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ADAPTIVE WATER RESOURCE PLANNING IN THE SOUTH SASKATCHEWAN RIVER BASIN: USE OF SCENARIOS OF HYDROCLIMATIC VARIABILITY AND EXTREMES[1]

David J. Sauchyn, Jeannine-Marie St-Jacques, Elaine Barrow, Michael W. Nemeth, Ryan J. MacDonald, A. Michael S. Sheer, and Daniel P. Sheer[2]

ABSTRACT: The South Saskatchewan River Basin is one of Canada's most threatened watersheds, with water supplies in most subbasins over-allocated. In 2013, stakeholders representing irrigation districts, the environment, and municipalities collaborated with researchers and consultants to explore opportunities to improve the resiliency of the management of the Oldman and South Saskatchewan River subbasins. Streamflow scenarios for 2025-2054 were constructed by the novel approach of regressing historical river flows against indices of large-scale ocean-atmosphere climate oscillations to derive statistical streamflow models, which were then run using projected climate indices from global climate models. The impacts of some of the most extreme scenarios were simulated using the hydrologic mass-balance model Operational Analysis and Simulation of Integrated Systems (OASIS). Based on stakeholder observations, the project participants proposed and evaluated potential risk management and adaption strategies, e.g., modifying existing infrastructure, building new infrastructure, changing operations to supplement environmental flows, reducing demand, and sharing supply. The OASIS model was applied interactively at live modeling sessions with stakeholders to explore practical adaptation strategies. Our results, which serve as recommendations for policy makers, showed that forecast-based rationing together with new expanded storage could dramatically reduce water shortages.

(KEY TERMS: climate oscillations; climate change resilience; drought; low flows; low-frequency hydroclimatic variability; Oldman and South Saskatchewan Rivers; mass-balance modeling; projected streamflows; stakeholder participation; statistical downscaling; water policy; water allocation.)

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INTRODUCTION: THE SOUTH SASKATCHEWAN RIVER BASIN ADAPTATION PROJECT

Communities and economies are exposed to the compounding effects of economic development and changing climate. In regions where water resources are in short supply and/or mostly allocated, the dominant risk is increasing vulnerability to hydrological drought. Adaptation planning to proactively manage this risk requires use of historical records and projections of the variability of water supplies. Most water

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resource structures and strategies are designed to manage short-term annual hydroclimatic variability and extremes. A scenario of more or less water on average in the long-term presents a different set of risks and involves a different set of adaptation strategies (Sauchyn *et al.*, 2015).

Watershed management and climate adaptation issues are complex and should be appropriately addressed not by any single initiative or sector, but rather by the collective knowledge and experience of communities, watershed groups, environmental organizations, government agencies, scientists, business leaders and industry sectors. The South Saskatchewan River Basin (SSRB) Adaptation to Climate Variability Project (http://albertawater.com/work/research-projects/ssrb-adaption, accessed December 25, 2014) brought together some of the most knowledgeable and experienced water users and managers in southern Alberta to explore opportunities to enhance the resiliency of the management of the Bow, Oldman, and South Saskatchewan River subbasins (Figure 1), building on previous collaborative work in the region (Sheer *et al.*, 2013). The diverse participants represented the major water users and a majority of the licensed water diversions (Table 1). All participants had experienced the impacts of droughts and floods, and were cognizant of the challenges after the Government of Alberta's decision to close the Bow and Oldman Basins to new water allocations in 2006. The stakeholders also recognized the need to be prepared for a wider range of possible future streamflow conditions, including water levels reaching unprecedented extremes in a warming global climate with reduced seasonal carry-over in snowpack and the potential for increased precipitation intensity (Larson *et al.*, 2011; MacDonald *et al.*, 2011). Presented with projections of future hydroclimate, and the simulated impacts of some of the most extreme scenarios, plus stakeholder observations, the project participants proposed and evaluated potential risk management and adaption strategies, i.e., optimizing existing infrastructure, building new infrastructure, changing operations to supplement environmental flows, reducing demand and sharing supply. This was done using a mass-balance model applied interactively at live modeling sessions with stakeholders through a process designed to identify and explore practical adaptation strategies based on the best data and knowledge in the river

