Project Title:

Predicting Alberta's Water Future (PAWF)

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Project Leader:
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Lead Institution:
University of Alberta

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Executive Summary

The development of a comprehensive calibrated and integrated dynamic water model of Alberta at the Provincial scale was a primary goal of the Predicting Alberta's Water Future (PAWF) grant. A fully integrated and calibrated model was developed for the entire Province of Alberta and these results project the future hydrology for the province of Alberta to 2070 under median climate change scenarios. This water model of the province was achieved by collecting and compiling significant amounts of geo-spatial and climate data from various sources for the province.

A total 48 global climate models (GCMs) and global warming scenarios were used to assess range of plausible conditions on water availability in 2255 delineated sub basin in the Province on a monthly time step for the 2010-2040 (near future), and 2040-2070 (far future) period. All sources of uncertainties associated with input data, hydrologic model, climate change models, and global warming scenarios were quantified. The water supply components included 'renewable water', 'fossil water', and recently through a complementary project the 'virtual water', in 2255 sub-basins in the province. For the renewable water resources, the project allowed quantification of blue water (i.e., surface water plus deep aquifer recharge), green water flow (i.e., actual evapotranspiration), green water storage (i.e., soil moisture), and stream flow in the province. For the fossil water a hydrologic model of glacier melting process was developed that allows quantification of fossil glacier water on monthly-daily time step and its contribution to the existing renewable water resources in the mountainous highland areas of the province.

The water model of Alberta was applied to predict future water availability and reliability under various climate change and global warming scenarios.

Evidence of significant inherent internal climate variability due to possible influences of a Pacific Decadal Oscillation (PDO) were detected in the southern half of the Province that leads to a large uncertainty prediction in climate change assessment. In other words, most of the global 48 models and scenarios tested predicted diverse direction of changes in the southern sub-basins, indicating significant potential risk in projecting water supplies for this part of the Province. However, in the northern part of the province, most of the 48 model-scenarios agreed very well in their projection of the climate meaning that confidence in projects in these regions could be quantified and was very high. The disparity between global model projections in the southern half of the Province and the northern half of the Province of Alberta indicates that there are significant effects of internal climate variability that need further investigation (e.g., influence of El Nino, PDO).

This model now allows for integration with scenarios of future demand to assess sector-based risks and opportunities, and for integration of future water availability (at both provincial scale and sub-watershed scale) into government policy and planning.

Gaps and the needs for further improvements in the existing data sources are highlighted. Given the rather large changes in hydrology, surface water availability and groundwater recharge as outlined in this report, it is imperative that adaptational responses by industry and policymakers take into account these future water availabilities. These future scenarios represent an essential tool for mitigation planning of possible environmental and economic risks as well as taking advantage of the opportunities afforded by seasonal water availability.

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Project Description

1.1 Introduction

With just two percent of Canada's water supply, Alberta accounts for two-thirds of the country's agricultural water use. Alberta is already facing periods of water scarcity in certain regions and at certain times. Pressures on water resources are mounting due to population growth, economic development, and the impacts of global climate change and spatial and temporal variability of water resources.

Understanding temporal and spatial dynamics of water scarcity is key for sustainability of freshwater supplies. Economic growth, increasing population, environmental concerns, and climate change are increasing the risk of surface water scarcity and threatening the sustainability of groundwater resources and water dependant systems (i.e., natural and human-based) (Beek *et al.*, 2011; Doll, 2009; Famiglietti, 2014; Mwangi *et al.*, 2016; Oki and Kanae, 2006). Global organizations and national governments have announced water stress as the largest global risk and the main reason for regional insecurity (Intelligence Community Assessment (ICA), 2012; World Economic Forum, 2015). Alberta's economy, one of the strongest in Canada, depends on industries that rely heavily on sufficient and reliable quantities of good quality water. Nonetheless, periodic water scarcity poses serious economic concerns as well as social and environmental consequences for many areas in the province. While much has been written about the impacts of climate change on water resources, particularly in terms of quantity, quality, and the effects on food production, not much is known about the effects on the other reliant sectors (i.e., energy extraction and production, forestry, hydropower generation, recreation, municipal and rural development) both at a local and regional level. Looking to the future, although demand for Alberta's water will be affected by population growth, economic development, and the associated increase in water consumption, other less predictable, yet accelerating, forces of change such as technology, global and regional economics, governance, and security issues regarding food and energy provision will also play a key role in shaping what could be a very different world from today. Planning for resiliency across Alberta's socio-economic sectors in the face of these uncertainties will require a systematic and detailed analysis of future climate and land use change effects on water resources at a finer spatial and temporal resolution. Resolving the challenges related to this natural resource based on: i) its availability and reliability, ii) its quality and potential impacts on the health of Albertans, iii) its use by various sectors (i.e., agriculture, energy extraction and production, forestry, hydropower generation, recreation, municipal and rural development), and iv) its role in sustaining economy and healthy ecosystems are compelling factors in almost all decisions (political and industrial) in the province. There is, however, a lack of holistic knowledge regarding provincial water supplies and water needs to explicitly address the spatial and temporal patterns of the differing sources. The knowledge gained by this research will provide the basis for a flexible, adaptive approach with built-in check-points for water availability under future climate change scenarios, and help to identify gaps that may exist in current policy, monitoring infrastructure, and management strategies.

1.2 Research Description

This project is unique in that it sought to develop tools, data sets, dynamic predictive modelling at an Alberta wide scale to facilitate a dynamic assessment of water availability and reliability. These tools consider the impacts of future climate variability and change, economic development, and population growth and establish a sound basis for synthesizing a comprehensive picture of current and future water risks and opportunities in the province. As such, it will be useful across these scales to inform future water policy for all water stakeholder groups in Alberta, including the public. It builds on an earlier study completed for AI-EES, called Dynamics of Alberta's Water Supplies (DAWS), to systematically assess potential risks triggered by climate variability and change, demographic trajectories, and economic developments to Alberta's water resources and dependent systems. This helps identify opportunities during periods of water surplus and development of management strategies to address water scarcity through the identification of adaptation options. This project uses a deliberate, participatory and advanced forward-looking approach to assessing and mapping all of Alberta's water security issues. It will greatly enhance current efforts by the province, and AI-EES, to develop and implement innovative management concepts to ensure the provision of safe, secure drinking water supplies to Albertans, healthy aquatic ecosystems, and reliable water supplies for a sustainable economy.

The Predicting Alberta Water Future's (PAWF) project is particularly important considering the anticipated development trajectories of Alberta, including the consequential extension of urban areas, increased agricultural development for food production, forestry for commercial lumber, hydropower generation, recreation and energy extraction and production (i.e., natural gas, oil, and oil sands) for domestic and international needs. The results of this project provide a comprehensive framework for managing current and future water resources to develop and implement innovative management concepts to ensure allocations of safe and secure drinking water supplies for Albertans, healthy aquatic ecosystems, and reliable quality water supplies for a sustainable economy, while ensuring that provincial and international apportionment agreements are met. Our teams goal was to integrate the various components of water risk both from a spatial and temporal perspective. The results are visualized using an ArcGIS platform incorporating layers of information used to derive conceptual models of water resources in Alberta for the future. The sub-projects of the PAWF main project, with their specific tasks, are summarized below.

1.2.1 Hydrological simulation, climate change assessment

Tasks:

- Calibration, validation, and uncertainty analysis of the SWAT hydrological model of Alberta using a set of updated data to predict water resources availability for main economic-water sectors (e.g. agriculture, energy, industry, and urban), application of the calibrated model to assess impacts of climate change on water supply taking the effect of other driving forces to global change, analysis of economic-water scenarios for an enhanced analysis of adaptation measures, scientific and technical coordination of project, and support during the implementation of technical aspects of project deliverables.

1.2.2 Glacier Simulation-Integration with SWAT

Tasks:

- Develop distributed models of glacier mass balance (snow accumulation and melt), glacier hydrology, and glacier dynamics for all the major glacier systems in the eastern slopes of the Canadian Rocky Mountains; embed the glacier model into SWAT; simulate glacier area, volume, and runoff response to climate change scenarios for the period 2010-2040 and 2040-2070.

1.2.3 Groundwater assessment

Tasks:

- Assessing the risk and opportunities with respect to Alberta's groundwater resources through a review of sources, related volumes, use patterns and trends, including an assessment of recharge (volume and distribution) at the sub-basin and major basin scale, and the implications of human development and climate change on the balance of recharge and groundwater storage reserves (where possible). This will incorporate future projections supported by other work packages (i.e., SWAT, ACRU) to provide a holistic view of groundwater as a viable offset to surface water, and the opportunity for alternative storage and management options (e.g., Conjunctive use, aquifer storage, and recovery, managed aquifer recharge).

1.2.4 Basin Yields and Climate Trends

Tasks:

- Identifying the spatial distribution of climate variability, estimating future basin yield, processing, downscaling and sharing critical climate time series for the period of 1950-2050, comparing simulated future hydrological behaviour between the SWAT model and the ACRU model, providing hydrological modelling results for selected watersheds, including the Oldman River basin, analysis of extreme events including flood and droughts.

1.2.5 Economic analysis

Tasks:

- Identifying direct economic impacts (outputs, wealth measures, etc.) of the agricultural sector (as the largest water user) but incorporating energy, industrial and urban water users, arising from alternative water availability cases for the broader economic and risk assessment. Initially direct economic impacts will be provided (outputs, returns) with economy wide impacts (employment, etc.) as well as broader general equilibrium impacts assessed in later stages. Economic values at risk measures will also be developed for the risk analysis component.

1.2.6 Scenario development

Tasks:

- Scenario developments with respect to the economic impact of irrigation versus non-irrigated areas and potential adaptation options in the face of climate change.

1.3 Project Objectives

The research project had the following objectives that will contribute to an enhanced understanding of Alberta's potential water supply and water demand over the next 50 years. Minor adjustments notwithstanding, all objectives are completely consistent with the original proposal *and all major deliverables have been met*.

1. **Assessment of water supply**: to quantify blue, green, and fossil water resources under various climate variability (mega-drought) and climate change (global warming) scenarios, using a calibrated province wide SWAT hydrologic model and providing results to describe water supply (in various forms) in the years 2010-2040 and 2040-2070.
2. **Integration of water demand in future climate change**: to integrate water demand from five specific 'sectors' including agriculture, energy, industry (manufacturing and forestry), municipal, and environment (nature-based demand) through three separate scenarios (base-case, high, and low demand) over the next 50 years.
3. **Water supply-demand analysis**: to assess the water use intensity in different regions of Alberta based on the water availability/reliability and the water demand of different sectors at present.
4. **Economic analysis:** We coupled the climate change modelling of Alberta's future water supply-demand to the province's economic future by examination of irrigation and non-irrigated areas and economic output.

1.4 Work Scope Overview

1.4.1 Project Budget:

$1,000,000 funded by AIEES (333,333 per annum)

AI-EES Funding:

Project Schedule			Cost Status		
(1)	X	Project on schedule	(1)	X	Cost unchanged
(2)	____	Project delayed	(2)	____	Cost overrun
(3)	____	Project cancelled	(3)	____	Cost underrun
(4)	____	Project complete			

1.4.2 Project Partners

Figure 1 illustrates the project team and the responsibilities assigned to each member. The team began with nine members from universities, research institutes and the private sector. In November of 2014, Bill Cosgrove who was responsible for scenario development withdrew from the project team.

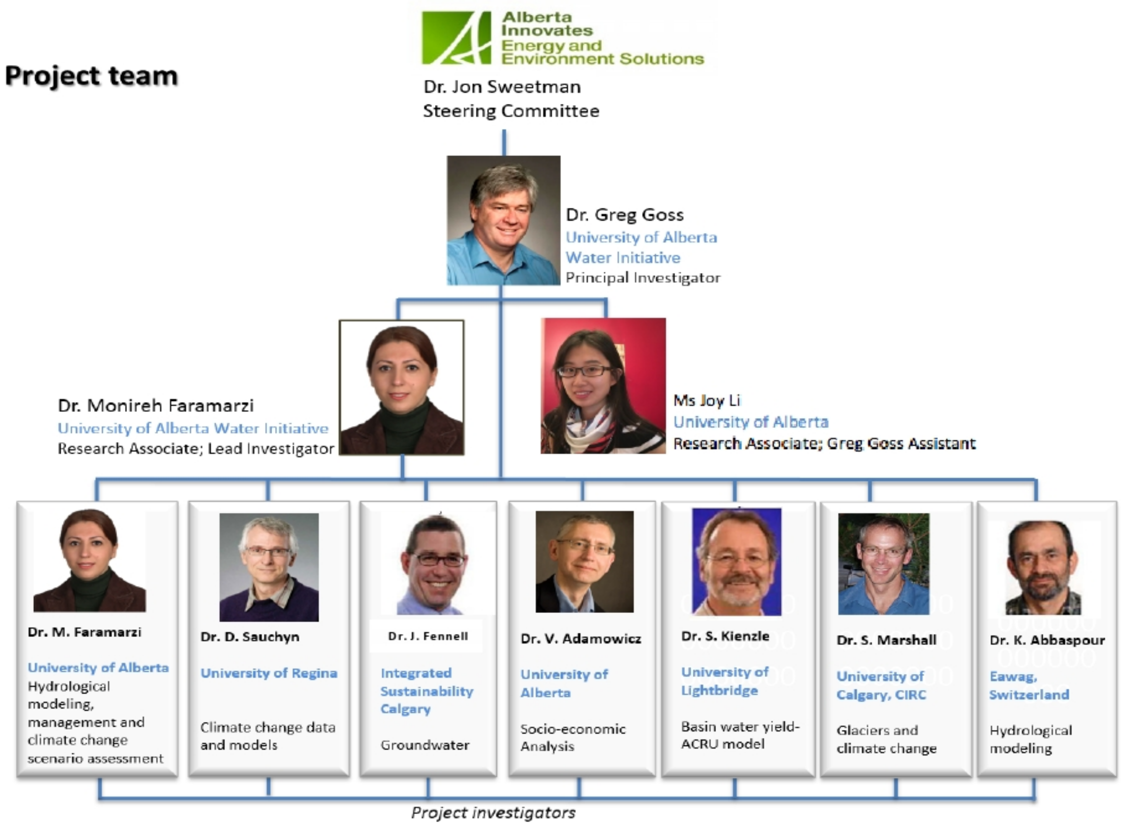


Figure 1. Project team members and structure.

2. *Approach and Results*

2.1 Literature Review

2.1.1 Climate change and integrated water resources management

In Alberta, half of the province's GDP relies heavily on the availability of water, with strong variances across sectors. Whereas agriculture represents 60-70% of Alberta's water withdrawals (17 cubic kilometers) and contributes to one-third of Canada's agricultural export, it only represents 1.4% of the provincial GDP. Conversely, the energy sector, which supports 23.4% of GDP, uses small amounts of water (less than 0.5 cubic kilometers). The adverse impact of climate change on water resources, demographic growth, and economic development place an unprecedented demand on the management of rivers, which are the main source of water supplies and provider of ecosystem services in Alberta and many other areas in the world (Vörösmarty *et al*., 2010). Inherent in the management of the watersheds are serious challenges in reconciling the limited water resources among all conflicting sectors (i.e. energy and food production, hydropower generation, forestry, recreation and rural development) while ensuring a sustainable economy and robust ecosystems.

A quantitative assessment of both water supply and demand processes in the past and future is essential to support resource planning and facilitate design and implementation of adaptation measures predicated on sound science, engineering and public participation (Ospina-Norena, 2009; Anghileri, 2011; IPCC, 2001). Despite this urgency, tools for prediction of changes in the ecosystem and human activities under different climate-driven scenarios for Alberta are limited in number. (e.g. Notter *et al*., 2011; Ospina-Norena *et al*., 2009; Anghileri *et al*., 2011; Lange *et al*., 2010; Eum and Simonovic, 2010). Previous studies have dealt primarily with the net impact of climate change on hydrological cycles (e.g. Abbaspour *et al*., 2010; Stegn *et al*., 2011; Chenoweth, 2011; Kienzle *et al*., 2012). More recently, the effect of land use-land cover change was added to these considerations (e.g. Pitman *et al*., 2011; Hasler *et al*., 2009; Mango *et al*., 2011). Nevertheless, proposed quantitative adaptation measures have primarily been based on the “status quo” situation (Betrie et al., 2011), or on a qualitative assessment of the future needs (Krysanova *et al*., 2010; Sowers *et al*., 2011). An integrated water resources management (IWRM) plan advocating for a systematic incorporation of water supply (with explicit quantification of its different sources), demanding a course of action under various climatic conditions (UNFCCC, 2006) simultaneously whilst taking environmental and economic constraints into account including assimilating with the concept of blue and green water resources (Falkenmark, 1995; Savenije, 2000; Falkenmark and Rockstrom, 2006), have not been well-utilized in current adaptation measures.

2.1.2 Climate change and water reliability

Droughts and floods are historically a common occurrence in Alberta and elsewhere in the world. Given the adverse economic effects of both types of extreme climate events, it is of great importance to assess the processes affecting the development of these events, including analysis of probability, intensity, duration, and frequency in the past and future.

A comprehensive review of drought research in Canada by Bonsal *et al*. (2012) and other studies by George *et al*. (2009) and Pitman *et al*. (2011) indicate a huge knowledge gap in the literature with respect to drought assessments. Among them are: (i) lack of systematic monitoring, modelling, and prediction of drought onset, intensity, and termination; (ii) their connection with major modes of climate variability including El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO) and the Atlantic Multi-Decadal Oscillation (AMO); (iii) their impacts on climate-sensitive operations (e.g. decline of crop yield during drought periods; limited rivers flows affecting availability of water for oil sands mining operations); (iv) integration of global and regional climate models with water balance models to address physical processes facilitating drought predictions; and (v) a comprehensive study of the entire region/province and the challenges of linking previous studies that have used different drought indices, spatial locations, and time periods.

Several studies have focused on adaptation measures to Canadian droughts. Rob de Loé (Global Environmental Change, 2001) discussed issues relating to the selection of proactive, planned adaptation measures for the near-term (next decade), in three different regions in Canada (i.e. Grand River basin, Ontario; southern Alberta; and the Great Lakes). A set of selection criteria is offered to illustrate how stakeholders can identify measures appropriate for managing for the near-term. In the study by Mahan *et al*., (Socio-Economic Planning Sciences, 2002), a novel network model was used in southern Alberta which allows the adaptation of market mechanisms for efficient allocation of surface water resources at different years of surplus, mean flow, and drought conditions. Though the study tended to support the present cautious approach by the Alberta Government to modify the mechanisms for water allocation, the methodology and databases used are crude. This level of sophistication ultimately affects the robustness and reliability of the results. Despite the usefulness of the previous studies, a dynamic predictive model integrating processes to represent the soil-plant-water-atmosphere relations and to quantify drought frequency, duration, and severity over a longer period of time (approx. 50 years) does not exist for Alberta. This can be achieved by integrating physical-hydrological models with global and regional climate models on a high time and space resolution. The outcome will facilitate analysis of different local-regional-national oriented management options to realize opportunities during water deficits in order to provide water security for various sectors relying on water, including improved environmental outcomes which are of primary importance to Alberta's sustainable growth.

2.1.3 Global Climate Change Impacts in North America

Climate change poses an increasing threat to sustainable freshwater resources. Many changes in the observed climate are unprecedented in recent history, particularly with increasing atmospheric temperatures, rising global average sea-level, widespread melting of snow and glaciers, shifting river flow characteristics, and increased greenhouse gas concentrations (IPCC, 2013; Jiménez Cisneros *et al*., 2014; Romero-Lankao & Ruiz, 2014). According to the recent Intergovernmental Panel on Climate Change (IPCC) report, there is some robust evidence on the significant increase of freshwater-related risks with increasing greenhouse gas concentrations (IPCC, 2013; Jiménez Cisneros *et al*., 2014). These changes have been attributed to the increasing influence of anthropogenic greenhouse gas (GHG) concentrations since 1750 (IPCC, 2007, 2013). The concentrations of carbon dioxide, methane and nitrous oxide have already exceeded the pre-industrial levels by 40%, 150% and 20%, respectively (IPCC, 2013). Using information collected from ice cores, there is an unprecedented concentration of greenhouse gases within the last 22,000 years that have also exceeded the highest concentrations recorded within the last 800,000 years (IPCC, 2013). Thus, the continued increase in greenhouse gas concentrations will continue to negatively impact freshwater resources in the 21st century.

Climate change impact studies project a doubling of greenhouse gas emissions to increase temperatures (Barnett *et al*., 2005; Schindler, 2001). A warmer climate will result in increasing evaporation, ultimately reducing the availability of freshwater resources for the region. In many cases, a considerable shift from the amount of snow to rain, along with changes in the runoff patterns associated with earlier spring melt, can adversely affect the water availability for peak-flow demand (Burn, 1994; Jiménez Cisneros *et al*., 2014; Lapp *et al*., 2005). Adverse risks of climate change have been projected for snow-dependent regions that rely on winter snowpack and summer melt (Burn, 1994; Sauchyn & Kulshreshtha, 2008). The western alpine regions of North America are expected to experience increasing winter flows, reduced snowpack and reduced summer low flows (Barnett *et al*., 2005; IPCC, 2013; Jiménez Cisneros *et al*., 2014). Extreme weather and climate phenomena are likely to continue in the 21st century (IPCC, 2013). Therefore, the potential adverse impacts of climate change will exacerbate increasing water demand and supply in these regions.

2.1.4 Regional Hydrological Impacts

The water resources in the Canadian Prairie region are largely influenced by annual snowpack and glacier melt in the ice fields of the Rocky Mountains. The Rocky Mountains are a considerable source of freshwater, contributing to 50-80% of the spring flows (Barnett *et al*., 2005; Mueller *et al*., 2011). Streamflow has already declined in the northern regions of the Rocky Mountains, with a projected 10% less flow by 2050 (Rood *et al*., 2005). A diminishing snowpack decline in the Rocky Mountains could mean altering the magnitude and the duration of peak spring flows for southern Alberta (Rood *et al*., 2008). In addition to increasing temperatures and decreasing volumes of snowpack, earlier snowmelt and decrease in summer soil moisture can also be expected (Barnett *et al*., 2005). Spring floods rejuvenate the riparian and floodplain areas within the region, where a variety of species depend on freshwater resources (Rood *et al*., 2008; Rood *et al*., 2005). Drought-risk regions that have experienced heavy precipitation events will continue to experience more frequent extreme events, and the expected increasing frequency and magnitude of droughts and flooding will subsequently affect the surface and groundwater quality of the region (Barrow *et al*., 2005; Jiménez Cisneros *et al*., 2014). Canada will likely experience some of the largest climate change impacts due to its geographic location in the mid-latitudes, and like many regions affected by drought and flooding, water-stress issues are likely to become a future trend.

2.1.5 From Global to Watershed Scale: Regional Climate Models

To project the hydrological impact of climate change, models require reliable sources of climatological data. Global Climate Models (GCMs) are commonly used to estimate the future climate change impacts on the hydrological response in combination with a hydrological model. However, model outputs from GCMs have a much coarser resolution compared to the climate data available at a finer, e.g. 10-km, resolution. GCMs resolutions are at 100-250-km scale and, therefore, lack the detailed information needed in regional hydrological models (Fowler *et al*., 2007; IPCC, 2007; Salathe *et al*., 2007). Thus, there is a great need for a higher spatial resolution input for hydrologic models.

The downscaling of GCM output from global to watershed scale is typically carried out using either statistical or dynamical downscaling techniques. Previous studies have focused on comparing both downscaling techniques (Lapp *et al*., 2009; Murphy, 1999, 2000; Teutschbein *et al*., 2011; Wilby *et al*., 1997), emphasizing the advantages and disadvantages of both. The statistical downscaling method utilizes 10 statistics in order to build relationships between the large-scale data against the regional variables (Beckers *et al*., 2009; Fowler *et al*., 2007; Wilby *et al*., 2004). These methods are computationally efficient, thus, making it an attractive option for climate impact studies (Fowler *et al*., 2007; Teutschbein, 2013; Wilby *et al*., 2002). Conversely, the dynamical downscaling method focused on the development of limited-area models or regional climate models (RCMs) (Teutschbein & Seibert, 2010). The extraction of local climate information using GCM output data as a boundary condition allows the local scale climate processes to be captured (Teutschbein & Seibert, 2010; Wilby *et al*., 2002). Despite these advantages, the main disadvantage of the dynamical downscaling method is its relatively expensive computational requirement to extract useful climate data and its dependence on boundary conditions (Teutschbein & Seibert, 2010). Statistical downscaling, on the other hand, is more desirable in terms of required computational power. Wilby *et al*. (2002) recommended the use of the statistical downscaling method for highly localized climate even if the reproduction of decadal and inter-annual climate variability is not quite appropriate (Fowler *et al*., 2007; Loukas *et al*., 2002).

Recently, much progress has been made with regional climate models (RCM) (Teutschbein & Seibert, 2010, 2012). RCMs can produce climate data at a much higher spatial and temporal resolution, using either downscaling techniques. Although most RCM outputs are at 25-60km spatial resolution, these datasets are still representative of the hydrologic components such as surface runoff (Jiménez Cisneros *et al*., 2014; Teutschbein & Seibert, 2010). Thus, RCM simulations attract more consideration for climate change impact studies using hydrologic models, and thus will be used in this study in southern Alberta.

Caution must be exercised, however, when dealing with the RCM data as these often have biases. Teutschbein and Seibert (2010) highlighted various RCM biases with a special focus on model errors. Biases can occur with inaccurate conceptualisation framework used by the model itself as well as the discretization and the spatial averaging within grid cells. To correct these biases, it is recommended to apply a bias correction technique to an ensemble of RCM simulations (Teutschbein & Seibert, 2010, 2012). Previous studies have shown that uncorrected RCM simulations are a large source of uncertainty in modelling hydrological response to climate change. Recently, Teutschbein and Seibert (2012) have shown that the use of highly bias-corrected RCM climate data performed considerably better than other corrected RCM climate data. Therefore, the bias-corrected RCM data will be applied in this study of Alberta soon.

2.2 Technology Development

The development of a calibrated integrated SWAT model of Alberta at the Provincial scale was a primary task of the Predicting Alberta's Water Future (PAWF) grant. Now that this model is developed, it allows for integration with scenarios of future demand to assess sector-based risks and opportunities, and for integration of future water availability (at both provincial scale and sub-watershed scale) into government policy and planning. We have successfully performed each of these tasks as described below:

- We used ensembles of climate variables predicted by various GCMs and RCMs to assess the impacts of climate change on water supply-demand patterns in Alberta. To the best of our knowledge, this has not been accomplished by any previous studies for entire Alberta or to this extent elsewhere.
- We integrated years of experience in global data collection, compilation, and analysis of climate change models (GCMs and RCMs) that existed in multiple labs in western Canada, which is a challenging task. This data was amassed for the province of Alberta before they were applied in hydrological models for the prediction of the impacts. These data are publically available upon request and will be integrated into the GoA data repository as it becomes available.
- According to IPCC reports, in a hydrological impact study of climate change the most important sources of uncertainty may arise from, in decreasing order, the emission scenarios, climate model parameterization (particularly for precipitation), downscaling and the hydrological model parameterization. We used ensembles of multiple climate models and scenarios to predict uncertainty inherent in the predictions of impacts of climate change on water resources components.

- We are now well experienced with the application of hydrological models and assessment of water resources in various scales of study and can apply these same principles to other area in Canada and across the world (e.g. Alberta (river basin scale), Africa (continent scale), Iran (country scale), South Africa (watershed scale), etc.).
- We also aided development of the ACRU agro-hydrological model which can be used to compare the results of simulated future hydrological behavior with that of SWAT model at selected watersheds and used the result to map potential evapotranspiration and many climate indices at a high spatial resolution.
- We quantified different components of water resources availability with a sub-basin spatial and monthly temporal resolution and for multiple decades over the past and future horizons (1983-2007, 2010-2040 and 2040-2070). The predicted water components were blue water, green water, fossil water and virtual water.
- We developed an analytic element groundwater flow model to assess the implications of continued human development on groundwater levels in the province to identify areas of potential drawdown in excess of expected changes due to climate.
- We estimated groundwater recharge at the sub-basin scale using documented coefficients of annual precipitation for arid to semi-arid regions, and refining the coefficients to consider surficial geology and land cover type.
- We modelled the implication of climate change under four scenarios (RCP 2.6 and RCP 8.5 both at Downscaled and Non-downscaled grids) to frame the range of anticipated impacts due to varying atmospheric CO_2 trajectories. Results were assessed at the sub-basin as well as major basin scale to determine impacts on near-surface groundwater levels.
- We are now using the results of the SWAT model to aid in quantifying the water demand of major crops (as the largest water users), energy production, hydropower generation, urban development, forestry, and recreation.
- We relied on the excellence of our project team and are developing relevant scenarios in balancing water availability and use in Alberta.
- Based on the concept of "Integrated Water Resources Management" which considers "water as an integral part of the ecosystem and economic and social good, whose quantity and quality determines the nature of its utilization" (Gregersen *et al.*, 2007), we considered socio-economic and environmental concerns to help develop future adaptation scenarios.
- We were linked to the SWAT developer team in the US as well as to the developer of the SWAT-CUP package which an automated calibration-uncertainty analysis tool, in Switzerland. This facilitated our capability to acquire their support in adjusting technical matters to adapt the model for local specific issues.
- In the first phase of the project (Dynamics of Alberta's Water Supply, or DAWS), a substantial amount of data was collected and analyzed to explore the gaps and develop this proposal. One of our key strengths was that we, as a multi-disciplinary and integrated team, were the most capable team for using this information and providing solutions to Alberta's water challenges.
- A significant proportion of the published studies on the modelling of blue, green, and fossil water resources, as well as climate change impacts studies, have been published by our team. Thus, we are fully aware of the current state of the art of the knowledge, what is needed to

make significant contributions to our knowledge-base, where best to present them, and how best to publish them.

- The measurement technology that was developed and implemented under this project involved the first glaciological application (to our knowledge) of time-domain reflectometry (TDR) probes to monitor meltwater percolation, storage, and refreezing in the glacier snow and firn. Our summer-long TDR study on Haig Glacier in 2015 gave us new insight into the reductions and delays in meltwater runoff associated with meltwater retention and refreezing on the glacier (Samimi and Marshall, in press).
- The ACRU-HYDAT Streamflow Verification Tool was developed to verify the simulated streamflow against observed streamflow data from the Water Survey of Canada. This tool also contains a variety of statistical as well as graphic analysis used in hydrological studies. It contains standard regression statistics such as regression coefficient (slope), the regression intercept, Pearson's correlation coefficient (r) and coefficient of determination (r^2). These also included dimensionless statistics such as index of agreement (d), Nash-Sutcliffe efficiency (NSE), and their modified versions. It is also important to include error index statistics such as root mean square error (RMSE), percent bias (PBIAS), the ratio of the RMSE to the observed standard deviation (RSR), the percent differences between simulated and observed variances, standard deviations, and means. Graphical techniques were included such as analyzing hydrograph and flow duration curves.

