South Saskatchewan River Basin Adaptation to Climate Variability Project

Climate Variability and Change in the Bow River Basin

Final Report

June 2013

ALBERTA waterSMART
Water Management Solutions

CCEMC
Funding climate change innovation.

Alberta Innovates
Energy and Environment Solutions

This study was commissioned for discussion purposes only and does not necessarily reflect the official position of the Climate Change Emissions Management Corporation, which is funding the South Saskatchewan River Basin Adaptation to Climate Variability Project. The report is published jointly by Alberta Innovates – Energy and Environment Solutions and WaterSMART Solutions Ltd.

Disclaimer

Information in this report is provided solely for the user’s information and, while thought to be accurate, is provided strictly “as is” and without warranty of any kind. The Crown, its agents, employees or contractors will not be liable to you for any damages, direct or indirect, or lost profits arising out of your use of information provided in this report.

Alberta Innovates – Energy and Environment Solutions (AI-EES) and Her Majesty the Queen in right of Alberta make no warranty, express or implied, nor assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information contained in this publication, nor that use thereof infringe on privately owned rights. The views and opinions of the author expressed herein do not necessarily reflect those of AI-EES or Her Majesty the Queen in right of Alberta. The directors, officers, employees, agents and consultants of AI-EES and the Government of Alberta are exempted, excluded and absolved from all liability for damage or injury, howsoever caused, to any person in connection with or arising out of the use by that person for any purpose of this publication or its contents.

Contents

List of Tables

List of Figures

Acronyms and Abbreviations

(A)ESRD	(Alberta) Environment and Sustainable Resource Development
AF	Acre-foot (or acre-feet). One AF = 1.23348 cdm.
BRID	Bow River Irrigation District
BROM	Bow River Operational Model
CDF	Cumulative Distribution Function
cdm (or dam^3)	cubic decametre. A cubic decametre is 1000 cubic metres.
cfs	cubic feet per second
EID	Eastern Irrigation District
GCM	Global Climate Model
GHGs	Greenhouse Gases
PARC	Prairie Adaptation Research Collaborative
PDF	Probability Distribution Function
PDO	Pacific Decadal Oscillation
SRES	Special Report on Emissions Scenarios
SSRB	South Saskatchewan River Basin
TAU	TransAlta Utilities
WID	Western Irrigation District

1 Executive Summary

While Alberta's economy is fuelled by hydrocarbons, it runs on water. The province is facing important water challenges, including an expanding population, accelerating economic growth, and the increasing impact of this growth on the environment. With the added challenge of climate variability and change, sound water management decisions are becoming more complex and more critical to Alberta's prosperity.

Climate changes, by definition. But how climate patterns could change and the effects these changes might have on local hydrologic regimes is not known with certainty. One goal of the SSRB Adaptation Project was to propose an adaptive and robust water management framework that takes into account the regional impacts of climate change. This required the development of a scientifically valid set of possible future streamflow conditions that would enable water users and managers to test water management alternatives under a range of potential future climate and hydrological scenarios.

The innovative methodology to develop the scenarios outlined in this report provided a range of plausible future flows. Five scenarios were then selected for use in a collaborative modelling session designed to look at impacts and potential adaptation options. Much of the range in hydrology from the five scenarios covers flow conditions that have been seen throughout the historical record and are well within the recent range of variability in terms of magnitude and duration. Most years in all five scenarios had flows with volumes and timing of water that would not require changes in operations to meet user needs. But because the purpose of this work was to identify strategies for adapting to flow changes that affect water users, scenarios were chosen to highlight impacts related to low-flow periods in the Bow River system.

Two of the scenarios produced average flows relative to the historical record, and their hydrology resulted in little or no impact on users. The other three scenarios did produce flows that affected users and highlighted the impacts on major licence holders. Among these potential impacts were much lower storage levels (and at times, no storage) for TransAlta reservoirs, reduced flows through Calgary as well as depleted storage in Calgary's Glenmore Reservoir, negative environmental implications for downstream aquatic health, and increased shortages for the river environment and for users on the Sheep and Highwood Rivers, and the three irrigation districts in the Bow River system.

These potential impacts present risks to the environment, regional economy, and society, but they also present an opportunity to identify adaptation options and build resiliency in the SSRB for responding to future climate variability and change. Such options were explored in the two-day collaborative modelling session based on the scenarios, and these options will be described in a separate report for the SSRB Adaptation Project.

2 Introduction

Alberta's heritage and its social, economic and environmental history are directly tied to its water resources. While Alberta's economy is fuelled by hydrocarbons, it runs on water, and the province's continued prosperity depends on sound water management decisions. In the face of climate variability and change, these decisions are becoming more complex and more critical.

Alberta is confronting important water challenges, including an expanding population, accelerating economic growth, and the increasing impact of this growth on the environment as the climate continues to shift.

The province's geographical landscape encompasses the spine of the Rocky Mountains on its western border, semi-desert plains in the south, parklands in central Alberta and boreal forest across the north. The mountain regions are the water towers for much of western Canada, while eastern and northern flowing rivers are vital to this province as well as downstream neighbours.

Both water supply and demand are variable, particularly between southern and northern regions. The health of Alberta's natural resources and its economic vitality depend on an integrated understanding of natural climate variability as well as improved management capacity to confront the prospects and potential impacts of climate change.

These challenges present a timely opportunity to capitalize on the knowledge and experience of community and business leaders, government departments, environmental organizations and watershed groups. Water and climate adaptation issues are complex, and cannot be solved by any single initiative or sector. Alberta has a history of successfully meeting sustainability challenges through multi-sector collaboration and engagement, and the South Saskatchewan River Basin Adaptation to Climate Variability Project will further enhance that legacy.[1]

2.1 Climate Change in Southern Alberta

The historic record demonstrates the wide range in climate variability in the South Saskatchewan River Basin (SSRB) over the last 600 years (see Figure 1). Current research suggests that the timing and nature of southern Alberta's water resources will continue to exhibit annual and seasonal variability (Rood *et al.,* 2008; Forbes *et al*., 2011; Kienzle *et al.,* 2011).

---

[1] See Appendix A for more information on this project.

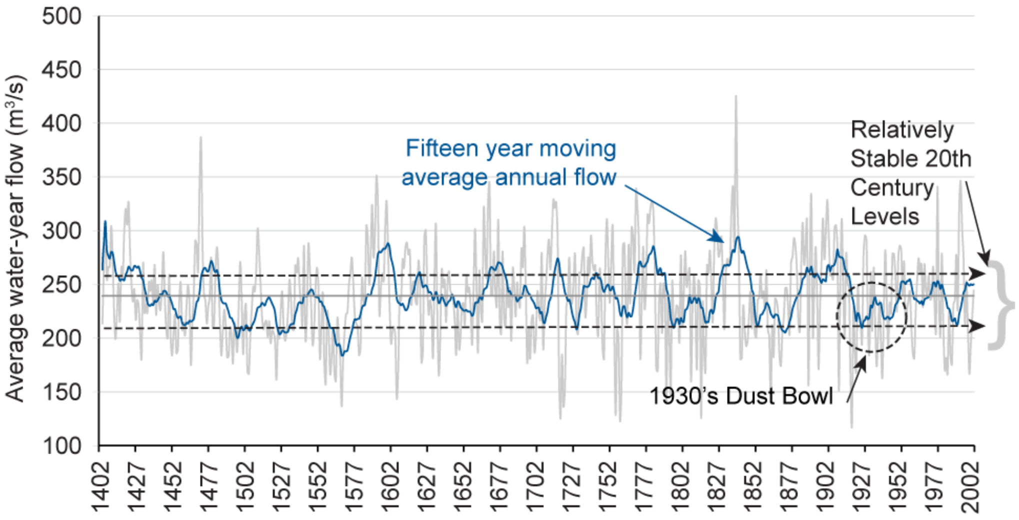

Figure 1. Historic Drought and Flood Record: South Saskatchewan River (Bow+Oldman) Flows

(from Axelson et al., 2009)

Water supply in the SSRB is affected by many factors. Natural climate variability and climate change pose a huge challenge to Alberta and to those downstream, as the headwaters for major east- and north-flowing rivers arise in Alberta. Global climate change impacts are likely to produce more extreme events and alter the timing of precipitation that supports surface water systems by shifting from primarily snowpack-driven events to more winter rainfall (Field *et al*., 2007; Sauchyn and Kulshreshtha, 2008). Melting of Rocky Mountain glaciers will produce lower natural summer flows and Alberta has limited storage options to capture the flow that does occur.

At the same time, global demand for products from irrigated agriculture is growing, and an expanding population and a thriving economy are placing ever-increasing pressure on water supplies in the region. Water is also needed to address environmental and recreational needs throughout the river system. The Government of Alberta acknowledged water supply pressures in the SSRB by closing new allocations in the Bow and Oldman basins in 2006 (Government of Alberta, 2006).

Alberta faces uncertain climate conditions; whether these are due to natural climate variability or actual climate change matters not. The province clearly needs a better collective understanding of how the sub-basins in the SSRB are responding to these changes. More robust and flexible water management strategies can then be developed to adapt to these changing conditions in a manner that best assures water for people, nature and the economy for years to come.

A 2008 report on the impacts of climate change on the Prairie Provinces (Byrne and Kienzle, 2008) illustrated various scenarios of projected climate change, based on the 1961–1990 climate normal, to the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099). With the exception of a few scenarios for the 2020s, all seven global climate models (GCMs) used in the study looked at forecasted climates that lie outside the range of natural variability, with most of the projected increases in temperature and precipitation occurring in winter and spring for both forest and grassland regions.

Most studies based on GCM output agree that earlier spring runoff, increased winter flows, lower summer and late fall streamflows, decreased glacial melt contributions, and lower snow accumulations can be expected under projected climate changes (Burn, 1994; Gan, 1998; Demuth and Pietroniro, 2003; Lapp *et al*., 2005; Sauchyn and Kulshreshtha, 2008). Earlier warming could contribute to an earlier spring runoff in two ways: earlier melt of snowpack, and an increase in the proportion of precipitation that falls as rain instead of snow. Shifts in earlier streamflow timing by one to four weeks in recent decades relative to conditions in the 1950s through the mid-1970s have already been observed (Stewart *et al*., 2004).

Several studies in the Rocky Mountains (Barnett *et al*., 2005; Rood *et al*., 2005; Rood *et al.*, 2008) show that annual flows have declined, winter flows (especially in March) were often slightly increased (most likely the result of more rain-on-snow events), spring runoff and peak flows occurred earlier, and summer and early autumn flows (July–October) declined at a rate of about 0.2% per year. These observed changes were greatest for the rivers that drain the east slopes of the Rocky Mountains toward the northern prairies (Barnett *et al*., 2005). It is possible that the overall decreasing trends in streamflow may have been masked to some extent by increases in glacier melt over the last 25 years (Bruce *et al*., 2003).

3 Developing Climate Scenarios for the Bow Basin

3.1 What makes the SSRB project climate scenarios different from previously developed scenarios?

The Prairie Adaptation Research Collaborative (PARC) has been developing climate scenarios for Alberta Environment and Sustainable Resource Development (ESRD) for some time. The early work (mid to late 2000s) involved GCM-based climate change scenarios and an assessment of the biophysical impacts of these projected climate changes. This work was province-wide and thus coarse scale.

The most recent work for ESRD, under the Prairies Regional Adaptation Collaborative[2] focused on water and climate variability, as opposed to changes in average conditions; for selected streamflow gauges, probability plots of future flows were generated. This work produced the methods that are being applied to the SSRB Adaptation Project. One of these gauges was in the Bow River Basin and a few were in the Oldman Basin.

For the SSRB Adaptation Project, the PARC research team generated probability plots of future flows for the Bow River below Bassano gauge in the Bow Basin where records go back more than a few decades. From the projections of annual average flows and the disaggregation of the annual data, they generated synthetic daily time series for each gauge in the Bow Basin, an

---

[2] The Prairies Regional Adaptation Collaborative is built on shared themes and a similarity of expected climate change impacts and vulnerabilities related to a changing moisture balance across the three Prairie Provinces. PARC participated in the Prairies Regional Adaptation Collaborative.

approach that had never been taken before. Although some groundwork was laid with the ESRD climate scenarios, it was substantially advanced as a result of the SSRB Adaptation Project.

3.2 Methodology

A foundational concept in water resource engineering is the assumption of stationarity – that climate and hydrology fluctuate within a constant range of variability represented by instrumental records (Milly *et al*., 2008). Basing the allocation, distribution and storage of water on the analysis of instrumental records also assumes that these observations adequately represent the long-term trends and variability in climate and water variables. Reconstructions of the climate and hydrology of the last millennium reveal fluctuations at time scales (multi-decadal) that exceed the length of most instrumental records (Sauchyn *et al*., 2008, 2011). This scale of variability is important to understanding the stationarity of the regional climate regime, and for water resource planning and management for infrequent events, specifically extreme and sustained low water levels.

The methodology applied to the Bow River Basin accounts for this inter-annual to decadal variability. Streamflow is modelled as a function of the ocean-atmosphere oscillations (see St. Jacques *et al*., 2010, 2013) that drive the natural variability of the regional hydroclimatic regime.

