnen and Hoekstra, 2010; Konar et al., 2013), such variation in rainfed and irrigated conditions may not be adequately considered, since global models are not adopted to represent the regional/local conditions. This often causes large uncertainty in the overall estimation of crop Y, ET, and VWC. Further, we aggregated our sub-basin based simulated data and calculated the weighted average VWC (Prov_AVG) of wheat, barley, and canola at the provincial level. The time-averaged provincial VWC of wheat, barley, and canola, weighted for both rainfed and irrigated conditions, are 797, 835 and 1239 m^3/tonnes, respectively (Figure 20). Hereafter, we will discuss VWT and VWF based on the weighted average of VWC.

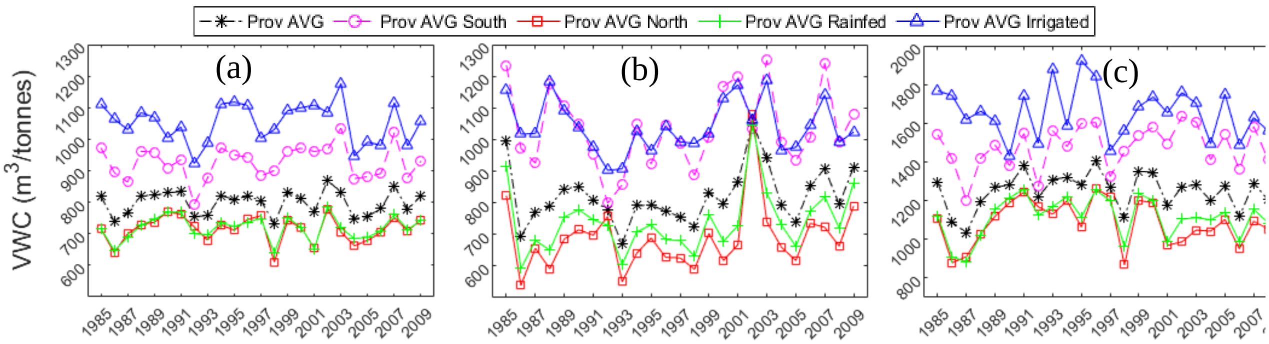

Figure 19. Temporal variation of virtual water content (VWC) of wheat (a), barley (b), and canola (c) aggregated to the provincial level. Definition of acronyms in the legend: Prov_Avg: Entire agricultural area (both rainfed & irrigated); Prov_Avg_South: Both rainfed & Irrigated, only for sub-basins those are located in the irrigated districts; Prov_Avg_North: Excluding the Irrigated districts; Prov_Avg_Rainfed: Purely rainfed for entire agricultural area; Prov_Avg_Irrigated: Purely irrigated (irrigated districts) (adapted from Masud et al., 2019).

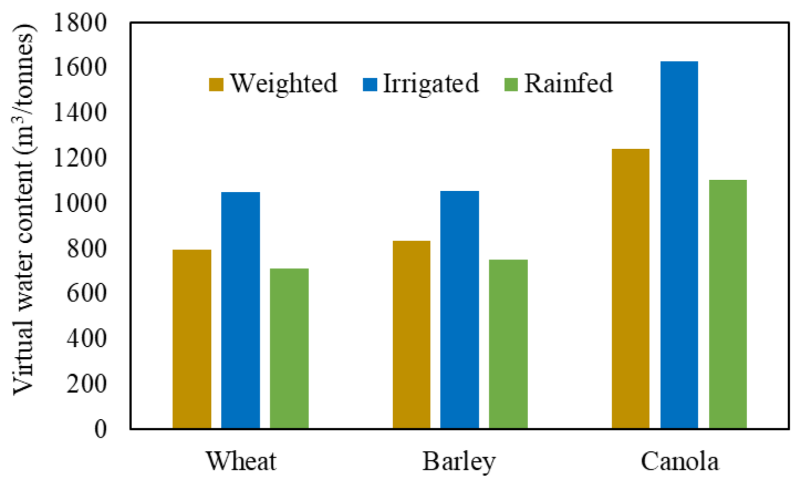

Figure 20. Long-term average (1996-2005) modeled virtual water content (VWC) of cereal crops at the provincial level (adapted from Masud et al., 2019).

We aggregated our subbasin-based data into a provincial scale to discuss the status of virtual water trade (VWT) in Alberta. Based on the available data on the volume of the three cereal crops imported and exported during the 1996-2005 period, we calculated the status of VWT of the province (Figure 21). Among these crops, wheat accounts for on average 65% of virtual water export followed by canola and barley that accounts for 25% and 10%, respectively (Figure 21a). There is a decline in the export during 2000-2003 as the province experienced a significant drought (Masud et al., 2018, 2019). The results showed that the average annual VW export was 3.76, 0.57 and 1.44 billion m^3 for wheat, barley, and canola, respectively with a total of 5.77 billion m^3 per year for historical period. Overall, the results showed that total virtual water import to the province was marginal with only about 0.05 billion m^3 annually

(Figure 21b). However, an increased amount of VW of barley was imported during the drought years, most likely because Alberta is among the largest beef producing jurisdictions around the world and barley was used as the main feed crop. Out of total average annual net virtual water exports of 5.71 billion m^3, about 66%, 9%, and 25% were traded through wheat, barley and canola in the form of grain crops (Figure 21 c). Other processed or consumed crops (e.g., beef, cattle, calve, poultry, and beverage) in our VWF calculations will further increase the volumes. As the VWT analyses depend on the existing import-export data, we projected future virtual water flow (VWF) rather than the VWT in the following section.

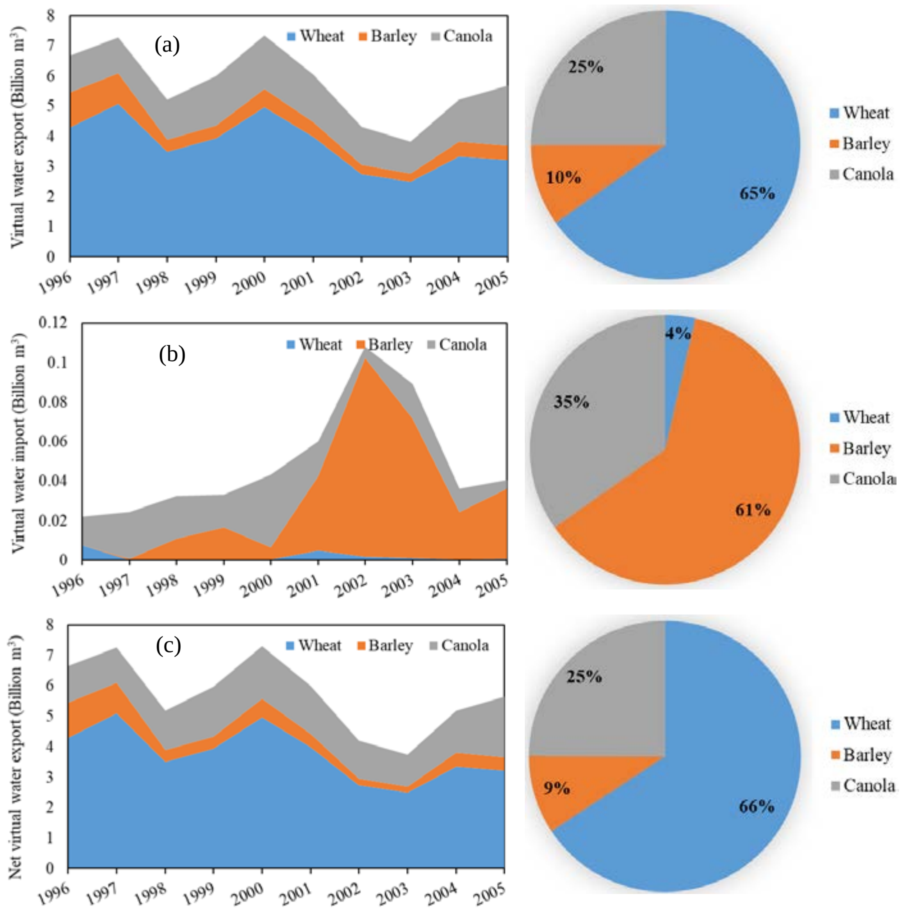

Figure 21. Modeled annual virtual water export (a), import (b), and the net virtual water export (c) from Alberta. Pie charts show their corresponding shares (adapted from Masud et al., 2019).