2.3 Method

This project combined different model chains to explicitly estimate the impact of global climate variability and change on different components of water resources availability including blue, green, and fossil water as well as water use/demand of different sectors (energy production, agricultural production, forestry, urban development, and recreation) over time and space (Figure 2). This required a broad compilation and analysis of climate variables (i.e. precipitation, temperature, wind speed, relative humidity, solar radiation, etc.) predicted by different Global Climate Models, also known as General Circulation Models (GCMs) and Regional Climate Models (RCMs) of Canada. The GCMs are suspected to represent climate change at global accuracy and therefore they need to downscale to local climate conditions. The impact on blue and green water supply and the risks associated with the dead sectors (i.e. Agriculture, oil and gas, industry, municipality and others) was quantified to assess the likely pressure on blue and green water resources availability in the past and future, taking demographic change into consideration. Physical and economic consequences of the climate change on irrigated and rainfed crops were investigated. We have built on this innovative coupling in the estimation of sustainable future production potentials, and will thus be able to present the first high-resolution estimates of present and future water supply-demand pattern and potentials. A second methodological innovation is an estimation of spatially and temporally explicit flood-drought risks required to discuss the vulnerability to Alberta's water and economic security in the future. Finally, the project has fostered the intensification of scientific collaboration across disciplines and national boundaries.

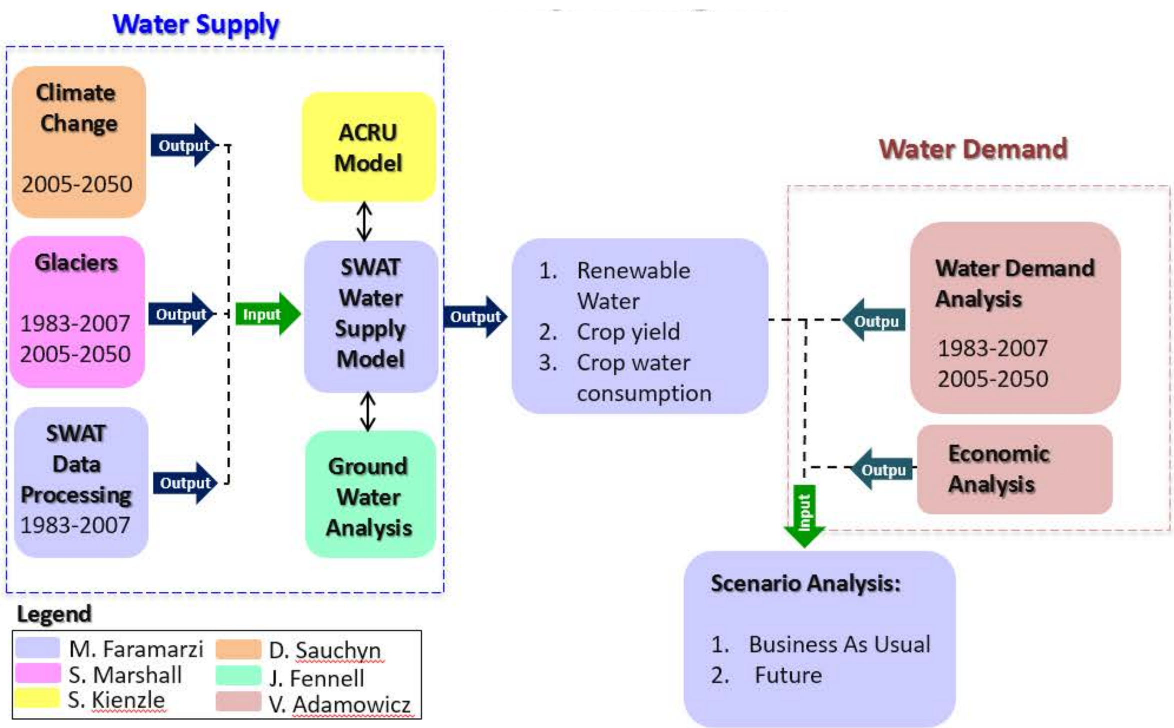


Figure 2. Schematic diagram of the working groups of the PAWF research project.

2.4 Modelling Details

2.4.1 Hydrological simulation, climate change assessment

To model Alberta's water resources, we used the hydrologic model Soil and Water Assessment Tool (SWAT) (Arnold *et al*., 1998) in combination with the Sequential Uncertainty Fitting program (SUFI-2) (Abbaspour 2007; Abbaspour *et al*., 2007) to calibrate, validate, and perform uncertainty analysis based on the available measured river discharge data. The modeled region of Alberta is shown in Figure 3. At the same time, the ACRU model was also used to support this research.

2.4.1.1 The SWAT simulator

SWAT is a computationally efficient simulator of hydrology and water quality at various scales. It is a mechanistic time-continuous model that can handle very large watersheds in a data efficient manner. The model is already used in the "Hydrologic Unit Model for the United States" (HUMUS) (Arnold *et al*., 1999; Srinivasan *et al*., 1998), where the entire U.S. was simulated with good results for river discharges at around 6000 gauging stations. This study is now extended within the national assessment of the USDA Conservation Effects Assessment Project (CEAP, http://www.nrcs.usda.gov/Technical/nri/ceap/ceapgeneralfact.pdf). A more recent large-scale SWAT application included the work of Gosain *et al*., (2006) where twelve large river basins in India were modeled with the purpose of quantifying the climate change impact on hydrology. SWAT is recognized by the U.S. Environmental Protection Agency (EPA) and has been incorporated into the EPA's BASINS (Better Assessment Science Integrating Point and Non-point Sources) (Di Luzio *et al*., 2002). This SWAT model was used to model the whole continent of Africa (Schuol *et al*., 2008a,b), and the country of Iran (Faramarzi *et al*., 2009) as well as smaller watersheds in Switzerland (Abbaspour *et al*., 2007), China (Yang *et al*., 2008), Canada (Shrestha *et al*., 2012; Seidou *et al*., 2012; Amon-Arma *et al*., 2013; Rahbeh *et al*., 2013; Trion and Caya, 2014; Fu *et al*., 2014) and many other jurisdictions around the world.

SWAT is developed to quantify the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land uses, and management conditions over long periods of time. The main components of SWAT are hydrology, climate, nutrient cycling, soil temperature, sediment movement, crop growth, agricultural management, and pesticide dynamics. In this study, we used Arc-SWAT (Olivera *et al*., 2006), where ArcGIS (ver. 9.3) environment is used for project development.

Spatial parameterization of the SWAT model is performed by dividing the watershed into subbasins based on topography. These are further subdivided into a series of hydrologic response units (HRU), based on unique elevation, soil, land use, and slope characteristics. The responses of each HRU in terms of water and nutrient transformations and losses are determined individually, aggregated at the sub-basin level and routed to the associated reach and catchment outlet through the channel network. SWAT represents the local water balance through four storage volumes: snow, soil profile (0–2 m), shallow aquifer (2–20 m) and deep aquifer (>20 m).

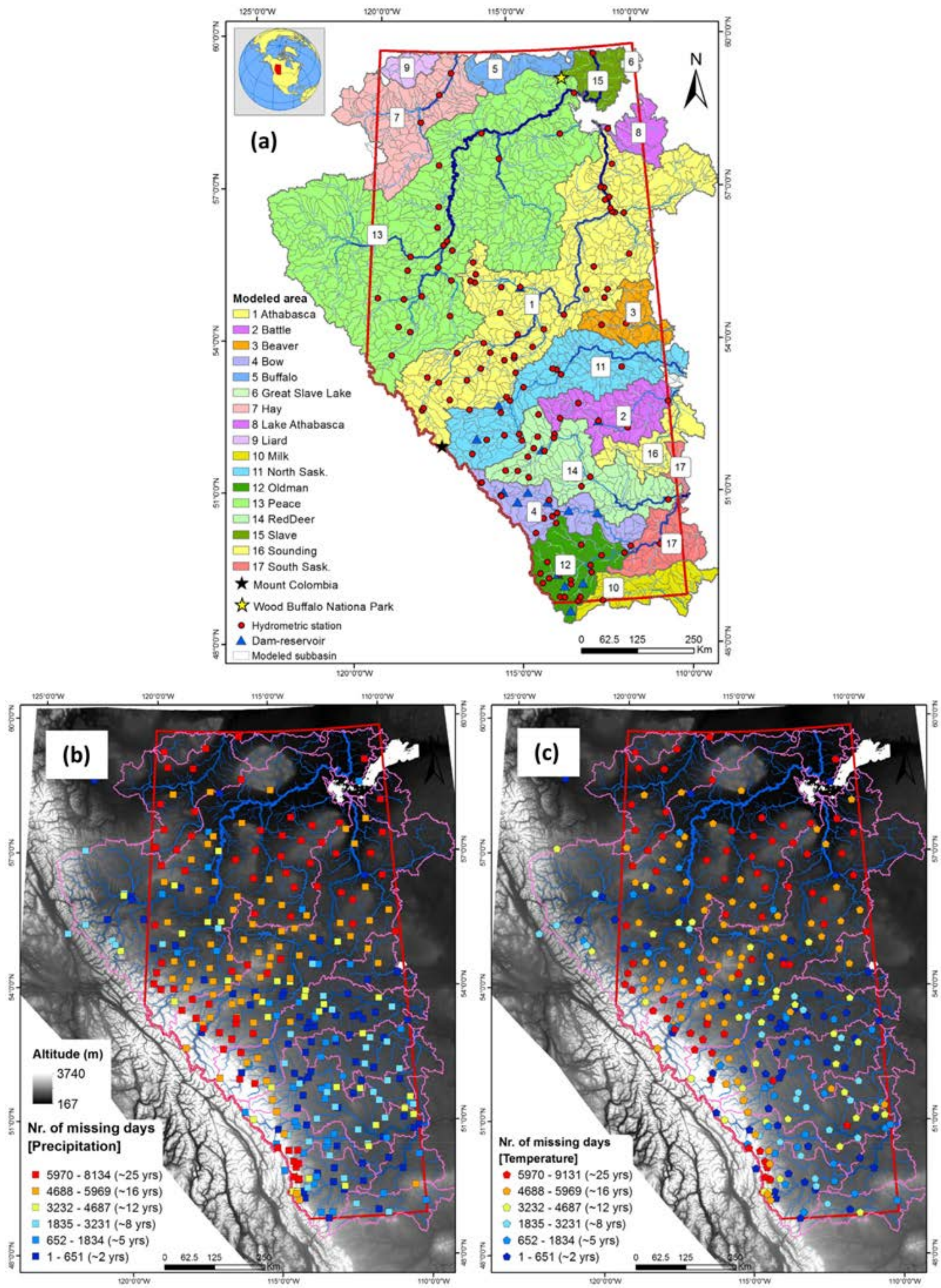


Figure 3. Map of study area presenting geographic distribution of the main river basins, hydrometric stations, dams-reservoirs and the modeled sub-basins (a); and distribution of the meteorological stations in different river basins of Alberta (b, c).
Different colors show the number of missing daily data during 1983-2007 in each station. (Source: Faramarzi *et al*. 2015)

The soil water balance equation is the basis of hydrological modelling. The simulated processes include surface runoff, infiltration, evaporation, plant water uptake, lateral flow, and percolation to shallow and deep aquifers. Surface runoff is estimated by SCS curve number equation using daily precipitation data based on soil hydrologic group, land use/land cover characteristics and antecedent soil moisture.

In this study, potential evapotranspiration (PET) was simulated using Hargreaves method (Hargreaves *et al*., 1985). Actual evapotranspiration (AET) was predicted based on the methodology developed by Ritchie (1972). The daily value of the leaf area index (LAI) was used to partition the PET into potential soil evaporation and potential plant transpiration. LAI and root development were simulated using the "crop growth" component of SWAT. This component represents the interrelation between vegetation and hydrologic balance. A more detailed description of the model is given by Neitsch *et al*., (2002).

2.4.1.2 The calibration program SUFI-2

The program SUFI-2 (Abbaspour 2007; Abbaspour *et al*., 2007; Abbaspour *et al*., 2004) was used for a combined calibration and uncertainty analysis. Inherent uncertainty in hydrological model outputs are associated with: (i) input (e.g., rainfall, temperature); (ii) the conceptual model by process simplification or by ignoring important processes (e.g., glacier melts, operation of large dams and reservoirs, potholes, irrigated agriculture); (iii) geo-spatial model parameters (non-uniqueness); and (iv) measured data (e.g., discharge used for calibration). SUFI-2 maps the aggregated uncertainties to the parameters, and aims to obtain the smallest parameter uncertainty (ranges). The uncertainty is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% (L95PPU) and the 97.5% (U95PPU) levels of the cumulative distribution obtained through Latin hypercube sampling. Starting with large but physically meaningful parameter ranges that bracket 'most' of the measured data within the 95PPU, SUFI-2 decreases the parameter uncertainties iteratively. After each iteration, new and narrower parameter uncertainties are calculated (Abbaspour, 2007), where the more sensitive parameters find a larger uncertainty reduction than the less sensitive parameters. In deterministic simulations, output (i.e., river discharge) is a signal and can be compared to a measured signal using indices such as R^2, Root Mean Square Error (RMSE), or Nash-Sutcliffe Efficiency (NSE). In our stochastic simulations where predicted output is given by a prediction uncertainty band instead of a signal, we used two different indices to check the performance of our 95PPU: the P-factor and the R-factor (Abbaspour, 2007; Abbaspour *et al*., 2004). These indices were used to quantify the strength of calibration and uncertainty measures. The P-factor is the percentage of measured data bracketed by the 95PPU. As all correct processes and model inputs are reflected in the observations, the degree to which they are bracketed in the 95PPU indicates the degree to which the model uncertainties are being accounted for. The maximum value for the P factor is 100%, and ideally, we would like to bracket all measured data, except the outliers, in the 95PPU band. The R-factor is calculated as the ratio between the average thickness of the 95PPU band and the standard deviation of the measured data. It represents the width of the uncertainty interval and should be as small as possible. R-factor indicates the strength of the calibration and should be close to or smaller than a practical value of 1. As a larger P-factor can be found at the expense of a larger R-factor, often a trade-off between the two must be sought.

2.4.1.3 Calibration setup and analysis

Sensitivity, calibration, validation, and uncertainty analysis were performed for the hydrology using river discharge data of 130 hydrometric stations in the province. As SWAT model involves large number of parameters, a sensitivity analysis was essential to identify the key parameters across different hydrologic regions. For the sensitivity analysis, 31 parameters integrally related to stream flow (Liu *et al*., 2008; Levesque *et al*., 2008; Holvoet *et al*., 2005; White and Chaubey, 2005; Abbaspour *et al*., 2007a; Faramarzi *et al*., 2009) were initially selected (see Faramarzi *et al*., 2016). We refer to these as the 'global' parameters. In a second step, these global parameters were further differentiated by main river basins to account for spatial variation in climate and management conditions (i.e., SCS curve number CN_2 of agricultural areas was assigned differently in Beaver River Basin from that of Milk River Basin areas; see Faramarzi *et al.*, 2016). This resulted in 1402 scaled parameters.

As different calibration procedures produce different parameter sets (Abbaspour *et al*., 1999; Abbaspour *et al*., 2007a; Schuol *et al*., 2008b; Yang *et al*., 2008), we used two different approaches here for a comparison of observed and simulated discharge data to provide more confidence in the results.

2.4.1.4 Input data

SWAT can run on different ranges of data availability. Clearly, the more the input data the better will be the output results. Table 1 and Table 2 summarize list of data used to develop and calibrate SWAT model of Alberta and to assess water supply-demand pattern in the province (see Faramarzi *et al*., 2015 and 2016).

Table 1. Input data sources used in the study to build and calibrate hydrological model of Alberta.

Dataset	Reference	Description
Digital elevation model (DEM) (m)	(Jarvis *et al.*, 2008)	From the Shuttle Radar Topography Mission of 90 m resolution
land use-land cover	http://www.geobase.ca/geobase/en/data/landcover/csc2000v/description.html	From the GeoBase Land Cover Product; 30 m resolution; the map distinguishes 36 landuse classes for Canada and 23 classes for our study area; the land use parameters were obtained from the SWAT user database and calibrated for more accuracy
Soil map and related physical properties	http://sis.agr.gc.ca/cansis/nsdb/slc/index.html	From Agriculture Agri-Food Canada, Soil Landscapes of Canada V3.2; map which represents more than 90 soil classes for our study area
precipitation (mm)[(a)]	http://climate.weather.gc.ca/	Daily data are collected for 300 meteorological stations (Fig. 1c)
Min/max temperature, humidity, wind speed, and solar radiation *		Daily data from the National Centers for Environmental Prediction's Climate Forecast System Reanalysis (CFSR); 0.3 degree resolution
Lakes, impoundments and potholes	(AAFC, 2012)	From the Prairie Farm and Rehabilitation Administration (PFRA) - Agriculture Agri-food Canada (AAFC, 2012). PFRA provides map of noncontributing areas at watershed level (Fig.1b)
dams/reservoirs outflow (m^3 sec^{-1})[(a)]		Daily data from the Alberta Environment Sustainable Resource Development (AESRD)
Glacier's area	http://www.glims.org/	From the map of glaciers From the Global Land Ice Measurement From Space (GLIMS)
Streamflow (m^3 sec^{-1})[(a)]	http://www.ec.gc.ca/rhc-wsc/	Daily data from the Environment Canada; data were collected for 130 hydrometric stations
Wheat yield (ton ha^{-1})	Agricultural Financial Services Corporation (AFSC)	Yields are distinguished for rainfed and irrigated crops at county scale
Planting/harvesting dates,ET (mm day^{-1})	http://agriculture.alberta.ca/acis/imcin	GOA (2011), McKenzie *et al.* (2011), Alberta Agriculture and Forestry (AAF)
Fertilizer (ton ha^{-1})		GOA (2004)
Irrigation districts (map)	http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr12911	From the Alberta Agriculture and Rural Development; and Statistics Canada

Table 2. Input data sources used to estimate water consumption of various sectors in Alberta.

Dataset	**Reference**	Description
Water consumption of the irrigated crops	ABENV (2007) http://www.assembly.ab.ca/lao/library/egovdocs/2007/alen/164708.pdf	Actual water use data are estimated, which is different from licensed data and allocation.
Per capita livestock water consumption	ABENV (2007)	-
Livestock population	http://www.statcan.gc.ca/eng/ca2011/index	Data are from 2011 Census of Agriculture (2014)
Per capita water use of municipality	ABENV (2007)	-
Population	http://finance.alberta.ca/aboutalberta/population-projections/index.html	The most recent projections of Alberta Treasury Board and Finance (2014), which are provided for Alberta's 19 census divisions (CDs). The CD data were interpolated for each river basin based on the area of each CD relative to the area of the river basin.
W/O ratio of in situ oil sand production	http://www.oilsandsreview.com/statistics/datasets.asp	Oil Sands Review datasets (2014)
W/O ratio for mining production	Canadian Association of Petroleum Producers (CAPP)	-
Water use of the gas and petrochemical	ABENV (2007)	20.6 percent of water use in the petroleum sector
Water use of the commerce	ABENV (2007)	Alberta Environment, commerce sector includes parks, recreation, golf courses, aggregate washing.gardening, food processing activities.
Water use of the industry	ABENV (2007)	industry sector consists of forestry, chemical plants, and fertilizer plants
Water use of the other	ABENV (2007)	Other sector is presented by water use of water management and environment conservation projects.
Licensed water well data	http://aep.alberta.ca/water/reports-data/alberta-water-well-information-database/default.aspx	Alberta Water Well Inventory Database
Municipal water use	Environment Canada (2011): https://www.ec.gc.ca/doc/publications/eau-water/COM1454/survey2-eng.htm.	2011 Municipal Water Use Report – Municipal Water Use 2009 Statistics, accessed September 12, 2015.

2.4.2 Glacier model development

The "glacier" working group (see Figure 1) developed new methods of modelling glacier response to climate change in the Canadian Rockies. Specifically, they developed a new parameterization of incoming longwave radiation, something that is seldom measured (Ebrahimi and Marshall, 2015), and they used this as well as climate reanalyses to introduce a perturbation method to model the distributed surface energy balance over the glaciers (Ebrahimi and Marshall, 2016). Energy balance physics, combined with a model of surface albedo evolution, provide the best possible estimate of daily snow and ice melt but are difficult to apply because of the detailed, high-elevation meteorological fields that are required. There are no long-term climate stations in the mountains and climate models do not resolve the glacier. Their method uses a perturbation approach to estimate meteorological fields and their changes in time (past and future). They have applied this on Haig Glacier for the historical period, using NARR climate reanalyses, and for future projections using GCM runs for the 21st century. Ongoing work is extending this across all the Canadian Rockies, for regional-scale glacier runoff scenarios (Marshall *et al*., in preparation). They are completing this work with climate model forcing from the best-performing NAARCAP simulations, as recommended by D. Sauchyn's PAWF research.

2.4.3 Basin yields and climate trends

2.4.3.1 ACRU model

ACRU is a catchment scale hydrologic model that was used in this study to enhance our understanding of the small-scale (detailed) hydrologic processes in southern Alberta. The automation of various data processing procedures was crucial in the ACRU model construction. Since the ACRU model required daily time-step input, all hydro-climatological input files were pre-processed accordingly. This involved assembling the observed hydro-climatological input time series to incorporate the following daily climate variables: relative humidity, sunshine hours, wind speed and solar radiation variables into the 100 km^2 resolution climate grids. It also involved the development of a GIS-based utility to facilitate and standardize the delineation of hydrological response units (HRUs) for the Oldman Reservoir Watershed. The calculation of correction factors was also required for precipitation, solar radiation, sunshine hours, relative humidity and wind speed, in order to transfer average data values from the 100 km^2 resolution climate grids to the much smaller HRUs. Before the application of the ACRU model is undertaken, two bias-corrected Regional Climate Model (RCM) time series were further downscaled to the existing 100 km^2 resolution grids and properly formatted for the ACRU model.

2.4.3.2 ACRU Hydro-Climatological Data File Generation

The original version of the Daily 10 km Gridded Climate Dataset from 1950-2010 (AAFC, 2008) contained climate information such as daily maximum temperature (°C), minimum temperature (°C) and total daily precipitation (mm), (Hutchinson *et al*., 2009), which was further improved by Hopkinson *et al*. (2011). The spatially interpolated surfaces for solar radiation, sunshine hours, relative humidity, and wind speed have been appended to the original data for the entire province of Alberta. The revised dataset now contains additional 4 hydro-climatological variables: solar radiation (MJ m-2 day-1), sunshine hours (hr day-1), relative humidity, and wind speed (km day-1) for the calculation of Penman-Monteith (Penman, 1948). This tool compiles seven variables for each 10km climate grid in an ACRU specific file format. Before compiling all seven variables into an ACRU formatted input file, it was important to create a spatially interpolated climate data surface pertaining to relative humidity, sunshine hours and wind speed. This process was automated by utilizing the ArcPy modules through Microsoft© Excel graphical user interface.

The following outlines the procedures used for this tool:

1) The Zonal Statistics tool is initiated using ArcPy module for each spatial data for 12 months. There should be 48 DBF files found in the folder at the end of this step (one for each of the four variables and each month).
2) The Fourier Transformation method is applied using the Harmonic Analysis tool in order to transform the observed 12 monthly values into daily values. This tool uses the original ACRU Fortran77 code. Therefore, no changes were made to code during this project.
3) Calculations are saved in an unformatted output, as a .TXT file.
4) Composite File subroutine is initiated to format the .TXT file into the appropriate ACRU input file.

2.4.3.3 RCM Downscaling for ACRU Simulations

All the regional climate model data have two datasets: one historical period ranging from 1971-2000 and one future period ranging from 2041-2070. The regional climate model data have spatial resolutions of 22 to 44 km^2. One of the requirements to effectively use the RCM projections is to spatially match the observed data's spatial resolution. Essentially, the reasons for matching the spatial resolution of the observed 10K climate grid time series are to replicate (a) the seasonality and magnitude of the 1971-2000 climate normal streamflow behaviour, (b) the use of the established parameter input files for the historical and future RCM simulations, and (c) enable the comparison of all future RCM projections. Since the regional climate model data and hydro-climatological data are available in spatially separated time series, it was important to spatially downscale the regional climate data using an area-weighting ratio based on the spatial overlay of the 10K climate grids and the RCM climate grids (see Figure 4).

The following outlines the procedure for downscaling each of the regional climate model datasets:

1) The 10K climate gridded dataset and the RCM grid file are spatially overlaid.
2) The area for the 10K climate grid and the RCM grid files are calculated.
3) The average for each temperature (minimum and maximum) and precipitation for the 10K climate grid are calculated by spatially overlaying the PRISM grid with the respective RCM

grid, resulting in spatially averaged grids for determination of correction factors (variable P10K-i and T10K-i,with i=1-12).

4) The 1971-2000 mean RCM precipitation and temperature were calculated for each month (variable PRCM-i and TRCM-i with i=1-12). The ArcGIS© Zonal Statistics as Table tool is run for each month and each variable on both spatial data (e.g. 12 months for each maximum temperature, minimum temperature, and precipitation) for each regional climate data.
5) The climate grid spatial data and regional climate grid spatial data are permanently joined. The ArcGIS UNION command results in a spatial overlay containing both input grids, and containing all associates data.
6) Any polygons that were not part of the spatial overlay are deleted. You can distinguish these polygons from the rest when the column contains a value of 0.
7) The monthly precipitation ratio and temperature differences between the RCM value and the 10K-grid based value are calculated as follows:
   Pratio-i = P10K-i / PRCM-i
   Tratio-i = T10K-i - TRCM-i
8) The area of the union polygons in meters squared and the percent area are calculated as follows:
   PperArea = PareaUNION / PareaRCM-i
   TperArea = TareaUNION /TraareaRCM-i
9) The percent ratio is calculated as follows:
   PperRatio = PperArea * Pratio-i
   TperRatio = TperArea + Tratio-i
10) The RCM-based daily precipitation time series (PRCM) and daily temperature time series (TRCM) for each 10K climate grid are calculated using the equation:
   PRCMcorr = PRCM * Pratio-i
   TRCMcorr = TRCM + Tratio-i

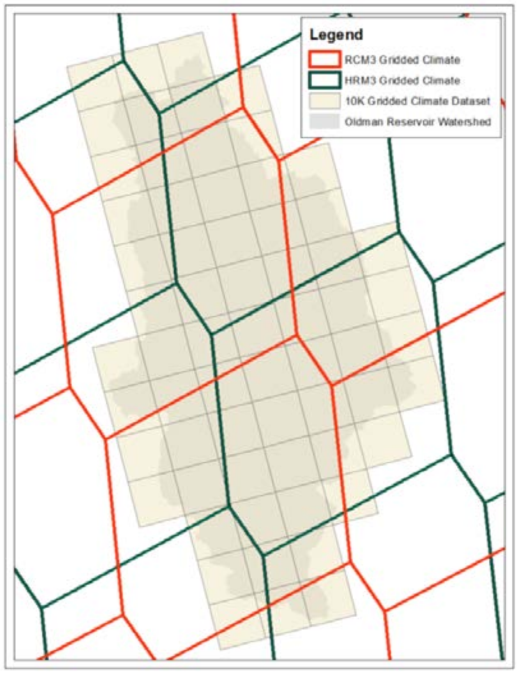


Figure 4. Two regional climate data: 1) HRM3 (warmer/drier) climate projection driven by GFDL and 2) RCM3 (cooler/wetter) climate projection driven by CGCM3.

2.4.3.4 ACRU Parameterization

The development of parameterization utility tools was a crucial step in creating an efficient model parameterization for any ACRU model user. The previous version of the modelling system had the ACRU MenuBuilder program, an interactive and user friendly program that allowed user prompts for direct information input on the parameter file called MENU (Smithers & Schulze, 1995). It operated independently of the ACRU model and contained 250 subroutines. The original MenuBuilder was rather a teaching tool than an operational tool, as data input was very time consuming, and filling in data for more than a few HRUs was not practical. When the ACRU model was adapted to include snowmelt routines and a range of other new variables a combination of spreadsheet (Excel) and Textpad software approach was used to manipulate the MENU file. Each variable needed to be filled in by the user for all HRUs at a time. The next sub-sections will discuss the procedures used to create the new model parameterization utility tools, which allows for a significantly faster, and automated creation of the MENU file.

The newly developed ACRU MenuBuilder v2.0 program enables the seamless manipulation of the MENU file without having to manually manipulate the file. The manual manipulation of the MENU file typically takes several minutes to set-up for each variable, one variable at a time. It already required testing the file against the ACRU model, to check whether the MENU file has not lost its fixed format, a limitation ushered by the original fixed-format Fortran code. The new utility tool enables a much more seamless approach to model calibration and parameterization of the ACRU model. The selection of a new parameter set is obtained by changing the parameter values in the menu input parameter (MIP) file. Once the Fortan script was called, the task of manipulating the MENU file was completed within a few seconds. Essentially, overcoming this challenge means that the calibration of the ACRU model is now possible for larger watersheds, especially with more than a thousand hydrological response units. The ACRU model parameterization is far more efficient, thus allowing more calibration runs, and consequently better simulation results within a given time frame. The Microsoft Excel© spreadsheet is utilized for the MIP file, instead of relying on other software (e.g. R, SPSS, MATLAB). This leads to a reduction of training of the ACRU model user. For accuracy purposes, the Microsoft Excel© macro calls the initialization and parameterization scripts and contains a log file system used to verify the parameterization process.

The following outlines the procedure for the automated initialization and parameterization of the variables for this study:

1) An empty MENU file is created with X number of hydrological response units.
2) The MIP file is initiated with X number of rows.
3) All parameters that need to be initialized once are defined using the MENU_INIT worksheet (e.g. area of HRU, slope of HRU, land cover code, associated climate file name, etc).
4) The Fortran initialization script is initiated using the Microsoft Excel© macro. The initialization script adjusts 46 parameters all at once.
5) Specific calibration parameters are defined using MENU_PARAM worksheet (e.g. flow routing parameters for surface and groundwater flows, soil depth, snow melt variable, and many more), which may be required to change more than once. Typically, parameters are updated one parameter at a time for manual calibration.
6) The parameterization script based on Fortran through the Microsoft Excel© macro is initiated.

2.4.4 Economic analysis

We estimated a yield response function by specifying a fixed-effect panel model as follows:

$$Y_{ijt} = \beta_{i0} + \beta_{i1}\theta_{ijt} + \beta_{i2}\tau_{ijt} + u_{ij} + \varepsilon_{ijt} \qquad (1)$$

where Y_{ijt} is the annual yield of crop i in county j during year t, θ and τ are vectors of climate variables and time trends, respectively, β_{i0} β_{i1} and β_{i2} are parameter estimates, u_{ij} is a county-level fixed effect, and ε_{ij} is an error term. As noted earlier, the model is estimated for the period from 1983 to 2007, for barley, canola, and spring wheat. The vector of climate variables, θ, includes measures of temperature, heat and precipitation calculated over the growing season; that is, from May to August. The length of the growing season was selected for the three crops based on the information from Alberta Agriculture and Forestry (2015). The time trend vector $\boldsymbol{\tau}$ consists of a linear and a quadratic form of time trend to capture technological progress and the improvement of agronomic practices. The county-specific effect, u_{ij}, is to reflect other time-invariant characteristics for each county such as soil quality.

Temperature and precipitation are the two common indicators of climate conditions used when estimating the climatic impacts on crop yields. A common approach in modelling temperature effects on crop yields is to use average temperature for a specific period (e.g., Cabas *et al*., 2010 and Cohn *et al.*, 2016). However, as argued by Schenkler and Roberts (2009), if temperature has a nonlinear effect crop yields may initially increase with temperature but then decrease when the temperature reaches a certain threshold. Using average temperature to study crop yields may mask the negative yield effect of extreme temperatures.