In this project, researchers drive the generalized-least-squares (GLS) regression models of annual streamflow using output from an ensemble of 50 runs generated by ten GCMs from the Phase 3 of the Coupled Model Intercomparison Project (CMIP3); these models were chosen because they simulate the spectral and geographic characteristics of relevant teleconnection patterns (Furtado *et al*., 2011; Lapp *et al*., 2011) (Table 1). The 10 GCMs that were chosen to had a total of 50 runs that were available for at the time of this project, and not all GCMs had uploaded data for all three SRES scenarios.

Table 1. The ten chosen coupled atmosphere-ocean models which archived the required fields, their details, and number of available 21st century runs per scenario

#	IPCC4 Model ID	Country	Atmospheric resolution	Oceanic resolution	Number 21st century runs		
					B1	**A1B**	**A2**
1	**CGCM3.1(T47)**	Canada	3.7°x3.7° L31	1.84°x1.85° L29	3	3	3
2	**CGCM3.1(T63)**	Canada	2.8°x2.8° L31	1.4°x0.9° L29	1	1	0
3	**ECHAM5/MPI-OM**	Germany	1.875°x1.865° L31	1.5°x1.5° L40	2	2	1
4	**GDFL-CM2.1**	USA	2.5°x2.0° L24	1.0°x1.0° L50	1	1	1
5	**MIROC3.2(hires)**	Japan	1.125°x1.12° L56	0.28°x0.188° L47	1	1	0
6	**MIROC3.2(medres)**	Japan	2.8°x2.8° L20	(0.5-1.4°) x1.4° L43	1	1	1
7	**MRI-CGCM2.3.2**	Japan	2.8°x2.8° L31	(0.5-2.5°) x2.0° L23	5	5	5
8	**NCAR-CCSM3**	USA	1.4°x1.4° L26	(0.3-1.0°) x1.0° L40	1	0	1
9	**NCAR-PCM**	USA	2.8°x2.8° L18	(0.5-0.7°) x0.7° L32	2	2	2
10	**UKMO-HadCM3**	UK	3.75°x2.5° L15	1.25°x1.25° L20	1	1	1

The GLS regression model is

$$
\begin{aligned}
Q = \; & -0.14 - 4.79\, trend - 8.81\, PDO - 4.91\, SOI \\
& -4.95\, PDO_{N1} - 5.81\, PDO_{P2} - 4.00\, SOI_{P2} + \varepsilon_t
\end{aligned}
\qquad (eqn\ 1)
$$

where:

Q denotes mean daily flow over the water year and is zero-meaned,
trend denotes a simple linear trend, and
the PDO and Southern Oscillation Index (used for ENSO) indices are standardized and lagged: *N1* denotes the climate index lags streamflow one year and *P2* denotes the climate index leads streamflow two years, and the error term ε_t follows an ARMA(2,1) residual model.

The GLS model captures a large proportion of the variance in the naturalized streamflow of 1928-1995 ($R^2_{\text{innov}} = 0.73$, $R^2_{\text{reg}} = 0.64$). However, there is mounting evidence of increased variability and more extreme hydroclimate in the warming atmosphere (see Kharin *et al.*, 2007; Durack *et al.*, 2012). Only physically-based climate models can provide credible projections of future hydroclimate.

Using climate oscillation data from these 50 runs from the ten GCMs and the GLS statistical model, researchers simulated and projected annual flows for the Bow River at Bassano for the period 1905 to 2096. Future climate is externally forced by rising greenhouse gases (GHGs), according to three GHG emission scenarios: the A2 (high emissions), A1B (medium emissions), and B1 (low emissions) scenarios from the Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al.*, 2000). The 20th century simulated flows and 21st century projected flows for the A1B SRES scenario are plotted in Figure 2, along with the gauge record and the all-model mean annual flow. The projected flows for the A2 and B1 emissions scenarios are very similar to those from the A1B scenario and are therefore not shown.

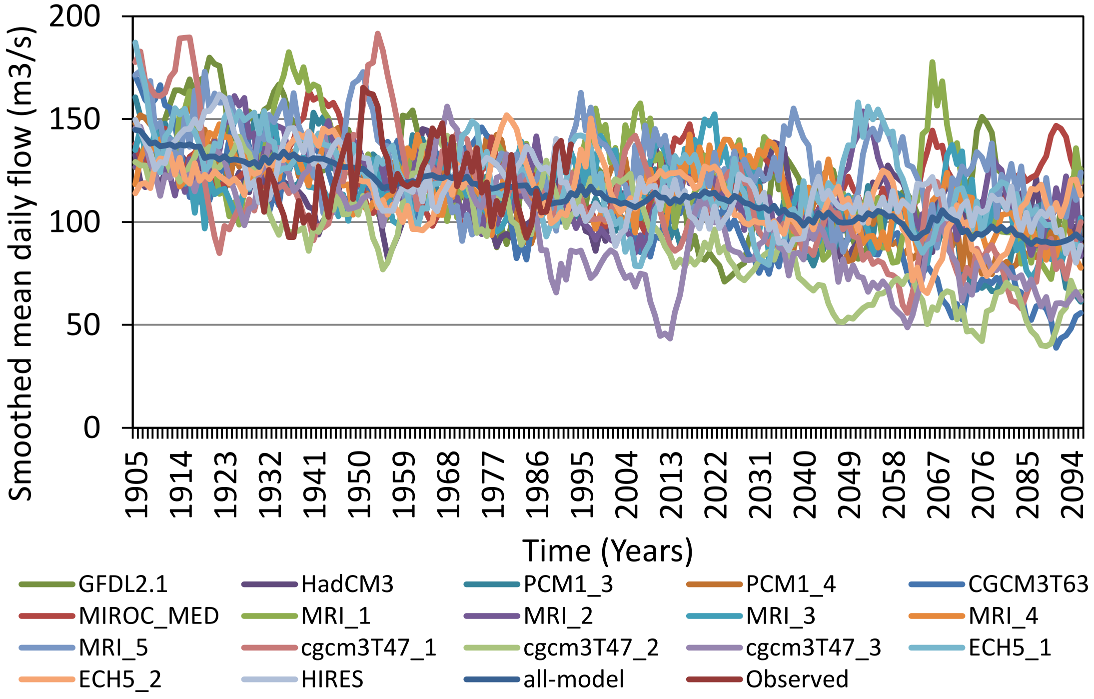

Figure 2. Simulated and projected streamflow, for 1905-2096, for the naturalized Bow River at Bassano

In Figure 2, each simulation corresponds to one of 17 runs of ten CMIP3 GCMs under the moderate A1B emission scenario. The observed gauge record and all-model mean also are plotted. Daily mean flow smoothed by a 5-point binomial filter.

The projections are of slightly smoothed mean daily flow over the water year (October 1-September 30), using a 5-point binomial smoother. The high-frequency residual variance removed by the low-pass filter was characterized using the historical flows from 1928-1995. It followed a Gaussian distribution ($\mu = -0.09$, $\sigma = 11.17$) which was randomly sampled in order to add back the missing high frequency variance. The outputs from the 50 simulations were re-sampled following Dettinger (2005, 2006) and St. Jacques *et al*. (2013), generating sufficient data for the construction of cumulative distribution functions (CDFs), from which the probability of exceeding critical values for hydrologic parameters can be determined.

Re-sampling these complete simulated flows (that is, projected low frequency plus added randomly generated Gaussian noise) 20,000 times produced the probability distribution functions (PDFs) shown in Figure 3 and the CDFs shown in Figure 4 for the selected years 2006, 2050, and 2096. These plots clearly show a future shift to lower mean annual flows and a greater probability of extreme low flows. From here on, analysis is concentrated on the period 2025-2054 because its relative immediacy is of concern for the stakeholders in the Bow River watershed.

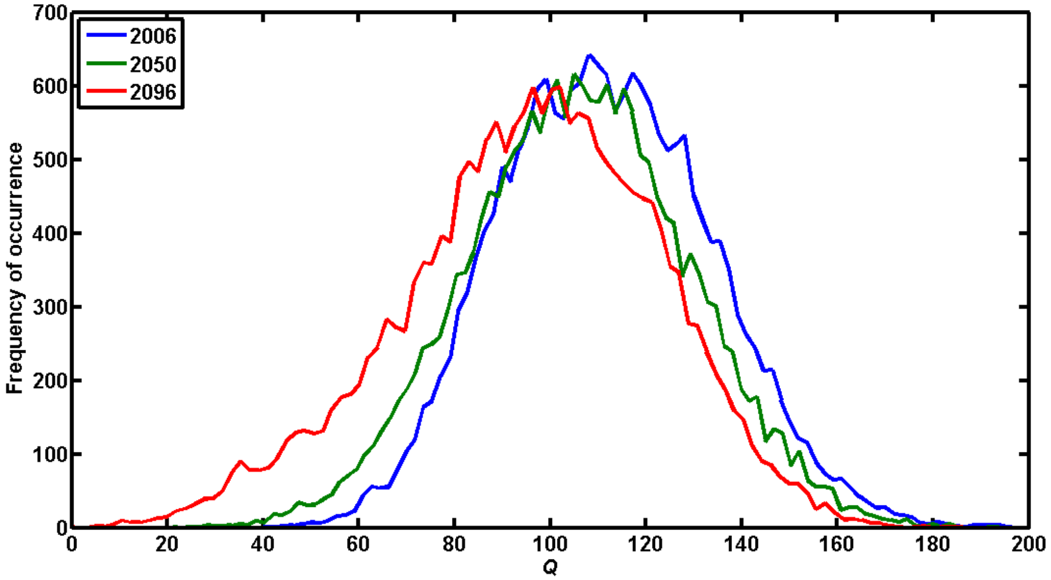

Figure 3. Probability distribution functions (PDFs) of mean daily flow for the naturalized Bow River at Bassano for the selected years 2006, 2050 and 2096

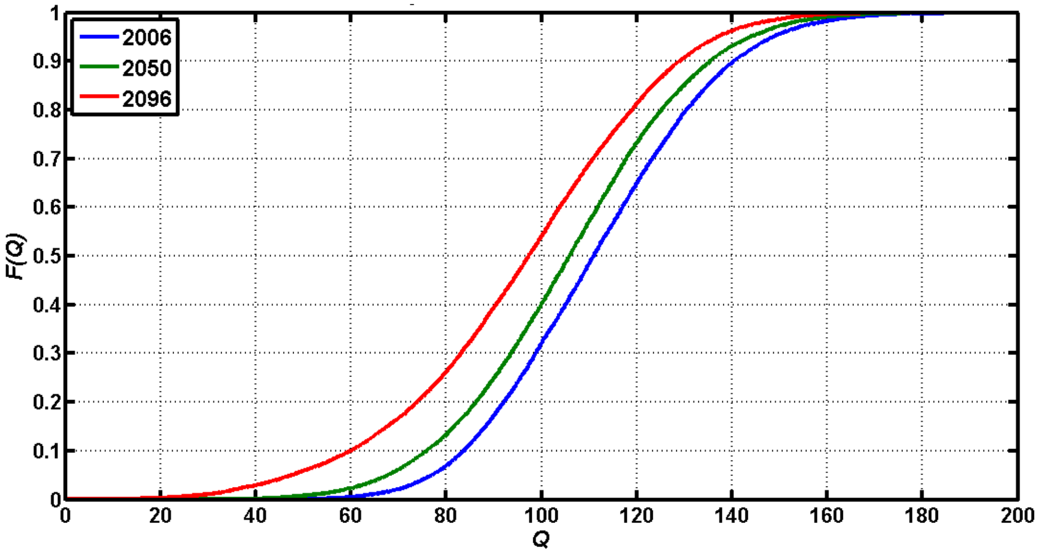

Figure 4. Cumulative distribution functions (CDFs) of mean daily flow for the naturalized Bow River at Bassano for the selected years 2006, 2050 and 2096

The GLS-based projection method of St. Jacques *et al.* (2013) produces projected annual mean flows whereas the SSRB Adaptation Project required projected daily flows. Researchers followed the approach of Woodhouse and Lukas (2006a, 2006b) of mapping projected mean daily flows to the daily hydrographs from analogue years. Appropriate analogue years were chosen using the QPPQ transform (or quantile translation) approach (Hughes and Smakhtin, 1996).

Processing of the projected and historical streamflow data to produce an ensemble of time series of projected (plausible) daily flows is illustrated in Figures 5 through 9. Figure 5 shows the average CDF of projected flows for the 30-year period (2025-2054) from the projected CDFs for the individual projected years as derived from the Dettinger resampling approach (e.g., Figure 4). Researchers also generated the empirical CDF in Figure 6 from the historical 1928-1995 mean daily flows of the naturalized Bow River at Bassano. In Figure 5, the red arrows show that there is a probability of 0.66 that mean daily flow will not exceed 115.3 m^3/s base on the projected flows, and in Figure 6 the red arrows show that for a probability of 0.66, mean daily flow does not exceed 128.8 m^3/s based on the historical record. These plots clearly show a future shift to lower mean annual flows and a greater probability of extreme low flows.