3.6.3 Future potential of virtual water flow (VWF)

Figure 22 shows the future export potential of wheat, barley, and canola regarding production and associated VWF. Here we calculated the export potential for each year and then averaged for the entire simulation period. The future potential of VWF have been calculated using local water demands of produced crops based on their cropping area, Y, and per capita consumption and population. We used a simplified approach for calculation of the local demands of demographic sector, since they are meager as compared to other water intensive sectors such as beef-cattle, poultry and beverage industries, where cereal crops are consumed in their production processes. Since the majority of these commodities are exported, we assumed that they are exported in the form of grains rather than processed crops. Future alterations in demand from these sectors are not considered, which requires a comprehensive assessment of future local consumption and production patterns based on socio-economic and demographic changes. With all these assumptions, our simulated results showed (Figure 21a) a great potential to export wheat and barley followed by canola, where the projected export potentials were 70, 60, 52 million tonnes of wheat, barley, and canola grains, respectively. The potential export of these grains resulted in a potential export of a large volume of virtual water by exporting canola followed by wheat and barley, as the VWC of canola is the largest among all three crops. A larger difference between RCP 2.6 and RCP 8.5 in potential VWT of canola is due to a higher Y and lower crop water use in RCP 8.5 than RCP 2.6 that resulted smaller VWC in RCP 8.5. Overall, the results showed export potential of 44, 32 and 62 billion m^3 of virtual water through export of wheat, barley, and canola grains, respectively that amounts to a total of 138 billion m^3. Earlier studies (Faramarzi et al., 2017, 2015) found a provincial level long-term average annual precipitation, water yield (surface water availability), and actual ET of 289.62, 66.14, and 224.36 billion m^3 for the historic period (1983-2007), respectively. Our projected total VWF through the export of wheat, canola and barley, in the form of both crop and processed foods, outweighed the total historical water yield and will accounted for about 47% of total precipitation and 61% of total ET due to ET from all vegetation and crop types. This imbalance between total provincial water yield and projected VWF has implications for long term sustainable VWT (Masud et al., 2019).

It is worth mentioning that we assumed future cropping area, management operations, and crop varieties remain the same as the historical conditions. In addition, cropping area in our study was based on crop density maps obtained from AAFC and we assumed that all grid-cells with >10% crop density values are allotted for cropping areas. Therefore, the area under cultivation for each sub-basin might be over estimated. As a result, the volume of export potential and VWF may also be overestimated.

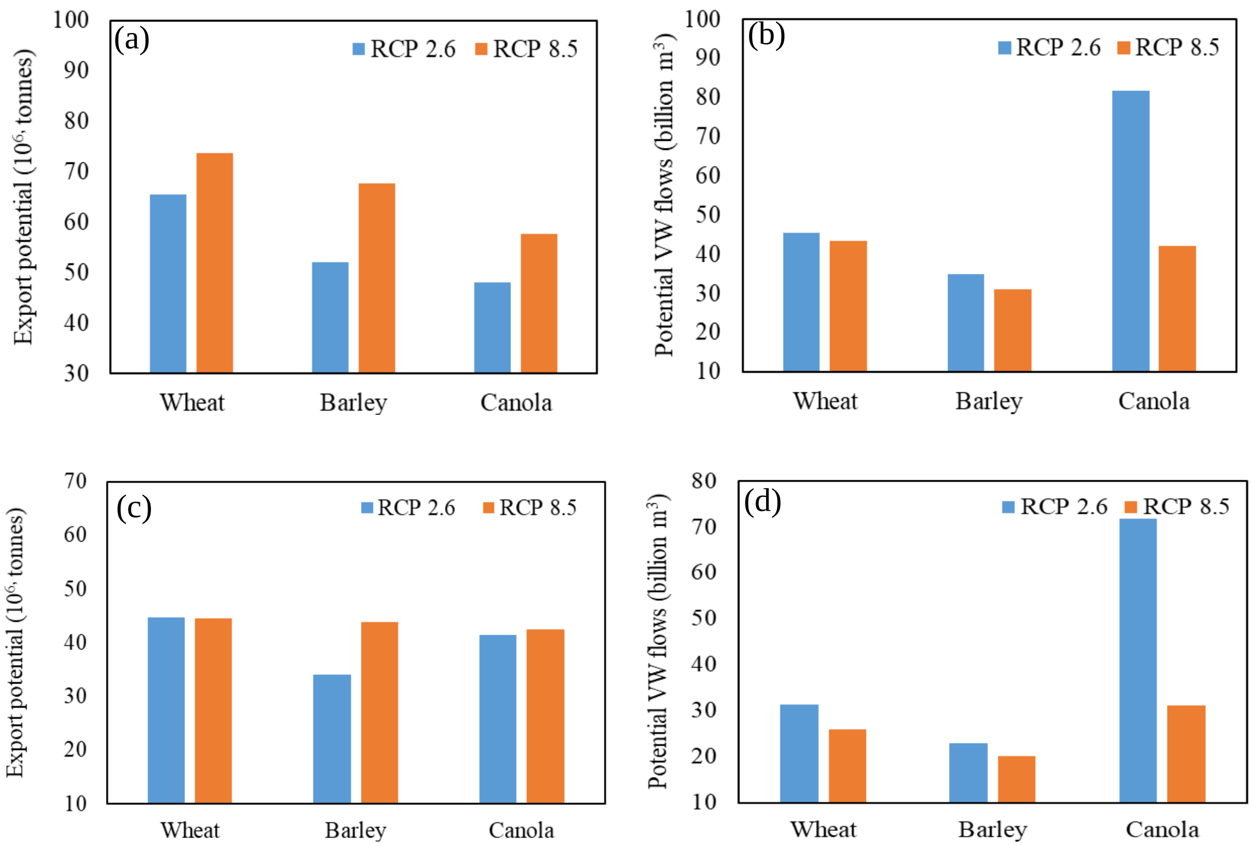

Figure 22. Projected annual export potential of cereal crops (a), and their corresponding virtual water flows (b) for the 2040-2064 period. (c) and (d) show the same results for the scenario, where only the top 90% of density values in the crop density maps were considered for future cropping areas (adapted from Masud et al., 2019).

3.7 Conceptual model for the water resources in the South Saskatchewan River Basin

The outputs from the involvement of the stakeholders during the one-day workshop allowed to understand the complex nature of the water resources problem in the SSRB. The efforts led to the development of a Causal Loop Diagram that connects the three key water sectors of the SSRB with the available water supply which drives the adaption measures to sustain the future socioeconomic developments and in the face of climate change. The developed Causal Loop Diagram is presented in Figure 14. Causal loop diagrams are important tools to represent the causal relationships or connections between two variables in a system. They produce graphical "maps" of our mental models of a system structure explicitly, thus improving our understanding of the interactions between the elements of a complex system and its various subsystems and communicating our understanding of the system to others. This focus on qualitative representation, and on identification of feedbacks, causes CLDs to be considered as conceptual models (Mirchi et al., 2012; Winz et al., 2008) that communicate both the characteristics of subsystems and stakeholders' differing perspectives; capture hypotheses about the causes of dynamics; and show the feedback loops that affect the behavior of various system elements and key variables (Sterman, 2000). In short, a CLD represents a holistic understanding of the system's structure, sets its boundaries, and identifies the key variables that contribute to the dynamics of a system

(Simonovic, 2009). Note that because a CLD is qualitative, it cannot be used to determine the behavior of a system, such as changes in variable values, dominance of different loops, or likely outcomes of policy interventions. It shows possibilities, not outcomes, since it is not a numerical model.