An approach incorporating extreme temperatures and based on daily growing degree days (GDD) was used to address this limitation in this study. GDD, a measure of accumulated heat, was calculated for the entire growing season from May to August by summing daily GDDs. Daily GDDs are calculated using daily maximum (T_{max}) and minimum temperatures (T_{min}) and a base temperature (T_{base}), as follows:

$$\mathrm{GDD} = \max\left(\frac{T_{max}+T_{min}}{2} - T_{base}, 0\right) \quad (2)$$

Based on Robertson *et al.* (2013) and following the approach by Miao *et al.* (2016), 5 °C was selected as the base temperature for calculating GDDs. Robertson *et al.* (2013) estimated crop yields as a function of different temperature and rainfall variables and reported critical minimum temperatures of 5 °C, 5 °C, and 5 °C for barley, canola, and spring wheat, respectively. They also reported critical maximum temperatures of 28 °C, 29 °C, and 29 °C for barley, canola, and spring wheat, respectively. Daily GDDs were calculated for days with minimum temperatures above 5 °C and maximum temperature below 29 °C. GDD was included in the yield response function both linearly and as a squared term, to allow flexibility in modelling the impact of heat on crop yields. To capture the impact of extreme (i.e., hot) temperatures on yields, an overheat degree days (ODD) for the entire growing season (from May to August) variable was defined and included in the model. ODD was calculated as the sum of daily GDDs for days with maximum temperatures above 29 °C.

Climate change not only concerns the magnitude of change in temperature but also the degree of temperature variability. Crop yields are affected by intra-annual temperature variability (McCarl *et al.*, 2008; Miao *et al.*, 2016). We therefore included monthly temperature deviations as explanatory variables. For each month in the growing season, this was calculated as the difference between average monthly maximum temperature and average monthly minimum temperature.

In the case of precipitation, not only the amount but also the timing of growing season precipitation is important. Thus, instead of seasonal total precipitation, monthly cumulative precipitation variables were defined and used in the model to capture the impact of timing of seasonal variation and seasonal shift in precipitation on crop yields.

For some cases, there are both irrigated land and rainfed land within a county. Due to data availability, we were not able to identify the locations of rainfed and irrigated land within a county. Therefore, we use a same set of climate variables for both irrigated and rainfed lands in a county.

Annual county-level crop yield data for barley, canola, and spring wheat were obtained from Agriculture Financial Services Corporation (AFSC) for the period from 1983 to 2007. The daily historical climate data (i.e., precipitation, maximum and minimum temperature) were obtained from the study by Faramarzi *et al.* (2015), where an extensive qualification of climate data was conducted using the Soil and Water Assessment Tool (SWAT), a process-based crop growth and a hydrology model. The study tested various climate time series from different sources (e.g., recorded data of meteorological stations, gridded data of regional, national and global models) to examine hydrological and crop simulation response of the input data. The authors used a data discrimination approach to find time series of locally representative temperature, precipitation, and other hydrological data at the sub-basin scale.

Projected values of daily climate data for two future periods (2010-2040 and 2040-2070) obtained from the Pacific Climate Impacts Consortium (PCIC, 2014; Cannon, 2015). The PCIC provides statistically downscaled Canada-wide climate data of the IPCC Coupled Model Inter-comparison Project (CMIP5) for precipitation, minimum and maximum temperature at a resolution of 300 arc seconds (~10 km). In this study, we used the widely accepted 'change factor' approach (Chen *et al*., 2011), to downscale the PCIC dataset based on the historical (1980-2010) climate data of Alberta (Faramarzi *et al*., 2015). The data were downscaled for two extreme scenarios of the IPCC Representative Concentration Pathways (RCP) (IPCC, 2014) including of RCP25 and RCP85.

A Wooldridge test (Wooldridge, 2002) was used to test for serial correlation. We failed to reject the null hypothesis of no autocorrelation for all specifications except canola on irrigated lands. We also used a Modified Wald test (Greene, 2000) to test for groupwise heteroscedasticity in a fixed effects model. The null hypothesis of homoscedasticity was rejected at the 1% level for all barley, canola, and spring wheat specifications. To account for the effects of serial correlation and heteroscedasticity, we used robust standard errors clustered at the county level (Hoechle, 2007).

2.5 Results of Model Simulations

2.5.1 The SWAT Model

One hydrological model of Alberta using SWAT to: (1) simulate detailed water supply processes including hydrology and irrigated agriculture; and to calibrate and validate the model using monthly hydrometric data from 130 stations and irrigated wheat yields of 13 irrigated districts is called SM1 (Figure 5; see Faramarzi et al., 2016). In this scenario model (SM1) we provided prediction uncertainty in the assessment of water supply to address the errors related to heterogeneous hydro-climatic and geo-spatial conditions, diverse management practices, and scarce data in remote areas and mountainous regions.

A multi-gauge and multi-objective calibration using crop yields and river discharges in the scenario model ensured proper apportioning of precipitation and soil water into surface runoff, actual evapotranspiration, and groundwater recharge. This improved model performance as compared to pre-calibration model (Figure 5a). Overall, 63% of the observed streamflow data were captured by the simulated 95PPU and the average r-factor was about 1.04 at the Alberta scale. While the average $bR^2$of the 130 stations were 0.48, it varied from 0.11 to 0.89 for individual stations (Figure 5b). Model performance of the pre-calibration step (Figure 5a) was considerably improved after calibration (Figure 5b). Except for the head-water stations in mountainous regions, most of the observed data (p-factor > 40%) were bracketed by relatively small 95PPU values (r-factor < 1.38) (Figure 5d).

In the pre-calibration exercise, we found that in snow-dominated regions temperature was the most influential parameter to the hydrology. We found MS precipitation and the CFSR temperature data best represented the trend and fluctuations of streamflow simulation (Figure 6a–e) prior to calibration. This model, was selected as our base model (e.g., SM1) for further sensitivity and calibration analysis and the results were further improved after calibration (Figure 6b–d, and Figure 6f).

We predicted uncertainty for different stations to map the errors related to climate, geo-spatial parameters, potholes, dams, glaciers, and (fossil) groundwater contribution where the data are not adequately represented and the process are simplified in the model (Figure 7c,d). More uncertainty in the predictions partially implies poorer data quality and quantity. For example, the lack of good quality climate data for northern remote areas adds more prediction uncertainty (e.g., Figure 7d, larger r-factor). Irrigated areas in southern watersheds posed another challenge in our large-scale hydrological model. In the SWAT model, simulation of crop yield and crop ET are closely related to nutrients, climate, and soil moisture, among other factors. As we only calibrated crop yield, we compared the simulated crop ET against available data from AAF to increase confidence on simulated crop ET. As shown in Figure 7g, h, most of the AAF data are bracketed within our simulated 95PPU. Similar to other output variables, the prediction uncertainty in irrigated wheat yield ensured an adequate representation of the errors related to model simplification, geo-spatial parameters, and other data affecting crop growth (Figure 7e,f). It is imperative to note the importance of uncertainty analysis in a distributed model, as it highlights the areas of data gaps and model process limitations. Our findings clearly provide direction for future data collection and model development attempts. We applied our calibrated validated model to assess water supply-demand pattern in the province (Figure 8). Using our subbasin-based monthly water supply data and water demand of various sectors, we found permanent water scarcity in some months of the southern river basins in Alberta. We showed that Accounting for Environmental flow requirement (EFR) to maintain excellent, good, and moderate levels of habitat quality, increases the number of months of water scarcity and the population exposed (Figure 9, and Figure 10).

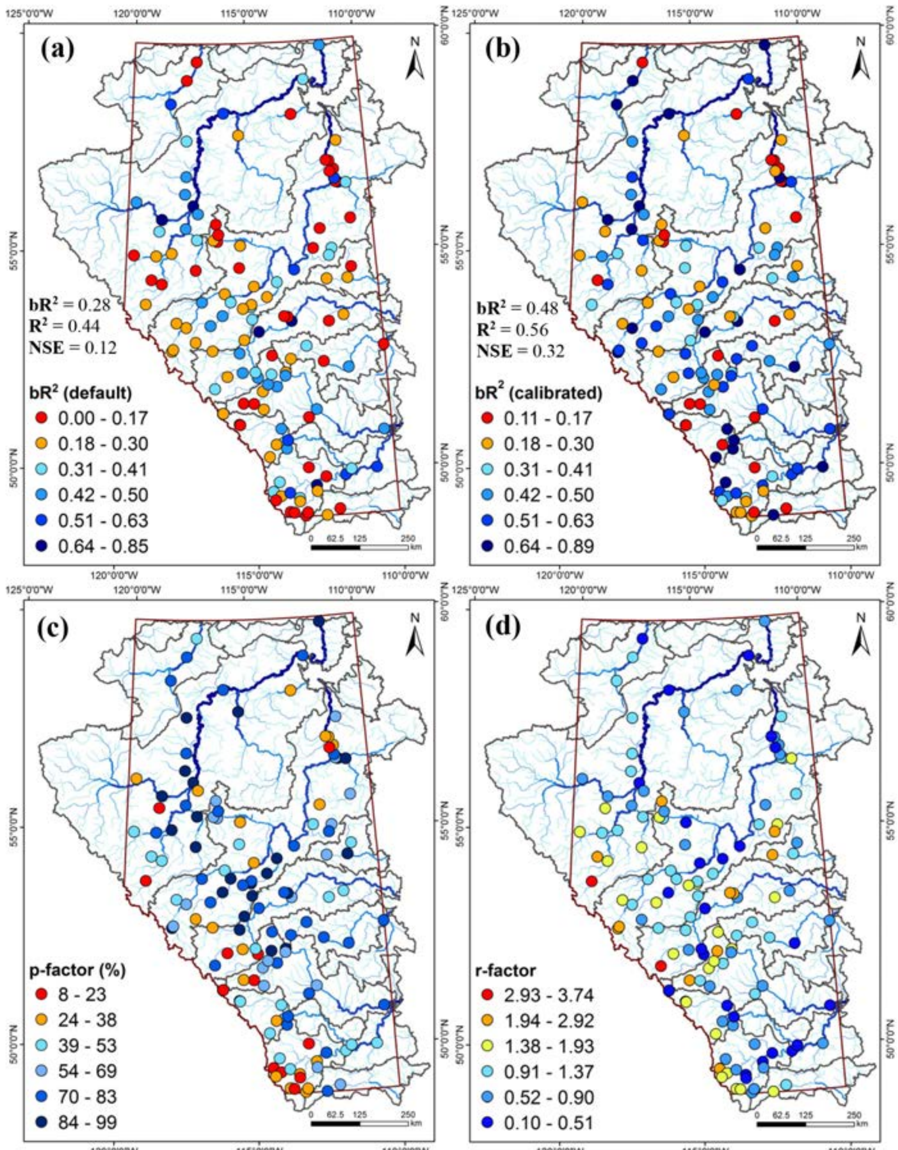


Figure 5. Model performance of pre-calibration (a), and post-calibration (b) at 130 hydrometric stations; and calibration-uncertainty performances including the p-factor (c) and the r-factor (d).
Provincial statistics (bR^2, R^2, and NSE) are provided in Figure 2a-b legend for the evaluation of model improvement. (Source: Faramarzi *et al*., 2016)

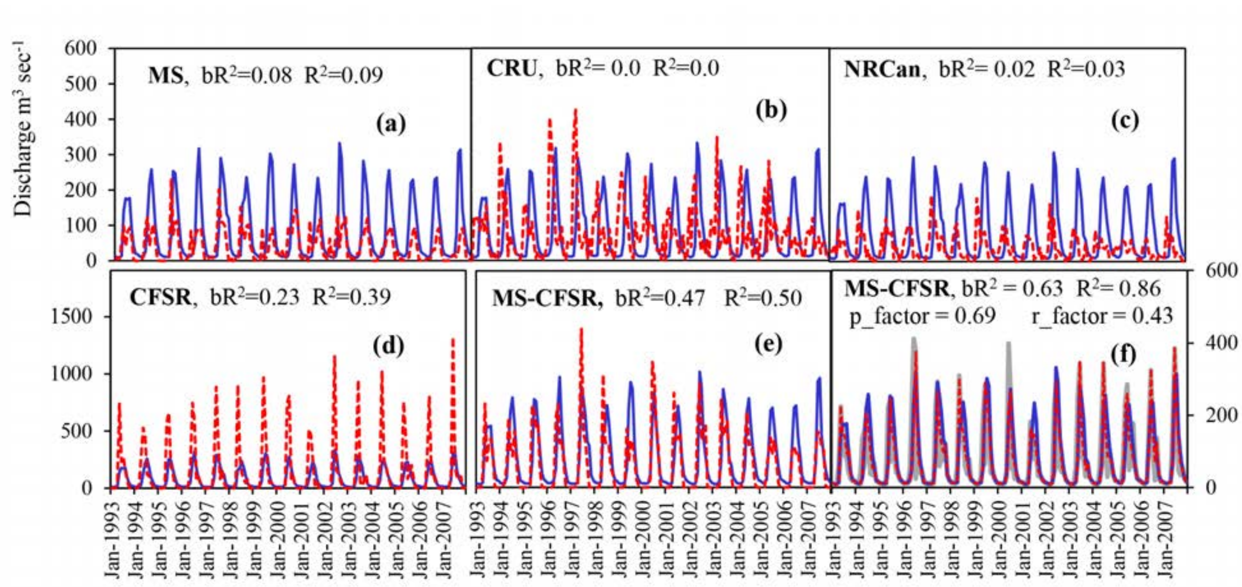


Figure 6. Observed (blue) and simulated (red) streamflow at Athabasca near Jasper station (drainage area of 386 km^2), located at one of the head-water tributaries of Athabasca River Basin and influenced by snow melt and glacier runoff, using different climate datasets. The gray band (f) is the 95% prediction uncertainty. (Source: Faramarzi *et al*., 2016)

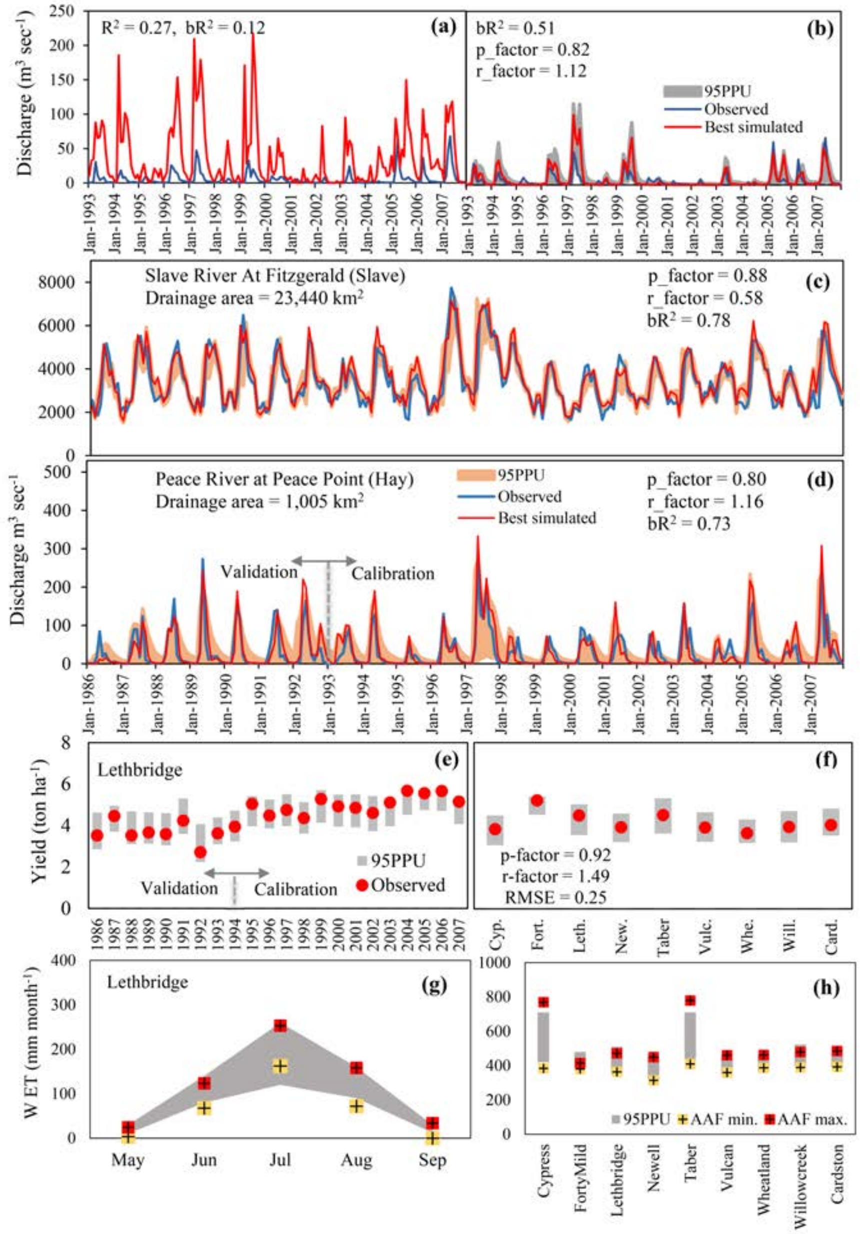


Figure 7. Calibration, validation and uncertainty results: observed and simulated streamflow for a selected station in Battle River (drainage area of 2598 km^2) without pothole (a) and with pothole (b); observed and simulated discharges for two selected hydrometric stations in different river basins (c,d).

The best simulation (red line) maximized the objective function and was used to narrow the uncertainty band in subsequent iterations; observed and simulated (95PPU) annual wheat yield of Lethbridge county (e) and the average annual yields of different provinces (f); and the observed (AAF) and simulated (95PPU) of the monthly wheat ET (WET) in Lethbridge (g); and total ET in different counties (h) over the years 1986–2007.

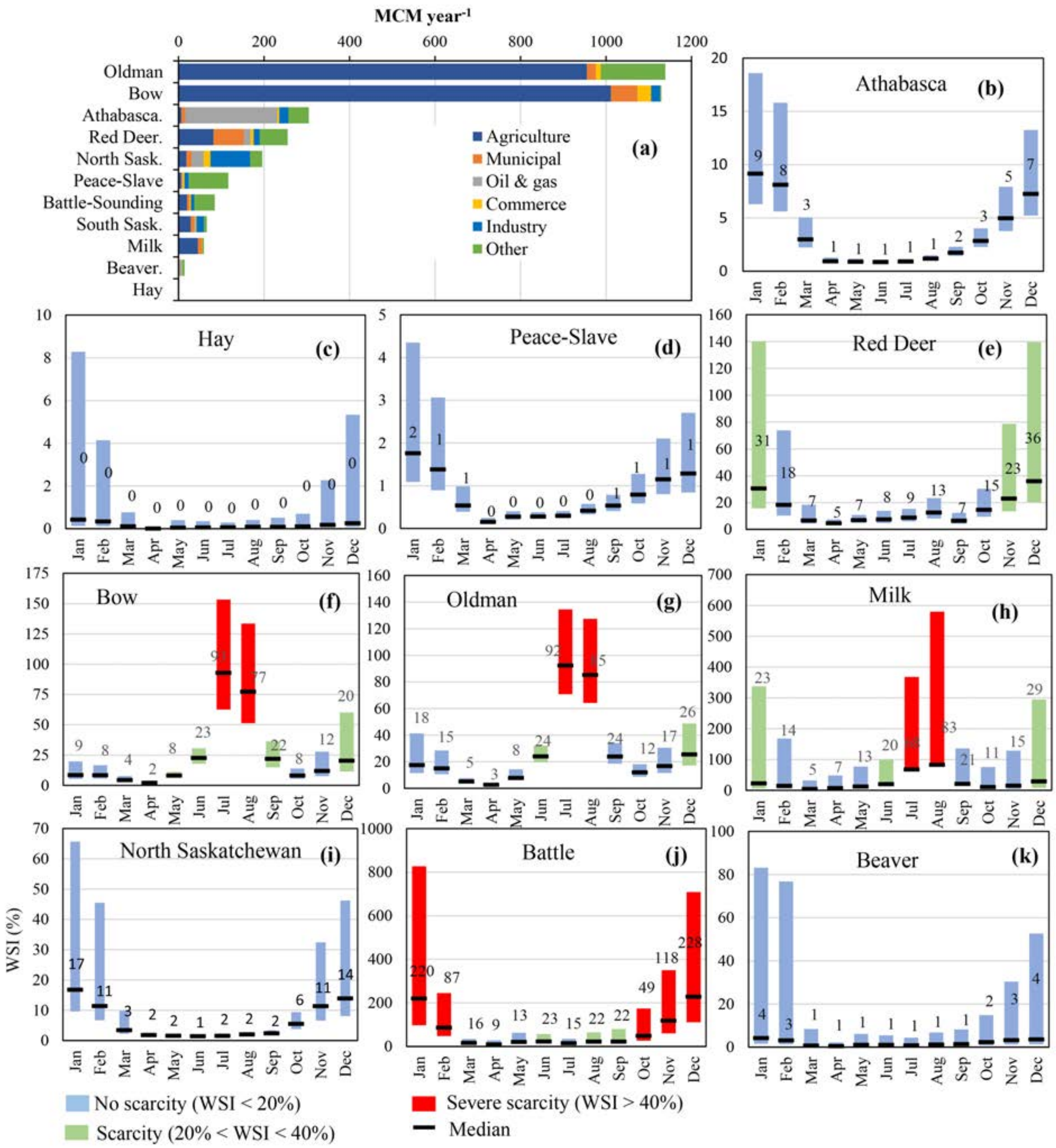


Figure 8. Estimated water use of different sectors (a), and computed monthly water scarcity indicators (b–k) for different river basins.
The WSI calculated as the ratio of water consumption to simulated renewable blue water resources (RBWR). The range is related to the use of L95PPU-RBWR and U95PPU-RBWRin the ratio. The colors, depicting severity of the scarcity, are specified based on the median of simulated RBWR (Source: Faramarzi *et al*., 2016).

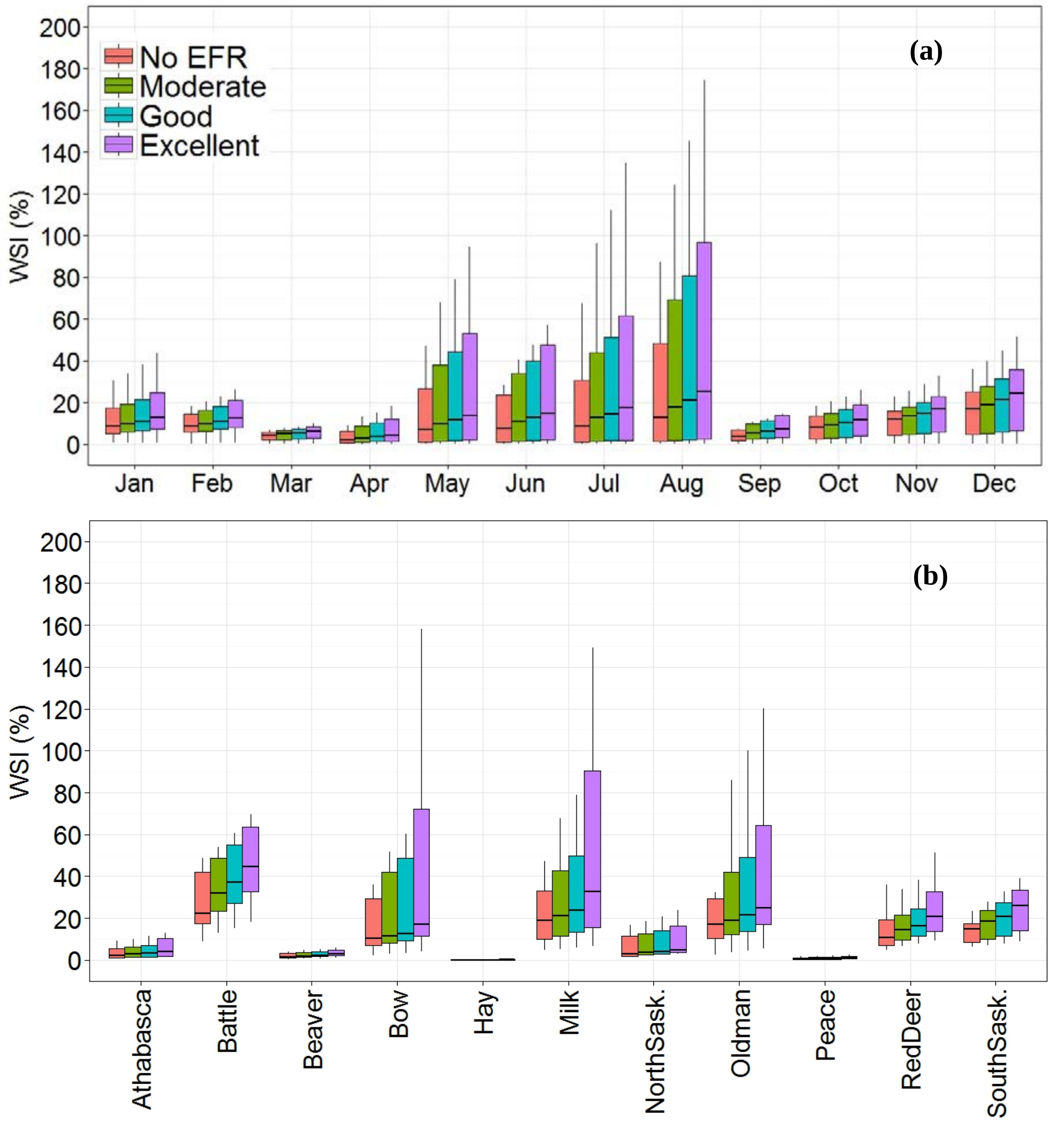


Figure 9. Comparison of water scarcity indicator computed under no EFR and various EFR scenarios in the province (2) and in different river basins (b).
Box plots were created using the long-term average median of the monthly WSI of different river basins (Source: Faramarzi *et al.*, 2016).

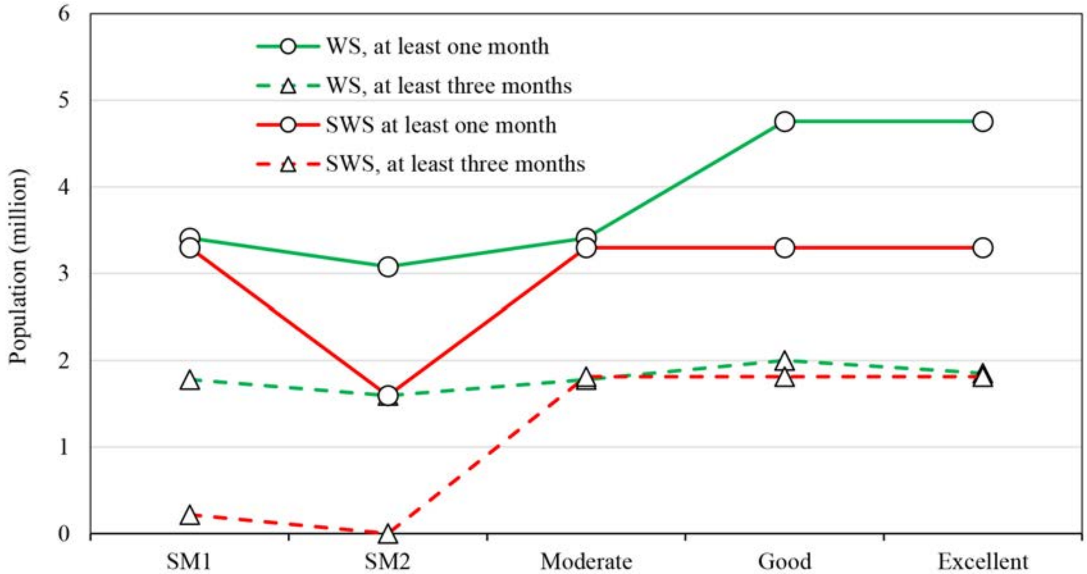


Figure 10. Comparison of the estimated population size exposed to different levels of water scarcity under various scenario models.
WS: Water Scarcity; SWS: Severe Water Scarcity (Source: Faramarzi *et al*., 2016).

2.5.2 Assessment of water yield

For the Castle River Watershed, ACRU was first calibrated for the period 1971-1980, which includes both very low and very high flow years, and has an average runoff similar to the entire 1950-2010 period. The runoff simulations were then validated for the 1971-2000 period, which is the period for which streamflow using the Regional Climate Models (RCMs) were set up. Additional statistics were calculated for the entire 61-year period ranging from 1950 to 2010. Additional analyses to compare simulated and observed streamflow included the shape of the annual and daily hydrographs and frequency distributions of high and low flows. Verification for the Swift Current Creek Watershed followed the same procedure but used different verification periods for several stream gauges due to the availability of observed streamflow records in that watershed. Once verification analyses revealed that the ACRU parameters were representing the bio-physical and hydro-meteorological properties of the respective watersheds correctly, the parameter set could be applied to simulate the future climate projections.

Table 3. Verification statistics for the Castle River Watershed.

Objective Function	Calibration: 1971-1980	Validation: 1971-2000	Historical period: 1950-2010
Difference in MAQ (%)	4.3	3.0	-0.1
r^2	0.80	0.74	0.74
Slope	0.84	0.77	0.77
Difference in Standard Deviation (%)	-6.3	-10.0	-10.6
Nash-Sutcliffe Coefficient	0.79	0.74	0.74

Table 4 summarizes the impacts of climate change on streamflows. The Castle River Watershed is projected to produce, on average, more streamflow, while the average peak flow will decrease. This reduction in peak flow is the result of decreased snow fall and snow pack accumulations, which is the main reason for the freshet flows in the spring when the snow melts during a short period of time. This also explains the earlier occurrence of peak flows, by about a week (Table 2). The earlier peak flow is also associated with an earlier groundwater recharge event, which results in an earlier decline of groundwater discharge, and thus much lower future flows in late summer and fall (Figure 11). Low flows are simulated to increase for four RCM projections, and only the warmer/drier RCM scenario results in a decrease in low flows (Table 4). The simulated increases can be explained by the fact that more precipitation falls as rain during the winter, thus increasing runoff during the time of lowest flows (Figure 11). Overall water resources may either increase or decrease, depend on which of the RCM projections will eventually be proven to be true. It appears, however, that water supply in this watershed will likely increase in the future, which will mean sustained or potentially expanding irrigated agriculture in the greater Oldman River Basin.

Table 4. Climate change impacts on streamflow for the Castle River watershed

	Baseline (71-00)	Cooler/wetter (2041-70	Warmer/drier (2041-70)
	Castle River		
Annual Runoff (million m³/year)	461	511	492
Peakflow (m³/s)	111	109	95
Peakflow Date (JD)	143	136	138
Low Flow (m³/s)	1.6	2.2	1.3

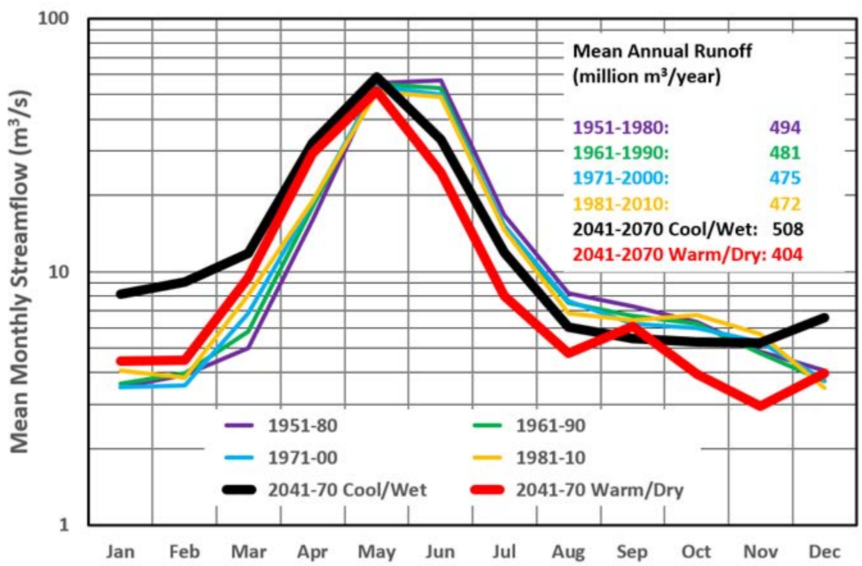


Figure 11. Mean annual hydrographs at the outlet of the Castle River Watershed for four historical and one future period, showing impacts based on two RCMs.