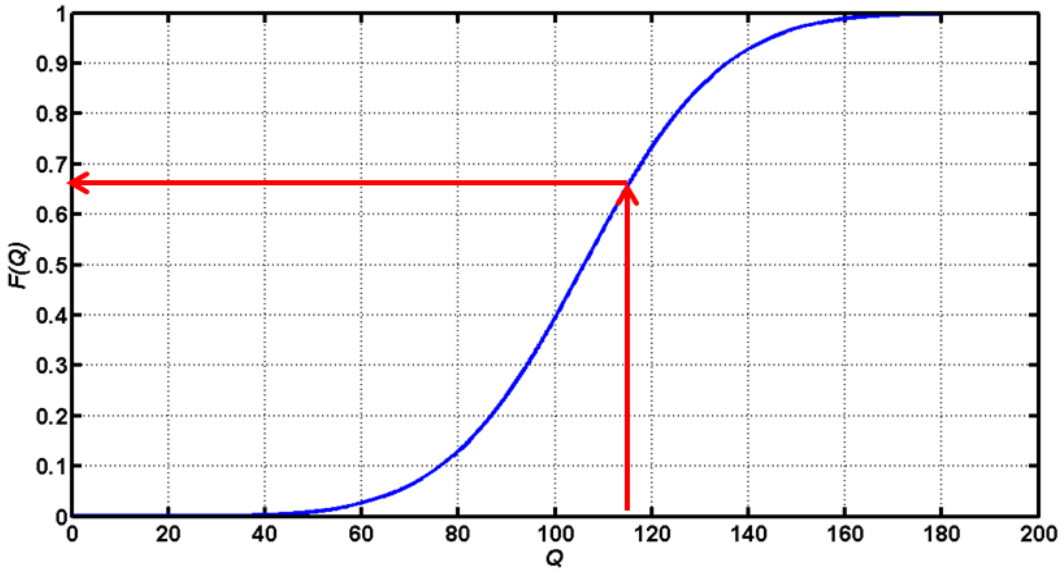

Figure 5. The CDF of projected mean daily flows of the naturalized Bow River at Bassano for the period 2025-2054

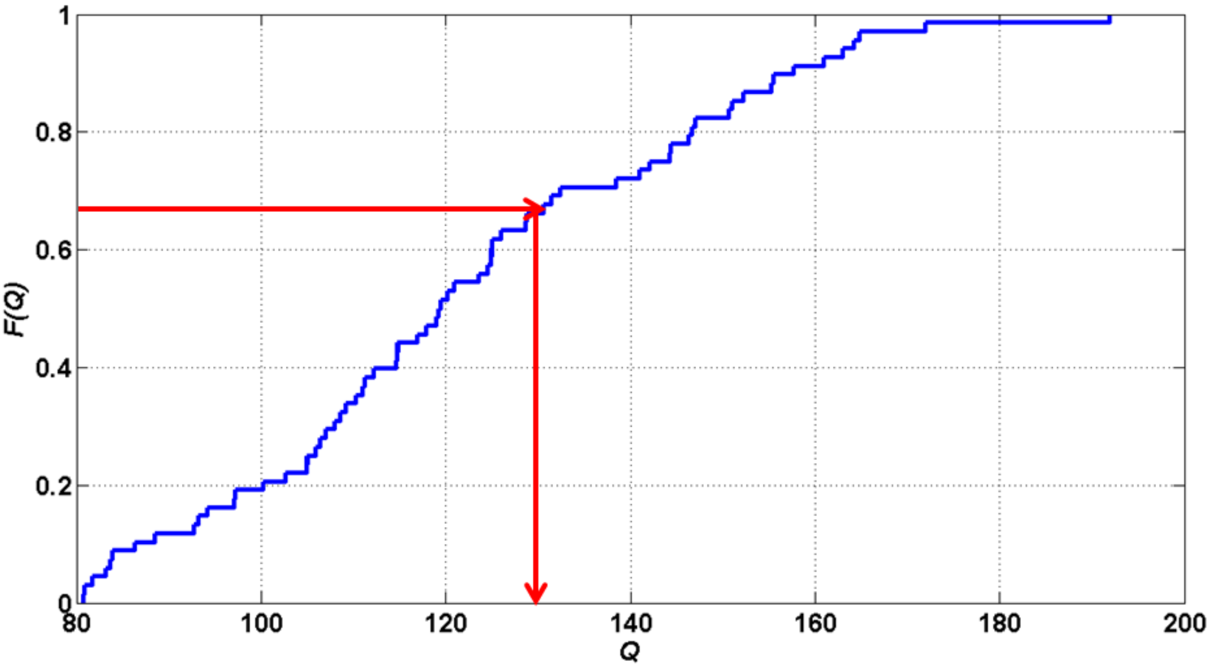

Figure 6. The empirical CDF of historical mean daily flows of the naturalized Bow River at Bassano for the period 1928-1995

By matching flows of equal probability using a QPPQ transform, a historical analogue for each run of a GCM and each future year was identified; that is, 50 GCM runs x 30 years = 1500 model years. For example, from a run with climate data from GCM MRI run 3 (emission scenario A1B), the statistical model projected a mean annual flow of 115.3 m^3/s for the year 2035. According to the CDF for the period 2025-54, there is a probability = 0.66 that this flow will not be exceeded. The historical flow of equal probability was 128.8 m^3/s in 1958. Thus the hydrology of 1958 is the closest analogue to the hydrology projected for 2035 using climate data from GCM MRI run 3 forced by GHG emissions according to the A1B scenario (Figure 7). The daily flows for 1958 were then log-normal scaled by the projected mean and projected standard deviation to arrive at the projected daily flows for 2035 as illustrated in Figures 7-9. The strong quadratic relationship between mean and standard deviation of the historical daily flows (Figure 8) permits scaling of both parameters. The advantage of mapping to analogue years using the QPPQ transform lies in the way relatively high-flow projected years (that would arise because of a projected negative PDO phase) are mapped to corresponding high-flow historical years (that arose from a known negative PDO phase), and similarly mapping projected low-flow years associated with a positive PDO phase to low-flow positive PDO phase historical years. There is accumulating evidence that the annual hydrograph form varies between the two PDO phases (St. Jacques *et al*., *in prep*.).

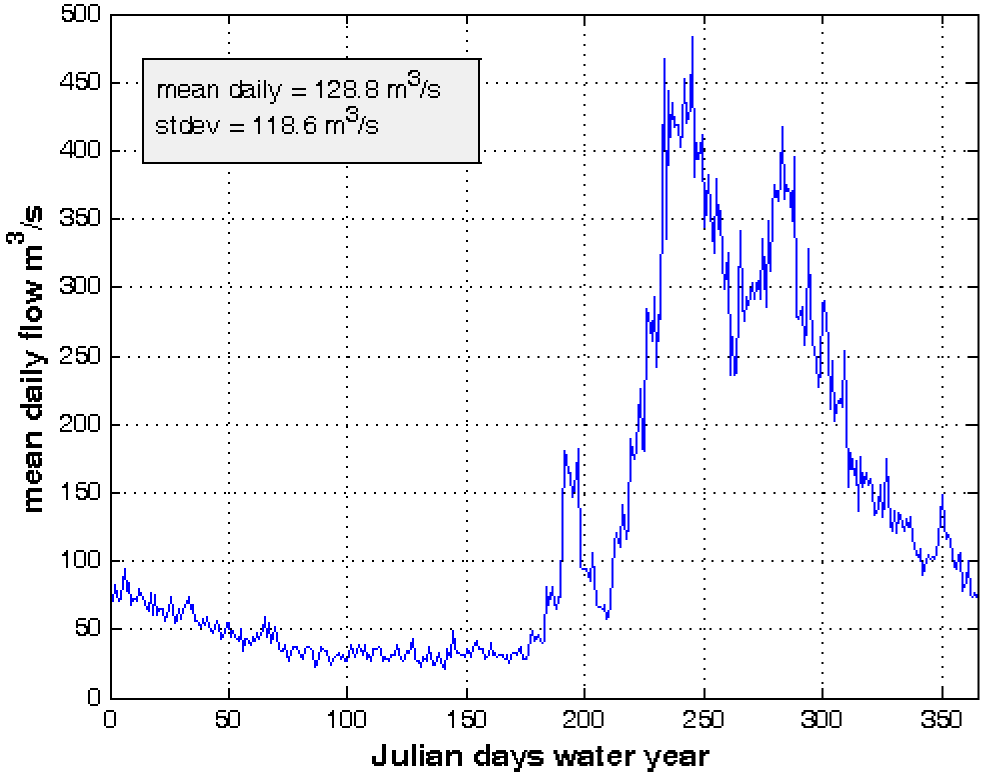

Figure 7. Historical mean daily flows for 1958 of the naturalized Bow River at Bassano

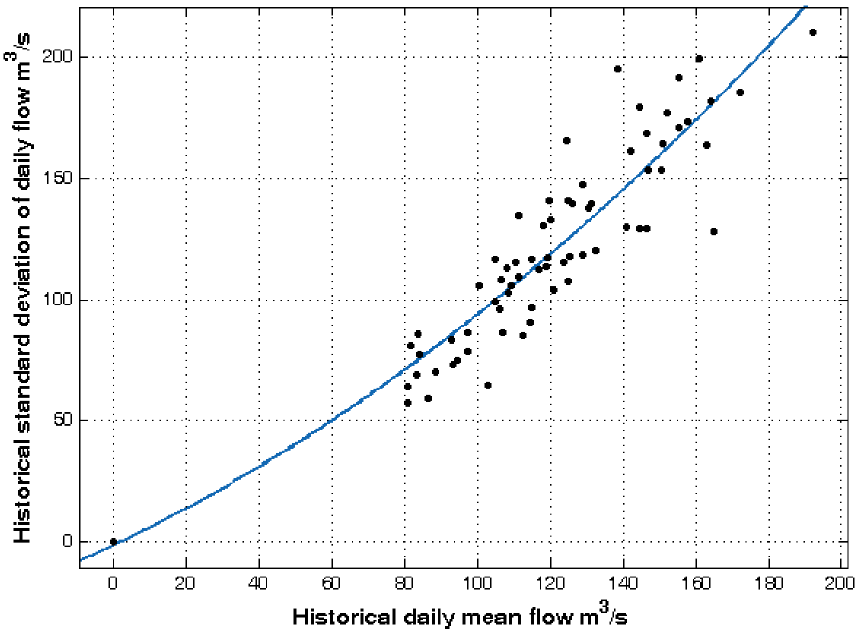

Figure 8. A scatterplot showing the strong quadratic relationship between the means and standard deviations of daily flow of the historical naturalized Bow River at Bassano (1928-1995)

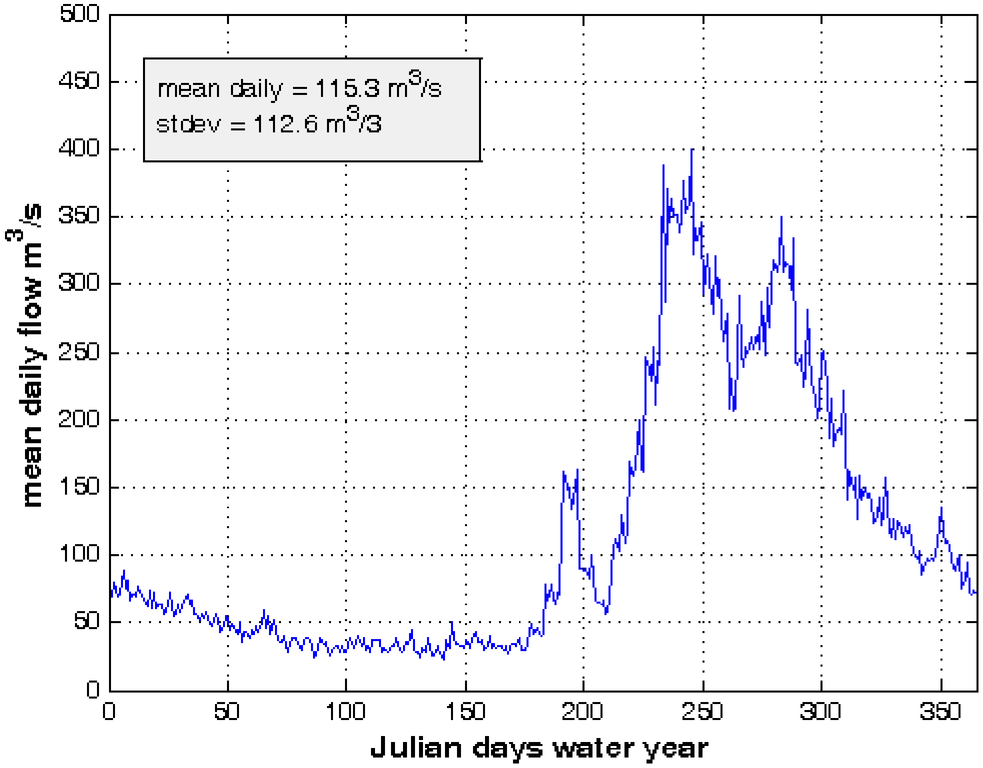

Figure 9. Projected mean daily flows for 2035 for the naturalized Bow River at Bassano simulated using output from the GCM MRI run 3, GHG emission scenario A1B

(Scale same as in Figure 7)

With global temperatures warming due to a changing climate, spring is projected to occur earlier in the year throughout western North America, including southern Alberta; in particular, snowmelt runoff timing will advance (Cayan *et al*., 2001; Stewart *et al*., 2004). This advance in peak flow has serious implications for reservoir and irrigation management during the growing season, particularly at the end of summer. Therefore, researchers included this advance in peak flow in the model for this project, following the approach of Stewart *et al*. (2004). A strongly significant linear relationship ($R^2 = 0.25$, $p = 0.0001$) exists between the date marking the timing of the center of mass of annual flow center timing (CT), where CT = $\Sigma\, t_i q_i / \Sigma q_i$, where t_i is the day of the water year and q_i is the daily discharge at Bassano, and Banff total winter precipitation (October-May) and Banff spring temperature (April-July).

$$\textbf{CT = 253.90 - 3.30 spring temperature + 0.04 winter precipitation} \qquad (\textit{eqn } 2)$$

The changes in CT for 2025-2054 were projected for each GCM run by driving the regression model in eqn. 2 with the projected spring temperature and winter precipitation from the GCM grid cell that contained Banff. Because the GCMs are biased, the projected changes in CT cannot be used directly to shift the hydrograph. Using the corresponding 20th simulation run for each GCM and emissions scenario, researchers calculated the mean CT for 1966-1995. Then, for a given run and projected year, researchers calculated the projected advance to be the projected CT minus the mean CT for 1966-1995. Researchers adjusted the projected daily hydrographs by the projected advances in spring runoff timing. For example, spring runoff is projected to advance 16 days in 2035 for the MRI run 3 A1B emissions scenario (Figure 10). These projected advances are comparable in magnitude to those found by Stewart *et al.* (2004) who included a few southern Alberta headwater gauges in their study.