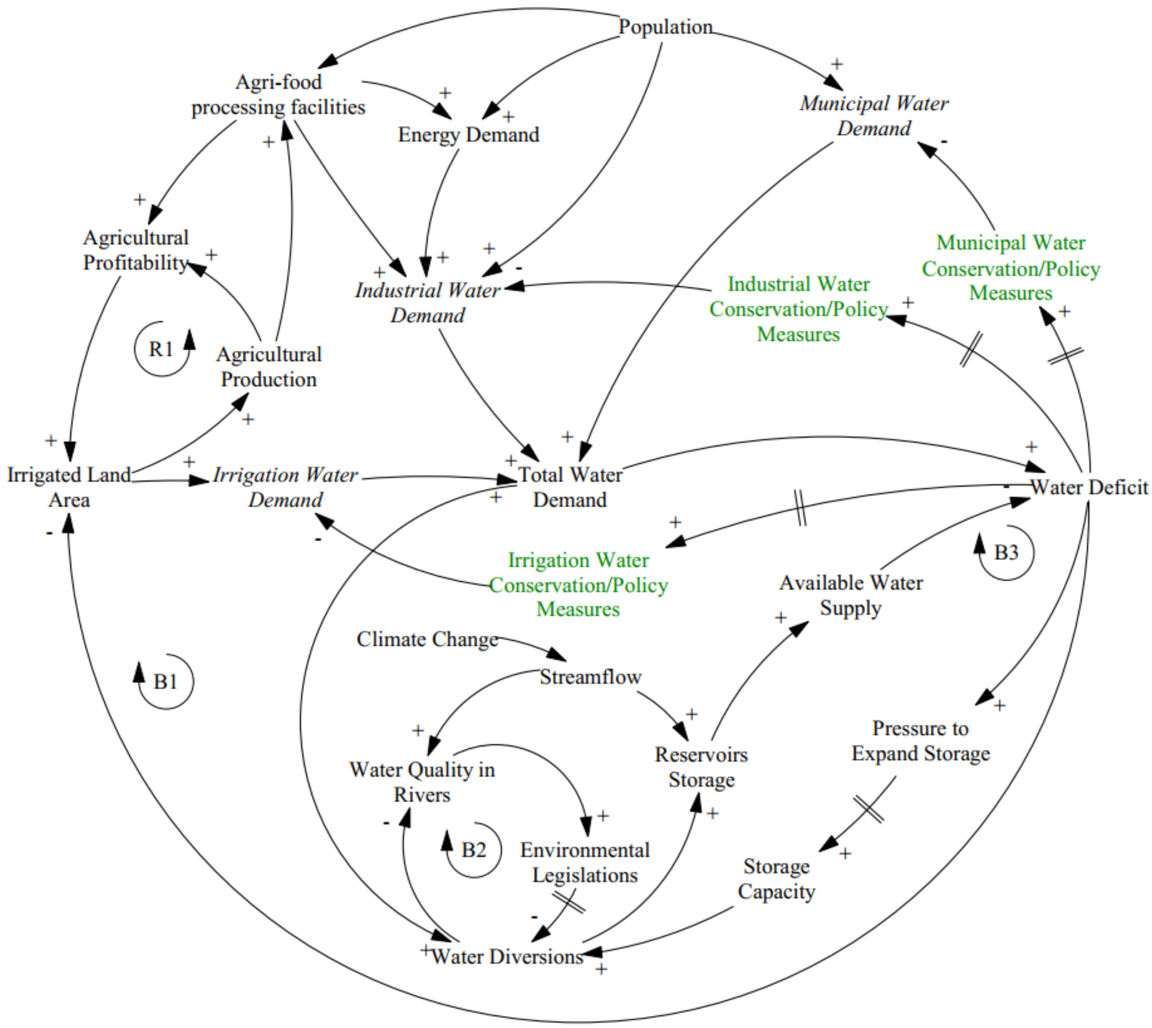

Figure 23. Causal Loop Diagram for the SSRB

To that end, a key component of SD modeling employed in this study was the involvement of the water resources management and planning stakeholders through a one-day workshop facilitated by WaterSMART held in Calgary in September 2019. The workshop included 17 participants (four from the research team, four from WaterSMART, and nine stakeholders) that represented Alberta Food Processing Association, Crop Sector Working group, Calgary Metropolitan Region Board, Alberta Agriculture and Forestry, Red Deer River Watershed Alliance, Alberta Irrigation Districts Associations, and Alberta Environment and Parks. The aim of the workshop was to allow the stakeholders to share their perceptions and insights to help the research team to develop a conceptual model for the problem of water scarcity in Alberta and more specifically for the SSRB and identify the boundaries for the water scarcity problem in Alberta.

More specifically, the workshop aimed to:

- Introduce the ACWA Project and where the project is to date
- Hear from stakeholders on their water issues and opportunities they see to help setup up a conceptual model for water scarcity in the SSRB
- Assist the researchers in setting the problem boundaries for the development of an integrated water resources systems model
- Assist the researchers in determining plausible future expansion scenarios for the agricultural, municipal, and industrial sectors
- Communicate the next steps for this work

Focus groups at the workshop were asked about their perceptions of water management in Alberta and, more specifically, in the SSRB for the three major water sectors (irrigation, municipal, and industrial). The group discussions provided inputs that will help the research team to prioritize challenges for the model to address when fully developed.

Table 1. Data used in some of these studies

Data type	Data set	Time span	Time step	Resolution	Source
Climate data	Temperature	1985-2009	Daily	10 × 10 km	Table 2 [GCM data]
	Precipitation	2040-2064			
	Solar radiation	1985-2009			
	Humidity				
	Wind speed				
Model conceptual	Potholes	2012			Faramarzi et al., 2015, 2017
	Glaciers	1985-2005			
	Vegetation cover				
	Soil				
	DEM				
	Streamflow				
Management measures	Reservoirs	Since compilation			
Agricultural managements	Fertilizer dose (kg)	-	Yearly	Soil zones of Alberta	Alberta Agriculture and Rural Development Alberta fertilizer guide. URL. http//:www1.agric.gov.ab.ca/$department/deptdocs.nsf/ all/agdex3894/$file/541-1.pdf
	N:P:K ratio	-	Yearly	Soil zones of Alberta	
Crop yield	Rainfed	1985-2009	Yearly	County	Alberta Agriculture and Rural Development https://www.agric.gov.ab.ca/app21/rtw/index.jsp
	Irrigated	1985-2009	Yearly	Census Agricultural Region	Alberta Financial Service Corporation https://www.afsc.ca/
Crop density maps	wheat, barley, canola			230 × 230 m	Agriculture and Agri-food Canada (https://open.canada.ca/data/en/dataset/ba2645d5-4458-414d-b196-6303ac06c1c9)
Irrigated districts				Provincial	Alberta Agriculture and Forestry https://www1.agric.gov.ab.ca/$department/ deptdocs.nsf/All/irr12911

Demographic	Population	1985-2009 2040-2064	Yearly	Provincial	Alberta Treasury Board and Finance https://finance.alberta.ca/
Consumption	Food consumption	1985-2009	Yearly	Provincial	FAOSTAT commodity balance sheets, http://www.fao.org/faostat/en/#data/FBS
Trade	Import-export data	1996-2005	Yearly	Provincial	Alberta Agriculture and Forestry https://www.agric.gov.ab.ca/app21/rtw/index.jsp

Table 2. List of General Circulation Models (GCMs) used in beef and barley crop growth study.

Model	Institution	Center
CanESM2	Canadian Centre for Climate Modeling and Analysis	CCCma
CCSM4	National Center for Atmospheric Research	NCAR
CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CERFACS
CSIRO-MK5	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	NOAA/GFDL
HADGEM2-ES	Met Office Hadley Centre (additional HadGEM2-ES runs by Instituto Nacional de Pesquisas Espaciais)	MOHC (INPE)
MIROC5	Meteorological Research Institute	MIROC
MPI-ESM-LR	Max Planck Institute for Meteorology	MPI-M
MRI-CGCM3	Meteorological Research Institute	MRI

Table 3. Parameter ranges for the SWAT model

No	Parameter	Definition	Initial range[a]
1	v__DAY{[],1}.mgt	Day operation takes place (planting)	1-30
2	v__DAY{[],5}.mgt	Day operation takes place (harvesting)	1-30
3	v__HEAT_UNITS{[],1}.mgt	Total heat units for plant to reach maturity	1300-2300
4	v__AUTO_NSTRS{[],11}.mgt	Nitrogen (N) stress factor of plant that triggers fertilization	0.85-0.95
5	v__AUTO_NAPP{[],11}.mgt	Maximum amount of mineral N allowed in any one application (kg N/ha)	30-40
6	v__AUTO_NYR{[],11}.mgt	Maximum amount of mineral N allowed to be applied in any one year (kg N/ha)	55-70
7	v__AUTO_EFF{[],11}.mgt	Application efficiency	1-1.2
8	v__AFRT_SURFACE{[],11}.mgt	Fraction of fertilizer applied to top 10mm of soil	0.2-0.5
9	v__AUTO_WSTRS{[],10}.mgt	Water stress threshold that triggers irrigation	0.85-0.95[b]
10	v__IRR_EFF{[],10}.mgt	Irrigation efficiency	60-85[b]
11	v__IRR_MX{[],10}.mgt	Amount of irrigation water applied each time auto irrigation is triggered (mm)	20-50[b]
12	r__CN2.mgt	SCS runoff curve number for moisture condition II	-0.4 – 0.4
13	v__ESCO.hru	Soil evaporation factor	0.01-1
14	v__EPCO.hru	Plant uptake compensation factor	0.01-1
15	v__OV_N.hru_	Manning’s n value for overland flow	0.01-0.8
16	v__LAT_TTIME.hru	Lateral flow travel time (days)	0-180
17	v__LAT_SED.hru	Sediment concentration in lateral and groundwater flow (mg/L)	0-5000
18	r__CANMX.hru	Maximum canopy storage (mm H2O)	0-0.3
19	r__HRU_SLP.hru	Average slope steepness (m/m)	-0.4 – 0.4
20	r__SOL_BD(1).sol	Soil bulk density in layer 1 of soil profile (g/cm3)	-0.4 – 0.4
21	r__SOL_CBN(1).sol	Organic carbon content in layer 1 of soil profile (% soil weight)	-0.4 - -0.1
22	r__SOL_ALB(1).sol	Moist soil albedo in layer 1 of soil profile	-0.4 – 0.4
23	r__ANION_EXCL.sol	Fraction of porosity from which anions are excluded	0-0.3
24	r__SOL_K(1).sol	Saturated hydraulic conductivity in layer 1 of soil profile (mm/hr)	-0.4 – 0.4
25	r__SOL_CRK.sol	Potential or maximum crack volume of the soil profile	-0.4 – 0.4
26	r__USLE_K(1).sol	USLE equation soil erodibility (K) factor in layer 1 of soil profile	-0.4 – 0.4
27	r__SOL_AWC().sol	Available water capacity of the soil layer (mm H_2O/mm soil)	-0.5 – 0.4
28	v__SHALLST.gw	Initial depth of water in the shallow aquifer (mm H_2O)	0-1000

29	v__ALPHA_BF.gw	Baseflow alpha factor (1/days)	0-1
30	v__SHALLST_N.gw	Initial concentration of nitrate in shallow aquifer (mg N/L or ppm)	0-10
31	v__GW_SPYLD.gw	Specific yield of the shallow aquifer (m3/m3)	0-0.4
32	v__GWSOLP.gw	Concentration of soluble phosphorus in groundwater (mg N/L or ppm)	0-1000
33	v__HLIFE_NGW.gw	Half-life of nitrate in the shallow aquifer (days)	0-365

[a] Minimum and maximum values of the parameter range. v and r indicate absolute and relative value, respectively. [b] These parameters were not considered for rainfed conditions.

Table 4. The minimum and maximum statistics for the county and CAR-based calibration and validation. The provincial average statistics are also provided.