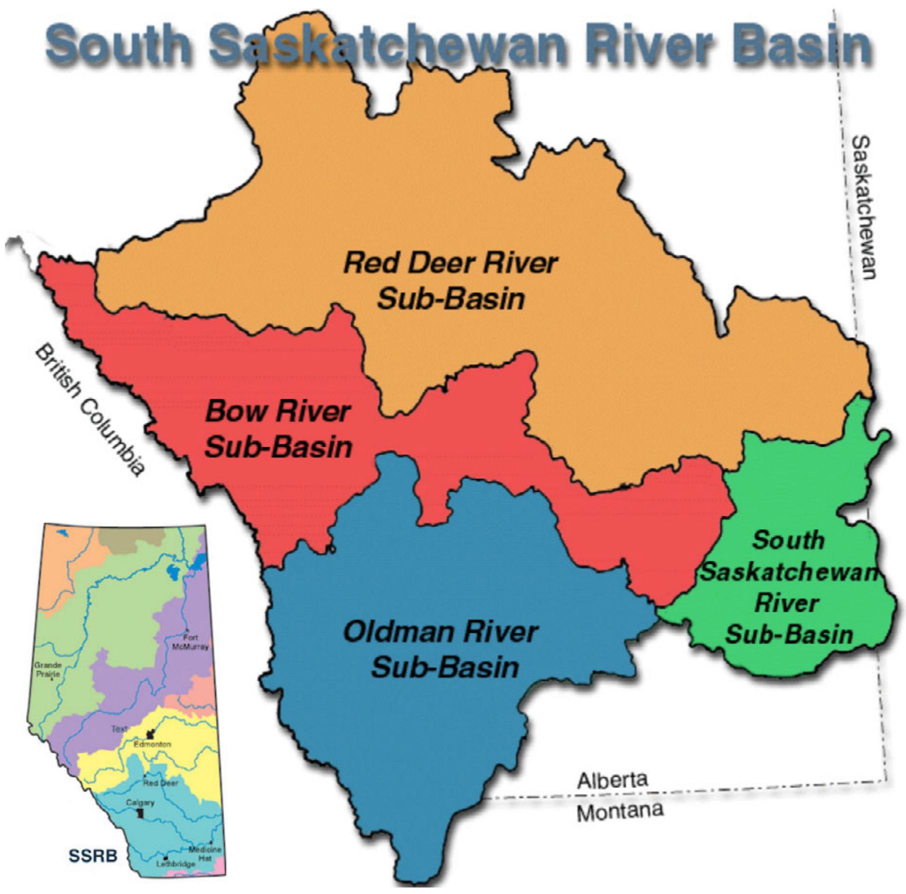

FIGURE 1. The South Saskatchewan River Basin (SSRB) Showing the Bow, Oldman, and South Saskatchewan Subbasins.

TABLE 1. Members of the South Saskatchewan River Basin (SSRB) Adaptation to Climate Variability Project.

Funders/Facilitators/Technical Assistance	Municipalities	Agriculture	Environment/Recreation	Watershed Groups
Alberta Innovates — Energy and Environment Solutions	City of Lethbridge	Alberta Agriculture and Rural Development	Alberta Environment and Sustainable Resource Development	Oldman Watershed Council
University of Lethbridge	SouthGrow	Alberta Irrigation Projects Association		South East Alberta Watershed Alliance
Alberta WaterSMART	Town of Cardston	Raymond Irrigation District		
HydroLogics, Inc.	Town of Coaldale	St. Mary Irrigation District		
Prairie Adaptation Research Collaborative	Town of Taber	Taber Irrigation District		
	Village of Milo	United Irrigation District		
	City of Medicine Hat	Northern Irrigation District		

basins. During this process, stakeholders identified and explored robust, integrative water resource management strategies as an adaptive response to the regional impacts of climate variability and change. This paper focuses on work in the Oldman and SSRBs (OSSK Basins); similar methods were previously applied to the Bow River Basin (Alberta WaterSMART and AIEES, 2013, 2014a; Sheer *et al.*, 2013). The purpose of this paper is to (1) describe this stakeholder-driven collaborative SSRB Adaptation Project, which tested water management alternatives with the OASIS (Operational Analysis and Simulation of Integrated Systems) river system model (Sheer *et al.*, 2013), (2) introduce our novel method of producing scenarios of future potential streamflow extremes that challenged the stakeholder working groups, and (3) present a synopsis of recommendations.