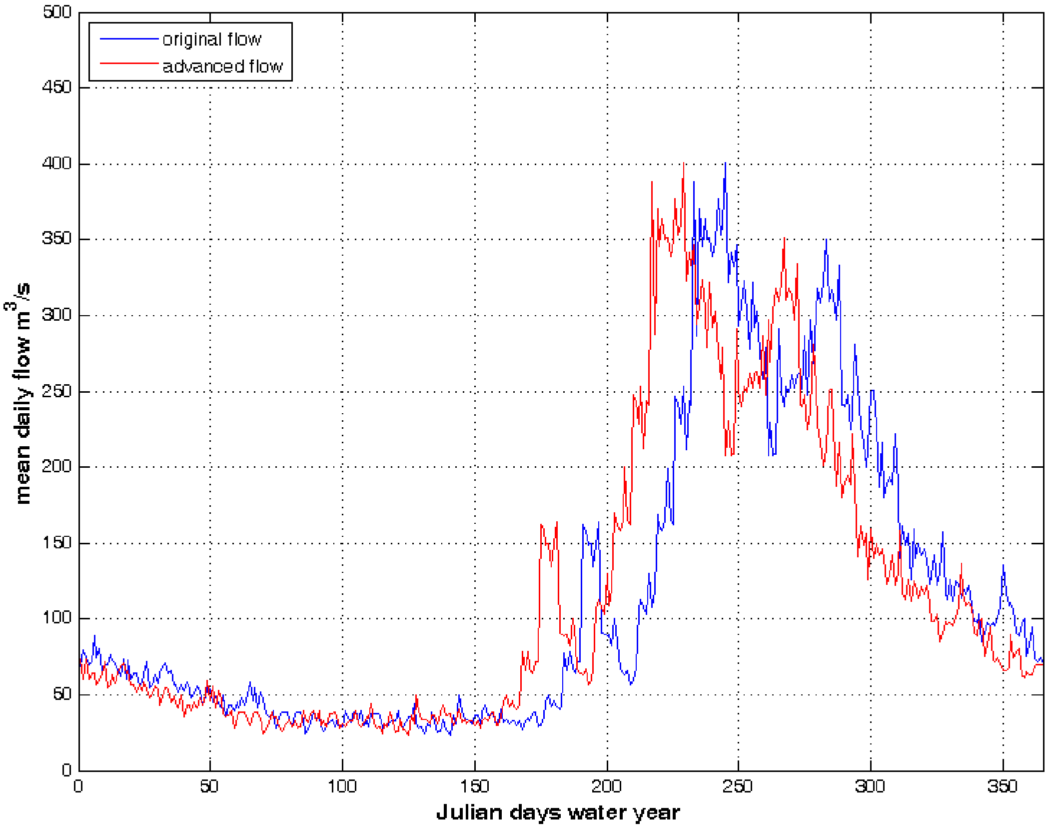

Figure 10. Projected 16-day advance in CT for 2035 for the MRI run 3 under A1B emissions scenario

The final step in this process was to perform a QA-QC of the code that was written to process the data. Dr. Elaine Barrow, adjunct professor with the University of Regina, examined the MATLAB code[3] of J.M. St. Jacques in a code review and confirmed that it appeared correct and properly designed. As well, the streamflow projection percentage declines are very similar to related work done in the South Saskatchewan River and adjacent basins (St. Jacques *et al.*, 2013) and the projected earlier spring peak result is comparable to those found by Stewart *et al*. (2004).

3.3 Assumptions and Limitations

There is a major advantage to the empirical approach of deriving plausible future daily streamflows from climate model projections and a statistical model of the teleconnection between sea surface temperature anomalies (PDO and the El Nino Southern Oscillation) and the hydrology of the Bow River Basin. Conventional approaches to developing scenarios of future water levels are based on the coupling of a dynamic hydrological model and “delta” scenarios of projected changes in mean climate (EBNFLO Environmental AquaResource Inc., 2010). This standard practice has the advantage of dynamically simulating the processes that generate runoff, but the disadvantage of requiring vast amounts of geophysical data to calibrate and validate the

---

[3] This is the high-level language and interactive environment for numerical computation, visualization, and programming.

model, thus limiting the domain of the model to a few decades (typically 1961-90) in terms of range of variability and extremes. The variability that is projected, using this conventional approach, is inherited from the calibration period. Unfortunately, the highest observed variability in the Bow River system occurred from about1930 to 1959 and not during the typical calibration period of 1961-1990. The scenarios produced are generally restricted to projections of changes in mean monthly or annual volumes or levels between past and future 30-year periods. However, watersheds and infrastructure are not managed for average conditions, but for extremes: flooding and, especially, drought.

The method adopted here explicitly incorporates the climate forcing of the inter-annual to decadal variability of the hydrological regime over the entire instrumental record of 1928-1995. Statistical models of streamflow at specific gauges are not calibrated to replicate a historical daily hydrograph but rather the dominant models of variability in the regional hydroclimate. By statistically linking this variability to climate forcing, the research team was able to re-evaluate the teleconnection between climate and hydrology for future years using output from climate models that, in its assessment, had the capacity to simulate the internal variability of the climate system that emerges under GHG forcing. The limitation of this novel approach is that no attempt is made to dynamically model the watershed hydrology; therefore, the mid-winter melting of snow over frozen ground in a warmer climate, for example, cannot be simulated. This limitation is not problematic where the objective is to determine the effect of changes in large-scale climate patterns on extreme water levels. The conventional approach is based on advanced hydrology and simple climatology analysis, while the innovative (scientific) approach taken for this project is based on advanced climatology and simple hydrology.

3.4 Selection of Climate Scenarios to Assess Impacts on Bow River Flows

The focus of this project was to build robust adaptation options in response to a range of scenarios that would test the system under periods of prolonged and extreme drought. Each of the 50 runs provided a 30-year sequence (2025-2054) that preserves the inter-annual persistence of low flows in future climates so the inter-annual relationship between PDO and flows is captured in each run, which is hard to do with GCMs. The aim of the future projections was to come up with a representative picture of what 2040 might look like; thus the 2025-2054 period was chosen to provide an outlook far enough from present that potential impacts are not immediate while giving a longer range outlook that is not too far into the future.

From those 50 runs, five were selected using a simple statistical procedure to rule out potential outliers and identify a maximum average, a median and three annual low-flow scenarios to reflect a realistic range of climate impacts and enable the discussion of potential management options. The 10th percentile of minimum flows was used to eliminate outliers of extreme low flows, and the medians of some flows were used because taking the average of average annual flows is meaningless. Each of these five scenarios is a 30-year time series of potential future climate; the scenarios were selected and named based on the criteria shown in Table 2.

Specifically, the “1yr Min” scenario was selected by taking the lowest annual average flow from all years of all scenarios, and selecting the flow at the 10th percentile. The “2yr Min” scenario was selected by taking the lowest summed 2-year (e.g., 2025+2026, 2026+2027) annual average flow from all years of all scenarios, and selecting the flow at the 10th percentile. The “3yr Min” scenario was selected by taking the lowest summed 3-year (e.g., 2025+2026+2027, 2026+2027+2028) annual average flow from all years of all scenarios, and selecting the flow at the 10th percentile. It has the lowest consecutive 3-year cumulative flow, but there are 27 other years with less severe flows. The “1yr Max” scenario was selected by taking the average of all 30 years for all 50 runs, and then taking the maximum of those 50 runs. The “2yr Median” scenario was selected by taking the sum of the annual average flows for 2 consecutive years (2025+2026, 2026+2027, etc.), and then taking the median run.

Table 2. Selection criteria and scenarios chosen for exploring adaptation options in the Bow River Basin

Selection Criteria	Scenario Run (GCM, Run, Emission Scenario)	Scenario Name
10th Percentile Lowest Annual Average Flow	CGCM3T47_3A2	1yr Min
10th Percentile Lowest 2yr Consecutive Minimum Annual Flow	CGCM3T47_2B1	2yr Min
10th Percentile Lowest 3yr Consecutive Minimum Annual Flow	CGCM3T47_3B1	3yr Min
Maximum of Annual Average Flow	MRI_5B1	1yr Max
Median of 2yr Consecutive Median Flow	CCSM3_1A2	2yr Median

There is concern, uncertainty and gaps in our understanding of the potential change in Bow River flow that might arise due to climate change and how this would affect operations and water users. Part of the intent of the SSRB Adaptation Project is to test proposed water management alternatives under a range of hydrological scenarios to find a preferred water management framework that considers the impacts of potential changes in climate. These five scenarios were the basis for a two-day modelling session that looked at adaptation options for managing the river.

4 Range of Hydrology Based on the Bow Basin Climate Scenarios

The five climate scenarios used in the two-day collaborative modelling session were selected to provide a range of plausible future flows and allow stakeholders to explore and test adaptation options. Much of the range in hydrology from the climate scenarios covers flow conditions that were seen throughout the historical record and are well within the range of variability seen in recent history in terms of magnitude and duration.

Figure 11 compares, at a weekly timestep, the 30-year average flow produced from each of the five chosen climate scenarios, with the 67-year average flow from the historical record in the model (1928-1995), and the two-year average flow from 2000-2001. 2000-2001 was a recent two-year period of low flows that were not in the modelling data; when plotted, this line provides some context for the average flow conditions that are produced for each of the five chosen climate scenarios. The plotted historical time series provides context for the hydrology produced by the climate scenarios. The average flow conditions and range of hydrology shown in Figure 11 generally reflect what are considered "normal" or average conditions.

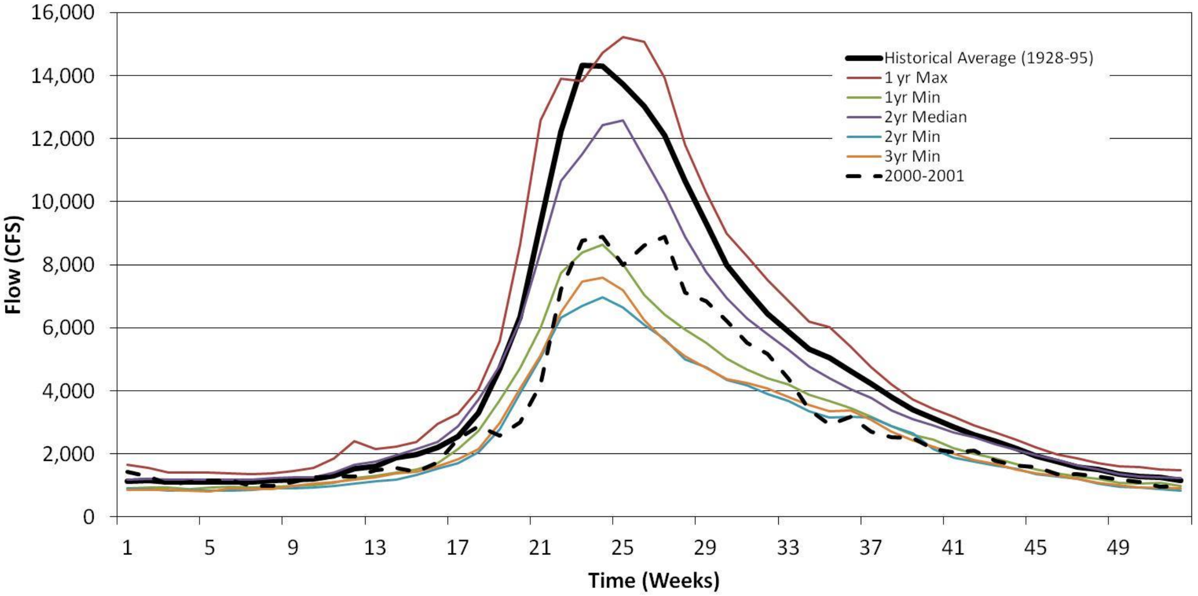

Figure 11. The 30-year average flow for 2025-2054 from each of the five chosen climate scenarios, with the 67-year average flow from the historical record in the model (1928-1995), and the 2-year average flow from 2000-2001

Some periods of hydrology from the scenarios are "not normal" or are more severe than what is seen in the historical record. This more extreme variability in flows was the focus of the adaptation modelling for the Bow River Basin. The scenarios chosen highlight the impacts of droughts of higher magnitude and duration than those seen in the historical streamflow record. These scenarios were selected to focus on lower flows and droughts for two main reasons. First, the methodology used to develop the scenarios shows the severe and extended droughts and in some years shows an earlier shift in the hydrograph. However, the methodology from downscaling annual flows to daily flows did not capture the peak high flood flows. The second reason is that droughts generally have a greater and longer impact on water users in the SSRB than floods; while very little can be done to control a large flood event, it may be possible to adapt operations for drought conditions.