	Calibration			Validation			Calibration			Validation		
	p-factor	r-factor	MSE	p-factor	r-factor	MSE	p-factor	r-factor	MSE	p-factor	r-factor	MSE
	Rainfed Wheat						Irrigated Wheat					
Minimum	0.93	1.5	0.03	0.6	1.4	0.03	0.87	2.08	0.05	0.2	2.58	0.59
Maximum	1	4.17	0.15	1	5.67	0.23	1	2.71	0.66	0.43	2.69	0.71
Average	0.99	2.69	0.07	0.83	3.88	0.1	0.96	2.45	0.26	0.32	2.64	0.65
	Rainfed Barley						Irrigated Barley					
Minimum	0.53	1.91	0	0.55	1.65	0.11	0.8	1.21	0.01	0.5	0.61	0.17
Maximum	1	8.04	2.1	1	8.93	2.3	1	3.22	0.61	0.93	3.66	1.9
Average	0.88	4.48	0.6	0.85	5.35	0.59	0.92	2.13	0.23	0.82	2.34	0.68
	Rainfed Canola						Irrigated Canola					
Minimum	0.93	2.62	0.04	0.7	3.43	0.01	1	4.64	0.06	0.7	3.85	0.03
Maximum	1	5.06	0.12	1	8.2	0.17	1	7.5	0.06	1	7.3	0.14
Average	0.97	3.46	0.07	0.91	5.97	0.06	1	5.99	0.06	0.9	5.88	0.09

Table 5. Model performance statistics in each Census Agricultural Region (CAR) during calibration and validation for rainfed crops.

		Wheat					
		Calibration			Validation		
	CAR	p-factor	r-factor	MSE	p-factor	r-factor	MSE
1	CAR1	0.93	2.01	0.06	0.7	1.4	0.06
2	CAR2	1	3.09	0.10	1	5.67	0.07
3	CAR3	1	4.17	0.05	0.6	4.15	0.22
4	CAR4A	1	1.5	0.03	1	2.64	0.03
5	CAR4B	1	2.1	0.03	1	4.57	0.03
6	CAR5	1	2.12	0.07	0.8	3.68	0.05
7	CAR6	1	3.21	0.15	0.6	5.55	0.13
8	CAR7	1	3.3	0.05	0.9	3.41	0.23
		Canola					
1	CAR1	1	3.15	0.09	1	3.95	0.027
2	CAR2	1	3.12	0.06	0.9	4.38	0.039
3	CAR3	0.93	2.62	0.07	0.7	3.43	0.170
4	CAR4A	0.93	4.27	0.04	1	7.57	0.014
5	CAR4B	0.93	2.82	0.05	0.9	7.37	0.062
6	CAR5	1	5.06	0.08	0.9	7.3	0.076
7	CAR6	0.93	4.01	0.12	0.9	8.2	0.052
8	CAR7	1	2.62	0.05	1	5.55	0.036

Table 6. Model performance statistics in each Census Agricultural Region (CAR) during calibration and validation for irrigated crops.

		Wheat					
		Calibration			Validation		
	CAR	p-factor	r-factor	MSE	p-factor	r-factor	MSE
1	CAR1	0.87	2.08	0.66	0.43	2.58	0.71
2	CAR2	1	2.71	0.05	0.2	2.69	0.59
3	CAR3	1	2.56	0.05			
		Canola					
1	CAR1	1	4.64	0.06	1	3.85	0.10
2	CAR2	1	5.82	0.06	0.7	6.5	0.14
3	CAR3	1	7.5	0.06	1	7.3	0.03

Table 7. Model performance statistics in each county during calibration and validation for rainfed barley

		Calibration			Validation		
	County	p-factor	r-factor	MSE	p-factor	r-factor	MSE
1	Acadia	0.58	1.91	0.38	0.92	1.65	0.21
2	Athabasca	0.80	2.91	0.60	0.75	4.94	0.97
3	Barrhead	0.80	5.29	0.77	0.67	5.62	1.30
4	Beaver	0.80	2.79	0.38	0.67	3.97	1.20
5	Big Lakes	0.80	3.61	1.50	0.83	5.33	0.50
6	Birch Hill	0.80	4.96	1.70	0.92	7.93	0.79
7	Bonnyville	0.67	2.56	0.85	1.00	5.38	0.12
8	Brazeau	0.73	3.95	0.81	0.67	4.33	0.43
9	Camrose	0.87	3.11	0.72	0.75	4.69	0.77
10	Cardston	0.80	2.28	0.62	0.67	2.37	0.42
11	Clear Hills	0.67	4.61	0.79	0.58	5.13	0.28
12	Clearwater	0.53	2.18	0.88	0.75	4.06	0.46
13	Cypress	0.87	2.66	0.80	1.00	2.09	0.27
14	Edmonton	0.60	3.14	2.10	0.55	4.52	1.60
15	Fairview	0.93	6.30	0.44	0.83	7.84	0.26
16	Flagstaff	0.87	2.03	0.38	0.75	5.16	0.85
17	Foothills	1.00	6.25	0.30	0.92	3.34	0.27
18	Forty Mile	0.87	2.87	0.23	1.00	2.86	0.23
19	Grand Prairie	0.93	2.91	0.32	1.00	4.18	0.22
20	Greenview	0.80	3.52	0.76	0.67	7.32	0.32
21	Kneehill	1.00	4.39	0.55	1.00	3.73	1.20
22	Lac La Biche	0.75	8.04	0.59	0.67	6.77	0.54
23	Lacombe	0.87	3.54	0.56	0.92	6.02	0.47
24	Lac Ste Anne	0.67	3.81	0.92	0.75	5.45	1.50
25	Lamont	0.93	5.04	0.32	0.75	6.01	0.86
26	Leduc	1.00	7.74	0.43	0.83	7.30	1.40
27	Lesser Slave River	1.00	2.04	0.00	0.67	4.26	2.30
28	Lethbridge	0.53	2.91	1.40	1.00	3.09	0.32
29	Mackenzie	1.00	5.03	0.59	0.67	6.76	0.18
30	Minburn	0.93	3.67	0.42	0.83	5.95	0.38
31	Mountain View	1.00	6.55	0.38	0.92	4.74	0.55
32	Newell	0.73	2.23	0.62	0.75	1.91	0.14
33	Northern Lights	0.93	3.77	0.43	0.75	5.95	0.41
34	Northern Sunrise	0.87	6.36	1.80	0.92	6.76	0.38
35	Paintearth	0.80	3.71	0.24	0.75	6.01	0.32
36	Parkland	1.00	6.54	0.58	0.75	6.85	1.20
37	Peace	0.93	7.35	0.34	0.83	8.34	0.65
38	Pincher Creek	1.00	2.62	0.52	0.67	2.69	0.69
39	Ponoka	1.00	6.75	0.24	1.00	8.61	0.54
40	Provost	0.93	3.15	0.19	1.00	3.72	0.28
41	Red Deer	1.00	7.02	1.20	1.00	8.55	0.32
42	Rocky View	0.87	6.49	0.75	1.00	4.58	0.47
43	Saddle Hills	1.00	6.92	0.71	0.83	7.50	0.31
44	Smoky Lake	0.73	5.14	0.70	0.58	7.37	0.98
45	Special Area02	0.93	2.78	0.19	0.92	4.29	0.11
46	Special Area03	0.93	3.40	0.12	1.00	3.22	0.14
47	Special Area04	0.87	3.30	0.19	0.83	4.23	0.22
48	Spirit River	0.93	6.55	1.20	0.83	7.19	0.44
49	Starland	0.87	3.60	0.70	1.00	6.03	0.40
50	Stettler	0.93	4.39	0.28	0.83	6.79	0.42
51	Stpaul	0.93	5.26	0.40	1.00	6.39	0.16
52	Strathcona	1.00	6.63	0.28	1.00	7.04	1.30
53	Sturgeon	1.00	5.20	0.42	1.00	6.46	1.10

	County	p-factor	r-factor	MSE	p-factor	r-factor	MSE
54	Taber	1.00	3.53	0.41	0.92	2.99	0.41
55	Thornhild	1.00	6.47	0.40	1.00	7.75	0.50
56	Two Hills	0.93	3.96	0.27	0.92	5.15	0.27
57	Vermillion	0.93	3.37	0.43	1.00	5.90	0.19
58	Vulcan	1.00	6.26	0.37	0.92	4.43	0.58
59	Wainwright	0.87	3.49	0.76	0.75	4.35	0.49
60	Warner	0.93	3.63	0.22	1.00	3.20	0.19
61	Westlock	1.00	7.69	0.52	1.00	8.61	0.69
62	Wetaskiwin	1.00	3.71	0.67	0.92	6.13	0.40
63	Wheatland	0.93	4.03	0.38	0.92	4.78	0.45
64	Willow Creek	0.93	4.70	0.39	0.67	3.97	0.65
65	Woodlands	0.80	7.44	0.75	0.92	8.93	0.84
66	Yellowhead	1.00	5.93	0.30	0.83	3.76	0.90
67	Smoky River	--	--	--	--	--	--

Table 8. Model performance statistics in each county during calibration and validation for irrigated barley

		Calibration			Validation		
	County	p-factor	r-factor	MSE	p-factor	r-factor	MSE
1	Cardston	0.87	2.19	0.61	0.93	1.91	0.70
2	Cypress	0.87	1.71	0.24	0.87	1.64	0.27
3	Forty Mile	0.93	2.25	0.39	0.83	2.40	0.50
4	Lethbridge	1.00	2.71	0.04	0.90	3.15	0.44
5	Newell	1.00	1.97	0.08	0.90	2.73	0.17
6	Rocky View	1.00	2.18	0.01	0.50	3.61	1.90
7	Taber	0.87	1.64	0.18	0.70	1.43	0.50
8	Vulcan	1.00	2.16	0.40	0.92	3.66	0.59
9	Warner	0.93	2.17	0.13	0.70	1.20	1.10
10	Wheatland	0.87	1.21	0.09	0.83	0.61	0.94
11	Willow Creek	1.00	3.22	0.35	0.92	3.40	0.37

4. Key Learnings

The key economic and societal impacts of future climate change in the Province of Alberta will be felt primarily through changes in our hydrology. The direct and in-direct costs of floods or drought are well known and the need to set priorities for adaptation is urgent. Science- based projects demonstrating our future hydrology are important to inform policy makers and other Government officials as they work to allocate resources for climate change adaptation, both temporally and spatially, in our Province. This 3-year ACWA project is an importance first step in understanding the future water status for the Province and was designed to aid policy makers as we need to further develop our strategies for adapting to our water future.