2.5.5 Economic analysis

The estimation results for the crop yield response models (i.e., barley, canola, and spring wheat) on rainfed and irrigated lands are presented in this section. Specifically, the relationships between yields and relevant climatic variables are highlighted. This is followed by an analysis of future climate change scenarios. These scenarios are used to simulate yields under climate change conditions.

The estimation results for crop yields are presented in Tables 5, 6 and 7 for barley, canola, and spring wheat, respectively. For each crop, four different crop yield response models are estimated; two each for rainfed (d) and irrigated (i) yields. All four versions include a common set of explanatory variables, including ODD, monthly precipitation, monthly temperature deviations, as well as a linear and quadratic time trend. The models differ in terms of the specification of GDD. In Model 1, an assumption of additive separability is made regarding the impacts of temperature and precipitation on crop yields. Thus, Models 1d and 1i for each crop include linear and quadratic GDD terms as explanatory variables. However, it can be argued that temperature and precipitation interact in terms of their effects on yield. This issue was explored by incorporating interaction terms for GDD and monthly precipitation into Model 2d and Model 2i., which replace the linear and quadratic GDD variables. Initially, the interaction terms were included with the linear and quadratic GDD variables. However, the interaction terms tended to "absorb" the yield impacts of GDD in the model results, and so the GDD variables were removed to form the final versions of Models 2d and 2i. We also tried a specification (Model 3) to include the linear and quadratic GDD variables and drop monthly precipitations instead of GDD. We examined the marginal effects to make a straightforward comparison. The numbers are very similar to the results from Model 1 and Model 2 reported in Table 5 on both significance and magnitude, which indicates our results are robust.

Table 5. Parameter estimates for barley yield response panel model.

Variables	Model 1d		Model 1i		Model 2d		Model 2i	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
GDD	1.268***	0.3671	2.845*	1.516				
GDD^2	-0.0004403***	0.0001265	-0.0008525*	0.0004402				
ODD	2.702	6.627	-19.20***	4.773	-2.224	7.009	-15.36**	6.073
May Prec.	0.3058	0.4862	-0.8970	0.5998	-2.036	1.480	12.31***	3.170
June Prec.	0.4412	0.2937	-1.872***	0.4897	-1.769*	0.925	-7.090**	2.444
July Prec.	2.610***	0.2636	-0.7686	0.7280	0.5485	1.599	-6.356	3.805
August Prec.	3.019***	0.3804	1.685**	0.7457	2.611*	1.501	-4.594	4.232
GDD X May Prec.					0.001706	0.001078	-0.008928***	0.002127
GDD X June Prec.					0.001725**	0.0007757	0.003280**	0.001591
GDD X July Prec.					0.001743	0.001228	0.003896	0.002424
GDD X August Prec.					0.0004583	0.001083	0.004728	0.002913
May Temp. Dev.	-55.23***	15.50	-73.59**	25.89	-73.69***	12.93	-76.65***	18.46
June Temp. Dev.	2.134	9.806	10.49	21.00	9.139	10.20	-2.915	16.57
July Temp.	-72.28***	10.70	-72.79***	23.17	-80.59***	11.02	-76.86***	18.47

Variables	Model 1d		Model 1i		Model 2d		Model 2i	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Dev. August Temp.								
Dev.	47.58***	9.518	45.67**	16.66	38.92***	9.039	60.54***	10.78
Time trend	12.73***	4.070	43.21***	10.79	12.98***	4.032	41.59***	12.63
Time trend squared	0.09108	0.1591	-0.6206	0.3903	0.06928	0.1624	-0.5563	0.4542
Constant	509.9***	282.4	270.3	1228	1723***	231.0	2652***	404.5
Number of obs.	674		255		674		255	

NB Model 1d and 2d are for crops on rainfed, and Model 1i and 2i are for crops on irrigated lands.
***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Robust standard errors are clustered at the county level.

Table 6. Parameter estimates for canola yield response panel model.

Variables	Model 1d		Model 1i		Model 2d		Model 2i	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
GDD	1.147***	0.1841	1.429*	0.6653				
GDD^2	-0.0003558***	0.0001000	-0.0004215*	0.0002126				
ODD	-14.80***	3.97	-17.18***	3.217	-15.93***	4.096	-14.19***	3.235
May Prec.	0.2469	0.2882	0.3226	0.2693	-1.292	1.167	6.203***	1.698
June Prec.	0.2425	0.1475	-0.6321***	0.1099	0.2324	0.9541	-0.6041	1.593
July Prec.	1.146***	0.1612	-0.8084*	0.4014	-2.601***	0.5834	-7.704***	1.578
August Prec.	1.758***	0.2494	2.362***	0.6808	1.285*	0.6600	-0.7947	2.638
GDD X May Prec.					0.001107	0.0008089	-0.003844***	0.001069
GDD X June Prec.					0.00001700	0.0006676	-0.0000770	0.001023
GDD X July Prec.					0.003024***	0.0004657	0.004873***	0.001089
GDD X August Prec.					0.0002800	0.0005007	0.002223	0.001730
May Temp. Dev.	-30.53***	6.485	-10.45	13.31	-39.11***	6.956	-14.27	10.14
June Temp. Dev.	7.225	6.578	2.978	7.119	8.841	6.840	-2.806	6.885
July Temp. Dev.	-46.94***	6.794	-14.04	8.893	-46.26***	6.819	-12.91	9.409
August Temp. Dev.	13.71***	4.899	15.65	13.65	8.564	5.315	21.09**	9.387
Time trend	-8.940***	2.515	1.095	4.614	-8.047***	2.595	0.9704	4.958
Time trend squared	0.7638***	0.09336	0.6107*	0.1377	0.7405***	0.09976	0.6286***	0.1528
Constant	76.27	157.2	-438.0	752.1	1092***	108.7	755.9**	271.6
Number of obs.	621		208		621		208	

NB Model 1d and 2d are for crops on rainfed, and Model 1i and 2i are for crops on irrigated lands.
***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Robust standard errors are clustered at the county level.

Table 7. Parameter estimates for spring wheat yield response panel model.

Variables	Model 1d		Model 1i		Model 2d		Model 2i	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
GDD	1.030***	0.2820	2.910*	1.384				
GDD^2	-0.0003243***	0.0001013	-0.001011**	0.0004188				
ODD	-15.20***	5.246	-15.32*	6.868	-15.66***	5.073	-13.32	7.493
May Prec.	1.348***	0.3350	0.2726	0.7985	0.9684	0.9447	14.28***	3.821
June Prec.	0.8724***	0.2413	-0.8382*	0.4080	-0.8816	0.6057	-1.710	1.645
July Prec.	2.019***	0.2322	-0.9420	0.7268	-0.8442	0.9382	-16.61**	5.476
August Prec.	2.085***	0.3065	1.772	1.088	2.931**	1.193	8.444	6.158
GDD X May Prec.					0.0002514	0.0007078	-0.008934***	0.002161
GDD X June Prec.					0.001313***	0.0004378	0.0003477	0.001153
GDD X July Prec.					0.002308***	0.0007189	0.009969**	0.003700
GDD X August Prec.					-0.0005984	0.0008733	-0.003936	0.003819
May Temp. Dev.	-61.92***	8.866	-13.43	25.93	-69.95***	7.995	-38.27	24.64
June Temp. Dev.	1.199	8.908	9.401	15.86	3.742	9.348	5.985	15.48
July Temp. Dev.	-49.34***	7.263	-40.73**	17.42	-51.08***	8.191	-56.92***	14.11
August Temp. Dev.	27.02***	5.630	56.64**	20.90	22.78***	5.879	55.03**	21.93
Time trend	-1.446	3.211	20.44*	11.01	-1.314	3.261	18.45	12.58
Time trend squared	0.6027***	0.1134	0.7715	0.4537	0.6036***	0.1168	0.8368	0.4847
Constant	609.6***	221.4	-1181	887.1	1523***	152.57	1487*	686.16
Number of obs.	677		176		677		176	

NB Model 1d and 2d are for crops on rainfed, and Model 1i and 2i are for crops on irrigated lands.
***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Robust standard errors are clustered at the county level.

Table 8. Marginal effects of GDD and precipitation on crop yields.

Variables	Model 1d	Std. err.	Model 1i	Std. err.	Model 2d	Std. err.	Model 2i	Std. err.
				Barley				
GDD	0.04965	0.1004	0.1947	0.2772	0.3650***	0.06020	0.1852	0.1744
May Prec.	0.3058	0.4862	-0.8970	0.5998	0.3258	0.4760	-1.560***	0.3969
June Prec.	0.4412	0.2937	-1.872***	0.4897	0.6182**	0.2764	-1.993***	0.3384
July Prec.	2.610***	0.2636	-0.7686	0.7280	2.961***	0.2669	-0.3010	0.7092
August Prec.	3.019***	0.3804	1.685**	0.7457	3.245***	0.4017	2.753***	0.6912
				Canola				
GDD	0.1603***	0.04370	0.1197	0.1086	0.2620***	0.04030	0.1022*	0.04730
May Prec.	0.2469	0.2882	0.3226	0.2693	0.2434	0.2673	0.2294	0.2158
June Prec.	0.2425	0.1475	-0.6321***	0.1099	0.2089	0.1412	-0.7239***	0.1125
July Prec.	1.146***	0.1612	-0.8084*	0.4014	1.593***	0.1767	-0.1301	0.3342
August Prec.	1.758***	0.2494	2.362***	0.6808	1.674***	0.2722	2.662***	0.4990
				Spring Wheat				
GDD	0.1235**	0.05540	-0.3358	0.2313	0.2325***	0.0535	-0.1508	0.1260
May Prec.	1.348***	0.3350	0.2726	0.7985	1.317	0.3435	0.02280	0.9008
June Prec.	0.8724***	0.2413	-0.8382*	0.4080	0.9391	0.2117	-1.155**	0.4630
July Prec.	2.019***	0.2322	-0.9420	0.7268	2.357***	0.2320	-0.7017	0.8229
August Prec.	2.084***	0.3065	1.772	1.088	2.101***	0.2887	2.163	1.204

NB Model 1d and 2d are for crops on rainfed, and Model 1i and 2i are for crops on irrigated lands.
***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
The marginal effects were calculated at sample means. Standard errors of the interaction terms were calculated using the delta method in Stata 12.

In examining parameter estimates in Tables 5 to 7 it may first be noted that the linear and quadratic time trends are mostly positive and significant for all crops. This is not surprising, because progressive technological advancement has increased crop yields in the region over the study period (Stewart *et al.*, 2009; Robertson *et al.*, 2013).

2.5.6 Response of Crop Yields to Temperature and Heat

As shown in Tables 5 to 7, the signs and statistical significance for the temperature and heat climate variables are robust across the different specifications for each crop. The coefficients for GDD and squared GDD are statistically significant at the 1% level for all three crops for both rainfed and irrigated models. The pattern of positive coefficients for the linear GDD term and negative coefficients for the squared GDD terms implies an inverse U-shaped relationship between crop yields and GDD. This indicates crop yields respond positively with increased GDD at a decreasing rate until GDD reaches some threshold level. Beyond that level, further increases in GDD tend to have a negative impact on crop yields. This pattern is consistent with Robertson *et al*. (2013), who estimated rainfed crop yield responses to climate variables for major crops in the Canadian Prairie region (including three Canadian Prairie provinces of Alberta, Saskatchewan, and Manitoba).

Comparing the GDD parameter estimates between rainfed and irrigated crops, the values are numerically smaller for rainfed crops. This may indicate that irrigated crops are better able to respond to increased heat due to moisture not being as limiting as for rainfed crops. The marginal effects of GDD on barley, canola, and wheat yields were computed using sample means for the explanatory variables (Table 8). For example, under Model 1, a 1% increase in GDD leads to an increase of 0.05% (0.5 kg/acre) in barley yields, 0.16% (0.8 kg/acre) for canola yields, and 0.12% (1.1 kg/acre) for spring wheat yields for rainfed. The corresponding yield increases are 0.19% (3.2 kg/acre), 0.12% (1 kg/acre) and -0.34% (-5.1 kg/acre) for barley, canola and spring wheat, respectively, for irrigated land. However, most of the marginal effects for irrigated crops (see Table 8) are not statistically significant.

ODD captures the occurrence of extreme temperatures; specifically, days with high temperatures. It would be expected that these conditions are harmful to crop yields and so the model coefficients for these variables should be negative. The results are generally consistent with this reasoning. The coefficients for ODD tend to be negative and statistically significant. The exception is rainfed barley yield in model 1d; the coefficient is positive but not statistically significant.

The model results also illustrate how temperature deviations affect crop yields. For rainfed yields, monthly temperature deviations in May and July tend to have negative and significant impacts, while monthly temperature deviations in August tend to have significant and positive effects. Temperature deviations in June tend to show no significant effect.

Temperature deviations in May are more likely due to low temperatures and nights with frost and snow in the region, which hinders soil warming and delays seeding. These factors are harmful to crop yields. Conversely, large temperature deviations in July and August are more likely an indicator of higher temperatures than usual or extreme heat, which can also be detrimental for crop yields. This result holds for July but not for August. However, the positive impact of August temperature deviations is consistent with findings for Ontario wheat yields by Cabas *et al.* (2010). Harvest in the study region usually starts in August. One explanation of the result for August is that warm and dry conditions in August indicated by large temperature deviations are good for harvesting. This may be also because these crops are tolerant to higher critical maximum temperatures in August than in July. For example, Robertson *et al*. (2013) investigated critical maximum and minimum temperatures for major crops in the Canadian Prairie region and found a pattern of higher temperature tolerance in August than in July and June. Specifically, they report critical maximum temperatures of 38 °C, 38 °C, and 40 °C in August for barley, canola, and spring wheat, respectively.

2.5.7 Response of Crop Yields to Precipitation

For rainfed yields, monthly precipitation during the growing season tends to have a positive impact on crop yields for barley, canola, and spring wheat. This is not surprising, given that water is an essential input for crop growth and the studied area has a semi-arid climate. The impacts tend not to be statistically significant in May and June for barley and canola but are statistically significant for July and August for all crops. The explanation for this pattern is that seeding for these crops is usually finished in May, so crop water demand is relatively low in May and June. Water demand is higher in July and early August to support plant growth and kernel/seed filling (Alberta Agriculture and Forestry, 2015). The significant precipitation effect in May and June for spring wheat likely arises because spring wheat has higher water demand compared with barley and canola (Alberta Agriculture and Forestry, 2015). This explanation is also confirmed by comparing the magnitude of the coefficients. As shown in Table 8, monthly precipitation in July and August tends to generate larger impacts on rainfed crop yields. For example, for Model 1d, a 1% increase in precipitation in July increases spring wheat yields by 2% while a 1% increase in precipitation in June only increases spring wheat yields by 0.87%. For Model 2d, a 1% increase in precipitation in July leads to a 3% increase in barley yields while a 1% increase in precipitation in June only increases barley yields by 0.62%.

Unlike the case for rainfed yields, it could be hypothesized that there is no significant effect of precipitation on irrigated yields. This hypothesis would be based on a presumption that the ability of producers to use irrigation water allows them to supplement moisture available from growing season precipitation. In other words, moisture would not be a limiting factor.

For irrigated yields, the model results for growing season precipitation variables are indeed not consistent with the results for rainfed yields. Precipitation in May and August tends to have positive impacts on irrigated yields for canola and spring wheat, with an exception of precipitation in May for barley, which shows a negative impact. However, precipitation in June and July has a negative impact on yields for all three crops and the impacts are all statistically significant in June.

Given the dry conditions of Alberta's crop production, irrigation is applied to maintain certain levels of soil moisture for crops. As noted earlier, in principle precipitation should not be a limiting factor for crop growth under irrigation. As indicated by Alberta Agriculture and Forestry

(2016), the recommended practice is for producers to irrigate to 90% of the soil capacity (based on soil texture), leaving the remaining 10% of capacity to be "filled" by precipitation. If it is assumed that producers follow this (or a similar) practice, then the model results for precipitation and irrigated yields are reasonable. Since precipitation is not fully predictable, irrigating 90% of the soil capacity can result in the possibility of what appears to be "over irrigating" in conditions of excess precipitation. In addition, June is the wettest month in this region and July is the time that requires the most water for crop development so that more irrigation water is applied. These factors increase the risks of "over irrigating" in these two months.

As discussed above, Model 1 assumes additive separability regarding the impacts of temperature and precipitation on crop yields while Model 2 incorporates interaction terms for GDD and monthly precipitation into the analyses. In general, the interaction terms between monthly precipitation and GDD are positive for all crops and are significant in June and July for rainfed yields. This is consistent with Cabas *et al*. (2010) who found that warm and wet conditions were favorable to crop yields. However, the results tend to be less consistent across crops under irrigation.

The marginal effects of GDD and precipitation on crop yields from Model 2 were calculated and compared with the results obtained from Model 1 (Table 8). As seen from Table 8, adding the interactions into the analysis produces very similar marginal effects in terms of magnitude and sign for both GDD and precipitation compared with that from Model 1. For example, a 1% increase in GDD results in a 0.26% increase in rainfed canola yields for Model 2 and a 0.16% increase for Model 1. For irrigated production, the marginal effects of GDD on canola yields are 0.10% and 0.12% for Models 2 and 1, respectively. Thus, the results from Model 1 and Model 2 indicate a consistent pattern. Specifically, GDD tends to have a statistically significant impact on rainfed crops but not irrigated crops. For growing season precipitation, Model 2 shows positive impacts on yields for the three crops on rainfed. For irrigated lands, precipitation tends to show negative impacts on yields in June and July, with that effect being statistically significant in June. These results are consistent with those for Model 1. Therefore, it is concluded that the models are relatively robust to different specifications of climate variables. The results from these models are now used to forecast the impacts of climate change on crop yields.

Table 9. Summary statistics of projected climate variables under both scenarios over all counties, from 2010 to 2034.

	Climate change scenario			
	CanESM2-8.5	Difference	CanESM2-2.6	Difference
Growing degree days (GDD)	1616.0	147.19	1673.1	204.25
Overheat degree days (ODD)	0.079813	-0.36112	0.11755	-0.32338
Precipitation in May (mm)	50.771	1.3105	59.259	9.7984
Precipitation in June (mm)	65.219	-16.950	80.326	-1.8435
Precipitation in July (mm)	54.714	0.59441	80.705	26.585
Precipitation in August (mm)	47.036	-2.6324	43.907	-5.7616
Temp. Deviation in May (°C)	14.361	2.7989	14.219	2.6565
Temp. Deviation in June (°C)	14.444	2.3094	14.153	2.0192
Temp. Deviation in July (°C)	15.163	1.0099	15.086	0.93316
Temp. Deviation in August (°C)	16.124	2.0883	14.894	0.85846

Source: Faramarzi *et al.* (2015).

NB *Difference* is calculated by using the average values of future climate data from 2010 to 2034 under both scenarios minus sample means of historical climate data from 1981 to 2007, respectively.

Table 10. Cross validation measures by model, crop, and land type.

	Model 1	Model 2
Barley – Rainfed		
RMSE	291.6*	310.6
MAE	240.6*	254.2
Barley – Irrigated lands		
RMSE	282.7	282.4*
MAE	228.1*	228.5
Canola – Rainfed		
RMSE	156.1*	159.3
MAE	124.4*	127.5
Canola – Irrigated lands		
RMSE	140.5	139.5*
MAE	113.7	111.5*
Spring Wheat – Rainfed		
RMSE	248.1*	252.9
MAE	199.8*	203.0
Spring Wheat – Irrigated lands		
RMSE	237.6*	241.7
MAE	189.6*	195.9

NB RMSE are the root mean square errors and MAE are the mean absolute errors obtained from a k-fold (here k=20) cross validation.
* indicate the smaller RMSE and MAE values across Model 1 and 2.

Table 11. Average effects of climate change on crop yield (percentage change relative to sample means from 1981 to 2007) under rainfed and irrigation, respectively, from 2010 to 2034.

	Barley		Canola		Wheat	
Climate scenarios	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
CanESM2-8.5	-14.26%	-3.93%	-16.58%	1.93%	-18.69%	0.57%
	(0.2706)	(0.1307)	(0.3483)	(0.1596)	(0.2804)	(0.2007)
CanESM2-2.6	-21.12%	-11.05%	-23.99%	-4.50%	-21.73%	0.003%
	(0.3233)	(0.1458)	(0.4097)	(0.1647)	(0.3457)	(0.1973)

NB The model used for yield forecasting is Model 1 for all the three crops. Numbers in parentheses are standard deviations.

2.5.8 Forecast Crop Yield under Climate Change

The empirical results presented in the previous section suggest that the impact of climate variables on crop yields differs between rainfed versus irrigated production. This section explores how future climate change will affect rainfed crops relative to irrigated crops. In undertaking this analysis, projections of temperatures and precipitation for a future climate scenario are required. There are several models available to provide climate change scenarios. Each of these models generates different projections based on unique sets of assumptions and modelling relationships. For this analysis, projections of future climate variables were based on the CanESM2 model. For more information about the model, please refer to Chylek *et al*. (2011). Specifically, CanESM2 Scenarios 85 and 26, representing "lower" and "higher" rates of warming, respectively were used. This climate model was selected because of the ability to downscale Canadian climate change projections to a gridded resolution of 10 km. The model provides information on daily maximum temperature, minimum temperature, and precipitation.

The output from CanESM2 was used to produce a set of projected climate variable values at the county level from 2010 to 2034 consistent with what was used in the original model estimation. Table 9 provides summary statistics for projected climate variables under both scenarios for the period 2010 to 2034 and shows the change in average values for these variables calculated over all counties (in the study area) from the historical climate variables over the period 1983 to 2007. On average, the two future climate scenarios are warmer (i.e., greater GDDs) than the historical climate, although the future climate scenarios tend to have fewer instances of extreme high temperatures. Both future scenarios have larger monthly temperature deviations for each month compared with the historical climate data. In addition, there is more precipitation in May and July, but less precipitation in June and August, when the future climate scenarios are compared with historical values.

When forecasting crop yields for the climate change scenarios, it was decided to use Model 1. This choice was made based on the accuracy of out-of-sample forecasting for each model. Specifically, a k-fold (k=20) cross validation was conducted for each crop using both rainfed and irrigated yields to assess the fit of the models to a data set that is independent of the data that were used to train the model. The validation process was initiated by splitting the dataset randomly into 20 partitions. From the resulting 20 subsamples, a random subsample was retained for use as validation data for testing the model. The remaining 19 subsamples were used as training data. The cross-validation process was then repeated 20 times. The advantage of this method is that each subsample is used as testing data exactly once. The root mean square errors (RMSE) and the mean absolute errors (MAE) were calculated from each of the 20 validation processes, with the mean values being compared for each model by crop and land type. The mean RMSE and MAE values are reported in Table 10. Based on both statistics, Model 1 outperforms Model 2 in forecasting the majority of the time. For the cases where the mean RMSE/MAE of Model 1 is larger than Model 2, the differences are negligible.

By using the projected variable values for the two climate change scenarios discussed earlier and the parameter estimates from Model 1, predicted annual yields for each crop were

Table 12. Decomposition of the effect of climate variables on crop yields (percentage changes relative to sample means of crop yields from 1981 to 2007) under two climate change scenarios.

	CanESM2-8.5		CanESM2-2.6	
		Barley		
Effect of	Rainfed	Irrigated lands	Rainfed	Irrigated lands
GDD	0.85%	0.29%	1.11%	0.47%
ODD	-0.06%	-0.08%	-0.06%	-0.07%
Temp. Dev	-13.00%	-5.33%	-19.28%	-8.09%
Total Temp. Effect	-12.20%	-5.12%	-18.23%	-7.69%
Precipitation	-1.97%	0.76%	-1.45%	7.83%
		Canola		
GDD	5.47%	1.23%	7.17%	2.42%
ODD	0.38%	1.06%	0.34%	0.94%
Temp. Dev	-18.42%	-7.83%	-25.12%	-8.10%
Total Temp. Effect	-12.57%	-5.54%	-17.60%	-4.74%
Precipitation	-2.70%	0.99%	-2.89%	7.51%
		Wheat		
GDD	2.24%	0.52%	2.97%	1.06%
ODD	0.39%	0.72%	0.37%	0.65%
Temp. Dev	-19.24%	-9.33%	-23.82%	-10.18%
Total Temp. Effect	-16.60%	-8.08%	-20.47%	-8.48%
Precipitation	-2.05%	0.71%	-0.14%	9.11%

calculated for the period 2010 to 2034. The average predicted yields for the 2010-2034 period for the three crops were then compared to sample means of crop yields between 1983 and 2007, for both rainfed and irrigated production, to quantify the overall impact of future climate change on average yields. Table 11 summarizes the percentage changes in the predicted average yields relative to the historical average yields and the corresponding standard deviations.

Under CanESM2-85 (i.e., “lower” rate of warming), climate change decreases barley yield under rainfed and irrigation production by 14.26% and 3.93%, respectively. Rainfed canola and spring wheat yields are also reduced, by 16.58% and 18.69%, respectively. However, there are slight gains in yields for these two crops under irrigation; 1.93% for canola and 0.57% for wheat.

Under CanESM2-26 (i.e., “higher” rate of warming), climate change is harmful to barley and canola yields for both irrigated and rainfed production. This climate change scenario leads to a reduction in rainfed spring wheat yield by 21.73%, but a marginal increase (0.003%) in irrigated spring wheat yield. By considering the results together, the negative effects of climate change are consistent for both scenarios in that the harmful effects tend to be larger for rainfed than for irrigated production. The three major crops in Alberta under rainfed production suffer from climate change while irrigated production for canola and wheat can benefit from these climate change scenarios.

The average impacts of projected climate variables were separated into temperature effects versus precipitation effects on crop yields using parameter estimates from Model 1 and the aforementioned two climate change scenarios for the three crops. The percentage changes in predicted crop yields relative to sample means of crop yields from 1981 to 2007 under two climate change scenarios were calculated with the results being presented in Table 12. The changes in GDD result in increased yields for all the three crops under both climate change scenarios. The percentage increases range from 0.29% to 7.17% depending on the crop and climate scenario. Changes in ODD lead to reduced barley yields but increases in yields for canola and wheat. Changes in temperature deviations cause the largest yield reductions for each crop under both climate change scenarios. The total temperature effect presented in Table 12 is the result of summing up the effects of GDD, ODD, and temperature deviation. Overall, the effect of temperature change on yields is negative with the effect tending to be greater for rainfed crops compared to irrigated crops. Future climate change in precipitation suggests the opposite effect for the three crops under rainfed versus irrigated production. The projected changes in precipitation cause yields to decrease by 0.14% to 2.89% for rainfed crops. In contrast, projected changes in precipitation cause irrigated yields to increase by 0.71% to 9.11%.

2.6 Project Outcomes

The Research activities and progress during the research period are given below:
For a full listing of scientific publications and listing of abstracts and titles of talks given, please see appendix.

2.6.1. Hydrological simulation, climate change assessment
Tasks:

- Calibration, validation, and uncertainty analysis of the SWAT hydrological model of Alberta using a set of updated data to predict water resources availability, estimation of the water demand of main economic-water sectors (e.g. agriculture, energy, industry, and urban), application of the calibrated model to assess impacts of climate change on water supply and demand pattern taking the effect of other driving forces to global change, analysis of economic-water scenarios for an enhanced analysis of adaptation measures, scientific and technical coordination of project, and support during the implementation of technical aspects of project deliverables.

Progress:

- Climate change data of at least 12 Global CMIP5 Climate Models (GCMs) from the Pacific Climate Impacts Consortium (PCIC) under various RCP scenarios were downloaded/processed for extreme future scenarios (i.e., RCP26, RCP85). This resulted in compilation of the daily data for a total of 48 model-scenarios taking the effects of downscaling efforts for the periods 1980-2010, 2010-2040 and 2040-2070. Separate SWAT projects were built for all PCIC datasets. This resulted in a total of 48 SWAT projects where calibrated-validated parameters of the historical period and climate change data were fed.
- The Regional Climate Models (RCMs) of Northern American Regional Climate Change Assessment Program (NARCCAP) have been bias corrected/downscaled using the hydrologically qualified climate data of Alberta for the 1940-1970 historic period that performs well for western Canada and capture the range of projected changes in temperature and precipitation. A total of 9 representative model-scenarios were selected for this purpose.
- The PhD student, Amr Gharib, from University of Alberta conducted a comprehensive literature review on flood-drought analysis. The water data of SWAT hydrological model of Alberta was analysed for the flood-drought assessment. The most reliable state of the art methods have been investigated for the Alberta watersheds. A robust and scientifically rigorous approach was developed to assess flood events in various watersheds across Alberta. Results were drafted for publication in a peer reviewed journal. The framework/method developed in this part of the research established a sound base for the future predictions of flood and drought risks in the province, which will be based on the future predictions of water availability by SWAT model and be considered for publication in other peer reviewed journal The results of both articles will be presented in American Geophysical Union 2016.

a. Dr David Sauchyn provided instrumental advice on data sources and climate change studies which contributed greatly to the project. This included discussion of the climate model inputs for hydrological modelling and providing advice on the selection and processing of climate model data. This was achieved by regularly corresponding with Monireh Faramarzi, and meeting with the entire project team in Edmonton and Calgary, including two meetings attended by Research Assistant Iulia Andreichuk. In addition, Dr Sauchyn provided Regional Climate Model (RCM) data for Alberta Watersheds for historic and future time frames, including:

- Completed the evaluation of 11 Regional Climate Models in terms of their capacity to simulate the climate of western Canada.
- Extended the evaluation of these RCMs to hydrologic parameters to determine how well the models simulate the surface hydrology of selected river basins – Bow, South Saskatchewan, Red Deer and North Saskatchewan.
- Provided Monireh Faramarzi with the projected daily weather data from future (2041-2070) runs of 10 RCMs for the SWAT modelling of future watershed hydrology. The climate data consisted of daily total precipitation, maximum and minimum daily temperature, radiation, average wind speed and daily average relative humidity.
- Developed a method of statistical downscaling of RCM data to the location of river gauges by regressing climate indices (e.g. SPEI) against river discharge.
- Using output directly from Regional Climate Models, dynamically downscaled the hydroclimate for Alberta watersheds capturing the quasi-periodic variability in the regional hydroclimatic related to the Pacific ocean-atmosphere oscillations (PDO, ENSO).
- For the inter-model comparison of paleo-hydrological models and basin hydrological models, we constructed flow duration curves (exceedence probabilities) from 900 years of weekly flow estimates for the Athabasca, North Saskatchewan and Bow Rivers. We then compared these paleo-stochastic flows to the runoff simulated by RCMs.

2.6.2 Glacier modelling

Tasks:

- Develop distributed models of glacier mass balance (snow accumulation and melt), glacier hydrology, and glacier dynamics for all of the major glacier systems in the eastern slopes of the Canadian Rocky Mountains; embed the glacier model into SWAT; simulate glacier area, volume, and runoff response to climate change scenarios for the period 2010-2050.