Figures 12-14, all of which use the same scale, show the range of maximum, average, and minimum daily natural flows produced from each of the projected 30 year scenarios relative to the 67 year historical record. Each figure shows the highest, average, and lowest flow for each Julian Day for the period of record.

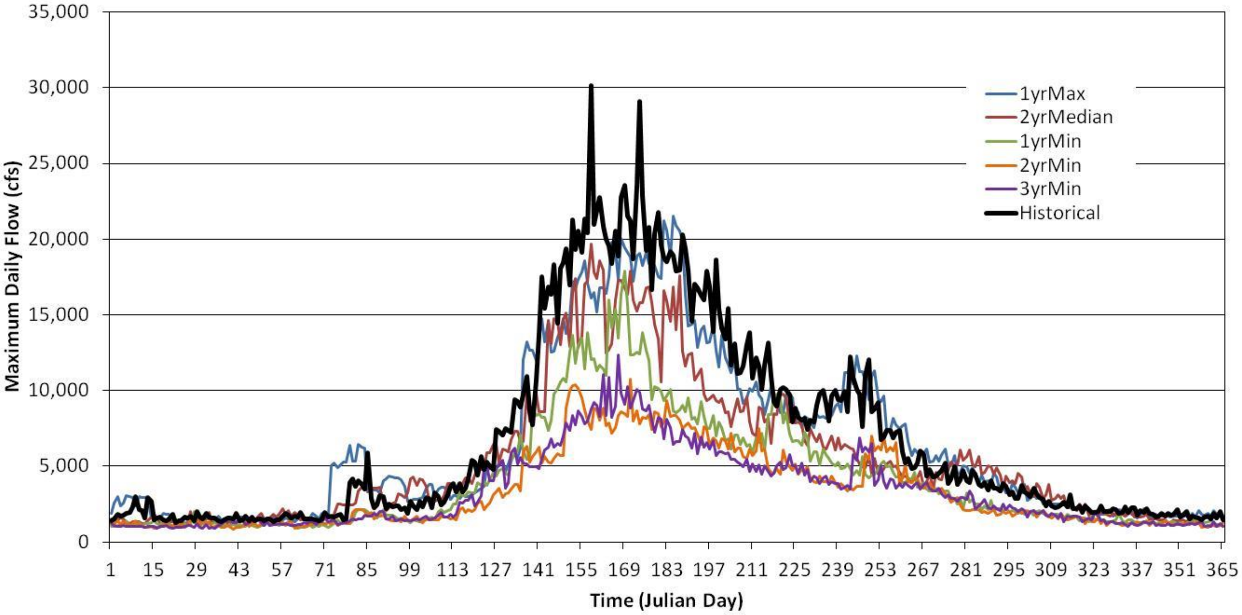

Figure 12. Maximum daily flows for each of the chosen projected climate scenarios, and the historical timeseries

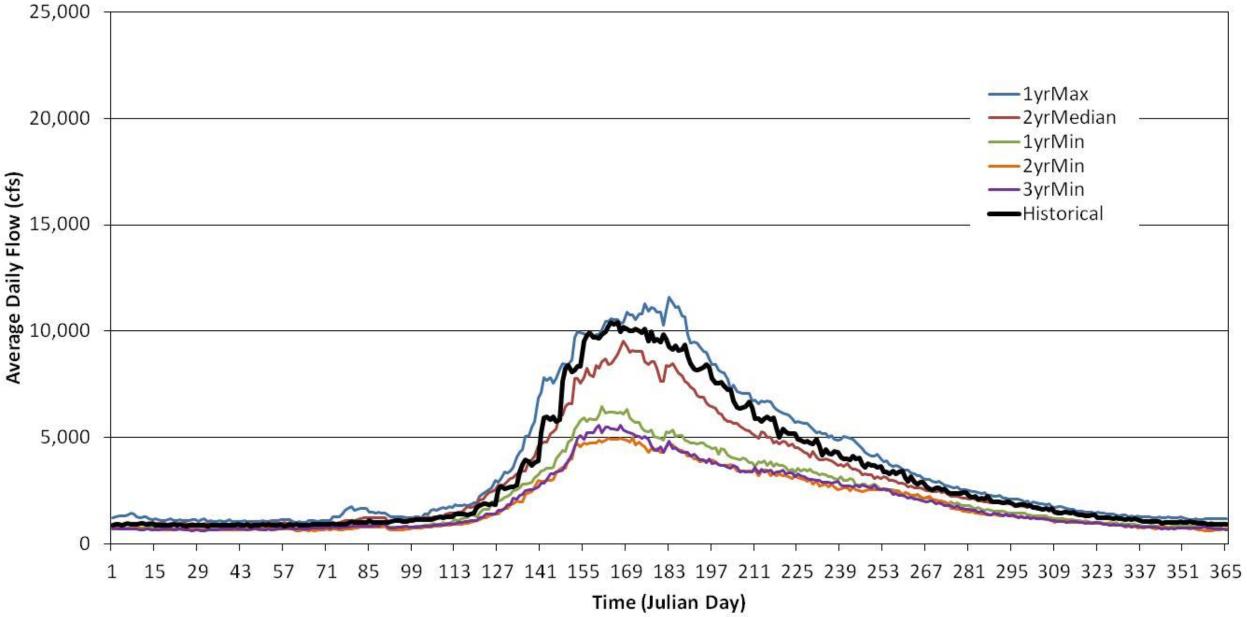

Figure 13. Average daily flows for each of the chosen projected climate scenarios, and the historical timeseries

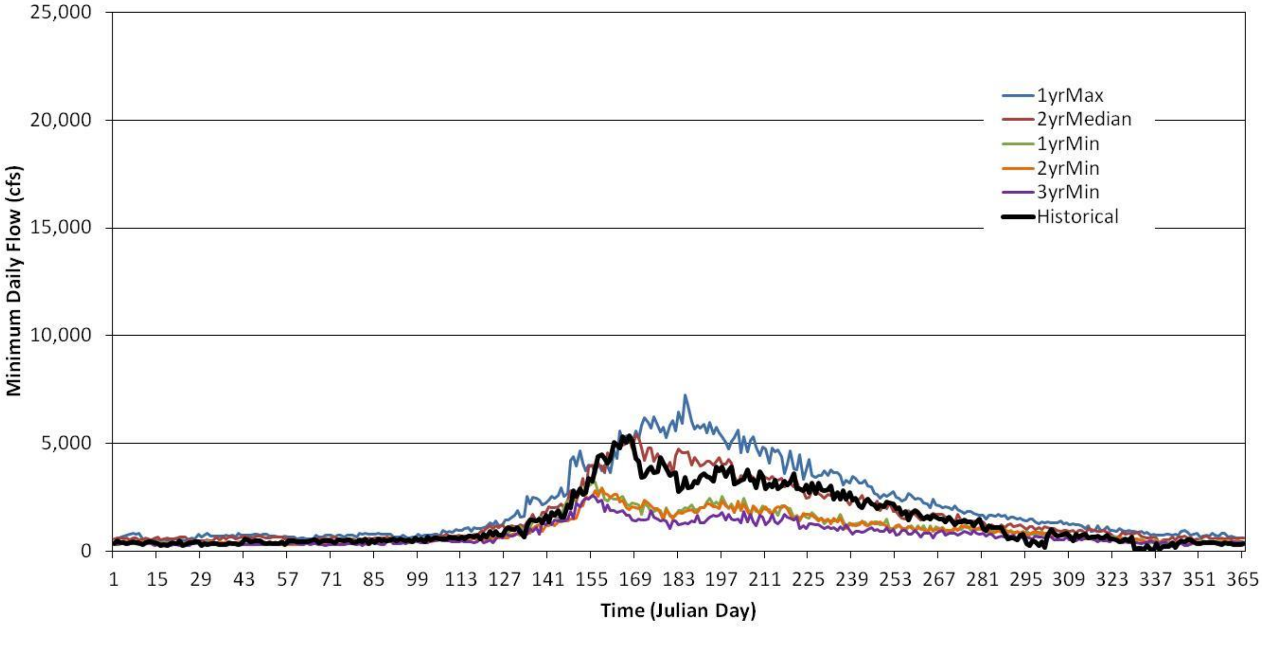

Figure 14. Minimum daily flows for each of the chosen projected climate scenarios, and the historical timeseries

Figures 12-14 show that, overall, the maximum, average, and minimum flows are lower most of the time for most of the scenarios than compared to the historical line. The 1yr Max scenario does show many higher average and minimum flows, but not as many of the high flows. Most of the years in all five scenarios were years that were fairly average and had flows with volumes and timing of water that would not require changes in operations to meet basin needs. This is the case with most long-term flow time series for both the historical record and future projections: most years there is enough water under current management practices and river system operations to meet the needs of water users and the environment. However, the purpose of this work was to identify robust strategies for adapting to changes in flows that could affect water users in the basin. Impacts from all the climate scenarios are in the following section.

5 Impacts on the River System Based on the Bow Basin Climate Scenarios

Projected impacts from changes in climate include droughts of greater magnitude and duration, a shift in the hydrograph with earlier spring runoff, and larger flood events. As mentioned above, the methodology for this work does not capture the impacts of a large flood event. A shift in the hydrograph is visible in some years, but does not produce a hydrograph that would create a shortage and cause water management problems. This methodology does not reveal impacts of an earlier spring freshet and a subsequent earlier recession of the hydrograph that would be seen by physically modelling a river basin and applying climate scenarios in the model to demonstrate these impacts, as has been done in previous work in Alberta (see Kienzle *et al*., 2011).

The chosen scenarios produced a range in hydrology. Some of the flows and the changes in hydrology negatively affected water users causing changes in storage, flow rates, and eventual shortages. Two of the scenarios (1yr Max and 2yr Median) were fairly "average" scenarios that produced average flows relative to the historical record. The hydrology from these scenarios resulted in no impacts on users (e.g., TransAlta reservoirs filled and storage was sufficient, flows at Calgary and below Bassano were adequate, Glenmore reservoir storage was adequate, and there were no shortages to the irrigation districts). The other three scenarios did produce flows that affected users and those impacts are discussed below. They highlight impacts on the major licence holders since, in the model, senior licence holders allow junior licence holders to take their water and senior licensees absorb any shortages in supply.

5.1 Impacts on TransAlta Storage in the Headwaters

With respect to flows in the Bow system, TransAlta Utilities' (TAU) storage is important, as it helps to augment flows in the winter and at times during the irrigation season. In the Bow River Operational Model (BROM), TAU storage is drawn down each year due to low inflows into the Bow River system in response to the climate scenarios, and because TAU's releases (in the model) are used to meet a targeted minimum flow of 1,250 cfs through Calgary. There is no formal agreement for TAU to provide these flows, but historically TAU releases more water in the winter from hydropower generation, resulting in a higher-than-natural minimum flow year round. This flow is typically needed to help assimilate return flows from municipal wastewater treatment plants.

In the 1yr Min scenario, impacts are seen throughout the Bow portion of the system due to a low-flow period from 2044-2052. As a result of those consecutive low-flow years, TAU's total system storage is below full supply level from 2044-2052; not until 2053 does it finally reach total system supply level. For four of the years when full system supply level is not reached (2046-2049), TAU live storage is at or near zero. As Figure 15 shows, for example, TAU storage is at zero for almost a month in the spring of 2049. TAU storage also reaches zero in 2046 and 2048 and almost hits zero in 2047. For a similar low-flow period in the 3yr Min scenario (2044-2047), TAU is again unable to fill all its reservoirs, which are well below normal operating storage levels; total system storage reaches zero for a month in the spring of 2047. The 2yr Min scenario produces low flows that only allow TAU reservoirs to reach full storage in one year (2047) from 2027-2054. Total system storage is nearly zero in 2039, with only 5,000 acre-feet

(AF) left for about a week, and again in 2040 with about 20,000 AF left for about a week. During this 27-year period, storage is roughly 100,000 AF below full system storage levels each year in which the system does not reach full storage.