Within this context, we conducted research on a number of projects and summarize our key learnings below:

Milestone 1: Quantification of the water future for the agricultural region of Alberta concerning the historical changes and the impacts on the water availability for dryland agriculture

Key Learnings: The climate in the agricultural region (white zone) of Alberta has already become warmer and drier, especially in lower latitudes, and our modelling results demonstrated that the climate will continue to become warmer and wetter due to an increased precipitation in near and far future periods. However, the increased precipitation does not necessarily generate larger water supply for agricultural lands when it is compounded with increased temperature. The projection of hydrological water balance suggested a larger increase of actual evapotranspiration and decrease of soil moisture, especially in the southern sub-basins, where the temperature was projected to increase with high precipitation. This implies that larger temperatures may offset the seemingly positive effects of higher precipitation in the future. Our results revealed that when aggregated to regional scale the blue water resources were expected to marginally increase but the spatial distribution will be different across the white zone.

Milestone 2**:** Investigate the impacts of climate change on future flooding in Alberta

Key Learnings: Floods in Alberta, Canada are generally intensifying with projected increases ranging from 2–104% depending on catchment. Most of 29 studied catchments across Alberta have consistently shown exacerbated changes in flood regimes including increases in the rate of occurrence of floods, shifts to earlier occurrences, increased variability of the events about the mean date of occurrence, whereas no significant change in the duration of floods was projected. Overall, future climate tended to decrease small floods and increase larger floods in some areas and the opposite pattern was projected in some other areas.

Milestone 3: Investigate the changes in the storage volume of geographically isolated wetlands of Alberta under climate change

Key learnings: Due to scarcity of high spatiotemporal resolution data related to GIWs, a direct hydrological simulation and projection of changes in their water storage volume at Alberta scale is not feasible.

However, utilization of existing best available data and application of newly developed Machine Learning techniques, revealed southern part of the province has relatively less WSV than the central and northern parts. That is likely due to the hotter and drier climate conditions and the presence of irrigated agricultural activities that are spread heavily across southern Alberta. The overall WSV for GIWs in Alberta is 550 million m^3, of which 31.76% were located in the Green Area, and 68.24% were located in the White Area. The northern areas, i.e. Athabasca and Peace River Basins, hold the greatest volume of WSV in GIWs, however the density of GIWs is larger in Battle, Slave, Red Deer, and North Saskatchewan River basins indicating that smaller GIWs in southern river basins are likely more vulnerable to future increases temperature and unreliable precipitation pattern in the province.

Milestone 4: Determine how spatial and temporal variation of hydroclimate conditions affect the uncertainty decomposition results.

Key Learnings: Our results demonstrate that the type of input climate model provides the greatest degree of uncertainty in our forecasting. Our results demonstrate higher discrepancies between RCMs forecasts (from NARCCAP) when compared to GCMs forecasts (from PCIC). In addition, our modelling demonstrates that there is a higher agreement (lower uncertainty) between climate model projections for near future projections compared to far future projections. In addition, hydrologic model uncertainty can dominate climate model uncertainties in the areas and times when a considerable lack of input data hinders a reliable model setup.

Milestone 5:

Predict changes in main crop yields, including of barley, wheat, and canola in Alberta sector.

Key learnings: The key learning from this aspect is that in the near and far future, there will be an enhanced grain (barley, wheat) and oil-crop (Canola) production. This is primarily through an increase in production in rain-fed crop while there will likely be marginal production increases in irrigated areas. However, implementation of different agricultural and water management practices and the use of different crop varieties than what was used in this study may generate different results in the future.

5. Outcomes and impacts

5.1 Peer review publications

2019 — Ammar, M.E., Gharib, A., Islam, Z., Davies, E.G.R., Seneka, M., Faramarzi, M., Future floods using hydroclimatic simulations and peaks over threshold: An alternative to nonstationary analysis inferred from trend tests, *Advances in Water Resources*. DOI: https://doi.org/10.1016/j.advwatres.2019.103463

2019 — Masud, B., Qian, B., Faramarzi, M., Performance of multivariate and multiscalar drought indices in identifying impacts on crop production, *International Journal of Climatology*. DOI: https://doi.org/10.1002/joc.6210

2019 — Vaghefi, S.A., Iravani, M., Sauchyn, D., Andreichuk, Y., Goss, G., Faramarzi, M., Regionalization and parameterization of a hydrologic model significantly affect the cascade of uncertainty in climate-impact projections, *Climate Dynamics*. DOI: https://doi.org/10.1007/s00382-019-04664-w

2019 — Chunn, D., Faramarzi, M., Smerdon, B., Alessi, D.S., Application of an intergrated SWAT-MODFLOW model to evaluate potential impacts of climate change and water withdrawals on groundwater-surface water interactions in west-central Alberta, *Water* 11(1): 110. DOI: 10.3390/w11010110.

2019 — Masud, M.B., Wada, Y., Goss, G., Faramarzi, M., Global implications of regional grain production through virtual water trade, *Science of the total environment* 659: 807-820. DOI: 10.1016/j.scitotenv.2018.12.392.

2018 — Masud, M.B., Ferdous, J., Faramarzi, M., Projected changes in hydrological variables in the agricultural region of Alberta, Canada, *Water* 1–20. DOI: 10.3390/w10121810.

2018 — Cordeiro, M.R.C., Lelyk, G., Kröbel, R., Legesse, G., Faramarzi, M., Masud, B.M., McAllister, T., Deriving a dataset for agriculturally relevant soils from the Soil Landscapes of Canada (SLC) database for use in Soil and Water Assessment Tool (SWAT) simulations, *Earth System Science Data:* 10(3) 1673-1686. DOI: 10.5194/essd-10-1673-2018.

2018 — Masud, M.B., McAllister, T., Cordeiro, M.R.C., Faramarzi, M., Modeling future water footprint of barley production in Alberta, Canada: Implications for water use and yields to 2064, *Science of the Total Environment* 616-617: 208-222. DOI: 10.1016/j.scitotenv.2017.11.004.

2017 — Gharib, A., Davies, E.G.R., Goss, G.G., Faramarzi, M., Assessment of the combined effects of threshold selection and parameter estimation of generalized pareto distribution with applications to flood frequency analysis, *Water* 9, 692. DOI: 10.3390/w9090692.

2017 — Ashraf Vaghefi, S., Abbaspour, K., Faramarzi, M., Srinivasan, R., Arnold, J.G., Modeling crop water productivity using a coupled SWAT-MODSIM model, *Water* 9: 157, w9030157, 15pp. DOI:10.3390.

2017 — Faramarzi, M., Abbaspour, K., Adamowicz, W.L., Lu, W., Fennell, J., Zehnder, A.J.B, Goss, G., Uncertainty based assessment of dynamic freshwater scarcity in semi-arid watersheds of Alberta, Canada, *Journal of Hydrology: Regional Studies* 9: 48-68.

2017 — Lu, W., Adamowicz, W., Jeffrey, S.R., Goss, G.G., Faramarzi, M., Crop yield response to climate variables on dryland versus irrigated lands, *Canadian Journal of Agricultural Economics* 00:1-21. DOI: 10.1111/cjag.12149.