Progress:

- PAWF student Samaneh Ebrahimi completed her PhD in 2016, developing a surface energy balance model for glacier melt and downscaling techniques to drive this model from climate model reanalyses (for the historical period) and future projections. Samaneh developed and tested this model for a single glacier in the Rockies (Haig), where we have an extensive dataset to calibrate and test the model. Her PhD research included several ideas on how to downscale and parameterize different energy balance fields, which drive snow and ice melt (Ebrahimi and Marshall, 2015, 2016). This model gives daily meltwater runoff, and was run for the past using NARR reanalyses and for the future using CMIPS projections from the GFDL model.

- We have now developed a distributed model to use the same framework for reanalysis- and climate model-driven scenarios for the full region of interest (the eastern slopes of the Rockies). Honours B.Sc. student Adrienne Schumlich was recruited (January to August, 2016) to carry out the necessary GIS and database development for this modelling, e.g. detailed topographic characterization and solar radiation modelling for the glaciers, but has now moved to U. Delaware to commence MSc studies. Undergraduate Research Associate Parisa Rahimian has picked up on this work and we are currently running Alberta-wide future projections using the NARRCAP scenarios of David Sauchyn, but with extended fields in order to apply a full energy balance model for the glacier melt. A manuscript is in preparation with these results, to be submitted to *Water Resources Research*.
- Graduate student Samira Samimi is working on field study and modelling of glacier hydrology, with a focus on meltwater retention in the glacier snow and firn and impacts of meltwater refreezing on glacier energy balance and summer runoff (Samimi and Marshall, in press). This research provides insights into how much meltwater is delayed within the glacier before it runs off to the proglacial rivers.
- The glacier energy balance and hydrology models are in MATLAB, and so far are not coupled within SWAT; we will investigate the possibility of incorporating this model directly into the SWAT model.

2.6.3. Ground water assessment

Tasks:

Assessing the risk and opportunities with respect to Alberta's groundwater resources through a review of sources, related volumes, use patterns and trends, and climate change on the balance of recharge and groundwater storage reserves/water level changes (where possible). This will incorporate future projections supported by other work packages (i.e., SWAT) to provide a holistic view of groundwater as a viable offset to surface water, and the opportunity for alternative storage and management options (e.g., conjunctive use, aquifer storage and recovery, managed aquifer recharge).

Progress:

- Completion of recharge estimates for the sub-basins using an area-weighted attribution of % precipitation, considering influences from vegetative cover and underlying geological materials (i.e., till, clay, sand, bedrock).
- Groundwater use projections (by major sector and by major basin).
- Submission of summary report to Principal Investigator, May 2015.
- Assessment of groundwater use by township (estimated unlicensed and AEP licensed wells).

- Development of an Analytic Element Model to assess future effects of groundwater use in Alberta under assumed growth scenarios (out to 2050).
- Submission of summary report to Project Investigator, December 2015.
- Preparation of datasets to support climate change assessment for groundwater quantity.
- Incorporation of SWAT model recharge calculation into Water Table Fluctuation model to determine water level changes under RCP 2.6 and RCP 8.5 (Downscaled and Non-downscaled) climate model scenarios (by sub-basin).
- Combining of climate-change related water level changes with Analytic Element Model results (extrapolated out to 2070 with 1st or 2nd order polynomial relationships) to determine sub-basins projected to experience the largest combined drawdown effects.
- Preparation of summary documentation, December 2016 (nearing completion).

2.6.4 Assessment of basin water yield and climate trends

Tasks:

- Identifying the spatial distribution of climate variability, estimating future basin yield, processing, downscaling and sharing critical climate time series for the period of 1950-2050, comparing simulated future hydrological behaviour between the SWAT model and the ACRU model, providing hydrological modelling results for selected watersheds, including the Oldman River basin, analysis of extreme events including flood and droughts.

Progress:

- The ACRU agro-hydrological modelling system is used to compare SWAT simulations with another physically-based model. The Castle River and the parts of the Waterton Rivers are now completed or near completion, and extensive statistical results are available for comparison with SWAT model results.
- In addition to the Castle River Watershed, streamflow simulations for historical (1950-2010) and future (2041-70) periods in the Waterton River Watershed and parts of the Oldman Reservoir Watersheds are now also available. However, final verification statistics and future streamflow statistics will only be available in February 2017. These can then used to compare ACRU simulations with SWAT simulations.
- Historical climate records for the period 1950 to 2010, at a spatial resolution of 10 by 10 kms, were analysed for 43 climate variables. This instrumental climate records could serve to map the recorded changes in climate variables across Alberta. A web site, albertaclimaterecords.com, was established to provide all data for each grid of 6833 grid cells (time series, trends, changes). A large list of variables, from annual and seasonal changes, to extreme low and high temperatures and precipitation, as well as growing season length, growing degree days, as well as heating degree days and cooling degree days were calculated. This web site serves both resource managers as well as public to understand the spatial distribution of both magnitude and direction of climate change across the province of Alberta. Four TV featurettes, eight newspaper articles (including New York Times and Canadian Geographic), and seven radio interviews emanated from

this web site. An accompanying publication in The Canadian Geographer has been principally accepted, and revisions are currently under way. This task is complete, with the exception of the manuscript revisions.
- Penman-Monteith potential evapotranspiration has been calculated for all 6833 grids that make up Alberta, and trends and trend statistics are available.
- In total, 11 regional Climate Models have been evaluated in terms of their capacity to simulate the climate of western Canada. The models were compiled and made available to the PAWF project on an FTP server. The evaluation of these RCMs has been extended to hydrologic parameters; how well do the models simulate the surface hydrology of selected river basins- Bow, South, Saskatchewan, Red Deer and North Saskatchewan. We also developed a method of statistical downscaling of RCM data to the location of river gauges by regressing climate indices (e.g. SPEI) against river discharge.
- For inter-model comparison of paleo-hydrological models and basin hydrological models, we constructed flow duration curves (exceedance probabilities) from 900 years of weekly flow estimates for the Athabasca, North Saskatchewan and Bow Rivers. We also initiated a comparison of these paleo-stochastic flows to the runoff simulated by RCMs.

2.6.5 Economic analysis

Tasks:

Identifying direct economic impacts (outputs, wealth measures, etc.) of the agricultural sector (as the largest water user) but incorporating energy, industrial and urban water users, arising from alternative water availability cases for the broader economic and risk assessment. Initially direct economic impacts will be provided (outputs, returns) with economy wide impacts (employment, etc.) as well as broader general equilibrium impacts assessed in later stages. Economic values at risk measures will also be developed for the risk analysis component.

Progress:

- Completed a set of estimates of current and future water use by sector and river basin for Alberta from 2010 to 2040 and 2040-2070.
- Begin developing an econometric model assessing the impacts of climate change on Alberta's economy.

2.6.6 Scenario development

Tasks:

Scenario developments with respect to the economic impact of irrigation versus non- irrigated areas and potential adaptation options in the face of climate change.

Progress:

Now that we have a model for the economic impact of irrigation (paper to be submitted in July 2016), we will perform a variety of simulations of different scenarios to examine the economic impact of irrigation adjustments during future climate scenarios.

2.7 Analysis of Results

2.7.1 Hydrological simulation, climate change assessment

2.7.1.1 Quantification of water resources at regional and sub basin levels for historic period (1983-2007)

Improved temperature and precipitation input through combination of multiple datasets, as well as snow related parameters in highland sub basins, resulted in a more accurate representation of the snow hydrology in these regions. Using the long-term average annual simulated data at subbasin level we found that of the 500–700 mm precipitation (Figure 12a) in the western high altitudes, about 150–560 mm is renewable blue water resources (RBWR) (Figure 12f). This water supplies most of the downstream sub basins in the south where the internal renewable blue water is meagre and agriculture is intensively practiced. The annual coefficient of variation (CV) (Figure 12 g), represents the reliability of water resources and gives practical insights for water resource managers and decision makers concerned with long-term planning for various economic sectors. Larger green water flow occurs in agricultural lands and irrigated districts (Figure 12h). This pattern corresponds well with the green water storage (Figure 12i) where it drops to its minimum depth in the agricultural lands. This implies that the high evaporative demand of crops, due to higher temperatures, must be compensated by soil moisture and eventually irrigation. Overall, the green water component showed less spatial and temporal variation compared to the blue water component. The high GWRCH in central and northern watersheds (Figure 12j) largely contributes to streamflow (i.e., base flow), soil evaporation, and plant water uptake. Therefore, only small amounts remain in shallow aquifers and will eventually end up in deeper aquifers allowing the formation of a more sustainable water resource (Figure 12k). This renewable groundwater has quite a meagre contribution to blue water resources as a whole (Figure 12f) but may, if not exploited, represent a resource in the future.

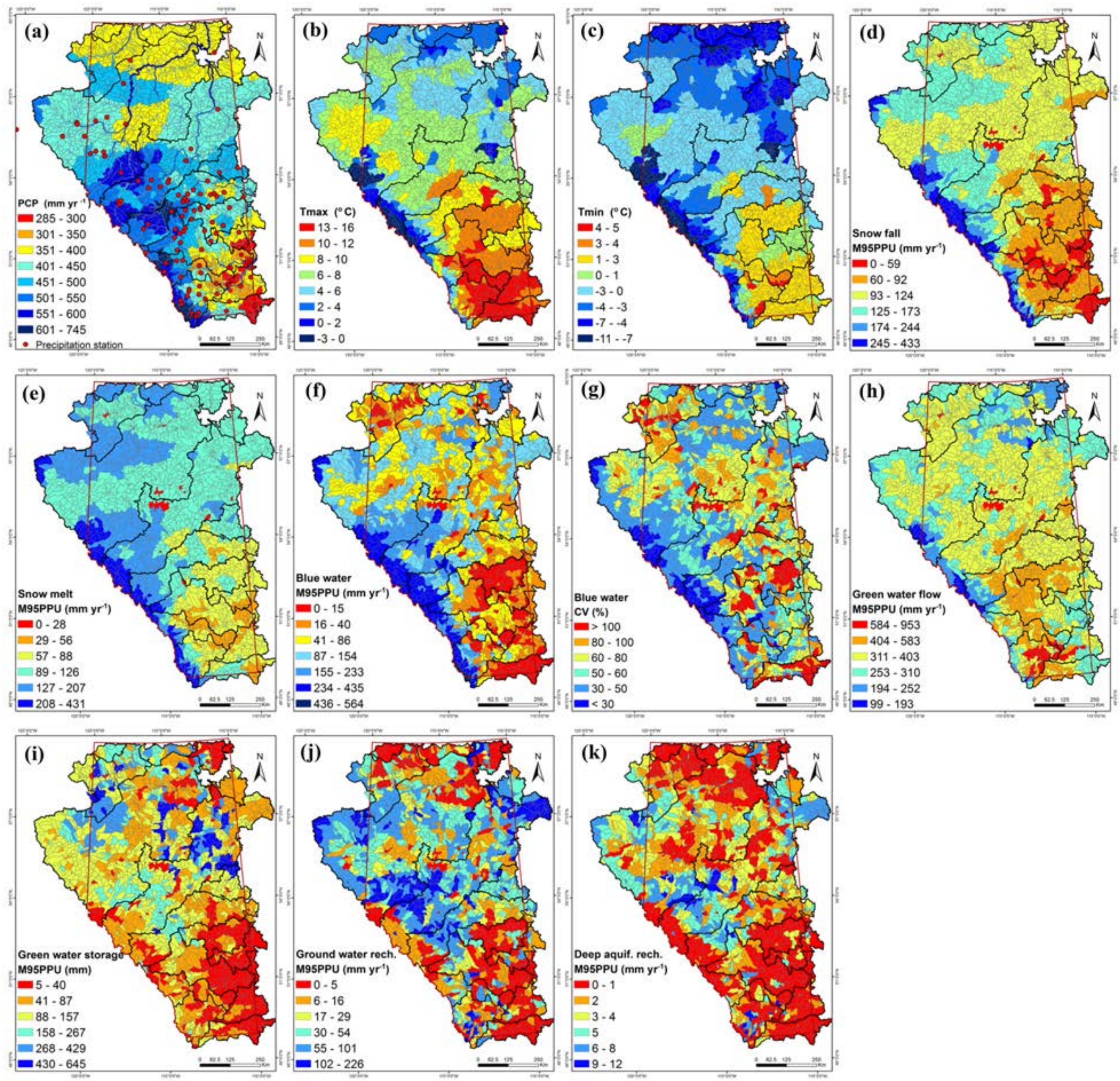
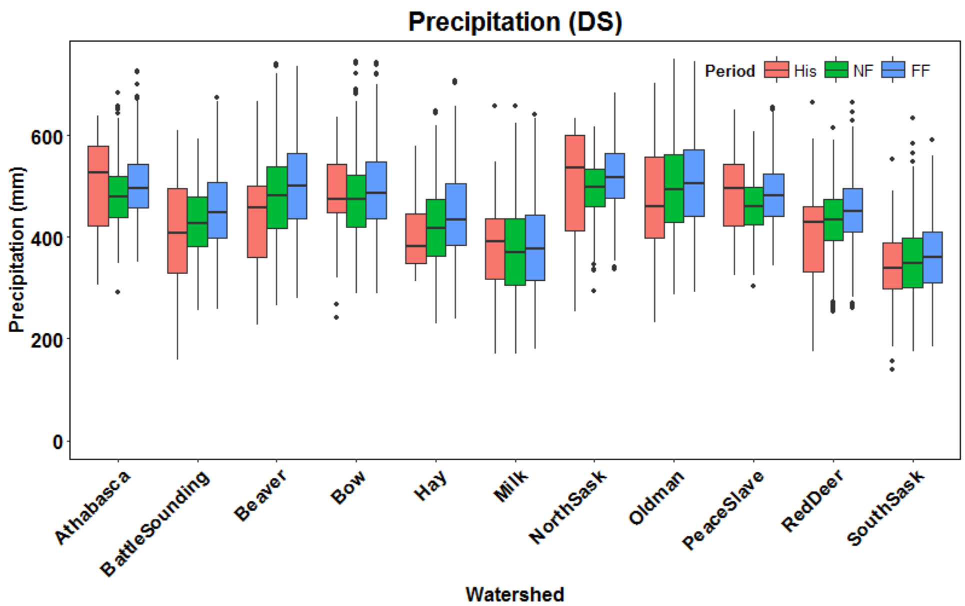


Figure 12. SWAT simulated precipitation (a), maximum and minimum temperature (b, c), snow fall (d), snow melt (e), and blue water (f), actual evapotranspiration (h), soil moisture (i), groundwater recharge (j), and renewable groundwater (k).
Averages based on monthly predictions of the M95PPU (i.e., median of 500 simulations) during 1986–2007 period (source Faramarzi *et al*., 2016).

2.7.1.2 Change in precipitation and temperature in the future

As already mentioned in previous sections we have utilized daily climate data of various climate models from the CMIP5 of the PCIC resource and downscaled the data for the near future (NF, 2010-2040) and far future (FF, 20140-2070) to assess the impacts of climate change on water various components of water resources including blue water (BW), green water flow (GWF, actual ET) and green water storage (GWS, soil moisture). Figures 13-15 show the predicted changes in precipitation, temperature and water resources components in the province. At the provincial scale, both precipitation and temperature increased in far future (FF, the year 2040-2069) compared to the near future (NF, the year 2010-2039) in all watersheds (Figure 13,14). In historic period (His, the year 1980-2009) mean precipitation is higher than that in few watersheds (i.e. Athabasca, Milk, NorthSask, and Peace-Slave) and is lower than that in another watershed. However, in historic period the observed temperature was always lower in near and far future periods in all watersheds

It is seen from the Figures 13,14 the temperature and precipitation will increase in all watershed in NF and FF periods. However, the pattern of increase is different from temperature to precipitation across the watersheds in the province.



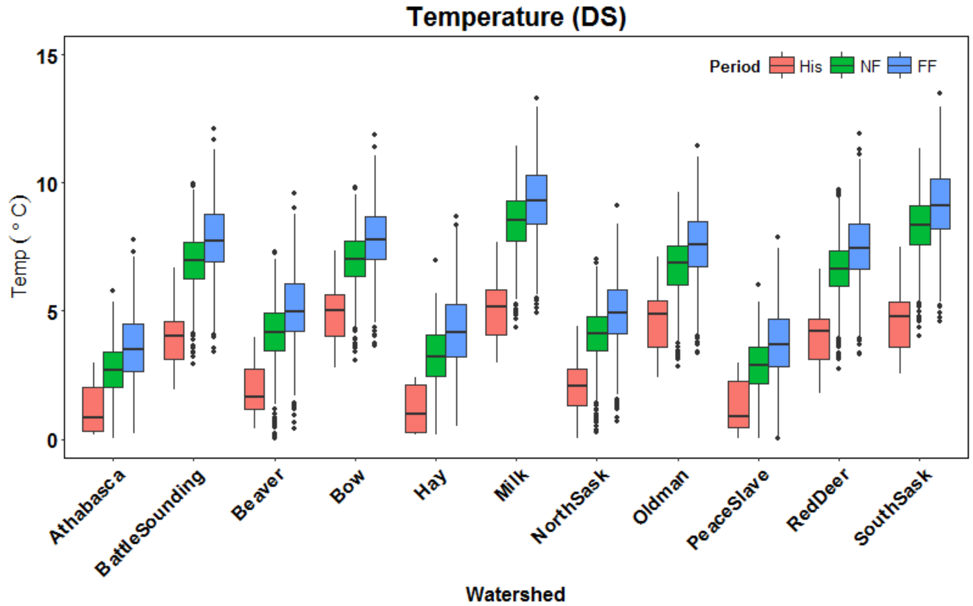
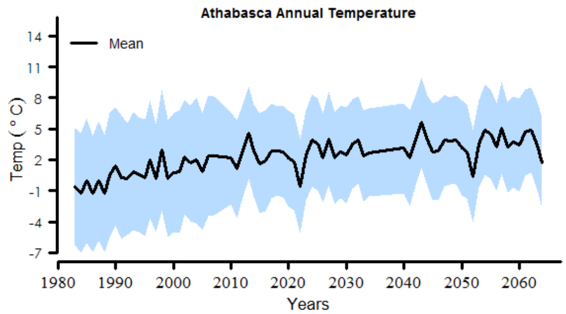
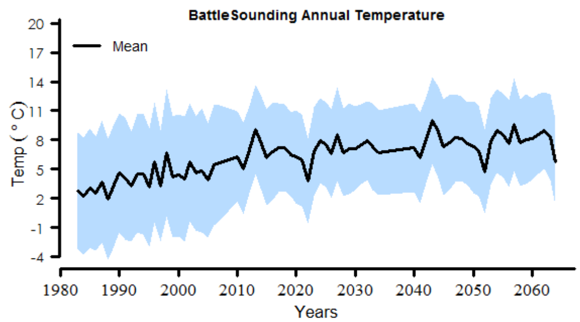
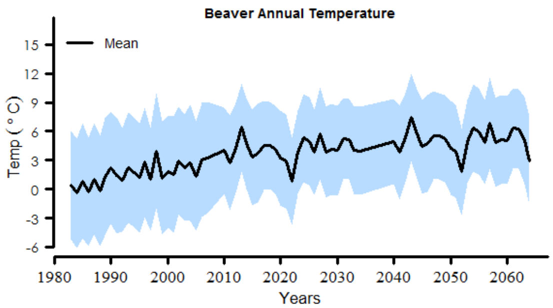


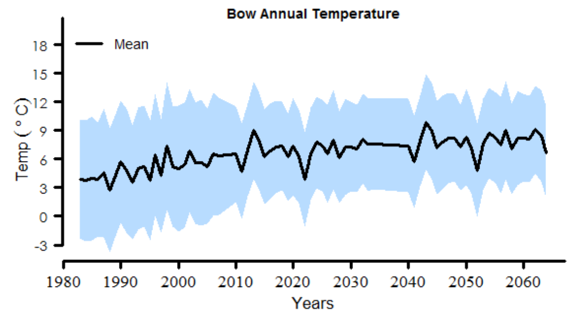
Figure 13. The long-term average precipitation and mean temperature from various models and scenarios under downscaled (DS) condition.

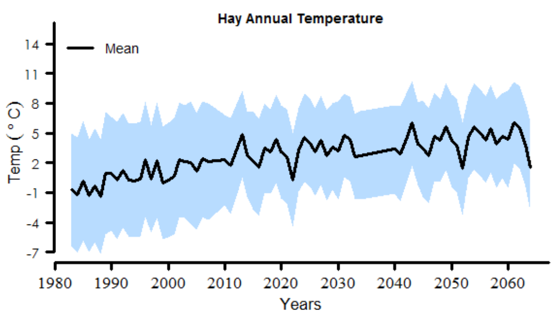
The box plots show the median, the 25th, and the 75th percentile of data out of various models and scenarios. Long term average for historic (His) period is from 1983 to 2007, near future (NF) period is from 2010-2034, and far future (FF) is from 2040-2064. In both NF and FF period the long-term averages were created by averaging the values from 9 different CMIP5 climate change models, under the two rcp 26 and rcp 85 scenarios.

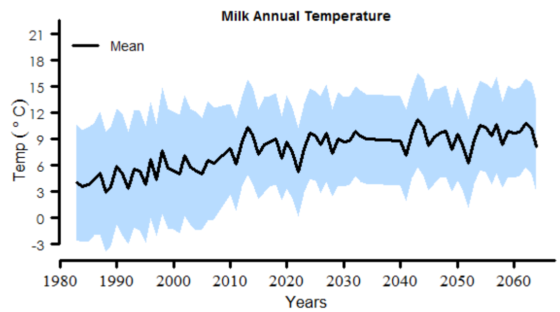

Athabasca Annual Temperature
Mean
Temp (° C)
14
11
8
5
2
-1
-4
-7
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years

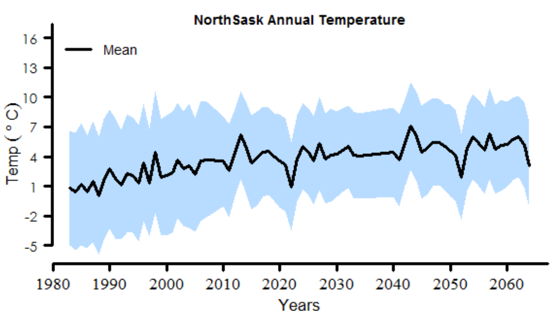

BattleSounding Annual Temperature
Mean
Temp (° C)
20
17
14
11
8
5
2
-1
-4
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years


Beaver Annual Temperature
Mean
Temp (° C)
15
12
9
6
3
0
-3
-6
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years


Bow Annual Temperature
Mean
Temp (° C)
18
15
12
9
6
3
0
-3
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years


Hay Annual Temperature
Mean
Temp (° C)
14
11
8
5
2
-1
-4
-7
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years


Milk Annual Temperature
Mean
Temp (° C)
21
18
15
12
9
6
3
0
-3
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years


NorthSask Annual Temperature
Mean
Temp (° C)
16
13
10
7
4
1
-2
-5
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years

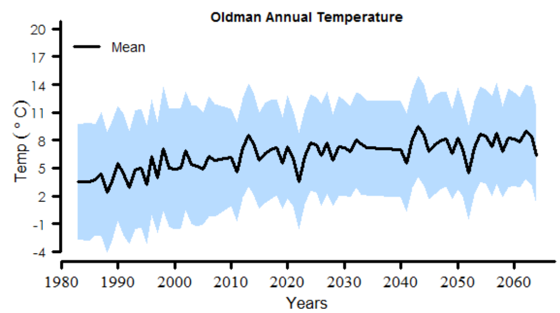
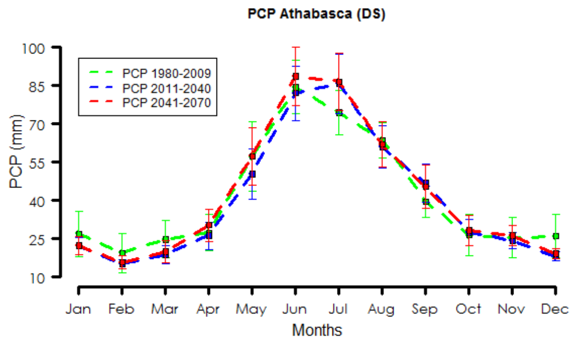
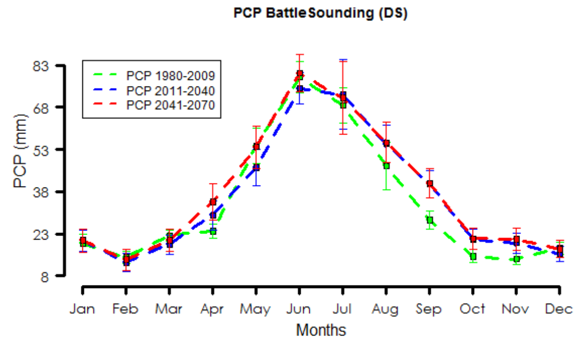
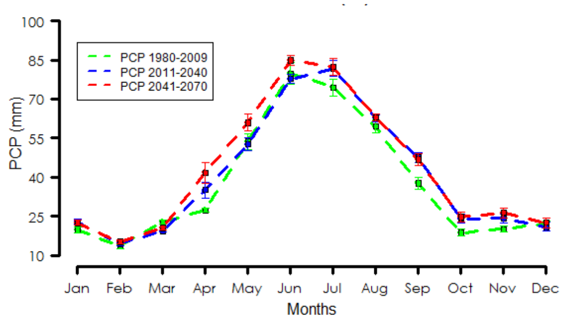

Oldman Annual Temperature
Mean
Temp (° C)
20
17
14
11
8
5
2
-1
-4
1980 1990 2000 2010 2020 2030 2040 2050 2060
Years

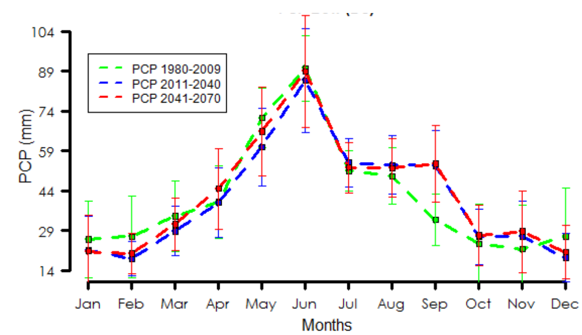
Figure 14. Annual maximum, minimum and mean temperature from historic to future periods (1983-2064) from various models and scenarios under downscaled (DS) condition in different watersheds.

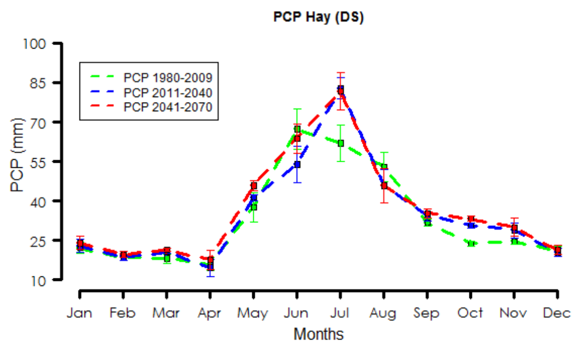
The blue shaded area represents the domain of the maximum and minimum temperatures averaged for all model scenarios (the upper band is the maximum temperature and the lowe band is the minimum temperature), and the black signal is the average of the mean temperatures for all model scenarios.

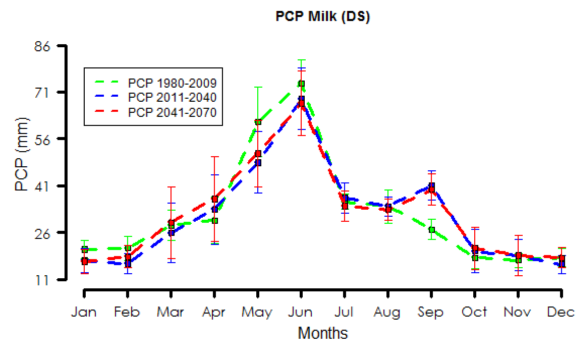

PCP Athabasca (DS)
PCP 1980-2009
PCP 2011-2040
PCP 2041-2070
PCP (mm)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months


PCP BattleSounding (DS)
PCP 1980-2009
PCP 2011-2040
PCP 2041-2070
PCP (mm)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months


PCP 1980-2009
PCP 2011-2040
PCP 2041-2070
PCP (mm)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months


PCP 1980-2009
PCP 2011-2040
PCP 2041-2070
PCP (mm)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months


PCP Hay (DS)
PCP 1980-2009
PCP 2011-2040
PCP 2041-2070
PCP (mm)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months


PCP Milk (DS)
PCP 1980-2009
PCP 2011-2040
PCP 2041-2070
PCP (mm)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months

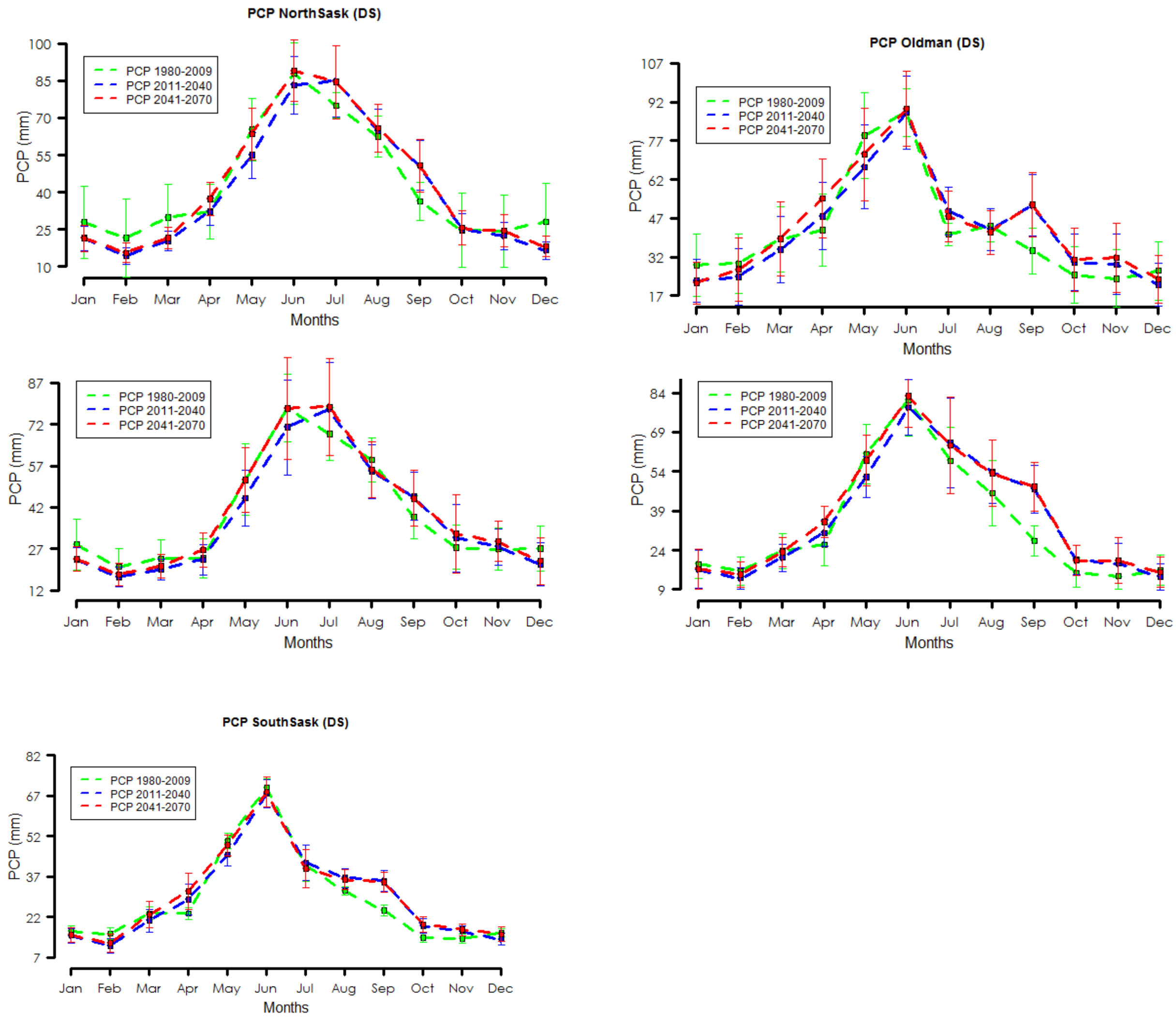
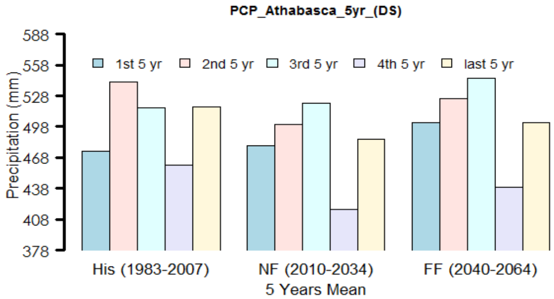
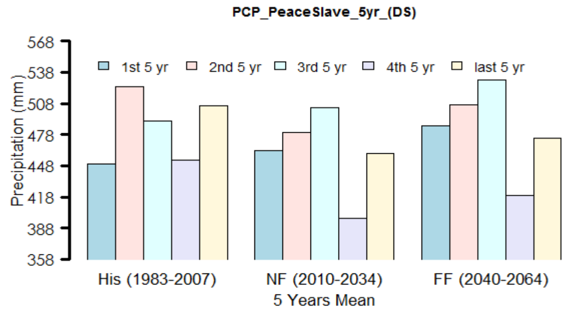
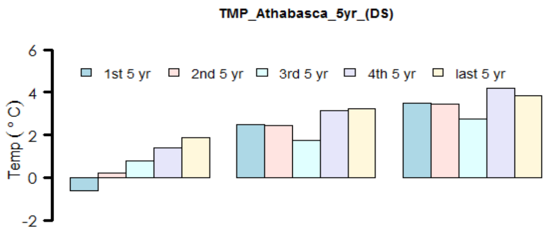
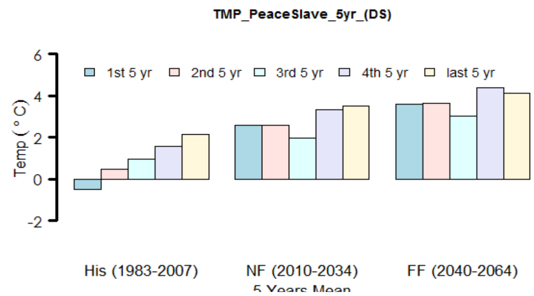


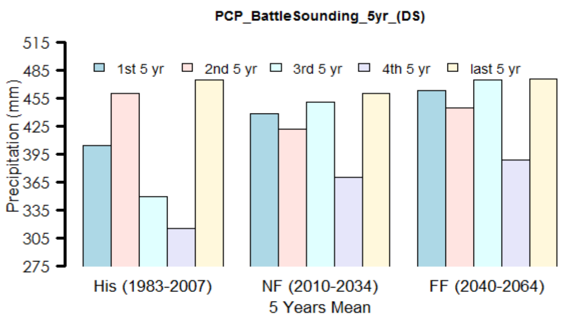
Figure 15. The long-term average monthly precipitation from various models and scenarios under downscaled (DS) condition in different watershed.