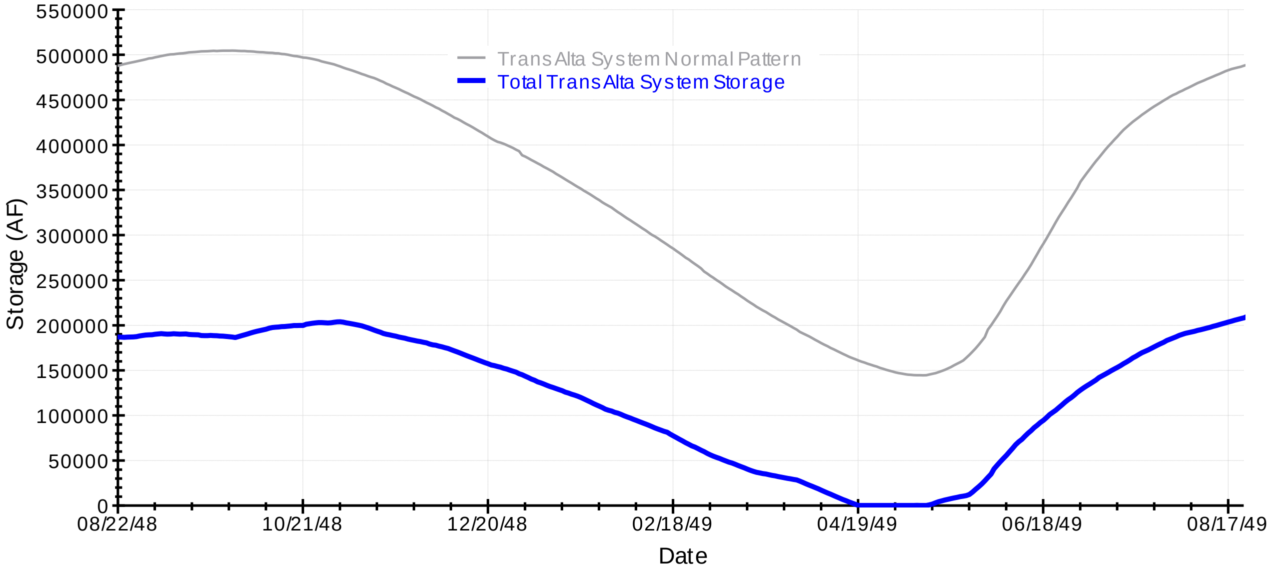

Figure 15. Live TAU storage in 2049 from the 1yr Min scenario, where total TAU system storage hits zero

5.2 Impacts on Flows through the City of Calgary and at Bassano

In the BROM, flows downstream of Bearspaw Reservoir are used as the measure of water that would flow through Calgary. A minimum flow target of 1,250 cfs below Bearspaw is set in the BROM, as Calgary typically relies on that flow rate to help assimilate return flows from its wastewater treatment plants. A target flow is a flow that the model will try not to break. Bassano is used as a proxy for environmental flows for the overall system as it is downstream of all major demands and inflows on the Bow River. A 400 cfs minimum flow target for Bassano is set in the BROM, but flows below Bassano ideally should be above 800 cfs during low-flow periods. Prolonged low flows below Bassano could negatively affect aquatic ecosystems, and could signal concerns about meeting apportionment. With TAU releases from storage, the 1,250 cfs target is typically met at Calgary, and thereby the 400 cfs flow at Bassano is similarly reached.

Low flows in the scenarios could affect both the city of Calgary and the reach below Bassano. During one low-flow period from 2044-2052 in the 1yr Min scenario, flows below Bearspaw drop below 1,250 cfs for 2-3 weeks, and are as low as 600 cfs in April of 2048 and 2049. A similar low-flow period (2044-2047) in the 3yr Min scenario also results in flows below Bearspaw hitting the 1,250 cfs minimum most of time, and dipping below 1,250 cfs for a week or two (to around 600 cfs) in spring of 2047 when TAU storage is exhausted and natural flow is low (around 600 cfs), as shown in Figure 16 (Flow is modelled flow, natural flow is calculated flow if there was flow impediments). Most of the 2yr Min scenario produces flows that are less than average, resulting in the 1,250 cfs minimum being met most of time. The only reason the

1,250 cfs target is met most of the time in this low-flow period is because of releases from the TAU reservoirs; this is typically how the system works, and what is modelled, but there is no formal agreement requiring TAU to make those releases.

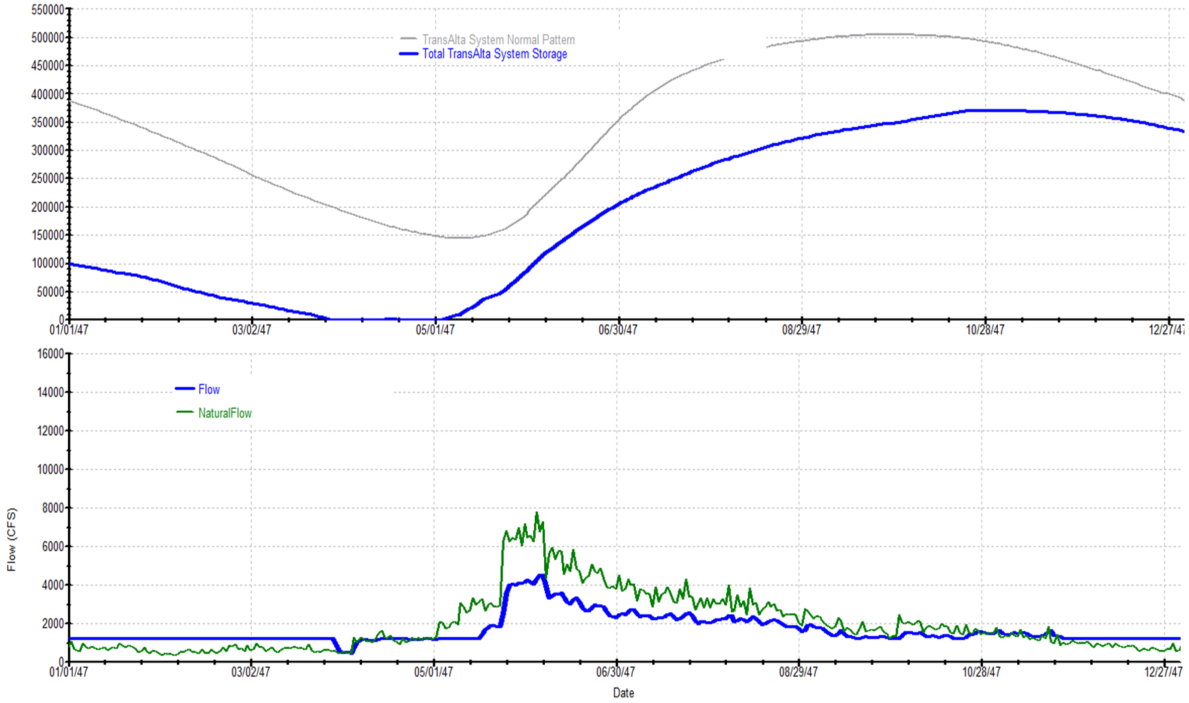

Figure 16. TAU Storage (top) and flow below Bearspaw reservoir.

Prolonged low-flow periods in the 1yr Min, 2yr Min and 3yr Min scenarios result in flows below Bassano staying at the 400 cfs minimum for most of the time (see Figure 17). The 400 cfs target is the lowest desirable flow below Bassano; ideally flows should be above 800 cfs.

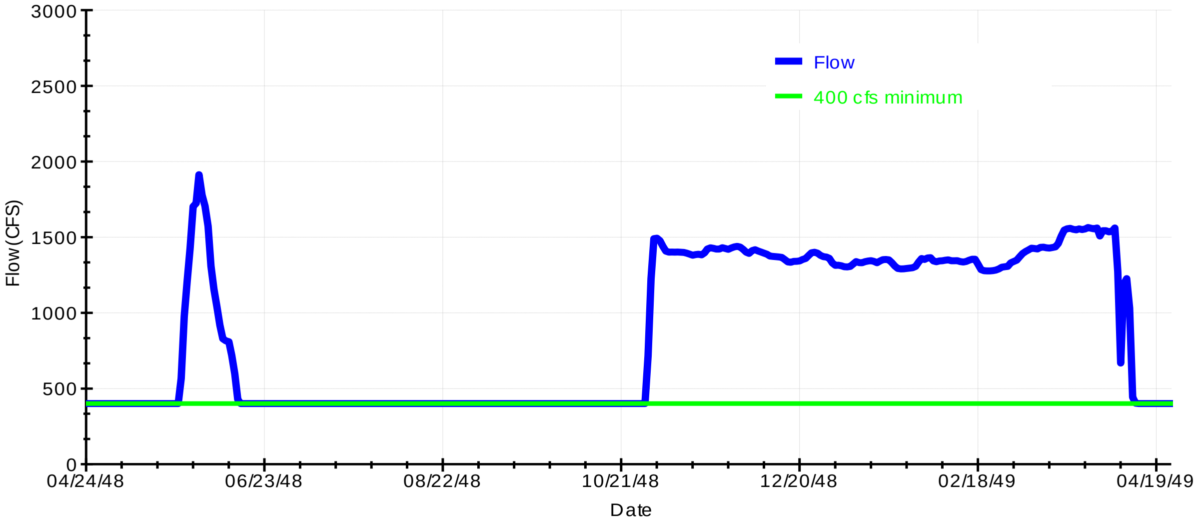

Figure 17. Flow below Bassano during a prolonged low flow period from the 1yr Min scenario

5.3 Impacts on Flows from the Elbow River into Glenmore Reservoir

Calgary’s Glenmore Reservoir, which is supplied by the Elbow River, is one source of drinking water for the city; the Bow River is the other source. Depleted storage in Glenmore could affect the city’s ability to meet demand, especially as Calgary continues to grow. If Glenmore was emptied due to prolonged low flows and unable to refill, the Bow River would likely not be able to make up the difference.

Another impact seen from the low-flow years in the 1yr Min scenario is on storage in the Glenmore Reservoir. During the 2044-2052 low-flow period in the 1yr Min scenario, Glenmore goes down to dead storage or the lower rule (no useable water) for four to five months each year in 2044-2048, with the exception of 2046 where it storage levels are quite low, but don’t reach empty. This impact also occurs in the 2yr Min scenario where Glenmore hits dead storage from two to four months each year in 2043, and 2044-2046 (see Figure 18 as an example). During these low-flow periods, the time Glenmore is at dead storage ranges from July to December, which is typically the greatest demand period. A similar impact is again seen in the 3yr Min scenario, where storage in Glenmore hits zero in 2043, 2044, and 2046, for about two months each year in the summer.

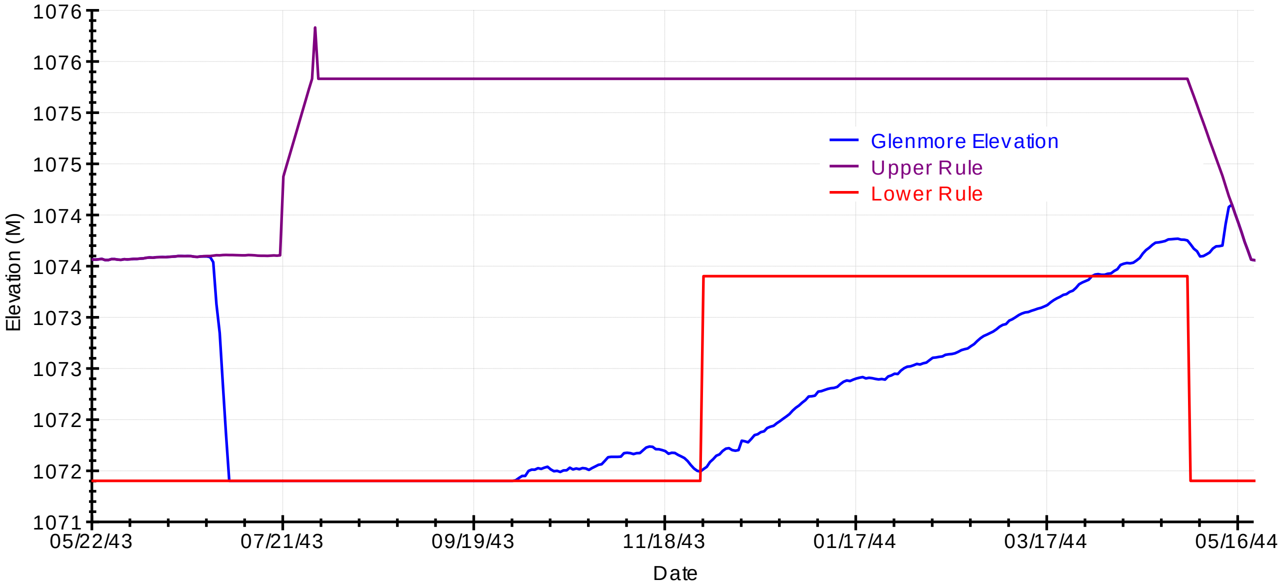

Figure 18. Glenmore Reservoir storage during a low flow period in the 2yr Min scenario, in 2033 where there is no storage for almost 2 months

5.4 Impacts on Flows and Shortages in the Highwood River System

The Sheep River is a major tributary to the Highwood River system, which is a major tributary to the Bow River. Concerns have been raised that the Highwood and Sheep Rivers do not have sufficient flow to support growing municipalities, including Okotoks, Black Diamond, Turner Valley, High River, and Longview. In this modelling work there are no shortages to any of these municipal demands on the Highwood or Sheep Rivers. On the Sheep River, municipal licences are some of the most senior licences in that basin, and in most instances are senior to the instream objectives (IOs). As a result, there are many shortages in the Sheep and Highwood Rivers to non-municipal users, and the IO is met less frequently as well. These shortages include demands on Mosquito Creek and Little Bow River, which both take diversion water from the Highwood. Municipal demands are modelled at full allocation based on modellers' understanding of the system and direction given by those more knowledgeable about the basin. Non-municipal (e.g., irrigation) demands are also modelled at full allocation; based on previous modelling work, this approach likely overstates both non-municipal demands and shortages. Shortages to the IOs are not overstated because only municipal licences are senior to the IOs and project modellers understood that full allocation for municipal use is correct.