2015 — Faramarzi, M., Srinivasan, R., Iravani, M., Bladon, K.D., Abbaspour, K.C., Zehnder, A.J.B, Goss, G., Setting up a hydrological model of Alberta: Data discrimination procedure prior to calibration, *Environmental Modelling & Software* 74: 48

5.2 Presentations in Conferences

[**Note:** list of presentations ended by *, †, and ‡ indicate: academic, non-academic (public), and both events, respectively]

2020 Faramarzi M., Adating to Changing Water in Alberta, 2020 Alberta Irrigation District Association Conference, February 03-05, Lethbridge, Canada, (Invited Speaker) ‡

2019 Masud B (supervised PDF), Faramarzi M., Performance of Drought Indices for Drought Risk Assessment on the Agricultural Production, CGU-IUGG conference, July 08-12, Montreal, (oral) *

2019 Masud B. (supervised PDF), Faramarzi M., The role of Alberta in global food security through virtual water trade, European Geophysical Union, Vienna, Austria, April 10, (poster) *

2019 Ammar M. (supervised PDF), Goss G., Faramarzi M., Adapting to changing water in Alberta, Alberta Innovates-Water Innovation Program Forum, Edmonton, Canada, May 23, (oral) ‡

2018 Faramarzi M., Masud, M. (supervised PDF), Agriculture potential in Alberta: the impact of climate change on crop yield and crop water requirement. Alberta Agriculture and Forestry, J.G. Donoghue Building, Government Office, Edmonton Alberta, December 14, (Invited speaker, oral) †

2018 Faramarzi M., Quan Cui (supervised PDF), Predicting water-related risks and opportunities for Alberta's wetlands, Alberta Ecosystem Services program, Alberta Innovates and Alberta Biodiversity Monitoring Institute, University of Alberta, November 21, (oral) ‡

2018 Chunn D. (supervised MSc), Faramarzi M., Alessi, D., Application of SWAT-MODFLOW Software to Evaluate Groundwater-Surface Water Interaction in West-Central Alberta. Resources for Future Generations-RFG conference, Vancouver, BC, June 16-21, (oral) ‡

2018 Faramarzi, M., Modelling hydrology for studying future water supply and adaptation in Alberta. Resources for Future Generations-RFG conference, Vancouver, BC, June 16-21, (Invited speaker) ‡

2018 Masud, B. (supervised PDF), McAllister, T., Faramarzi, M., The virtual water content of barley production in Alberta: implication for water use and yields to 2064. Resources for Future Generations-RFG conference, Vancouver, BC, June 16-21, (oral) ‡

2018 Faramarzi, M., Modelling Alberta's Water Future: Challenges from Input Data to Hydrology and Climate Change. Canadian Geophysical Union-CGU conference, Niagara Falls, Ontario, June 10-14, (oral) *

2018 Faramarzi, M., Adapting to changing water in Alberta: assessment of future water endowments to study regional water, food, energy, and environment dynamics. Canadian geophysical Union-CGU conference, Niagara Falls, Ontario, June 10-14, (poster) *

2018 Faramarzi M., Future water supply and adaptation. Alberta Land Institute: Land, Water and Society 2018, Edmonton, Alberta, May 30-31 (Invited speaker). ‡

2018 Faramarzi M., Goss G., Adaptation to changing water in Alberta. Alberta Innovates Water Innovation Program (WIP) Forum, Edmonton Alberta, May 23-24 (oral). ‡

2018 Faramarzi, M., Assessment of future water endowments: establishing a robust foundation to study regional water, food, energy, and environment dynamics. 8th GEWEX Open Science Conference: Extremes and Water on the Edge, Canmore, Alberta, May 6-11, (poster) *

2018 Masud, B. (supervised PDF), McAllister, T., Faramarzi, M., Water footprint analysis of barley production in Alberta: implication for water use and yields to 2064. 8th GEWEX Open Science Conference: Extremes and Water on the Edge, Canmore, Alberta, May 6-11, (oral) *

2018 Cui, Q. (supervised PDF), Cranston, J., Kariyeva, J., Iravani, M., Faramarzi, M., Modeling and uncertainty analysis of wetland's water storage volume in Alberta, Canada. 8th GEWEX Open Science Conference: Extremes and Water on the Edge, Canmore, Alberta, May 6-11, (poster)*

2018 Faramarzi, M., Assessment of water resources endowments: establishing foundation to study water-food-energy and environment dynamics, Campus Alberta Innovates Program Chair Conference, Lethbridge, Canada, March 20-21, (poster) ‡

2018 Faramarzi, M., Is climate change a good news for barley crops?, Western Barley Growers Association, Calgary, Alberta, March 7-8, (Invited speaker) †

2017 Masud, B. (Supervised PDF), Goss, G., McAlister, T., Corderio, M., Legesse, G., Adamowicz, V., Jeffrey, S., Faramarzi, M., Predicting water related risks and opportunities for Alberta's beef industry, *54th Alberta Soil Science Workshop*, February 15-17, Lethbridge, Alberta, Canada, (poster) ‡

2017 Masud, B. (supervised PDF), McAllister, T., Goss, G.G., Faramarzi, M., Assessment of climate change impacts on crop production and water use in Alberta, *Canadian Geophysical Union (CGU)*, May 28-June1, British Colombia, Canada, (oral) *

2017 Vaghefi, S. (Supervised PDF), Faramarzi, M., Goss, G., Predicting Alberta's water future, Alberta Innovates Water Innovation Program Forum, May 25, Edmonton, Alberta, Canada, (oral) ‡

2016 A.I. Gharib (Collaborated- PhD), A., Faramarzi, M., E.G. Davies, G.G. Goss, Assessing combined effects of threshold selection and parameter estimation of generalized pareto distribution on future projection of floods, American Geophysical Union (AGU), 12-16 December, 2016, San Francisco, USA, (poster)*

2016 Beets L. (Supervised PDF), Faramarzi M., Chunn D. (Supervised PDF), Alessi D., Goss G., Integrating groundwater and surface water hydrology in the Fox Creek area: risks and opportunities for the oil and gas industry, 2016, Oil Sands Science Symposium, November 22-23, 2016, Calgary, Canada, (poster) ‡

2016 Masud, B. (Supervised PDF), Goss, G., McAlister, T., Corderio, M., Legesse, G., Adamowicz, V., Jeffrey, S., Faramarzi, M., Predicting water related risks and opportunities for Alberta's beef industry, *ALMA Future Fare*, October 13, Edmonton, Alberta, Canada, (poster) ‡

2016 Faramarzi, M., G. Goss, Adapting to changing water in Alberta, Alberta Innovates Energy and Environment Solution (AI-EES) Water Innovation Program Forum, May 30-31, Calgary, Canada, (oral) ‡

2015 Faramarzi, M., K. Abbaspour, R. Srinivasan, G. Goss, Application of the Soil and Water Assessment Tool to predict freshwater availability in Alberta, Alberta Soil Science Workshop, February 17-19, 2015, Edmonton, Canada, (poster) ‡

2015 Faramarzi, M., W., Adamowicz, D., Sauchyn, S., Kienzle, S., Marshall, J., Fennell, K., Abbaspour, J., Brisbios, G. Goss, Predicting Alberta's water future, Canadian Water Network, March 10-12, 2015, Ottawa, Canada, (poster)‡

2015 Faramarzi, M., K. Abbaspour, G. Goss, Application of SWAT model to quantify blue and green water resources in Alberta, American Geophysical Union Assembly, May 3-7, 2015, Montreal, Canada, (poster) *

2015 Faramarzi, M., G. Goss, Predicting Alberta's Water Future, Alberta Innovates Energy and Environment Solution (AI-EES) Water Innovation Program Forum, May 26-27, Calgary, Canada, (oral) ‡

5.3 Seminars, Symposia, Meetings & Workshops

2019 Faramarzi M., Ammar M., Goss G. (supervised PDF), Adapting to changing water in Alberta, Stakeholder Workshop, Organized by Watershed science modelling laboratory and Alberta WaterSMART Ltd, September 13, (oral) †

2019 Faramarzi M., The Quandary over Water Resources: Global Implication of Regional Food and Energy Production through Virtual Water Trade, IIASA- International Institute for Applied System Analysis, Vienna Austria, 6-10 July, (invited speaker) *

2019 Faramarzi M., Modelling hydrology for studying future water security and adaptation in Alberta, Workshop organized by my lab at the University of Alberta, Participants from: Alberta Environment and Parks; Associated Engineering Alberta Ltd., January 18, (oral) †

2018 Faramarzi M., Du X. (supervised PDF), Developing regional water quality models in Athabasca River Basin, Workshop organized by my lab at the University of Alberta, Participants from: EMSD of Alberta Environment and Parks, November 27, (Invited speaker, oral) †

2018 Faramarzi M., Ammar M. (supervised PDF), Loiselle, D. (supervised MSc), Modelling hydrology, flood, and nutrients for studying future water security and adaptation in Alberta. Educational Workshop for Alberta Environment and parks Water Experts, Edmonton, Alberta, September 28, (Invited speaker, oral) †

2018 Faramarzi M., Ammar M. (supervised PDF), Quantifying changes in flood regimes and frequency curves under climate change in Alberta using multi-model ensemble simulations, A workshop organized by Alberta Environment and parks for water experts in Water Policy Branch, September 10, (Invited speaker, oral) †

2018 Faramarzi M., Loiselle D. (supervised MSc), Modelling hydrology for studying future water security and adaptation in Alberta, Seminar organized by the City of Calgary for us to present our results to their internal water experts, August 21, (Invited speaker, oral) †

2018 Faramarzi, M., Assessment of water resources endowments: establishing foundation to study water-food-energy and environment dynamics, Poly Technique University, Montreal, Canada, July 27 (Invited speaker, oral)*

2018 Faramarzi, M., Assessment of water resources endowments: establishing foundation to study water-food-energy and environment dynamics, Concordia University, Montreal, Canada, July 26 (Invited speaker, oral)*

2017 Faramarzi, M., Future water supply and adaptation, *Agri-Environmental partnership of Alberta (AEPA),* December 20, Edmonton, Alberta, Canada, (Invited speaker, oral) †

2017 Faramarzi, M., Goss G., Adaptation to changing water in Alberta, *Alberta Water* Council (AWC), October 26, Edmonton, Alberta, Canada, (Invited speaker, oral) †