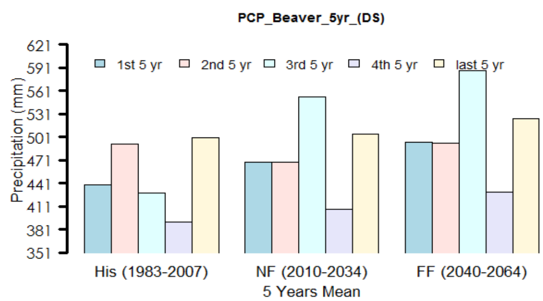

PCP_Athabasca_5yr_(DS)
Precipitation (mm)
588
558
528
498
468
438
408
378
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

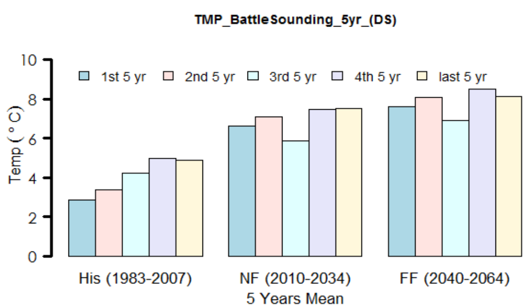

PCP_PeaceSlave_5yr_(DS)
Precipitation (mm)
568
538
508
478
448
418
388
358
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

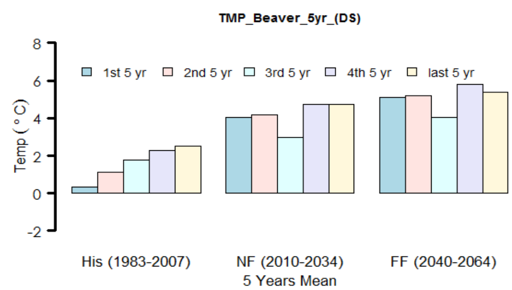

TMP_Athabasca_5yr_(DS)
Temp (° C)
6
4
2
0
-2
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr

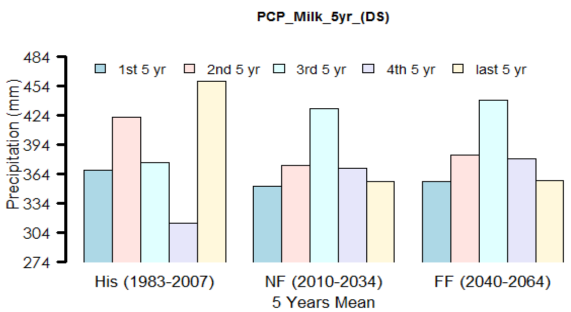

TMP_PeaceSlave_5yr_(DS)
Temp (° C)
6
4
2
0
-2
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)

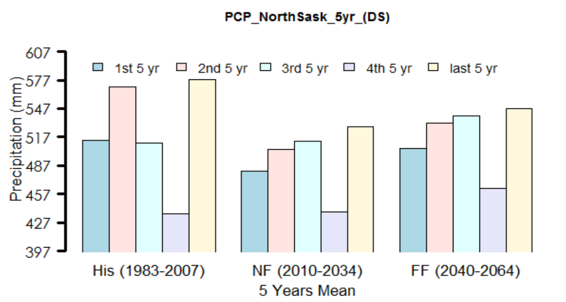

PCP_BattleSounding_5yr_(DS)
Precipitation (mm)
515
485
455
425
395
365
335
305
275
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

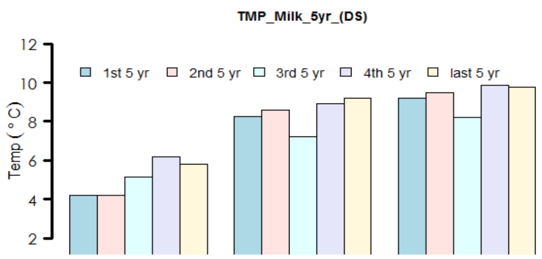

PCP_Beaver_5yr_(DS)
Precipitation (mm)
621
591
561
531
501
471
441
411
381
351
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

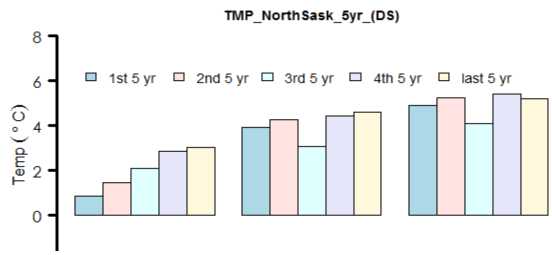

TMP_BattleSounding_5yr_(DS)
Temp (° C)
10
8
6
4
2
0
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

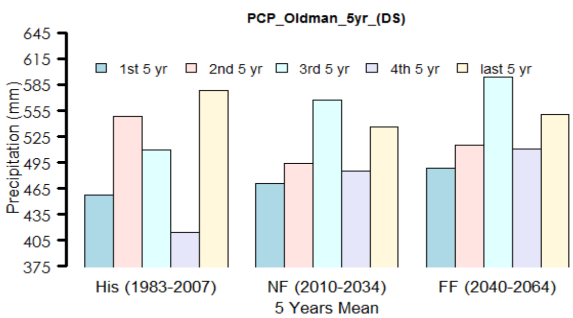

TMP_Beaver_5yr_(DS)
Temp (° C)
8
6
4
2
0
-2
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

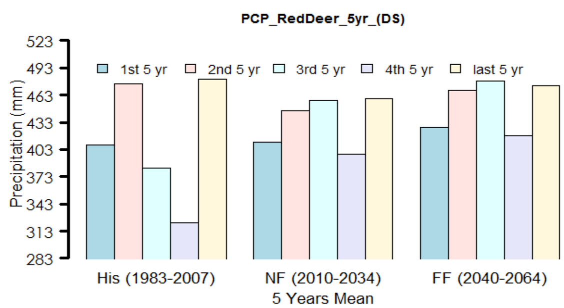

PCP_Milk_5yr_(DS)
Precipitation (mm)
484
454
424
394
364
334
304
274
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

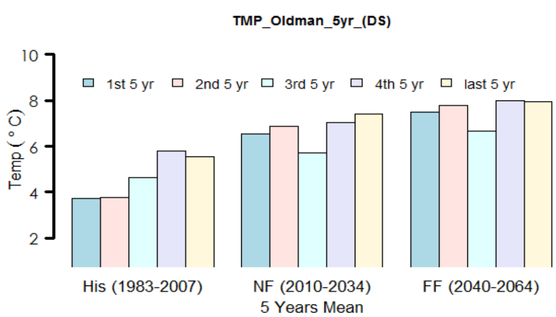

PCP_NorthSask_5yr_(DS)
Precipitation (mm)
607
577
547
517
487
457
427
397
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean

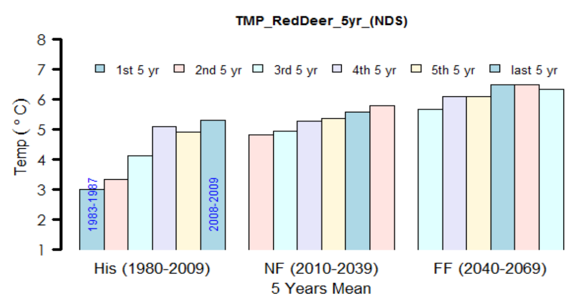

TMP_Milk_5yr_(DS)
Temp (° C)
12
10
8
6
4
2
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr


TMP_NorthSask_5yr_(DS)
Temp (° C)
8
6
4
2
0
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr


PCP_Oldman_5yr_(DS)
Precipitation (mm)
645
615
585
555
525
495
465
435
405
375
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean


PCP_RedDeer_5yr_(DS)
Precipitation (mm)
523
493
463
433
403
373
343
313
283
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean


TMP_Oldman_5yr_(DS)
Temp (° C)
10
8
6
4
2
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
last 5 yr
His (1983-2007)
NF (2010-2034)
FF (2040-2064)
5 Years Mean


TMP_RedDeer_5yr_(NDS)
Temp (° C)
8
7
6
5
4
3
2
1
1st 5 yr
2nd 5 yr
3rd 5 yr
4th 5 yr
5th 5 yr
last 5 yr
1983-1987
2008-2009
His (1980-2009)
NF (2010-2039)
FF (2040-2069)
5 Years Mean

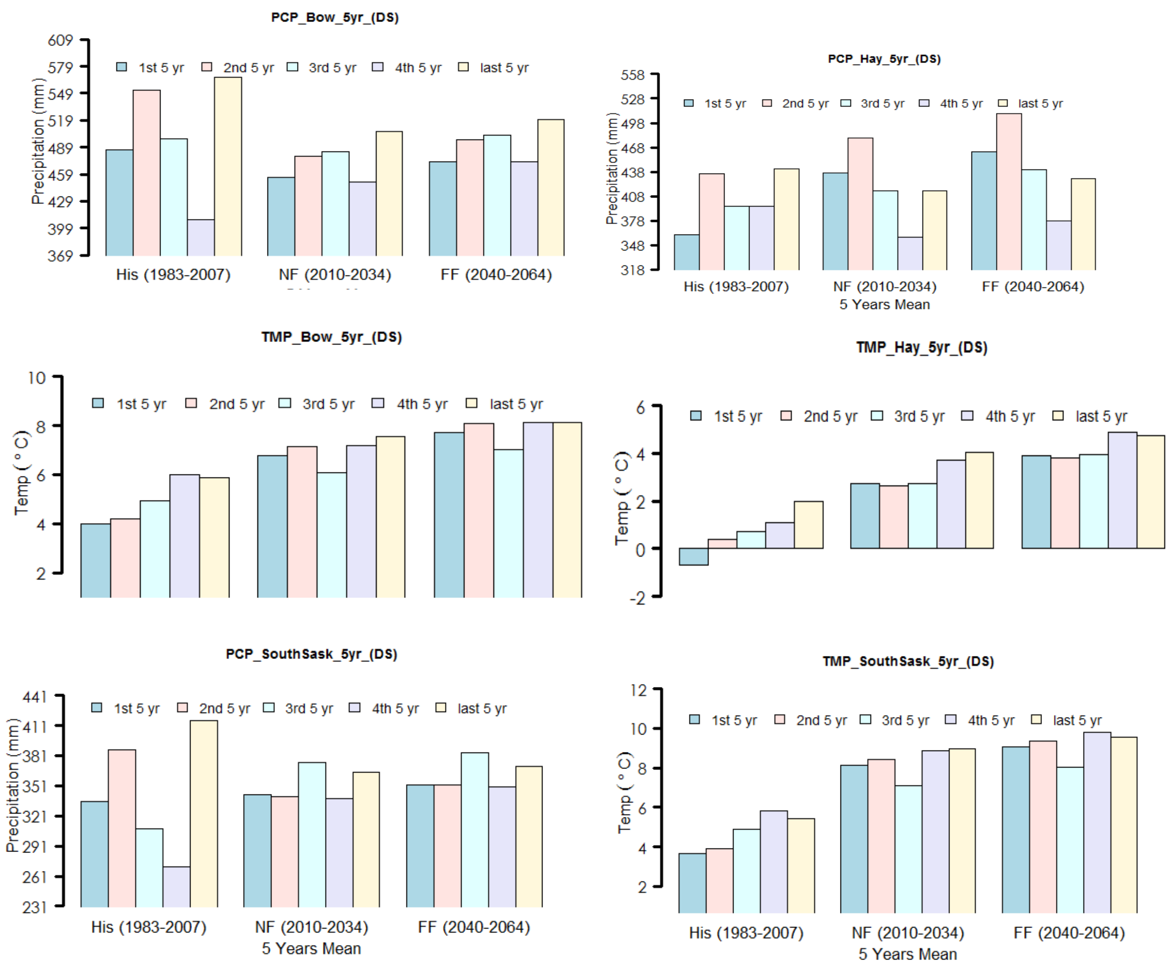


Figure 16. The five-year average precipitation and mean temperature from various models and scenarios for the historic and future periods.

2.7.1.3 Change in different types of water resources availability in the future

Using the weighted-area average data, it is found that the Peace-Slave river basin has the highest amount of blue water (BW) during the historic, NF (Figure 18) and FF (Figure 19) periods, followed by Athabasca and North Saskatchewan watersheds. In rest of the watersheds, the lowest amount of blue water is available in Milk and South Sask. watershed. The highest amount of PET is observed during the historic period, NF, and FF periods in Peace Slave watershed followed by Athabasca watershed. As the size of these two watersheds is large the mean PET of these two watershed is higher than 90 Km^3 Yr^{-1}. The lowest amount of PET is found in Beaver watershed which is around 10 Km^3 Yr^{-1}. All other watersheds have PET between 20 to 40 Km^3 Yr^{-1}.

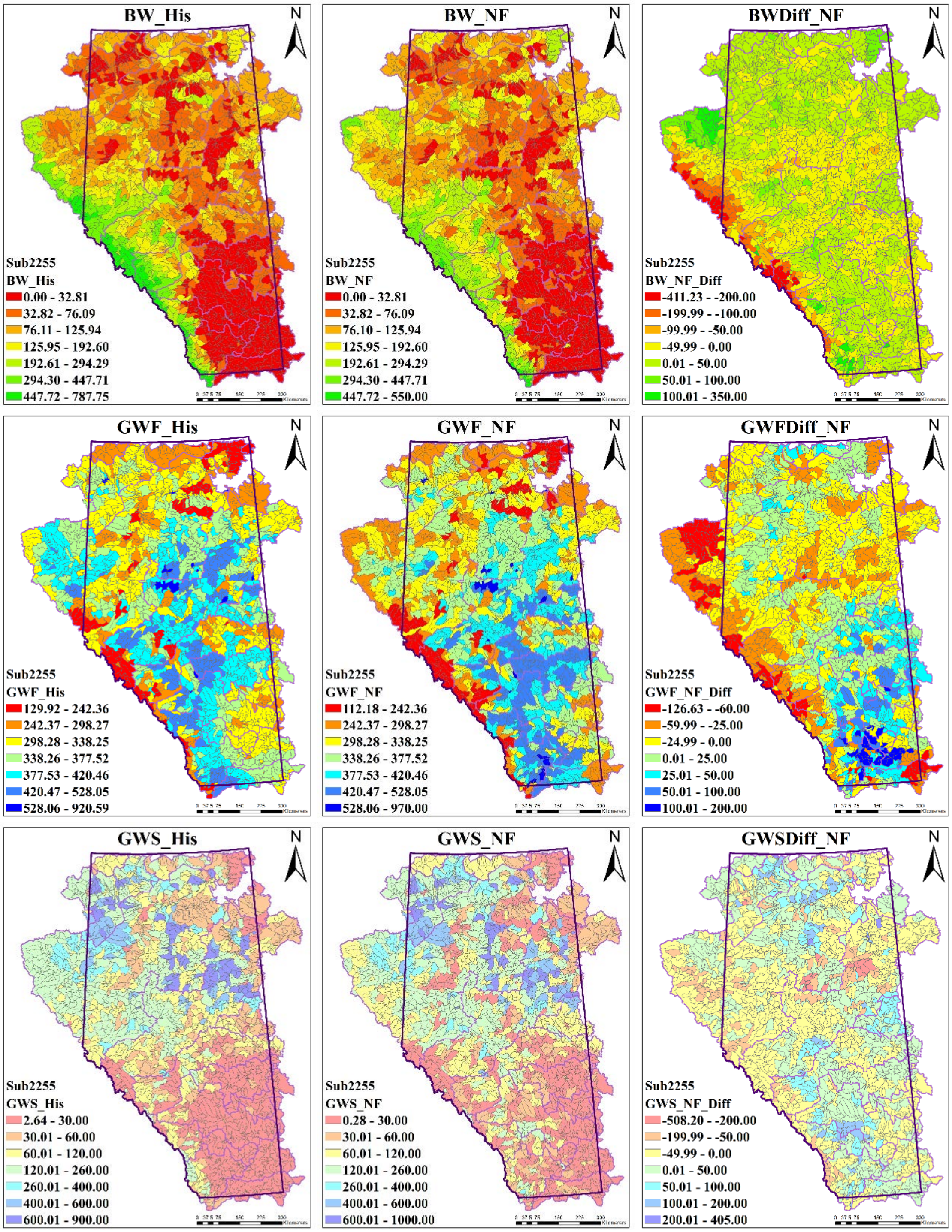


Figure 18. Subbasin based spatial pattern of blue water (BW), green water flow (GWF), and green water storage (GWS) for the historic (left column) and NF (middle column) periods. The right column shows the difference between NF and historic periods. The difference is calculated by subtracting historic data from future data. The NF data are based on the average projections of the models under RCP 2.6 scenario.

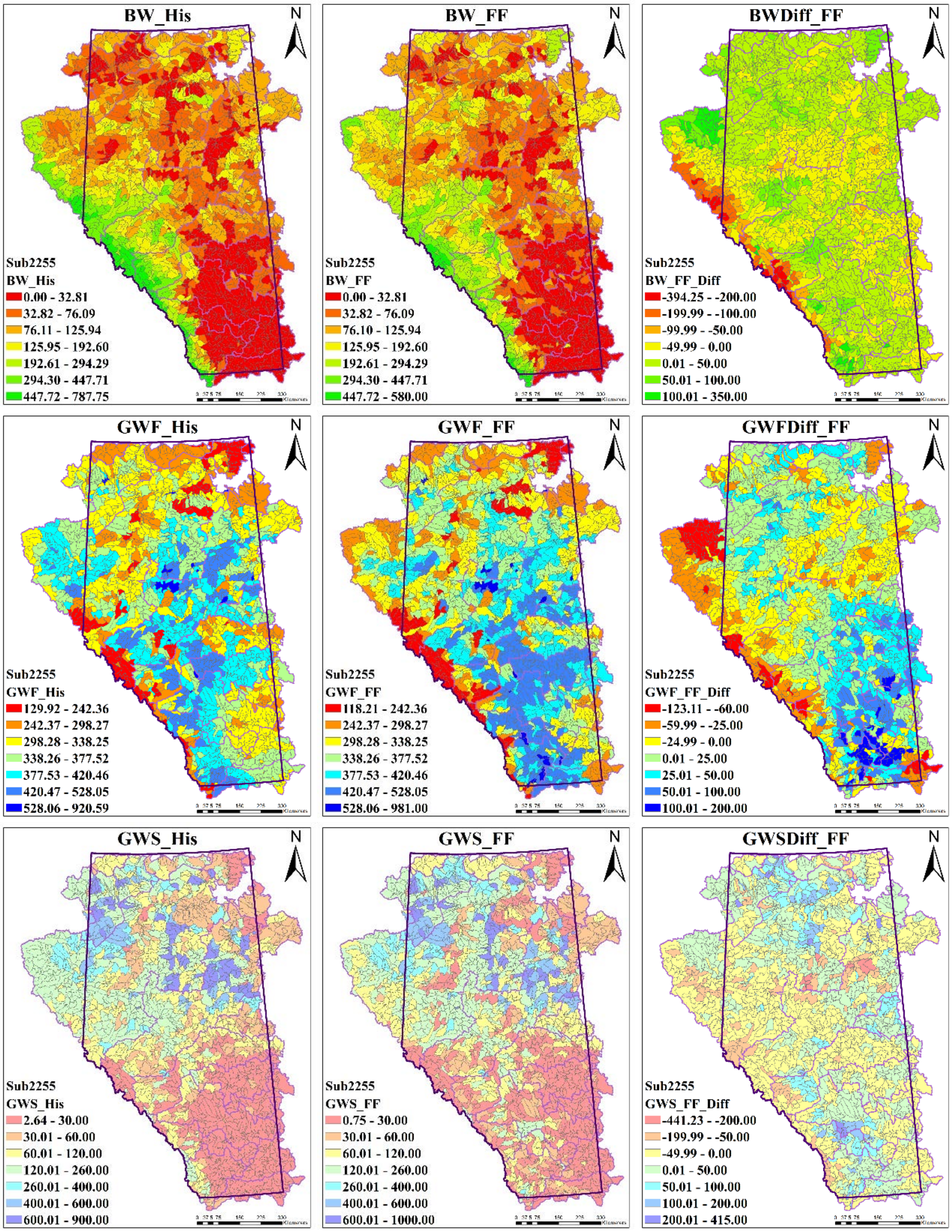


Figure 19. Subbasin based spatial pattern of blue water (BW), green water flow (GWF), and green water storage (GWS) for the historic (left column) and FF (middle column) periods. The right column shows the difference between FF and historic periods. The difference is calculated by subtracting historic data from future data. The FF data are based on the average projections of the models under RCP 2.6 scenario.

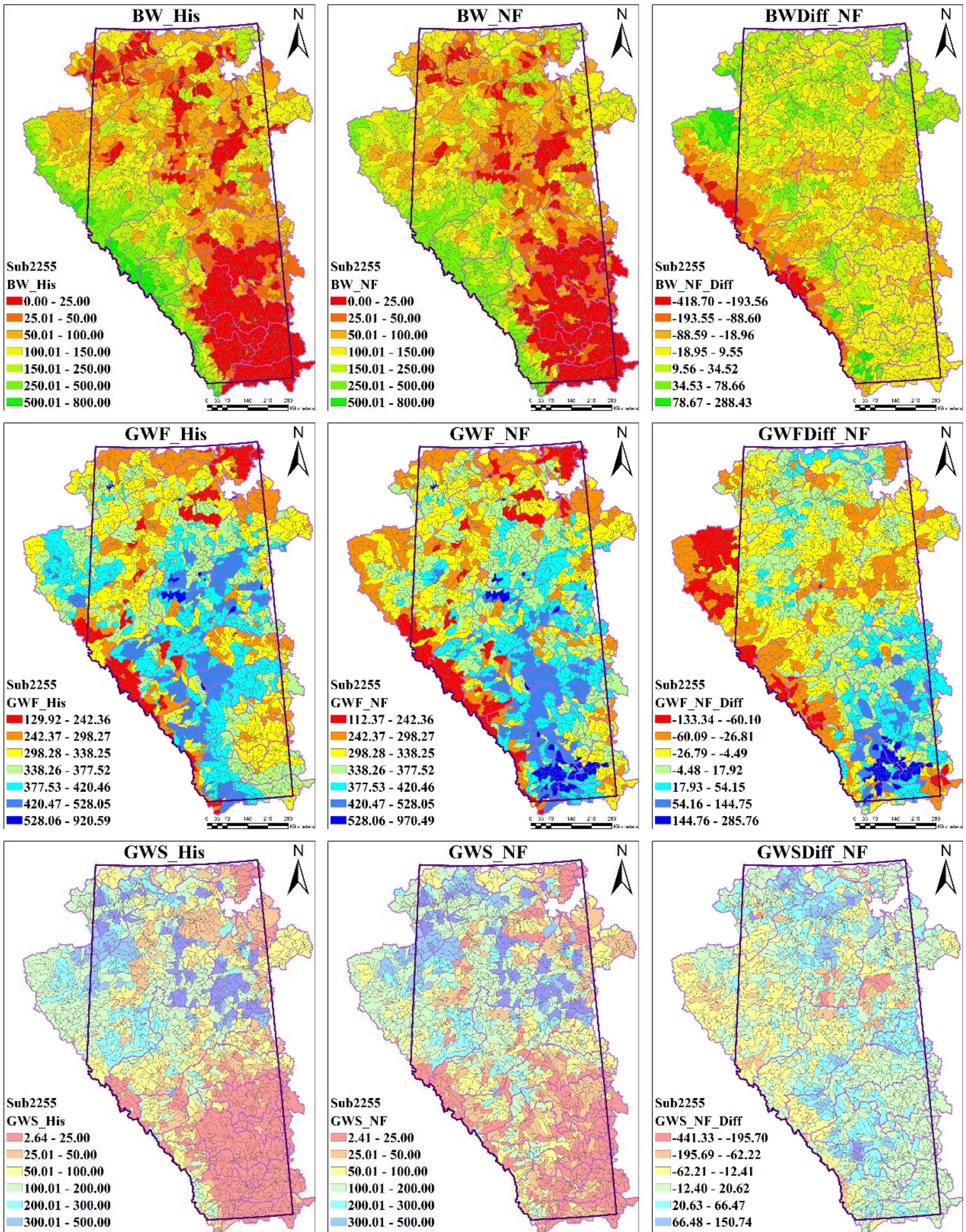


Figure 20. Subbasin based spatial pattern of blue water (BW), green water flow (GWF), and green water storage (GWS) for the historic (left column) and NF (middle column) periods. The right column shows the difference between NF and historic periods. The difference is calculated by subtracting historic data from future data. The NF data are based on the average projections of the models under RCP 8.5 scenario.

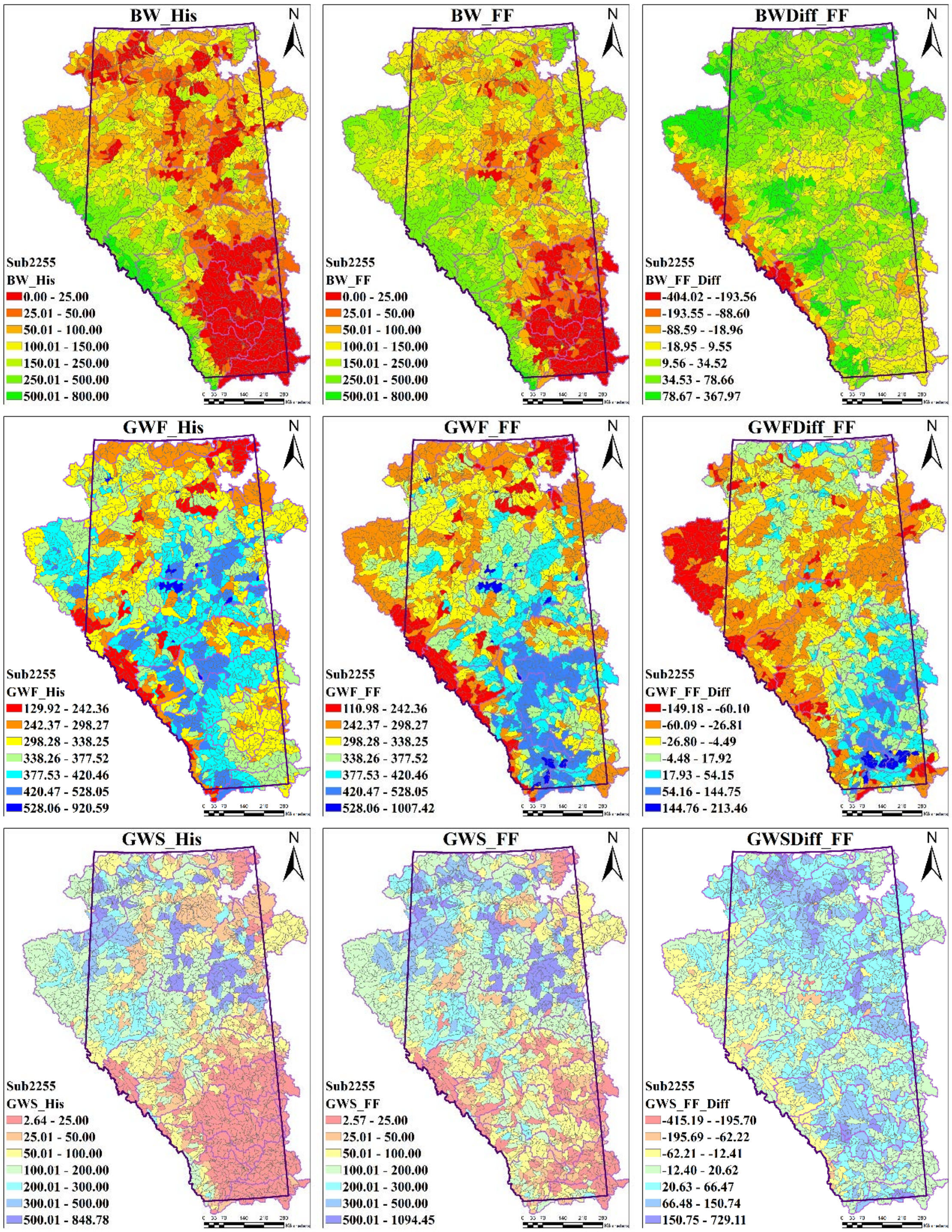


Figure 21. Subbasin based spatial pattern of blue water (BW), green water flow (GWF), and green water storage (GWS) for the historic (left column) and FF (middle column) periods. The right column shows the difference between FF and historic periods. The difference is calculated by subtracting historic data from future data. The FF data are based on the average projections of the models under RCP 8.5 scenario.