Shortages are also conservative based on how the model deals with reach losses in the river. Based on the natural streamflow data and local understanding of the system, it was determined that reach losses needed to be accounted for. A reach loss occurs when the river becomes a contributing stream in certain reaches; that is,the river water contributes to groundwater flows rather than groundwater flows contributing to surface water flows. In the model these reach losses were modelled as a high priority demand, pulling the water from the river to account for the water that "disappeared" in the natural flow data in certain reaches (e.g., when flows downstream of a point saw a drop in the flow record). In the future scenarios produced from the climate models, reach losses were averaged, keeping the overall volumes of withdrawal, but smoothing out the spikes in reach losses in the historical record. As a result, reach losses in the future scenarios are more conservative because they are monthly averages rather than the daily, more abrupt changes in the historical record. Similarly, future demands are unknown and would vary dependent on climate. Some demands are modelled as annual patterns of use, future water demands that were not already patterns were converted to monthly averages. The difference in timeframe (30 years for future demands vs. 67 years in the historical record), averaged demands, and averaged reach losses prevent legitimate comparison of these future scenarios to historical model runs, so the 2yrMedian scenario was created for comparison. The 2yrMedian scenario is intended to be representative of the historical record as it reflects neither extreme high nor extreme low annual flows present in the other scenarios. Based on work to date, it is uncertain to what degree shortages are understated because of reach losses, or to what degree they would be overstated from modelling full allocation.

Under the 3yrMin scenario, non-municipal users on both the Sheep and Highwood Rivers experience increased shortages compared to the 2yrMedian. This is illustrated by Figure 19 which shows increased shortages to non-municipal users in the Highwood Basin for the 3yrMin scenario relative to the 2yrMedian scenario. Flows in the 3yrMin are roughly 30% less over the 30 years than the 2yrMedian in the Highwood and Sheep Basins, leading to the increase in shortages under a drier scenario.

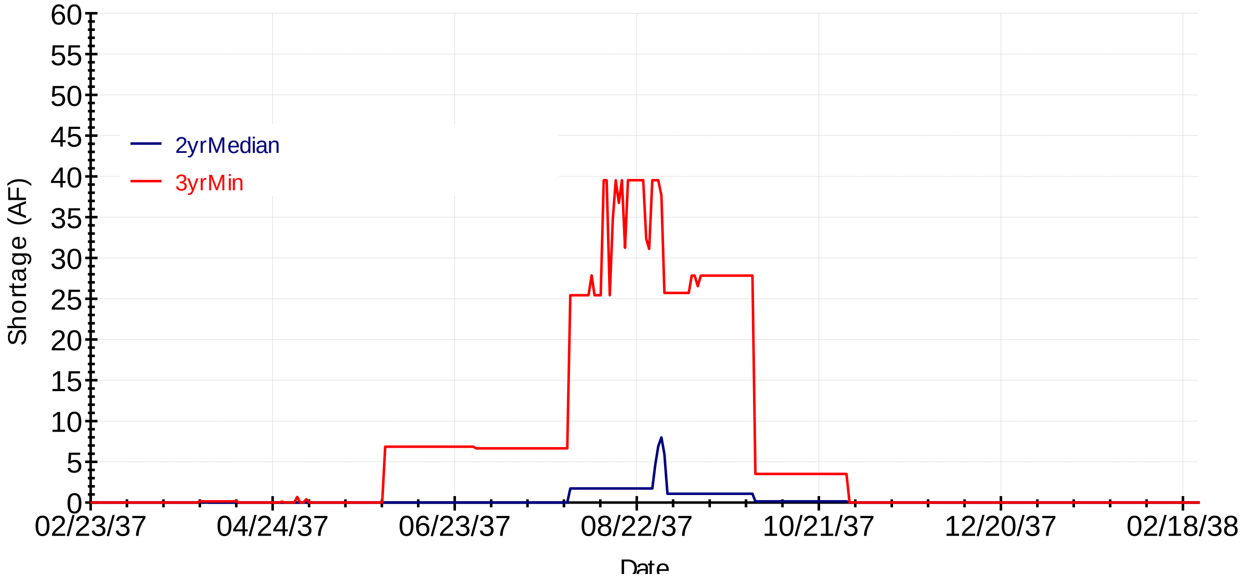

Figure 19. Shortages on the Highwood River in 2036-37 under the 2yrMedian and 3yrMin scenarios

IOs in the Highwood are set in the model as a continuous minimum flow of 150 cfs. IOs in the Sheep River are modelled as a seasonal pattern at the mouth of the river, above the confluence with Threepoint Creek, and on Threepoint Creek itself. The IO used for the Highwood is just downstream of the Little Bow Diversion, and upstream of the Sheep confluence. The IO used for comparison on the Sheep is at the mouth of the river. In comparing the frequency at which the IO is met under the 3yrMin scenario versus the 2yrMedian (again, a surrogate for historical conditions), the IO is met less frequently in the 3yrMin (dry scenario) than the 2yrMedian (surrogate historical). This difference in the IO being met for each basin is seen in Table 3, which shows that, over the 30-year period (10,950 days). Under the 3yrMin conditions, the IO in the Highwood is met 12% less frequently than under the 2yrMed, and the Sheep IO is met 24% less frequently than under the 2yrMed. As both these tributaries provide significant spawning habitat for the Bow River, additional analysis is needed to determine the consequences of these extended low flow periods. Figure 20 illustrates an example from the 3yrMin of the Sheep IO being met less frequently when compared to conditions representative of the historical record (e.g., the 2yrMedian).

Table 3. Number of days in the 30 year scenarios where the IO in the Highwood and Sheep are not met

Scenario	Highwood	Sheep
2yrMed	4112	1421
3yrMin	5336	4104

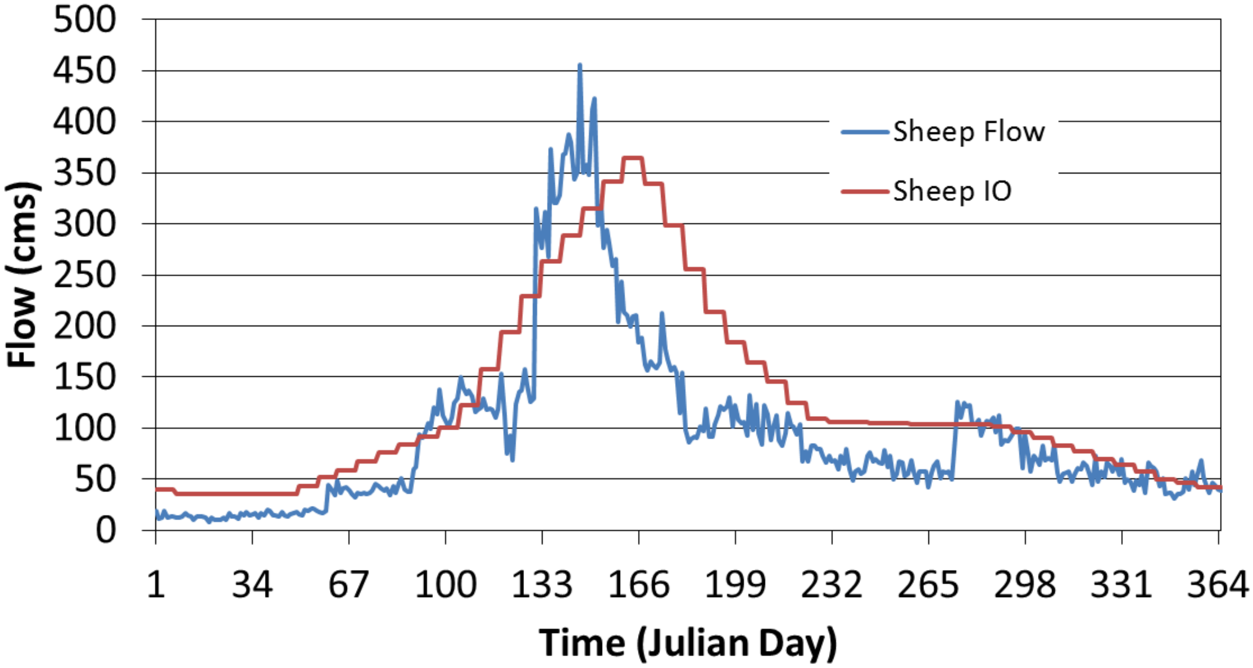

Figure 20. Comparison of the flow in the Sheep River at the mouth and the associated IO in 2046 of the 3yrMin scenario

5.5 Impacts on Irrigation Districts in the Bow Basin

The Bow River Basin contains three irrigation districts: Bow River Irrigation District (BRID), Eastern Irrigation District (EID), and Western Irrigation District (WID). Each district relies on water from the Bow River to deliver water to irrigation farmers. The districts all have storage that can be used to meet some demands, but river flows are still required to meet some demands and replenish storage.

During a prolonged low-flow period (2044-2052) in the 1yr Min scenario, shortages appear in the BRID and EID systems in 2048. Although the shortages are likely all manageable (as suggested by the irrigation district managers), they affect water users in the system. The shortages are likely less than they could be, since during the low-flow period for this scenario, TAU is forced to meet the 1,250 cfs flow through Calgary (according to the model rules). The TAU release increases river flow, which allows the irrigation districts to make their withdrawals from the river. If the 1,250 cfs target was not maintained by TAU releases, the flow would likely not meet instream objectives, thus not permitting the districts to make river withdrawals, resulting in more shortages. There are no shortages to the WID in any of the scenarios, as they have first call on water coming down the river.

The 2yr Min and 3yr Min scenarios both produce shortages to the BRID and the EID that are double the volume of shortages seen in the 1yr Min scenario. In the BRID, the 2yr Min results in shortages in 2053; the 3yr Min scenario produces shortages in 2043 and 2046 (see Figure 20). Shortages to the EID occur in 2027, 2036, 2040, and 2049-51 during the 2yr Min scenario, and in 2038, 2039, and 2054 during the 3yr Min scenario. These shortages are about 60 af larger in magnitude compared to what they have seen in the historical, but the length of time the shortage is present is more prolonged than seen in the historical. The shortages in the historical record were deemed as manageable by the irrigation district representatives, it is unclear if a shortage as see in Figure 20 would also be manageable.

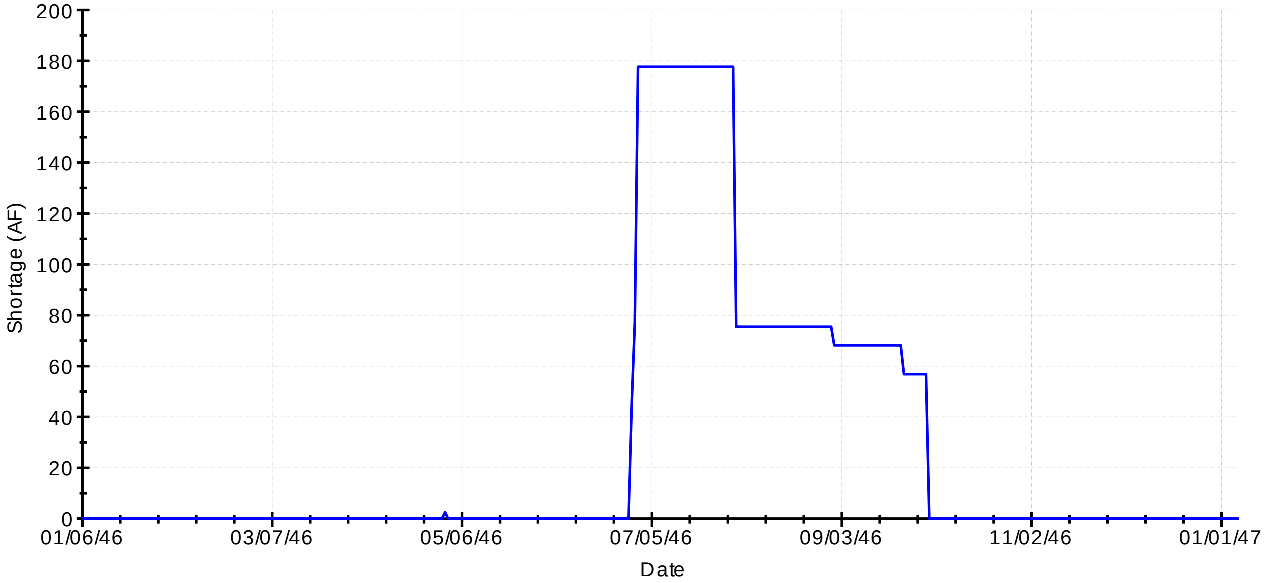

Figure 21. Shortages in 2048 for the BRID

6 Conclusions

An important focus of the SSRB Adaptation Project was to build robust adaptation options in response to a range of future climate scenarios that would test the Bow River system under periods of prolonged and extreme drought. The work described in this report lays the foundation for developing adaptation options by projecting the impacts of changes in climate in the SSRB.

The aim of the projections was to come up with a representative picture of what the year 2040 might look like; thus the 2025-2054 period was chosen to provide an outlook far enough from present that potential impacts are not immediate while giving a longer range outlook that is not too far into the future. The methodology to develop the scenarios outlined in this report provided a range of plausible future flows. Five of these scenarios were chosen for use in a modelling session that looked at impacts to the river and adaptation options for managing the river under possible future climates.

The five chosen scenarios produced a range in hydrology, and most of the years in all five scenarios were fairly "average" with volumes and timing of water that would not require changes in operations to meet user needs. But the selected scenarios did highlight the impacts of lower flows and droughts.