2017 Faramarzi M., Predicting Alberta's water future: risks and opportunities for Alberta's beef industry, *Cow-Calf Council Meeting, Alberta Beef Producers (ABP),* October 03, Calgary, Alberta, Canada, (Invited speaker, oral) †

2017 <u>Masud, B. (Supervised PDF</u>), Faramarzi, M., Climate change in Alberta is both a risk and an opportunity, *ATLAS Talk, Earth and Atmospheric Sciences Seminar Series*, October 13, University of Alberta, (oral) †

2017 <u>Masud, B. (Supervised PDF</u>), Faramarzi, M., Predicting Alberta's water future: risks and opportunities for Alberta's beef industry, *Cow-Calf Council Meeting, Alberta Beef Producers (ABP),* October 03, Calgary, Alberta, Canada, (Invited speaker, oral) †

2017 <u>Iravani, M. (Supervised Research Associate</u>), Faramarzi, M., Climate change and forage availability in Alberta, *Cow-Calf Council Meeting, Alberta Beef Producers (ABP),* October 03, Calgary, Alberta, Canada, (Invited speaker, oral) †

2017 Faramarzi, M., Agricultural water availability and use, *Alberta Innovates Workshop* on: Testing a Framework for Agricultural Land Accounting, June 6-7, University of Alberta, (Invited speaker, oral) †

2017 Faramarzi, M., Green and blue water consumption and excess nutrient, *Alberta Innovates Workshop* on: Testing a Framework for Agricultural Land Accounting, June 6-7, University of Alberta, (Invited speaker, oral) ‡.

2017 Faramarzi, M., Modeling Future water resources in Alberta, Guest Lecture, *INT D 280 The Mountain World: An Introduction to Interdisciplinary Mounatin Studies, Torry B1, March 27, University of Alberta,* (Invited speaker, oral) *

2017 Goss, G., Faramarzi, M., Alberta's Water Future*, World Water Week: Water Matters*, EPCOR, March 24, Edmonton, Alberta, Canada (contributed talk) ‡

2017 <u>Masud, B. (supervised PDF</u>), Mc Alister, T., Goss, G., Faramarzi, M., Assessment of water demand of rainfed and irrigated barley production in Alberta: implication for regional water and food security, *Workshop on Modelling of Cumulative Effects in Integrated Resource Management:*

Challenges and Opportunities, Alberta Environment and Parks, March 16-17, Edmonton, Alberta, Canada, (oral) ‡

2017 Faramarzi, M., Uncertainty prediction in assessment of water resources in Alberta: from input data to hydrology model and climate change, *Workshop on Modelling of Cumulative Effects in Integrated Resource Management: Challenges and Opportunities, Alberta Environment and Parks*, March 16-17, Edmonton, Alberta, Canada, (oral) ‡

2017 Faramarzi, M., Assessment of future water endowments: establishing a robust foundation to study the dynamics of water, food, energy and environment, *Environmental Monitoring and Science Division, Alberta Environment and Parks,* February 22, Edmonton, Alberta, Canada, (oral) †

2017 Masud, B. (Supervised PDF), Goss, G., McAlister, T., Faramarzi, M., Assessment of water demand of rainfed and irrigated barley production in Alberta: implication for regional water and food security, *54th Alberta Soil Science Workshop*, February 15-17, Lethbridge, Alberta, Canada, (oral) ‡

2017 Faramarzi, M., Modeling the effects of climate change on water supply in Alberta, *Water policy Branch* (Modelers, Planners, and Managers), *Alberta Environment and Parks*, January 25, Edmonton, Alberta, Canada, (oral) †

2017 Faramarzi, M., Assessment of future water endowments: establishing a robust foundation to study the dynamics of water, food, energy and environment Alberta, *Guest lecture*, January 25, Tara McGee, ESB 1-31, (invited speaker) *

2016 Faramarzi, M., Goss, G., Masud, B., Predicting Alberta's Water Future, *Alberta Environment and Parks and City of Edmonton*, Water policy Branch (Modelers and Experts), December 14, Edmonton, Alberta, Canada, (invited speaker) †

2016 Faramarzi, M., Goss, G., Predicting Alberta's Water Future, *Alberta Environment and Parks and City of Edmonton*, Water policy Branch, October 25, Edmonton, Alberta, Canada, (invited speaker) †

2016 Faramarzi, M., Assessment of future water endowments: establishing a robust foundation to study the dynamics of water, food, energy and environment Alberta, *ATLAS Talk, Earth and Atmospheric Sciences Seminar Series*, October 14, UofA, AB, Canada, (oral) *

2016 Faramarzi, M., Goss, G., Modelling the effects of climate change on future water supply in Alberta, *North Saskatchewan Watershed Alliance Educational Forum*, October 4, Sherwood Park, Alberta, Canada, (invited speaker) ‡

2016 Faramarzi, M., Goss, G., Predicting Alberta's Water Future, *Alberta Environment and Parks, Water policy Branch*, June 23, Edmonton, Alberta, Canada, (oral) †

6. Benefits

There are several benefits that resulted from this project during the different phases of the project. The modeling workflows developed in the first task can be used to apply new GW–SW interaction scenarios with a multitude of both natural and anthropogenic influences. Use of this model can help scientists track water resources more accurately and can inform the decisions made by policymakers whose priority is to ensure that this vital resource can remain available to all who need it.

This task tested the robustness of one such model, SWAT–MODFLOW, in an area of diverse climate and hydrogeology, and included both pumping and climate change to determine the relative effects on the study watershed. The relatively user-friendly and cost-effective code tested here performed successfully under highly variable hydro(geo)logic and weather conditions while incorporating a deeper, more complex bedrock system than any prior SWAT–MODFLOW model. The model also included additional factors, such as snow influence, that had not been included in previous SWAT–MODFLOW studies. The implementation of this SWAT–MODFLOW model proved that GW has a heavy influence on the hydrology of the Little Smoky River watershed, discharging significant volumes of water into the rivers and tributaries of the study area. This reinforces the importance of examining SW and GW as one system, as the demands placed on one have direct effects on the other.

Second, the findings of the task that quantified the changes in the agro-hydrological variables of the agricultural regions in Alberta will help in understanding anticipated changes in hydrological variables and decision-making regarding the regional agricultural water resources management. The information about the ET and WD for barley (as an example) may help agricultural managers and planners to adopt different strategies to cope with climate change and maintain sustainable expansion in the future. Increased food demand has to be met by agriculture intensification. In the agriculture sector in Alberta, climate change may lead to a major shift and extension of croplands favoring proper environment for water demand of crop growths. A key finding from this project is increasing temperature in Alberta's agricultural region. This rising temperature trend could increase the risk of plant diseases, insects' infestations, and invasive weeds. Warming temperature also results in longer frost-free seasons which is undoubtedly favorable for the Alberta agriculture. However, the extreme temperature could increase the likelihood of heat-wave related reduction in crop production and consequently in other agricultural industry such as beef-cattle and milk production in the dairy industries in Alberta.

Third, the prediction of the future changes in the flood characteristics for Alberta will help minimizing potential risks of future flood events and for future development in terms of designing safe infrastructures such as storage reservoirs. These conclusions were based on the examination of changes in flood properties in terms of both seasonality and design discharges with climate change in a set of unregulated catchments in Alberta using ensemble simulations. The use of a spatially-distributed hydrological model allowed determination of changes at individual catchments, which was necessary because the examined catchments – both tributaries and main stems – had a wide range of climatic and hydrologic characteristics. Independent peaks over threshold data allowed examination of changes in several flood properties, including the rate of occurrence, timing, and duration, and regularity of exceedances as well as magnitudes of the 20- and 50-year flood events under ensembles of projections for two climate scenarios.

Fourth, defining different sources of uncertainty will help decision makers and scientists to better deal with the issue of uncertainty and also help to identify the necessary research and/or data acquisition required to reduce uncertainty and improve decision confidence.

Finally, the project provided the scientific basis for decisions to be made about future water scarcity in the province and set the foundational base on how adaptation measures can alleviate/mitigate economic, social and environmental impacts. While we provided the most sophisticated predictive modeling for natural, anthropogenic and climate induced changes in water dynamics, the application and use of these tools required training. These tools have the potential to become a key component of the decision-supporting tools for governmental entities dealing with agriculture and industry, including forestry, health and environment. This project accordingly provided the necessary Highly Qualified Personnel (HQP) to allow knowledge transfer of how to use these models for decisions and furthermore, a series of workshops and talks in the province will increase the profile, understanding and update of these models into water policy.

7. Recommendation and next steps

A few extensions and further research are recommended. First, it is noteworthy that the causes behind the changes of hydrological variables such as increasing atmospheric greenhouse gases due to anthropogenic actions, natural climate variability, and the effect of management and dam operations on water availability were not explicitly addressed in this study. The results of trend analysis could be influenced by the time period used for the analysis. Hence, the results need to be interpreted carefully. However, the information on projected changes will undoubtedly be useful in adaptation-related decision-making.

Additionally, the results of the future changes in floods assumed no human modifications (e.g., changes in land use), and no fluvial transportation (e.g., construction of dams) or natural changes in landscapes – such as those caused by forest fires – to occur in the future, which will undoubtedly affect runoff generation processes. Therefore, future studies should aim to quantify the relative impacts of these and other factors through socio-hydrological modeling approaches that incorporate hydrologic responses to human interactions. It is also worth noting that adaptation measures aimed at mitigating flood risks in the future will have potential impacts on both water availability and water demand for the different water sectors studied in the ACWA project. These impacts need to be taken into consideration in future research efforts.