2.7.1.4 Groundwater recharge

The method to estimate groundwater recharge to each sub-basin of the province used area-weighted surficial geology, regionally-distributed precipitation, and allocated percentages of annual precipitation, as documented in the literature (and varying by sediment type).

Previous estimates of recharge for Alberta have been calculated by Alberta Environment (AENV, 2009). Using the "baseflow separation" approach, the average annual recharge volume was determined to be on the order of 15 to 25 billion cubic meters (or km^3). This estimate assessed by employing a second method of estimating recharge using a similar approach as the one used for this study (i.e., applying a percentage of average annual precipitation based on underlying sediment type). This approach resulted in a total provincial groundwater recharge volume of roughly 26 km^3 per year (on average).

Results of this assessment resulted in an overall estimate of 19 km^3 (see Table 13), which falls short of the previous estimate made by Alberta Environment by about 26%. The likely reason for the difference is the selection of differing recharge coefficients for each sediment type and their appropriateness based on documented values (Scanlon *et al.*, 2006; Beringer, 1987; Smerdon *et al*., 2008). Regardless of the difference, the new estimate falls within the 15-30 km^3 range previously reported (AENV, 2009). As a test of model sensitivity, the percentage of precipitation applied to each land and sediment type was varied equally for each land, sediment, and region type by +/-0.5%. This resulted in recharge values of 20.4 km^3 and 17.6 km^3, respectively.

Table 13. Distribution of estimated recharge in Alberta and calculated values compared to previous Alberta Environment 2009 estimates.

River Basin	Average recharge estimate for this study (mm/yr)	Previous AENV estimate using similar approach (mm/yr)	% of Previous Estimate	Area (km2)	Volume Recharge (km3/yr)
Athabasca	36.7	52.0	70.6	142,358	5.23
Beaver	39.2	47.0	83.5	15,264	0.60
Bow	15.0	36.0	41.5	25,287	0.38
Buffalo	31.0	--	--	13,948	0.43
Hay River	28.1	29.0	97.0	46,358	1.30
Milk	14.4	27.0	53.2	6,302	0.09
North Saskatchewan	31.2	45.0	69.4	92,863	2.90
Oldman	16.7	44.0	37.9	26,129	0.44
Peace	30.4	38.0	80.1	205,195	6.25
Red Deer	22.7	39.0	58.1	50,595	1.15
South Saskatchewan	12.5	21.0	59.6	19,181	0.24
Total	277.9	378.0	73.5	643,481	19.0

2.7.1.5 Groundwater stress

Groundwater use by sector was assessed for each major basin in Alberta, and indicates the differences between sector use of groundwater (i.e., municipal and agricultural in the south; oil and gas development in the north)

Projections of increased groundwater use by 2050 were achieved using groundwater use data provided by AENV 2007 (by major basin). Regression lines and associated equations were developed for each major river basin, and each sector, to allow calculated estimates to be established out to 2050. For most cases, regression lines were linear in character, and associated data points indicated a low degree of dispersion (R^2 = 0.85 to 0.99). Logarithmic regression lines were required to describe groundwater use projections for the petroleum sector for the Athabasca and Peace/Slave basins. In both cases dispersion of data points from the established regression lines was notable (R^2 = 0.76) but acceptable. Based on moderate case estimates, the top five basins showing the largest increase in groundwater use include (from highest to lowest):

- Athabasca
- Red Deer
- North Saskatchewan
- Peace/Slave
- Bow

Three basins also reveled a declining trend in groundwater use. These were (from highest to lowest):

- Beaver
- Hay
- South Saskatchewan

The results of the estimation process are provided Table 14.

Table 14. Estimation of changes in GW use by basin.

Basin	Total GW use in 2010 (m^3)	Projected GW use in 2050 (m^3)	Volume increase (m^3)	% Change
Milk	1,017,000	1,678,000	661,000	65
Oldman	6,893,000	10,783,000	3,890,000	56
South Saskatchewan	714,000	685,000	-29,000	-4
Bow	19,007,000	27,636,000	8,629,000	45
Red Deer	19,762,000	33,314,000	13,552,000	69
North Saskatchewan	23,478,000	34,760,000	11,282,000	48
Beaver	6,512,000	1,980,000	-4,532,000	-70
Athabasca	55,238,000	84,570,000	29,332,000	53
Peace/Slave	4,519,000	13,165,000	8,646,000	291
Hay	359,000	135,000	-224,000	-62
Total	**137,499,000**	**208,706,000**	**71,207, 000**	**52**

2.7.1.6 Future implications for groundwater (under human development)

Simulations of potential effects due to growth in several unlicensed and licensed water wells were conducted using an Analytic Element Model developed for the province. The code uses governing equations for groundwater flow and influences from various sinks on connected systems. Results of the modelling indicate several areas where notable effects may occur over the next 35 years (under the modelling assumptions of development growth). The main areas include: (see Figure 22):

- North and east of the City of Edmonton
- Cold Lake and area north towards Winefred Lake (northern Beaver River basin)
- the Athabasca Oil Sands mining area north of the city of Fort McMurray
- west of the Red Deer-Calgary corridor
- north of the town of Grande Prairie
- east of the town of Peace River

Simulations were conducted to include unlicensed and licensed groundwater withdrawals. Results indicated no notable change in the hydraulic head because of groundwater withdrawals ranging up to a drop of less than a 10% in some areas. However, up to 25% or more head decline was noted in areas where the greatest number of existing and projected unlicensed water wells exist (near the major population centers), and in areas where large industrial licenses exist to support either for oil sands mining activities or thermal in situ development.

Simulated influences on baseflow contributions to major watercourses were also conducted, with the most notable effects occurring in the lower reaches of the North Saskatchewan and Athabasca rivers (Figure 22). Reductions in baseflow contributions as much as 0.6 to 0.9 m^3/s, respectively (or approximately 19-28 million m^3/y), were simulated. When compared to annual median flows of those rivers (7 billion m^3 and 20 billion m^3, respectively) the decrease is on the order of 0.3% or less.

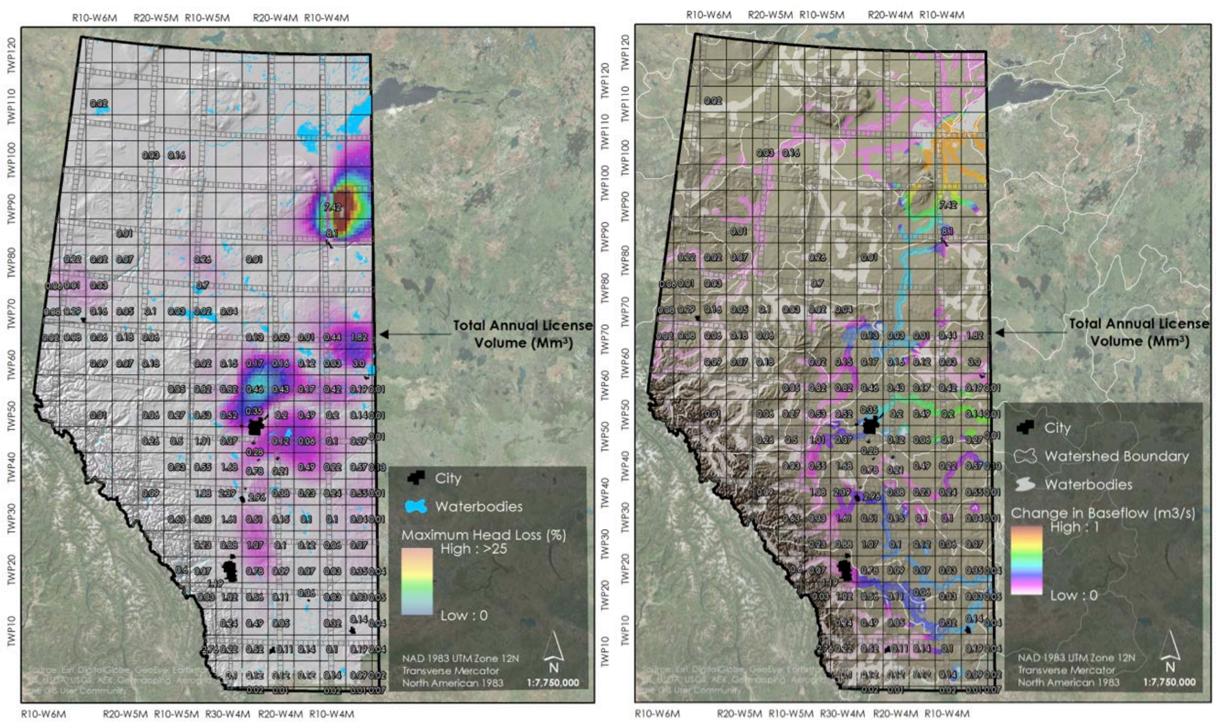


Figure 22. Locations of major projected drawdown impact by 2050 due to human development (left panel) and implications for baseflow contributions to major rivers (right panel).

2.7.1.7 Effects of climate change (and human development)

Effects of climate change on provincial groundwater resources (from 2010-2070) were assessed using output files of near-surface recharge provided by the SWAT model. Each sub-basin was modeled using an area-weighted approach to determine an average Specific Yield (S_y) value for each sub-basin was taken. Surficial geology, as mapped by the Alberta Geological Survey, was used to determine the unique S_y value for each sub-basin by taking the percentage of area within the polygon associated a particular sediment type, and then determining the intrinsic S_y value. Calculations were then conducted to determine the estimated change in water levels (increase or decrease) using the Water Table Fluctuation method (Healy and Cook, 2002).

Two climate change scenarios were assessed – RCP 2.6 (low severity) and RCP 8.5 (high severity) to bracket possible influences of future CO_2 forcings caused by human development out to the year 2100. Results from both downscaled and non-downscaled versions were incorporated. In general, impacts to the water table elevation were assessed to be minor (i.e., the range of ±3 m, and median values across all major basins of less than a 0.5m decline). The distribution of impacts from climate change (using the RCP 2.6 and 8.5 downscaled scenario) is shown in Figure 23.

A combined influence from climate change and human development were also conducted to identify areas of greatest possible future drawdown impact. The distribution of combined impacts is also shown in Figure 24. The most notable influences were found to occur in the oil sands development area and eastern North Saskatchewan basin, where projected drawdowns of greater than 65 m are simulated. The next most notable impact was east of the Red Deer-Calgary corridor where projections of up to 30 m of drawdown occur.

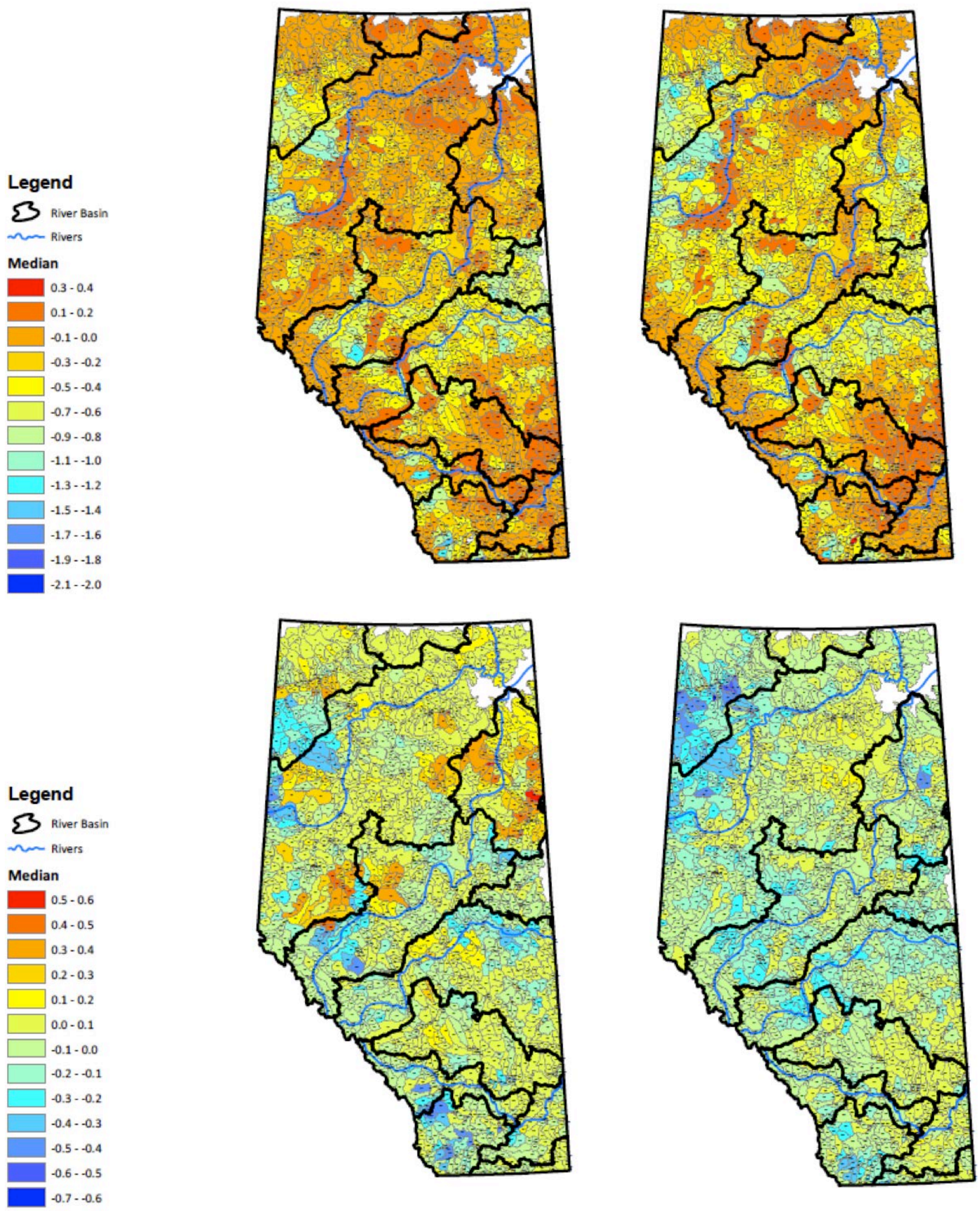


Figure 23. Distribution of projected median groundwater level changes for RCP 8.5 (upper panels) and RCP 2.6 (lower panels) scenarios.
Downscaled versions are on the left and non-downscaled version on the right *(NB positive values represent a water level increase).*

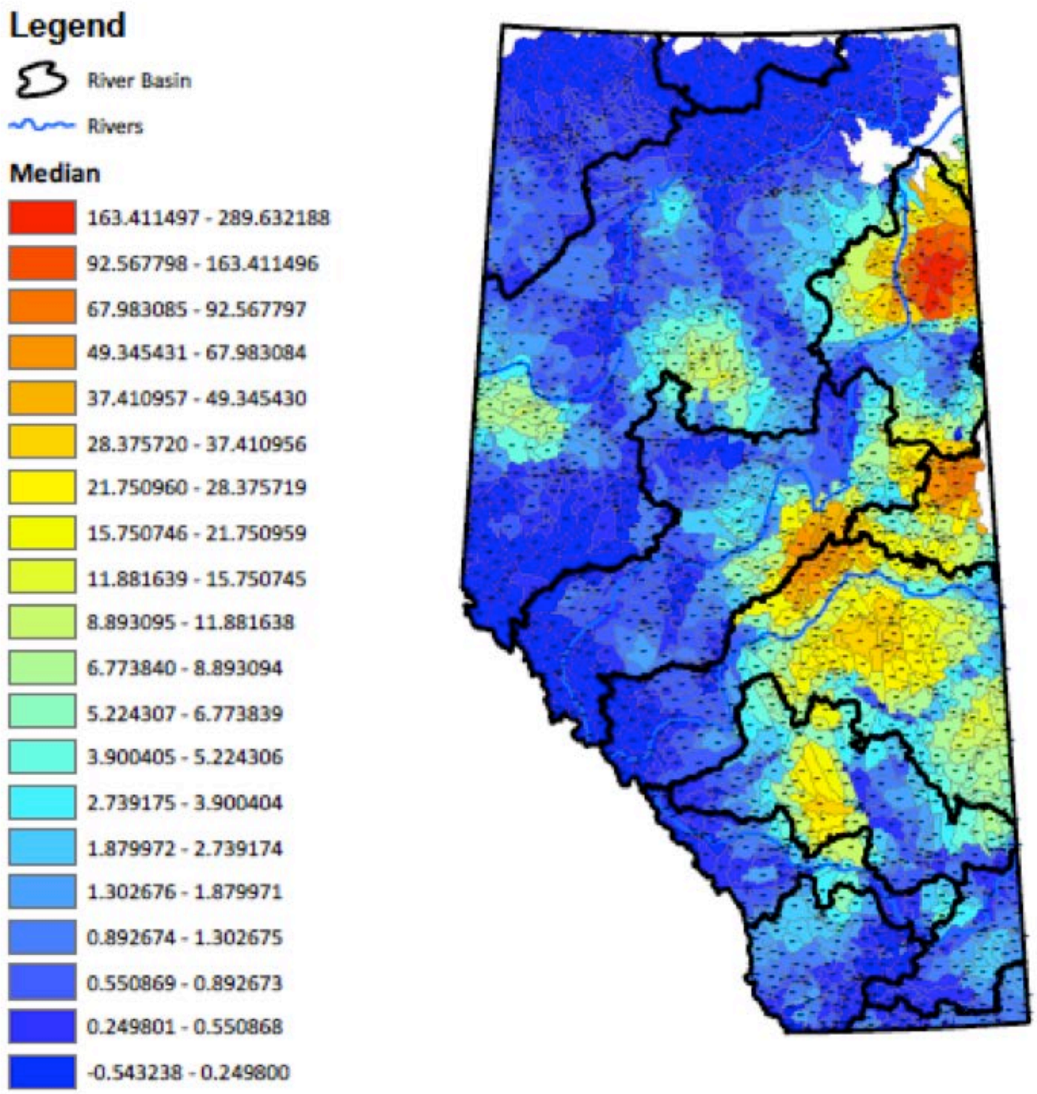


Figure 24. Distribution of projected median groundwater level changes due to climate change plus human development by the year 2070.
(NB negative values reflect a water level increase).

2.7.2 Economic assessment

Yield response to intra-seasonal climatic conditions for three major crops (i.e., barley, canola, and spring wheat) under irrigated and rainfed production in southern Alberta, Canada is investigated in this paper. A panel data approach with fixed effects is used that considers a variety of climate variables including seasonal growing degree days, overheat degree days, and monthly precipitation and temperature deviations. The effects of climatic conditions on aggregated crop yields are investigated using the estimation results. The empirical results for rainfed crops are consistent with several Canadian studies (e.g., Carew and Smith, 2006; Cabas *et al*., 2010; Robertson *et al.,* 2013); specifically, warming and increased precipitation tend to be beneficial for crop yields. The results also indicate that timing of precipitation and temperature deviations influences yields differently in terms of the size and significance of the impacts. For example, the precipitation impacts in May and June are smaller and less significant than July and August on crop yields. For irrigated lands, the positive effect of GDD still holds but the impact of precipitation tends to be negative in June and July. This may be because of "over irrigating" in the field due to unpredictable precipitation and risk averse responses by producers to the potential for droughts.

Using two regional projections of climate change, we forecasted that climate change results in decreased crop yields for all the three crops (barley, canola, and spring wheat) under rainfed production. Conversely, canola and spring wheat yields under irrigated production are likely to increase slightly. Irrigation is widely considered an important adaptation to changing production conditions under climate change. The forecasting results of this study also demonstrate this point. Samarawickrema and Kulshreshtha (2008) noted that in the South Saskatchewan River Basin, the higher productivity of irrigated farms was due to additional water supply relative to rainfed production. High summer temperatures increase plant evapotranspiration that is beneficial for crop growth when there is no moisture constraint. In addition, due to additional water availability, irrigation provides conditions conducive to growing high value-added crops such as potatoes and sugar beets, which are not normally planted under rainfed in the province. On the other hand, a warmer and longer growing season may benefit rainfed agriculture in Alberta if there is no moisture constraint. Climate change is projected to decrease stream flows in the basin, together with the requirement of irrigation infrastructure rehabilitation, indicating potentially higher costs and reduced premiums in applying irrigation to crop production.

3. Relevance and Impact

3.1 Important Lessons Learned

The results of the combined PAWF research effort provide a compelling picture of overall warming and changes in weather extremes for the Province of Alberta. It can be confirmed that Alberta's climate is warming stronger than the global average and that we are experiencing and will experience much greater winter temperatures, especially in the Northern regions of the Province. Annual average temperatures have increased already by 1 - 2°C in the South, and by 2 - 4°C in the North, with winters showing the strongest warming (up to 8°C), and summer the weakest warming (often 1°C or less). It is expected that these trends will continue, even under environmentally friendly scenarios (RCP 2.6). Generally, and with few exceptions, the number of very cold days, when the minimum temperature falls below -10°C, has about halved across Alberta since the 1950s, and the number of heatwaves has roughly doubled. Except for regions with high elevations, snowfall is being replaced by rainfall (because of shorter winters) and the growing season has already lengthened by between 2 and 5 weeks per year. This means that historical temperature records are no longer a true indicator of the future, and society must adapt to the new conditions.

By performing and combining multiple scenario analysis for each of the 2255 subbasins identified for the Province of Alberta, we have identified areas of extreme climate variability with a high degree of discordance between models. These areas, south and east of Calgary primarily, display the greatest variance in model predictions yet these areas overlap with the area of the greatest data acquisition suggesting that this is not an issue of data gaps but more an inherent climactic variability in this region of the Province. Though our investigation and recent data analysis of tree ring records by a team member (Sauchyn), we have come to understand the potential importance of long term oscillations in weather patterns in the Western Prairie regions termed the Pacific Decadal Oscillation. The importance of this oscillation is not yet currently accounted for in models using 25-35 years of historical data and integration of the PDO into the algorithms underlying the SWAT model is key to and improving resolution of projections of our model in regions influences by this weather pattern.

Assess the effects of climate change on Alberta's groundwater resources output from the University of Alberta's SWAT model has been used in conjunction with the WTF method. Results of this component of the groundwater assessment, as it applies to Alberta's water future, indicate that the implications for groundwater resources, from even the most conservative climate change scenario (RCP 2.6), are minor. At best, modelled changes to the water balance of the province results in a slight decrease in median water levels of less than 0.3 m, and more in the order of 0.1 m (as shown in Figure B and in Appendix 1). However, in some instances water level increases are projected across contiguous areas of the province (particularly in the northern half) as well as in some of the headwater areas of the eastern slope of the Rocky Mountains. Compared to the projected drawdown impacts related to human development over the next 55 years, the influence of climate change on Alberta's groundwater resources is minor by comparison.

The economic components of the project identified some important lessons that were previously not identified, to the best of our knowledge, in on-going research in this area. First, while the agricultural sector is particularly influenced by climate shocks, our analysis shows significant economy-wide impacts of climate shocks – especially temperature shocks. Second, within agriculture it is expected that irrigation provides a mechanism that increases resilience to climate shocks, however, we find that even irrigated areas are affected by adverse climate impacts, particularly precipitation increases in certain months. Finally, a projection of water use from 2010-2040 that is based on typical economic drivers shows that water use is expected to increase in Alberta over this period and agriculture will remain the largest water user with over 60% of Alberta's overall water use.

3.2 Prospective for Albertans

The results of the hydrological and climate analysis demonstrate that even under climate friendly scenarios, Alberta is going to experience large changes in the climate and subsequently, large changes in the hydrology of the province. We can expect colder and wetter spring months and warmer and drier winter months, with significant changes in snow pack, snow melt, timing and volume of river freshet and changes in overall water yield and water availability for the near (2010-2040) and far future (2040-2070) in the Province. Results of the groundwater assessment have revealed certain areas of the province where continued human development, and related groundwater use, may result in notable drawdown of available head in aquifers being used to support rural development and industries.

These findings will hopefully inform future monitoring efforts by provincial agencies to track changes that may occur in critical areas (over time) and assist with the development of suitable management actions/strategies to ensure the sustainability of Alberta's water supplies for use by Alberta's industrial and municipal sectors, while also ensuring sustainability/restoration of our environment. By providing both a spatial and temporal aspects of the changes in surface water availability, these results allow Albertans to understand and the specific spatial and temporal risks of changing hydrology on people and industries. Our model projections present an opportunity to prepare Albertans to adequately adapt to our water future to ensure a healthy environment and a healthy economy. Our economic analysis indicates potential severe implications, in terms of impacts on GDP, and specifically agricultural outputs, associated with climate change and climate variability. This information should be used as input in determining applicability and adequacy of future water demand management schemes and conservation practices, as well as mechanisms to improve the resilience of Alberta's economy to future climate and future hydrology.

3.3 Policy Regulation

In addition to numerous talks and presentations at scientific venues, our results have been shared in several venues with relevant stakeholders including the Water Policy branch of Alberta Environment and Parks, the intergovernmental Water Council, AEMERA, the WPAC's in various watersheds, numerous public interest groups, Alberta Watersmart and local governments (e.g. presentations to City of Edmonton and Strathcona county etc). More specifically regarding Water policy and integration of our results, Dr's Goss and Faramarzi, plus other team members, have recently been engaging directly with several working groups throughout the GoA to facilitate transfer of the information generated by these models to appropriate policy making bodies.

Importantly, outputs of the surface and groundwater assessments have been shared with the numerous industrial and other sectors including presentations to ABMI, COSIA, EPCOR, and City of Edmonton. Moreover, we have planned workshops as part of ongoing activities with the Beef producers and other stakeholders in Southern Alberta We are working diligently to ensure that the results are available if needed to help inform future policy and monitoring/management initiatives.

3.4 Immediate Benefits and Future Impacts

The results of the funded PAWF study will directly impact our current decision making about preparing for future climate change induced impacts on our surface and groundwater supplies. The development of a calibrated dynamic water projection model is important to provide a solid, scientifically sound set of results to allows water managers to prioritize scarce funding and establish temporal and spatial plans for resource allocations for climate adaptation policy. Results of the surface and groundwater assessments will hopefully raise awareness of the future changes in water availability and allow for dynamic planning tools to be developed that allow for as support of communities and industries reliant upon adequate water for future economic and environmental sustainability. Knowledge of the inventory and possible future pressures will assist with management initiatives, and possibly impetus to enact adaptive management strategies including drought-proof our communities, industries and environmental that rely on water.

4. Overall Conclusions

This is the first large scale dynamic hydrological model of the Province of Alberta that described the spatial and temporal aspects of hydrology in detail. Prior to the project, the water modelling for the province of Alberta was either fractured into smaller geographical units, modelled with low resolution and limited datasets or eliminated significant components (e.g. glacier inputs, groundwater etc.) from the hydrological analysis. Our team combined to develop a comprehensive, calibrated and integrated dynamic water model of Alberta at the Provincial scale. This was a monumental effort and a significant achievement of the Predicting Alberta's Water Future (PAWF) grant was bringing together some of the leading water research modelling teams within the Province to work collaboratively to develop this model. As a result, this water model of the province was achieved by collecting and compiling significant amounts of geo-spatial and climate data from various sources for the province. Furthermore, rather than running only a few scenarios, we compared 8 global climate models (GCMs) and global warming scenarios were used to assess range of plausible conditions on water availability in 2255 delineated sub basin in the Province on a monthly time step for the 2010-2040 (near future), and 2040-2070 (far future) period. All sources of uncertainties associated with input data, hydrologic model, climate change models, and global warming scenarios were quantified. The water supply components included 'renewable water', 'fossil water', and recently through a complementary project the 'virtual water', in 2255 sub-basins in the province. For the renewable water resources, the project allowed quantification of blue water (i.e., surface water plus deep aquifer recharge), green water flow (i.e., actual evapotranspiration), green water storage (i.e., soil moisture), and stream flow in the province. For the fossil water a hydrologic model of glacier melting process was developed that allows quantification of fossil glacier water on monthly-daily time step and its contribution to the existing renewable water resources in the mountainous highland areas of the province. Finally, the economic analysis conducted suggest key areas for refinement of practices still exist in irrigated areas, at least with respect to past practices for operations of irrigated versus not-irrigated area. However, this study was hampered by a lack of finer scale spatial and temporal information regarding crop production and economic indicators (e.g. GDP)

Regardless of some of the abovementioned shortcomings with respect to economic analaysis, this model now allows for integration with scenarios of future demand to assess sector-based risks and opportunities, and for integration of future water availability (at both provincial scale and sub-watershed scale) into government policy and planning.

5. Future Steps

5.1 Technology and Research Gaps

While the developed model gives a reasonably high level of confidence in water availability and water projections for many areas of the province in the near and far future, there are still needs for further improvements/refinement to increase confidence on some areas with high climactic variability. Furthermore, given the rather large changes in hydrology, surface water availability and groundwater recharge and availability as outlined, it is imperative that adaptational responses by industry and policymakers alike responds to these future scenarios to both mitigate the possible environmental and economic risks in areas with altered water yields and take advantage of the opportunities afforded by seasonal water availability because of climate change. A more rigorous system of impact modelling would be useful to refine some of the results generated by this study. It is understood that the AGS is currently addressing this need under the PGIP (provincial groundwater inventory program); therefore, any future efforts would need to be coordinated with this agency. A more refined understanding of actual recharge is warranted either through further research, measurements, and calculations. This will enhance any future water balance assessment, and inform proper resource allocation decisions. The establishment of enhanced water level and groundwater quality monitoring in areas currently devoid of such monitoring would provide the basis to assess the efficacy of future impact projections in key areas of the province.