Some of the flows and the changes in hydrology negatively affected water users causing changes in storage, flow rates, and eventual shortages. Two of the scenarios (1yr Max and 2yr Median) were fairly "average" scenarios that produced average flows relative to the historical record, and their hydrology resulted in limited impacts on users. The other three scenarios did produce flows that affected users and highlighted the impacts on major licence holders in particular.

The three low-flow scenarios affected the ability of TAU to fill its storage system, to the point where the system was actually empty at times. Low flows could affect the city of Calgary in two ways: a) reduced flow through the city could affect water quality due to lack of assimilative capacity in the river, and b) depleted storage in Glenmore Reservoir combined with low flows on the Bow River could make it difficult for the city to meet its water demands. Low flows would also negatively affect downstream aquatic ecosystems. The scenarios also projected increased shortages for non-municipal water users on the Highwood and Sheep rivers, as well as less frequently met IOs. Finally, shortages were identified for the three irrigation districts that are served by the Bow River system.

The five scenarios described in this report informed stakeholders about the potential impacts in the region and gave them an opportunity to identify adaptation options and build resiliency in the SSRB for responding to future climate variability and change. Such options did emerge from the two-day collaborative modelling session based on the scenarios, and these options are described in a separate report for the SSRB Adaptation Project.

References

Axelson, J. N., D. J. Sauchyn, and J. Barichivich. 2009. “New reconstructions of streamflow variability in the South Saskatchewan River Basin from a network of tree ring chronologies, Alberta, Canada,” *Water Resour. Res.*, 45, W09422, doi:10.1029/2008WR007639.

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier. 2005. “Potential impacts of a warming climate on water availability in snow dominated regions,” *Nature* 438: 303-309.

Bruce, J.P., H. Martin, and P. Colucci. 2003. Climate change impacts on boundary and transboundary water management. A Climate Change Action Fund Project A458/402, Natural Resources Canada. 161 pages.

Burn, D.H. 1994. “Hydrologic effects of climatic-change in West-Central Canada,” *Journal of Hydrology* 160(1-4): 53-70.

Byrne, J. and S.W. Kienzle. 2008. “The Prairies,” in Lemmon, D., F. Warren, E. Bush, and J. Lacroix, eds.: From *Impacts to Adaptation: Canada in a Changing Climate,* 2007, Report to the Government of Canada, Chapter 7.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. “Changes in the onset of spring in the western United States”. *Bulletin of the American Meteorological Society,* 82: 399-415.

Demuth, M.N., and A. Pietroniro. 2003. *The impact of climate change on the glaciers of the Canadian Rocky Mountain eastern slopes and implications for water resource-related adaptation in the Canadian Prairies: Phase I- Headwaters for the North Saskatchewan River Basin.* Report for the Climate Change Action Fund- Prairie Adaptation Research Collaborative, 1-111.

Dettinger, M.D. 2005. “From climate-change spaghetti to climate-change distributions for 21st century California,” *San Francisco Estuary and Watershed Science* 3:1-14.

Dettinger, M.D. 2006. “A component-resampling approach for estimating probability distributions from small forecast ensembles,” *Climatic Change,* 76: 149-168.

Durack, P.J., S. Wijffels, and R.J. Matear. 2012. “Ocean salinities reveal strong global water cycle intensification during 1950 to 2000,” *Science* 336, 455; DOI: 10.1126/science.1212222.

EBNFLO Environmental AquaResource Inc. 2010. *Guide for Assessment of Hydrologic Effects of Climate Change in Ontario,* prepared for Ontario Ministry of Natural Resources and Ministry of the Environment in partnership with Credit Valley Conservation, June 2010.Field, C.B., L.D. Mortsch, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running and M.J. Scott. 2007. “North America. Climate Change 2007: Impacts, Adaptation and Vulnerability,” Contribution of Working Group II to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds., Cambridge University Press, Cambridge, UK, 617-652.

Forbes, K.A., S.W. Kienzle, C.A. Coburn, J.M. Byrne, and J. Rasmussen. 2011. “Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada,” *Climatic Change* 105(3): 555–565.

Furtado, J.C., E. Di Lorenzo, N. Schneider and N.A. Bond. 2011. “North Pacific Decadal Variability and Climate Change in the IPCC AR4 Models,” *Journal of Climate* 24:3049-3067.

Gan, T.Y. 1998. “Hydroclimatic trends and possible climatic warming in the Canadian Prairies. Water Resources Research,” *American Geophysical Union* 34(11): 3009–3015.

Government of Alberta. 2006. News release: Alberta implements Water Management Plan for the South Saskatchewan River Basin. Accessed on December 20, 2012 at http://www.gov.ab.ca/acn/200608/2043260C967C4-CBB8-C14F-F0EFFFCE8EF4EF81.html.

Hughes, D.A., and V. Smakhtin. 1996. “Daily flow time series patching or extension: a spatial interpolation approach based on flow duration curves”. *Hydrological Sciences,* 41: 851-871.

Kharin, V.V., F.W. Zwiers, X. Zhang, and G.C. Hegrel. 2007. “Changes in temperature and precipitation extremes in the IPCC ensemble of Global Coupled Model simulations,” *Journal of Climate* 20: 1419-1444.

Kienzle, S.W., M.W. Nemeth, J.M. Byrne, and R.J. MacDonald. 2011. “Simulating the hydrological impacts of climate change in the upper North Saskatchewan River basin, Alberta, Canada,” *Journal of Hydrology*, doi:10.1016/j.jhydrol.2011.01.058.

Lapp, S., J. Byrne, I. Townshend, and S. Kienzle. 2005. “Climate warming impacts on snowpack accumulation in an Alpine watershed: a GIS based modeling approach,” *International Journal of Climatology* 25(3): 521–536.

Lapp, S.L., J.M. St. Jacques, E.M. Barrow, and D.J. Sauchyn. 2011. “GCM projections for the Pacific Decadal Oscillation under greenhouse forcing for the early 21st century,” *International Journal of Climatology*, doi:10.1002/joc.2364.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. “Stationarity Is Dead: Whither Water Management?” *Science* 319(5863): 573-574.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner, H-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N. and Dadi, Z. (2000): Emissions Scenarios; special report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, 599 pp.

Rood, S.B., G.M. Samuelson, J.K. Weber, and K.A. Wywrot. 2005. “Twentieth-century decline in streamflows from the hydrographic apex of North America,” *Journal of Hydrology* 306(1-4): 215-233.

Rood, S.B., J. Pan, K.M. Gill, C.G. Franks, G.M. Samuleson, and A. Shepherd. 2008. “Declining summer flows of Rocky Mountain Rivers: Changing seasonal hydrology and probable impacts on floodplain forests,” *Journal of Hydrology* 349(3-4): 397-410.

Sauchyn, D. and S. Kulshreshtha. 2008. “Climate change impacts on Canada’s Prairie Provinces: A summary of our state of knowledge,” from “Prairies” in *From Impacts to Adaptation: Canada in a Changing Climate 2007*, edited by D. Lemmen *et al*., Government of Canada, Ottawa.

Sauchyn, D., A. Pietroniro, and M. Demuth. 2008. “Upland Watershed Management and Global Change – Canada’s Rocky Mountains and Western Plains,” Chapter 3 in *Mountains, Valleys and Flood Plains: Managing Water Resources in a Time of Global Change,* Routledge.

Sauchyn, D., C. Perez-Valdivia, and J. Vanstone. 2011. “Modes and forcing of hydroclimatic variability in the upper North Saskatchewan River Basin since 1063,” *Canadian Water Resources Journal* 36(3): 205-218.

Stewart, I.T., D. R. Cayan, and M.D. Dettinger. 2004. “Changes toward earlier streamflow timing across western North America,” *Journal of Climate* 18: 1136-1155.

St. Jacques, J.M., D.J. Sauchyn, and Y. Zhao. 2010. “Northern Rocky Mountain streamflow records: global warming trends, human impacts or natural variability?” Geophysical *Research Letters* 37: L06407, doi:10.1029/2009GL042045.

St. Jacques J.M., S. Lapp, Y. Zhao, E. Barrow and D.J. Sauchyn. 2013. “Twenty-first century northern Rocky Mountain river discharge scenarios under greenhouse forcing”. *Early on-line Quaternary International,* doi:10.1016/j.quaint.2012.09.011.

St. Jacques, J.M., Y.A. Huang, Y. Zhao, S.L. Lapp and D.J. Sauchyn. (in prep a) Detection and attribution of variability and trends in Canadian Prairie Provinces' streamflow. To be submitted to Canadian Water Resources Journal.

Tebaldi, C., K. Hayhoe, J.M. Arblaster and G.A. Meehl. 2006. “Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events”. *Climatic Change,* 79: 185-211.

Woodhouse, C.A. and J.J. Lukas (2006a) “Drought, tree rings and water resource management”. *Canadian Water Resources Journal*, 31: 297-310.

Woodhouse, C.A. and J.J. Lukas (2006b) “Multi-century tree-ring reconstructions of Colorado streamflow for water resources planning”. *Climatic Change*, doi: 10.1007/s10584-006-9055-0.

Glossary

Global Circulation Model (GCM): (also known as a global climate model), describes climate behavior by integrating a variety of fluid-dynamical, chemical, or even biological equations. GCMs are often used to provide climate projections of future climates.

Hydrograph: graph showing the rate of flow (discharge) versus time at a specific point in a river or other flowing body of water, typically expressed in cubic meters or cubic feet per second (cms or cfs).

Hydroclimate: a systematic structure for analysing how the climate system causes time and space variations (both global and local) in the hydrologic cycle.

Stationarity: defined as a quality of a process in which the statistical parameters (mean and standard deviation) of the process do not change with time.

Teleconnection: in atmospheric science teleconnection refers to climate anomalies being related to each other at large distances (typically thousands of kilometers).

Appendix A: SSRB Adaptation Project Introduction Memo

South Saskatchewan River Basin Adaptation to Climate Variability Project
May 2012

A new project being launched this spring will harness the energy and creativity of southern Albertans to explore practical options for adapting to climate variability and change. Water is fundamental to community sustainability and growth, and the way water is managed in the South Saskatchewan River Basin (SSRB) will become even more important in the face of changing weather patterns and climate.

In January 2012, the Climate Change Emissions Management Corporation awarded funding for the *SSRB Adaptation to Climate Variability Project*. The funds were provided to Alberta Innovates-Energy Environment Solutions and WaterSMART Solutions Ltd. to support the first stage of this adaptation work.

This initiative will build on and integrate existing data, tools, capacity and knowledge of water users and decision makers to improve understanding and explore how to manage for the range of potential impacts of climate variability throughout the SSRB's river systems. This understanding will support collaborative testing and development of practical and implementable adaptive responses to climate variability, from the local community scale to the provincial scale. Using existing analytical and decision-support tools, the project will engage many people and groups to build:

- a common understanding of feasible and practical mechanisms for adapting to climate variability and change, and
- increased capacity for an informed, collaborative and adaptive approach to water resource management throughout the SSRB. This will enable organizations, communities and individuals to assess their risks in near real-time and determine their most suitable responses to climate variability within the physical realities of SSRB river flows, requirements and infrastructure.

The first stage of the project is divided into four coordinated phase:

Foundational Blocks: Initial Assessment

The first phase of the work is an initial assessment of the data, tools, capabilities, processes and frameworks that already exist and could form elements of the foundational blocks to support integrated water management by water users, decision makers and other interested parties over the long term. This work will identify the core resources for the project, identify critical gaps to be addressed, and ensure existing knowledge, tools, and experiences are leveraged, while avoiding duplication of work already completed or underway.

Bow River Basin: Adaptation and Live Test Year

The second phase will re-engage Bow River Project participants and engage new participants with an interest in the Bow River Basin to: advance climate adaptation decision making related to water resources, explore climate variability scenarios, identify impacts and risks to the river system and its users, and identify adaptation options. Participants will also document the net benefits of re-managing flows in the Bow River and identify infrastructure options that could assist with adaptation strategies. All of this work will provide support for a 'virtual' river test year, or perhaps an actual test year of modified flow, to better match the three Water for Life goals

Oldman River Basin and South Saskatchewan River Modelling

In the third phase, participants will model the Oldman River Basin (Oldman River and Southern Tributaries, including the Belly, St. Mary and Waterton Rivers), and the South Saskatchewan River to the Alberta border. Users, decision makers and others in the Oldman and South Saskatchewan River (OSSK) Basins will form a river consortium and set principles to guide and inform the model-based work, incorporating an environmental and climate adaptation focus. A comprehensive river system model for the OSSK Basins will be developed. Inputs to the SSRB from the Milk River will be part of this data, but the Milk will not be explicitly modelled. Throughout the model building, participants will discuss work that has been or is being done, and possible next steps in building the capability and capacity for adaptation around river management in the SSRB.

Foundational Blocks: Development

The final phase will see development of new adaptation foundational blocks. This work will be based on the gaps identified in the initial assessment, which may include acquiring, updating, or purchasing useful data and tools for future work to develop adaptation options for integrated river management.

This project will take approximately two years to complete. It should significantly advance climate adaptation resilience in the SSRB, leave a legacy of data, information and tools, and inform similar future work throughout the rest of the SSRB. We hope, with subsequent support, to then expand the work to encourage climate adaptation throughout the entire SSRB.

Project updates and reports can be accessed through the Alberta WaterPortal at: www.albertawater.com

If you have any specific questions regarding this work, please contact AI-EES or WaterSMART Solutions Ltd.