The application of hydrologic models could be limited if the initial model of a watershed is not set up cautiously and accurately due to lack of adequate input data, and if the uncertainty range of initial model parameters becomes wide due to improper model setup.. This has been addressed in the literature (Faramarzi et al., 2015), which leads to the challenge of decision making under uncertainty condition. We recommend to use similar framework as the one developed in this phase of the study to investigate other similar spatial-data demanding and physically-based models such as VIC, Noah-MP, CLM, HydroGeoSphere, or similar models in climate-impact projections and to investigate the sensitivity of different hydrological models (HM-S) in the analysis of the uncertainty cascade. It might be possible that more physical-based models such as Noah-MP would probably show less parameter uncertainty in comparison with more parameterized models. However, a robust assessment using a similar approach as this study is required for robust conclusion.

Further, adaptation measures are to undergo comprehensive systematic literature review in order to bring experiences from other jurisdictions around the world on adaptation strategies to climate change and socioeconomic developments. This will identify potential policy interventions for basin-level competition over water resources beside those identified in the SSRB Roadmap that might provide great adaptation potential for the basin. The outcome of this step is essential as it will directly allow engaging both stakeholders and policymakers to iteratively examine a wide range of adaptation strategies and collaborate proactively to develop sustainable future management strategies for the basin. Also, we propose to iteratively examine proposed potential mitigation strategies and feedback to our stakeholders on the likely impact with regard to congruence between water demand, availability, and supply. To this end, next steps will include building a System Dynamics simulation model that represents that conceptual model developed for the SSRB through integrating the outcomes from this project and the results obtained through its different phases. This model, potentially called Alberta Water Policy Simulator, will allow testing the strategies for adaptation when completed under both climate change and future developments, which will facilitate communicating the corresponding risks and opportunities of the identified adaptation strategies to policymakers.

8. Knowledge Dissemination

In addition to the significant numbers of publications, conference presentations and public presentations/media forums as listed in Section 5 (above), a key component of SD modeling employed in this study is the involvement of the water resources management and planning stakeholders through a one-day workshop facilitated by WaterSMART held in Calgary in September 2019. The workshop included 17 participants (4 from the research team, 4 from WaterSMART, and 9 stakeholders) that represented Alberta Food Processing Association, Crop Sector Working group, Calgary Metropolitan Region Board, Alberta Agriculture and Forestry, Red Deer River Watershed Alliance, Alberta Irrigation Districts Associations, and Alberta Environment and Parks. The aim of the workshop was to allow the stakeholders to share their perceptions and insights to help the research team to develop a conceptual model for the problem of water scarcity in Alberta and more specifically for the SSRB and identify the boundaries for the water scarcity problem in Alberta. During the workshop, beside the insights we gained in developing the conceptual model for the SSRB, the results of the different phases of the project were presented and communicated to the participants. Their feedbacks were noted and are planned to be incorporated into future research to (1) provide answers to "what-if" questions to help in adapting to changes in climate and socioeconomic developments in the basin, and (2) enable further strategy development and testing to address the challenges for a sustainable future water management in the SSRB.

Another workshop is recommended after the completion of the Alberta Water Policy Simulator. The simulator will have "sliders" that represent different policies or adaptation measures where participants move sliders and tick checkboxes in the interface to indicate their policy choices. Once participants are satisfied with their policy selections, they can run the model forward from the one year to the next, or alternatively, they can see the economic, social, and environmental consequences as they move the sliders in response to their choices. Simulations from AWPS will respond to actions of the participants by offering immediate and sometimes surprising feedback results. It will allow the participants (e.g., policymakers) to explore potential solutions, to improve their understanding of the complex water system of SSRB and trigger their curiosity without experiencing real consequences.

9. Conclusions

Water has always been a key underpinning of Alberta's development. Decisions made about water play a critical role in shaping Alberta's economic, social and environmental future. Resolving the challenges related to water: its availability, its use by the irrigation, municipal, and industrial sectors, and its role in sustaining healthy ecosystems and environments are compelling factors in almost all political decisions in the province. Alberta is witnessing major expansions in the three key water users namely irrigation, municipalities, and, industries (e.g., livestock, food processing, unconventional oil and gas among others) that will collectively increase provincial water demands in the future. Additionally, future changes in the climate are expected to alter the spatial and temporal water supplies for the province. These pressures together with the potential changes in climate suggest higher water demands and less reliable water supplies in the future. Therefore, understanding the dynamics of Alberta's water system in space and time is necessary to avoid increased social, economic and environmental risks to the growth potential of the SSRB through the most effective adaptation measures and policy alternatives. This project aimed to: 1) develop an integrated groundwater-surface water (GW-SW) model to simulate the regional hydrogeological conditions for Alberta; 2) quantify the future changes in the evapotranspiration, soil moisture, deep aquifer recharge, and water yield for the agricultural region of Alberta; 3) assess the impacts of climate change on future flooding in Alberta; 4) determine the contribution of Alberta's hydrologic model parameterization and regionalization to the overall climate-impact uncertainty chain and use this method to determine how spatial and temporal variation of hydro-climate conditions affect the uncertainty decomposition results; 5) predict changes in crop production and yield variabilities under both rainfed and irrigated agriculture and to explore risks and opportunities to export potentials of the province and to discuss trade-offs with environmental and water issues; and 6) develop a conceptual model that represents the competition for water between the three major water users namely irrigation, municipalities, and industries and identify the potential adaptation strategies at the river basin scale that can provide adaptation potential for the basin.

The conclusions of the project can be summarized as follows:

- Results revealed that the climate in the agricultural region of Alberta had become warmer and drier during the His period. Seasonal and annual precipitation is expected to increase by 1% and 3% in the NF, while they are projected to increase by 5% and 7% in the FF. The mean seasonal and annual temperature is likely to increase by 1.21 and 1.33 ◦C in the NF while they are expected an increase by 2.14 and 2.32 ◦C in the FF, respectively. ET and SM distribution in the future has a resemblance with temperature and precipitation distribution. For instance, a region with high temperature is projected to have high ET and low SM. The projected increase in blue water resources (DA and WYLD) is meager and it varies over time and space.
- Floods in the selected 29 catchments of Alberta, Canada, are generally intensifying with changes in the climate in the mid-21st century except in a small number of catchments. About 2/3 of the catchments are expected to experience higher 50-year floods with projected in- creases of 2–104% (mean = 29%, median = 20%) for RCP 2.6 and 7– 86% (mean = 32%, median = 25%) for RCP 8.5. Further, most of the studied catchments have consistently shown exacerbated changes in flood regimes for both climate scenarios. These changes include projected increases in the rate of occurrence of floods, shifts to earlier occurrences, increased variability of the events about the mean date of occurrence, whereas no significant change in the duration of floods was projected.

- Climate models and hydrological model parameterization and regionalization are the dominant sources of the uncertainty. The share of uncertainty varied over different seasons. During spring and summer seasons the climate models are key contributors to the overall uncertainty along with hydrologic models and other sources. For the winter and spring, the contribution of HM-P and HM-R decreased, while other sources shared more uncertainty in overall cascade. In general, results showed a higher discrepancy between RCMs results (from NARCCAP) compared to GCMs results (from PCIC). The results showed that there is a slightly higher agreement among climate model projections in near future scenarios compared to the far future.

- Our results for the historical 1985-2009 and future 2040-2064 periods revealed that: i) Future climate change leads to an increase in cereal crop yields and a decrease in VWC; ii) The VWC varied substantially in time and space and for different production conditions (rainfed and irrigated); iii) The area-based weighted average VWC of both rainfed and irrigated crops at provincial level revealed that the VW flow of wheat grain from Alberta to more than a hundred countries in the world has led to a global annual water saving of 4.897 billion m^3 during 1996-2005, however the local environmental and water foot prints in agricultural lands of Alberta should be further investigated; iv) Higher precipitation, compounded with increased temperature and elevated CO2 concentrations in the future projected increases in the export of virtual water through export of cereal crops. However, it may exceed local hydrologic water balance components and be affected by local water resources availability and low renewal rates. Our results indicated that total VWF through the export of cereal crops, in the form of both grain and processed foods, may outweigh the total historical water yield and will account for about 47% of total precipitation and 61% of total ET due to ET from all vegetation and crop types; v) For a sustainable VWT strategy, future water renewals, as well as environmental impacts, should be predicted using locally adapted modeling tools.

- Our early models for System dynamics were developed though interaction with specific water sector stakeholders in a meeting facilitated by Alberta WaterSmart. The Causal Loop Diagram (CLD) model developed connects the three key water sectors of the SSRB with the available water supply. Importantly, when finally built, tested and applied, it will allow collaborative stakeholder the tools for decision making to scenarioize the adaption measures needed to better sustain the future socioeconomic developments in the face of climate change. CLDs are only considered as conceptual models that will ultimately project feedback loops that will affect the behavior of various system elements and key variables. CLD represents a means to understand and project scenarios and allow for decision support but given that CLD is qualitative and not quantitative, it only shows possibilities, not outcomes, since it is not a numerical model.

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