There is a clear need to further refine models of glacial melt in the more northern basins since the model developed only used projections of glacial melt from the Haig glacier and applied these across the provincial scale. Similarly, the developed model used simplified assumptions regarding

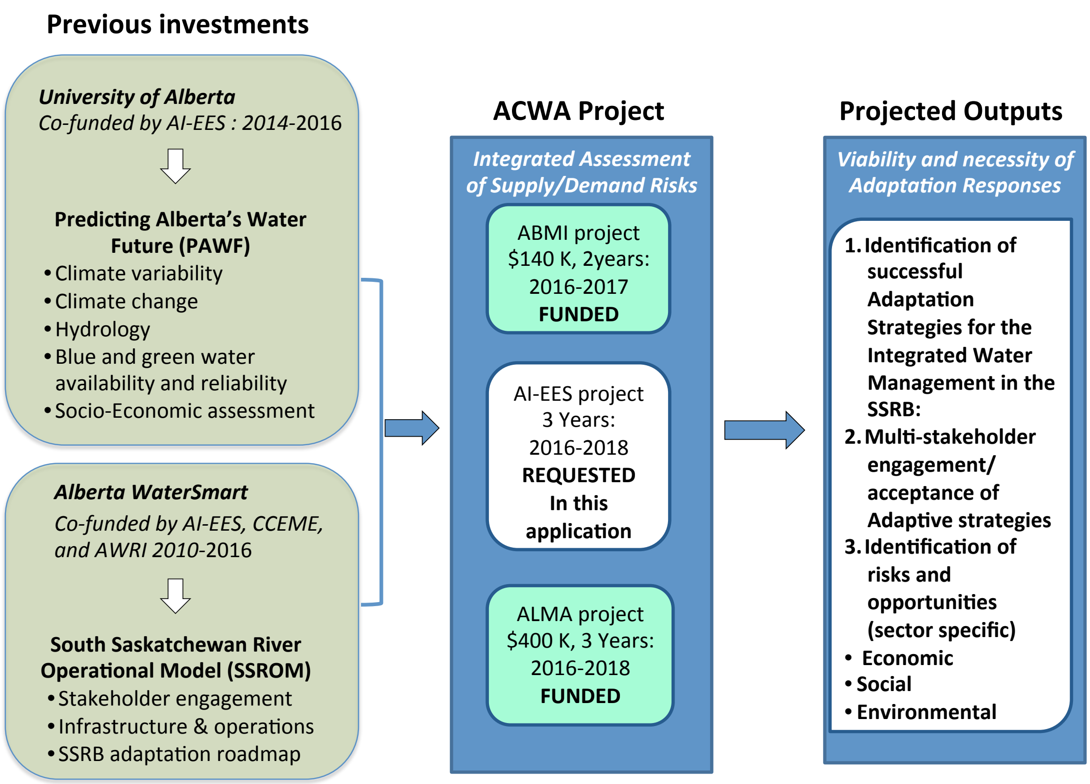
5.2 Implementation Barriers

One of the biggest implementation barriers for this type of modelling has historically been a lack of computational infrastructure able to handle these very large datasets and computationally intensive modelling exercises. With the recent investments in Dr Faramarzi through the CAIP chair program and the funds provided by the Faculty of Science to Dr Faramarzi, these barriers to implementation are being alleviated somewhat. The recent announcement from the Government of Canada (Budget 2017) to improve implementation of high capacity computational infrastructure is welcome news in the computational community. In the meantime, we are working diligently with stakeholders to encourage uptake and implementation of our results into industrial operational plans or private/public system projections.

A significant implementation barrier is that the model, once developed, requires expertise to extract the large amounts of data generated. While we are working as diligently as possible to get the information to stakeholders, including the GoA, we find that resources needed to extract the necessary information to be generally unavailable. Similarly, the expertise to work with these advanced projections is limited within the government and industry. Therefore, support for advanced teaching and training in modelling is essential to improve implementation of data generated by these advanced modelling programs.

5.3 Next Steps for Research Innovation

The result of this PAWF project established a key basis to convey to stakeholders the risks and opportunities to their future growth scenarios because of changes in future local water availabilities. Long-term integrated water management requires all sectors of the economy: agriculture, ecosystem services, municipal, industrial and energy (both oil and gas and hydroelectric) to collaborate to ensure there is enough water, when we need it, to ensure a strong economy. To facilitate these results being used in industry, government and the public, we have developed three projects with the 'Adapting to Changing Water in Alberta (ACWA)' as a compiling project that will integrate the results of our PAWF water supply projections with the water demands of agriculture as measured through our other project, funded recently by Alberta Livestock and Meat Agency (ALMA), and the a third project addressing the future water needs of ecosystem and wetlands funded by Biodiversity Monitoring Agency (ABMI). While these grants will be held separately (for accounting reasons), the overall goals of the three grants align towards the projected outputs of ACWA (see the following figure).



Specifically, the next steps we envisage as follow up research projects are to:

1) Integrate process-based ground water simulation model with the surface water simulation model developed through PAWF project. This integration facilitates management of future surface and ground water supply and demand as linked resources.
2) Leverage the parallel (cash contribution) WD scenarios of a recently funded 3-year project ($400 K total funding) by Alberta Livestock and Meat Agency (ALMA) in 2016, entitled "Predicting Water Related Risks and Opportunities for Beef Industry". This project will assess impacts of climate change on WD of beef (feed to meat) in Alberta under irrigated and rainfed conditions and various production systems (i.e., grazed, industry, mixed) taking hydro-climatic, economic, agro-management factors, and climate change scenarios and models into account. This grant supports our understanding of "agricultural demand" as a key component of integrated water management for the Province.
3) Leverage WD data of a 2-year project ($140 K total funding) by Alberta Biodiversity Monitoring Institute (ABMI) in 2017, entitled "Predicting ecosystem risks and opportunities resulting from adaptation measures and agricultural/industrial/municipal water use". This project will assess dynamic relationships of water availability at local and provincial scales to examine the consequences for ecosystem services provided by wetlands, with emphasis on the impacts of wetland management and reclamation. This grant supports our understanding of "ecosystem services" as a key component of integrated water management for the province.
4) Link WD of the step 2 (agricultural demand) and 3 ("ecosystem demand") with demands of other key water use sectors (hydropower, municipal, industry, oil and gas) as provided by Alberta Water Smart. Recently, the WD scenarios have been developed for the South Saskatchewan River Basin (SSRB). We will conduct exclusively with the SSRB stakeholders to inform them of risks to their WD scenarios. However, it should be noted that the integration of WA and WD scenarios as provided by this project for the SSRB will inform us how to integrate WA/WD scenarios for other basins in Alberta. This project will then allow us to develop accurate roadmaps to explore opportunities and risks in the face of climate change and climate variability.
5) In parallel, we will continue to improve existing water supply scenarios by integration of longer-term trends in climate variability (e.g. Pacific Decadal Oscillations (PDO)) into existing models of water supply to better project future WA.
6) Involve both stakeholders and policymakers to improve/validate existing strategies of the SSRB Adaptation Roadmap using the models and data of steps 1-4. We propose to iteratively examine proposed potential mitigation strategies (e.g. changes in cropping patterns that affect water use, changes in land area under irrigation in concert with land use patterns, effects of changes in allocations/demands by different sectors) and feedback to our stakeholders on the likely impact regarding congruence between WD and WA and WS. To this end, AWS has strong stakeholder relationships in the SSRB while the UofA team have been closely communicating and collaborating with several industries, NGOs, stakeholders to communicate our WA and WS results within GoA. We have given a number of workshops to discuss and translate our model results of water availability with Alberta Geological Survey and Alberta Environment and Parks in Water Policy Branch.

6. Communications Plan

We have been very active in communicating our research findings through various formal and informal occasions. We have presented, discussed, and engaged local, national and international audiences to communicate, inform, and take feedback from various scientific, policy and public communities. We have presented and published our results in local, national, international conferences and workshops with the very recent one on AEP Modelling Workshop on March 16-17, where most of their internal modelling projects and very few external ones (e.g., the PAWF project) were presented. The methods, results, and application have been discussed within GoA through sequential meetings conducted at various levels (i.e., stakeholders, policy makers and planners, experts and modellers) within Alberta Environment and Parks, Alberta Agriculture and Forestry, and other dependent institutions in the province. We have given numerous public presentations and been featured in A more detailed list of our peer-reviewed publications, the conferences, meetings, symposium is provided in section 7.2.

7. Scientific Achievements

7.1 HQP Development

Name	Level of training	Project
Samaneh Ebrahimi	Ph.D.	Development of energy balance models to simulate mountain glacier melt from downscaled reanalysis or climate model data, which were adapted to 'mountain range scale' for ensembles of glaciers for the PAWF simulations
Samira Samimi	M.Sc.	Glacier hydrology research in the Canadian Rockies, to establish delays in meltwater runoff associated with meltwater storage and refreezing
Adrienne Schumlich	BSc	Database development for Alberta glaciers, topographic characteristics (slope, aspect, elevation distributions), and hydrological catchments, for distributed glacier melt modelling
Parisa Rahimian	RA	Climate model downscaling and distributed glacier melt modelling for future climate change projections in the Canadian Rockies
Rufa Doria	PDF	Analyses of RCM data
Charmaine Bonifacio	M.Sc.	Development of ACRU tools to automate many spatial analyses and parameterization tasks, and apply ACRU for watersheds in the Oldman River Basin – MSc was successfully defended in Oct. 2016
Colin Langhorn	M.Sc.	Setup of Alberta databases needed for climate trend analyses, including soils data, and setting up crop yield models in

		southern Alberta – MSc successfully defended in Apr. 2016
Tim Anderson	M.Sc.	Climate change impact simulations in the Castle River Watershed – successfully defended in Aug. 2015
Markus Mueller	RA	Carry out database and GIS work to support project deliverables
Amr Gharib	Ph.D.	Assessed state of the art methods in the flood and drought assessment and applied the Threshold Level Method for flood and drought analysis in Alberta watersheds (provincial coverage) using the historical flow predictions of the SWAT hydrological model
Jannatul Ferdous	RA	Climate change data gathering, report writing.
Christine Clark	RA	Expend the 1950 to 2010 climate trends web page to include 43 (instead of the current 6) climate indices
Joy Li	R.A.	Administrative and climate change report writing, editing and key support for PI's/
Juliia Andreichuk	M.Sc.	Research on projected water supplies from the South Saskatchewan River and statistical downscaling of hydroclimatic data from RCMs
James Dickenson	M.Sc.	Development of paleohydrology models for the Rocky Mountain watersheds
Lisette Beets	M.Sc.	Integrating GW and surface water hydrology in Fox creek basin
Wes Lu	RA	Incorporated "blue water" variables (the output of SWAT model) into the VARX (Vector Autoregression with Exogenous variables) model employed in his thesis to compare the results with the original VARX model results and investigated the economic resilience of irrigated versus non-irrigated crop production in a river basin in Alberta under the framework of climate change. Compiled a database and model structure to form the basis for the optimization modelling under alternative water availability scenarios.
Hawley Campbell	RA	Constructing the mathematical programming model to examine agricultural sector outcomes under alternative water availability scenarios.

7.2 Publishing and Conference Presentations

6.2.1 Peer-Reviewed Journals:

- Monireh Faramarzi, Raghavan Srinivasan, Majid Iravani, Kevin D. Bladon, Karim C. Abbaspour, Alexander J.B. Zehnder, and Greg G. Goss. Setting up a hydrological model of Alberta: data discrimination analyses prior to calibration. Environmental Modelling & Software. 74 (2015): 48-65. DOI: 10.1016/j.envsoft.2015.09.006.
- Monireh Faramarzi, Karim C. Abbaspour, W.L. (Vic) Adamowicz, Wei Lu, Alexander J.B. Zehndere, Greg G. Goss, Uncertainty based assessment of dynamic freshwater scarcity in semi-arid watersheds in Canada. Journal of Hydrology: Regional Studies (Accepted Nov 25, 2016).
  Amr Gharib, Evan Davies, Greg Goss, Monireh Faramarzi. Assessment of the combined effects of threshold selection and parameter estimation of Generalized Pareto Distribution with applications to flood frequency analysis: Case study Alberta, Canada (under preparation).
  Faramarzi *et al*., Assessing the impacts of climate change and variability on freshwater resources in Alberta (under preparation)

  Wei (Wes) Lu, Wiktor (Vic) Adamowicz, Scott Jeffery, Greg Goss, Monireh Faramarzi, Crop Yield Response to Climate Variables on Rainfed versus Irrigated Lands, (Submitted to Canadian Journal of Agricultural Economics, under review)
- Wei (Wes) Lu, Sandeep Mohapatra and Wiktor (Vic) Adamowicz. Economic impact of climate change on the Alberta economy; a VARX approach. (MSc thesis, defended).
- Bash, E.A.R. and S.J. Marshall, 2014, Estimation of glacial melt contributions to the Bow River, Alberta, Canada, using a radiation-temperature melt model. *Annals of Glaciology*, 55, 138-152.
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- Samimi, S. and S.J. Marshall, in press. Diurnal cycles of meltwater percolation, refreezing and drainage in the supraglacial snowpack of Haig Glacier, Canadian Rocky Mountains. *Frontiers in Earth Science – Cryospheric Sciences*.
- Marshall, S.J., S. Ebrahimi, A. Shumlich and P. Rahimian. Projections of future glacier runoff in the Canadian Rocky Mountains. In preparation for *Water Resources Research*.

- Sauchyn, D. and Kerr, S. 2016. Drought from a Paleoclimatic Perspective, Chapter 2 in: Harry Diaz, Margot Hurlbert, James Warren (Editors), Vulnerability and Adaptation to Drought: The Canadian Prairies and South America, University of Calgary Press.
- Sauchyn, David; Bedoya, Mauricio, González-Reyes, Álvaro; Muñoz, Ariel; Velez Upegui, Jorge Julian. In press. ENSO Signals and Impacts along a Semiarid to Humid Transect Across the Americas. Proceedings of the 9th Biennial Rosenberg International Forum on Water Policy, University of Southern California.
- Barrow, EB and DJ Sauchyn. In press. An Analysis of the Performance of RCMs in Simulating Current Climate over Western Canada. Thee International Journal of Climatology.
- Bonsal, B, Cuell, C, Wheaton, E, Sauchyn, D and Barrow, E In Press An Assessment of Historical and Projected Future Hydro-Climatic Variability and Extremes over Key Southern Watersheds in the Canadian Prairies, International Journal of Climatology
- Gurrapu, Sunil, Jeannine-Marie St-Jacques, David J Sauchyn, and Kyle R Hodder, 2016 The Influence of the Pacific Decadal Oscillation on Annual Floods in the Rivers of Western Canada Journal of the American Water Resources Association, 52(5):1031-1045 DOI: 101111/1752-168812433
- Andreichuk, Iuliia; Dena McMartin, David Sauchyn 2015 Long-term availability of water for solution potash mining in Saskatchewan, Proceedings of Mine Water Solutions in Extreme Environments, April 12-15, 2015, Vancouver, Canada, InfoMine © 2015, ISBN: 978-0-9917905-7-9
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- Kienzle SW: Has it become warmer in Alberta? Mapping trends of temperature climate indices for the period 1950-2010 across Alberta, Canada. Canadian Geographic (Accepted with revisions)

6.2.2 Media

- Troy Media, Reported by Stefanie Kletke, 2014, Creating a picture of Alberta's Water Future, Available at: http://www.troymedia.com/2014/09/07/creating-a-picture-of-albertas-water-future/
- New Technology Magazine, 2014, The Water Question: Predicting Alberta's Water Future, Available at: http://www.newtechmagazine.com/index.php/oilpatch-news/feature/11404-the-water-question
- Greg Goss, Monireh Faramarzi, 2015, Predicting Alberta's Water Future (PAWF), In: Alberta Water Report 2015: Bridging the Gaps Between Science and Business, German-Canadian Centre for Innovation and Research. Available at: https://lnkd.in/eaNaKX4

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- Kienzle SW Dec. 11, 2015: **Newspaper article** in The Producer: *It's not your imagination: winters are really getting warmer*
- Kienzle SW Dec. 19, 2015: **Newspaper article** in St. Albert Gazette: *Yes – it's getting warmer*.
- Kienzle SW Dec. 22, 2015: **U of L News Release**: *New U of L website highlights Alberta's warming climate*, with colour map
- Kienzle SW Dec. 23, 2015: **Radio interview** with CJOC: *New web site developed at University of Lethbridge tracks Alberta climate trends*
- Kienzle SW Dec. 23, 2015: **Radio interview** with Country 95.5: *U of L develops database to track climate change in Alberta*
- Kienzle SW Dec. 23, 2015: **Newspaper article** in Pincher Creek Voice: *New U of L website highlights Alberta climate records*
- Kienzle SW Dec. 30, 2015: Front Page **Newspaper article** in Lethbridge Herald (with colour map and continuing on Page 2): *New U of L Website highlights Alberta's warming climate*
- Kienzle SW Jan. 04, 2016: **Radio interview** on CBC Edmonton
- Kienzle SW Jan. 05, 2016: **Live Radio interview** on CBC Calgary – The Eye Opener
- Kienzle SW Jan. 08, 2016: **Global News Lethbridge TV** feature
- Kienzle SW Jan. 14, 2016: **Global News Edmonton TV** feature (podcast available)
- Kienzle SW Jan. 19, 2016: **Radio Interview** with Country 95.5: Impact of climate change to producers (all day on news)
- Kienzle SW Feb. 08, 2016: Co-hosted Science Radio and TV-Correspondent **Bob McDonald** (co-hosting, transportation, meetings, socializing)
- Kienzle SW Mar. 22, 2016: **Radio Interview** with Corus Entertainment (Peter Wall's Morning Show): World Water Day: Climate change impacts on water resources (aired 5 times on March 24 and 25 on Calgary and Edmonton radio stations)
- Kienzle SW May 05, 2016**: New York Times** interview and Article "Dry Winter and Warm Spring Set Stage for Wildfire in Canada".
- Kienzle SW June 2016 Edition: **Canadian Geographic**,: "Climate Change Solutions: Off the Charts" – Article (Circulation: ~ 150,000)
- Kienzle SW June 27, 2016: **Public Lecture**: Lethbridge Library,:" How did the climate change between 1950 and 2010 and what does it mean?"
- Kienzle SW Nov. 16 2016 : **Public Lecture**: Galt Gardens "Did it really get warmer in Alberta
  between 1950-2010? Better Climate Information for a Better Future"

- Kienzle SW Nov. 16, 2016: **Global News Lethbridge TV** featurette ”It’s really getting warmer in Alberta due to human emissions”.

6.2.3 Presentations in Conferences, Symposia, Meeting, and Public:

- Kienzle SW 2016: How did the climate change between 1950 and 2010, and what does it mean? Lethbridge and District Horticultural Society, July 27, 2016 (Invited presentation)
- Kienzle SW 2016: High-resolution mapping of climate indices and their trends across Alberta, Canada. 13th International Meeting on Statistical Climatology, Canmore, June 06-10, 2016.
- Kienzle SW 2016: Global change: Alberta’s climate change mapping project. Invited three-hour seminar at the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal. Pietermaritzburg, South Africa, May 11, 2016.
- Kienzle SW 2016: Trends of climate and weather extremes across Alberta for the period 1950 - 2010. Alberta Beef Producers AGM 2016. Calgary, Feb. 12, 2016 (invited presentation)
- Kienzle SW 2016: Mapping climate trends and weather extremes across Alberta for the period 1950 – 2010. Irrigated Crop Production Update Conference. Lethbridge, Jan. 19-20, 2016 (invited presentation)
- Kienzle SW 2015: Mapping climate trends across Alberta for the period 1950 – 2010. Alberta Irrigation Project Association Water Conference, Lethbridge, Nov. 24-25 (invited presentation)
- Kienzle SW 2015: Dealing with challenges of determining climate change impacts. Graduate Seminar Series at the Department of Geography, Ludwig-Maximilians-University, May 21, 2015. (Invited presentation)
- Faramarzi M, Adamovicz V, Sauchyn D, Kienzle SW, Marshall S, Fennell J, Abbaspour KC, Brisbois J and Goss GG 2015: Predicting Alberta’s Water Future (PAWF). Canadian Water Network: Connecting Water Resources 2015 Conference. March 10-12, Ottawa.
- Kienzle SW 2015: Spatial downscaling and correction of precipitation and temperature time series to high resolution hydrological response units in the Canadian Rocky Mountains. European Geophysical Union Conference, Vienna, Apr. 12-17 (Invited presentation).
- Kienzle SW 2015: Building a basis for water resources planning in Alberta using hydrological and crop models and climate indices. Seminar Series at the Department of Geography, Ludwig-Maximilians-University, Munich, Apr. 29, 2015 (Invited presentation).
- Kienzle SW 2015: Calculation and mapping of climate indices trends for Alberta, Canada. Seminar Series of The African Centre for Global Change and Water Resources Research (UNESCO Water Centre), Pietermaritzburg, South Africa, Feb. 15, 2015 (Invited presentation).

- Bonifacio C, Kienzle SW, Xu W and Zhang J 2014: Improvements of Physically-Based Hydrological Modelling using the ACRU Agro-Hydrological Modelling System. Eos Trans. AGU Fall Meeting Supplement, Abstract H41A-0796.
- Langhorn C, Kienzle SW, Doria R, Jiskoot H and Cheng H 2014: Parameterization of FAO's AquaCrop Model by Integrating a Hydrological Model and Climate Indices. Eos Trans. AGU Fall Meeting Supplement, Abstract B33E-0223.
- Sauchyn, D.J. 2016. Adaptation Planning in the Agricultural and Water Sectors in Western Canada, Adaptation Canada 2016, National Symposium on Climate Change Adaptation, 12-14 April 2016, Ottawa.
- Sauchyn, David; Mauricio Bedoya, Álvaro González-Reyes, Ariel Muñoz, Jorge Julian Velez Upegui. 2016. El Niño Tele-Connections and Their Role in Drought, 9th Biennial Rosenberg International Forum on Water Policy, Panama City, 25-27 January, 2016
- Sauchyn, D.J. 2015. Availability of Agricultural Water in a Warming Climate, Canadian Climate Forum, 12-13 November 2015, Ottawa, ON
- St-Jacques, J; I Andreichuk, D Sauchyn and E Barrow (2016) Examining Projected Run-off in the South Saskatchewan River Basin in NARCCAP and CCCma RCM Data, Annual Meeting of the Canadian Water Resources Association, 25-27 May, Montreal
- Gurrapu, S; J-M St. Jacques, DJ Sauchyn, KR Hodder (2016) The influence of the Pacific Decadal Oscillation on annual floods in the rivers of Western Canada, Annual Meeting of the Canadian Water Resources Association, 25-27 May, Montreal
- Andreichuk, Iuliia; Dena McMartin, David Sauchyn. 2015. Long-term availability of water for solution potash mining in Saskatchewan, Mine Water Solutions in Extreme Environments, 2015 April 12-15, 2015, Vancouver, Canada
- Razavi, S; A Elshorbagy, H S Wheater, D Sauchyn, G Sapriza, K P Chun. 2015. Evaluation of Paleo-Hydrologic Extremes and Their Uncertainties, AGU-GAC-MAC-CGU Joint Assembly, Montreal, Canada, 3-7 May 2015
- St-Jacques, JM, D.J. Sauchyn, J Dickenson, ER Cook. 2015. Low-frequency Variability in the North and South Saskatchewan Rivers over the Past Millennium, AGU-GAC-MAC-CGU Joint Assembly, Montreal, Canada, 3-7 May 2015
- St-Jacques, J.M., D.J. Sauchyn, E. Barrow, M.W. Nemeth, R.J. MacDonald, A.M.S. Sheer and D.P. Sheer. Adaptive water resource planning in the South Saskatchewan River Basin: use of scenarios of hydroclimatic variability and extremes. 27th Pacific Climate Workshop, Pacific Grove, California, Mar. 8-11, 2015
- Gurrapu, S; A Chipanshi, D Sauchyn, A Howard. 2015. Assessment of SPEI as a Tool for Representing Drought in the Agricultural Landscapes of the Southern Canadian Prairies, AGU-GAC-MAC-CGU Joint Assembly, Montreal, Canada, 3-7 May 2015
- 2017 Faramarzi, M., Uncertainty prediction in assessment of water resources in Alberta: from input data to hydrology model and climate change, AEP Modelling Workshop, March 16-17, Edmonton, AB, Canada.

- , Alberta Environment and Parks, February 22, Edmonton, Alberta, Canada.
- 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.
- 2017 Masud, B., 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 Masud, B., Goss, G., McAlister, T., Corderio, M., Legesse, G., Adamowicz, V., Jeffrey, S., Faramarzi, M., 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., 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.
- 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.
- 2017 Faramarzi, M., Assessment of future water endowments: establishing a robust foundation to study the dynamics of water, food, energy and environment Alberta, Alberta Environmental Monitoring and Science Division, Alberta Environment and Parks, February 22, Edmonton, Alberta, Canada.
- 2017 Faramarzi, M., Modelling the effects of climate change on water supply in Alberta, Water policy Branch (Modelers, Planners, and Managers), January 25, Edmonton, Alberta, Canada.
- 2017 Faramarzi, 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.
- 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.
- 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.
- 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, EAS-Tory, October 14, UofA, AB, Canada.

- 2016 Masud, B., Goss, G., McAlister, T., Corderio, M., Legesse, G., Adamowicz, V., Jeffrey, S., Faramarzi, M., Faramarzi, M., Predicting water related risks and opportunities for Alberta's beef industry, ALMA Future Fare, October 13, Edmonton, Alberta, Canada.
- 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.
- 2016 Faramarzi, M., Goss, G., Predicting Alberta's Water Future, Alberta Environment and Parks, Water policy Branch, June 23, Edmonton, Alberta, Canada.
- 2016 A.I. Gharib, M. Faramarzi, 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.
- M. Faramarzi, 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.
- 2015 M. Faramarzi, K. Abbaspour, R. Srinivasan, G. Goss, Application of the Soil and Water Assessment Tool to predict freshwater availability in Alberta, Alberta Soil Scince Workshop, February 17-19, 2015, Edmonton, Canada.
- 2015 Faramarzi, M., W., Adamowicz, D., Sauchyn, S., Kienzle, S., Marshall, J., Fennell, K., Abbaspour, J., Brisbois, G. Goss, Predicting Alberta's water future, Canadian Water Network, March 10-12, 2015, Ottawa, Canada
- 2015 M. Faramarzi, 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.
- 2015 M. Faramarzi, G. Goss, Predicting Alberta's Water Future, Alberta Innovates Energy and Environment Solution (AI-EES) Water Innovation Program Forum, May 26-27, Calgary, Canada.
- Faramarzi M. Predicting Alberta's Water Future (PAWF). Inaugural Workshop for the Joint UofA-NWAFU Research Center in Agricultural Water Management, May2-3 2016, Edmonton, Alberta, Canada. Oral presentation.
- Faramarzi M. Predicting Alberta's Water Future, Feb 2016, Departmental Lecture Seminar Series, Biological Sciences, University of Alberta.
- Faramarzi M. Predicting Alberta's Water Future, Feb 2016, Guest lecturer at the Graduate course, Department of Environment and Civil Engineering, University of Alberta.
- Faramarzi *et al*., 2015, Predicting Alberta's Water Future (PAWF), Canadian Water Network: Connecting Water Resources 2015, March 10-12, Ottawa, Canada.
- Faramarzi *et al*., 2015, Application of the Soil and Water Assessment Tool to predict freshwater availability in Alberta, Alberta Soil Science Workshop, February 17-19, Edmonton, Alberta.

- Faramarzi *et al*., Application of SWAT model to quantify blue and green water resources in Alberta, Canadian Geophysical Union 2015, May 3-7, Montreal, Canada.
- Faramarzi M., 2015. International meeting on 'Himalayan Climate Change: debris Covered Glacier Response, Water Availability, Biodiversity and Ecosystem Response', 12-14 August, University of Leeds, England.
- Faramarzi M., 2015, Wetland Research Workshop organized by Alberta Biodiversity Monitoring institute (ABMI) and the Alberta Land Institute, 5 Nov., University of Alberta, Edmonton.
- Faramarzi M., Predicting Alberta's Water Future, 2015, Guest lecture for graduate students at the CIVIL Environmental Engineering department, 30 Nov., NREF 2-016, University of Alberta, Edmonton, Alberta.
- Marshall, S.J., 2015. Energy balance vs. degree day modelling of glacier mass balance. CMOS annual congress, Whistler BC, June 2, 2015.
- Goss G., Faramarzi M., Predicting Alberta's Water Future, 2015. AI-EES Water Innovation Program Forum, 26-27 May, Calgary, Alberta.
- Goss, G *et al*., 2015, Analysing Water Availability, Water Use and Water Forecasting in a Changing Climate Identifying Risks and Opportunities for the Hydraulic Fracturing Industry. Shale Gas Water Forum, Sep 16, Calgary, Alberta.
- Goss G., 2015, Water Management for Multistage Hydraulic Fracturing: Research Gaps, Challenges and Opportunities. PTAC Water Forum, Dec. 9, Calgary, Alberta.
- Goss G., 2015, Provided input into Alberta Water Research And Innovation strategy (3 meetings with GoA in reporting period)
- Goss G., 2015, Met multiple times with Alberta WaterSmart during reporting period to co-ordinate opportunities for sharing information and future collaborations with this organization.
- Fennell J., Predicting Alberta's Groundwater Future, Watertech 2016, Banff AB.
- Marshall, S.J., 2015. Challenges in modelling glacier response to climate change. Invited talk, IUGG Congress, Prague, CZ, June 24, 2015.
- Perroud, M. and S.J. Marshall, 2015. First steps towards the nesting of a glacier mass balance algorithm in the Canadian regional climate model. IUGG Congress, Prague, CZ, June 26, 2015.
- Samimi, S. and S.J. Marshall, 2015. Meltwater Runoff and Storage Based on Dielectric Properties of the Supraglacial Snowpack on Haig Glacier, Canadian Rocky Mountains. American Geophysical Union Fall Meeting, Dec 12-18, 2015, San Francisco, CA.
- Ebrahimi, S. and S.J. Marshall, 2016. A perturbation approach to modelling sensitivity of glacier energy balance to climate change. European Geophysical Union congress, April 17-22, 2016, Vienna, Austria.

- Marshall, S.J., 2016. Sensitivity of glacier energy balance to meteorological variability. International Mountain Cryosphere Workshop, March 15-19, 2016, Riederalp, Switzerland.
- Lu, W., W. Adamowicz and S. Mohapatra. 2015. The impact of climatic shocks on Alberta’s economy. Department of Resource Economics and Environmental Sociology Workshop, University of Alberta, Edmonton. October 8
- Lu, W. 2015. The impact of climatic shocks on Alberta’s economy. Presented at the University of Alberta Oilsands Student Delegation Primer, University of Alberta, and Edmonton. October 21
- Lu, W., W. Adamowicz and S. Mohapatra. 2015. The impact of climatic shocks on Alberta’s economy. AAEA (Alberta Agricultural Economic Association) and REESSA (Resource Economics and Environmental Sociology Students' Association) Joint Conference, Red Deer, Alberta. April 30

8. Final Financial Report

Budget Summary: update the following table so that the information is current as of the end of the reporting period.

Total Project Budget	**Total AI-EES Grant Budget**	**Total Project Expenditures to Date**	**AI-EES Total Contribution to Date (include current invoice)**
$1,000,000	$1,000,000	$	$1,000,000

Detailed Expenditures: In the following table, specify all project expenditures to-date, corresponding to specific tasks detailed in the project plan.

Task	**Cost Jan 1 2014– Dec 31 2016**	
Data collection, compilation, and analysis; development of the calibration-validation tool (SWAT-CUP-SUFI2); reviewing literature; communication and team meetings; building networks and engaging stakeholders through meeting with various governmental organizations (ESRD, AGS, ABMI, AWS) and researchers at U Alberta; publishing; economic analysis (Greg Goss, Monireh Faramarzi, Vic Adamowicz, U Alberta)	Materials and Supplies	
	Equipment and Vehicles	
	Travel and Hospitality (project meetings)	
	Salaries and commitments	
	Overhead	
Basin yields and climate trends (Stefan Kienzle, U Lethbridge)	Sub-grant	
Glacier simulation; glacier runoff projections; integration with SWAT (Shawn Marshall, U Calgary)	Sub-grant	
Basin yields and climate trends (David Sauchyn, U Regina)	Sub-grant	
Groundwater recharge, use, and stress (Jon Fennell)	Collaboration	
	Total	
* The expenditure categories shown in this document as prescribed by AIEES do not correspond to the categories shown in the original submission. Reconciliation can be arranged upon AIEES request.		