STUDY AREA

While Alberta's economy is fuelled by hydrocarbons, it runs on water that is derived mostly from the Rocky Mountains, the water towers of western Canada (Schindler and Donahue, 2006). The sustainable use of Alberta's natural resources and its economic vitality depend on an understanding of climatic and hydrologic variability and the adaptive capacity to confront the prospects and potential impacts of climate change. Alberta faces significant water challenges driven by an expanding population, accelerating economic growth, and the interaction between economic development and a changing climate. Nowhere in Canada are these issues more pressing than in southern Alberta, where the South Saskatchewan River has been declared as one of Canada's most threatened rivers (WWF-Canada, 2009). Water supplies in the SSRB (Figure 1) are under serious pressure and scrutiny. These pressures were acknowledged through the closure of three of the four sub-basins to new water allocations, following drought and historically low water levels in 2001 (Rood and Vandersteen, 2010). The southern tributaries of the Oldman River, especially the St. Mary River, have become overallocated. The Government of Alberta continues to investigate opportunities to increase traditional on- and off-stream storage, and other storage options including the use of aquifers, gravel beds, wetlands, and other natural features.

Canada's most extensive irrigation system in southern Alberta takes advantage of the mountain snowpack and augments this natural storage with approximately 50 reservoirs, distributing the stored water to farms, communities, and industries (McGee *et al.*, 2012). Irrigation districts in southern Alberta represent about 60% of Canada's irrigated land. The senior and major water users in the region hold licences for 85% of the allocated water. Improved irrigation efficiency has enabled expanded acreage. The high productivity of the irrigated land has attracted food processing and other industries, which also require assured supplies of water.

Water management in the SSRB, and particularly in the Oldman River subbasin, is complicated by the origin of one of the southern tributaries in the United States (U.S.). Water use in this subbasin is subject to International Joint Commission agreements. There are interbasin diversions from the St. Mary River in the SSRB to the Milk River, another international river and a tributary to the Missouri River (Oldman Watershed Council, 2010). The evaluation of water management measures is also complicated by the implications of riparian First Nations reserves and their economic and environmental interests. Due to excessive water withdrawal, the riverine environment along the lower St. Mary collapsed (Rood *et al.*, 1995). This river reach defines the boundary for the Blood/Kanai reserve. In the SSRB Project, the international and First Nations aspects of the basin were handled in a simplified way, in part because there were no U.S. or First Nations participants in the study.

THE WATER MANAGEMENT SIMULATION MODEL

At the core of the SSRB Adaptation Project are river basin management models built on the OASIS simulation software platform, which is the product of years of development by HydroLogics, Inc. and its partners (Sheer *et al.*, 2013). Most of the data and many of the operating rules included in the OASIS platform are taken directly or derived from models developed by Alberta Environment and Sustainable Resource Development (AESRD). Those models are based on AESRD's Water Resource Management Model (WRMM) platform.

The OASIS-based model is particularly flexible, transparent, completely data-driven, and effectively simulates water facility operations. In the Oldman subbasin, the HydroLogics models combines the areas modelled in separate WRMMs into a single model, allowing a more comprehensive and complete evaluation of combined benefits in those areas. For the SSRB Adaptation Project, water management models were developed for the Bow, Oldman, and South Saskatchewan River subbasins to simulate current water demand, water management infrastructure, and operations, and thereby to assess scenarios of water supply and demand, infrastructure, operational changes, and a variety of ecosystem values chosen by stakeholders. The models allow users to understand integrated demands and operations throughout the entire system, and evaluate the impacts and benefits that could accrue from changes in operational or storage strategies, as well as changes in demands, climate, and land use. Once a model was developed, we evaluated a "base case" scenario representing a conservative version of current operations. From this "base case" scenario, changes in the system were modeled and differences among scenarios evaluated. For the purposes of this article, the OSSK model and modeling work will be the primary focus (Figure 2).

The OSSK model computes a daily mass balance, accounting for streamflow and operational management of the rivers and all major tributaries. Like the prior WRMM, the OASIS model is constructed with a weekly time-step, which is then disaggregated to daily values based on long-term flow statistics and using a random component. Shorter-term hydrologic conditions (e.g., peak flows) are only modestly represented, although comparisons among model runs should reflect shifts in these flows. The model does not explicitly account for groundwater or for scenarios that include conjunctive use of groundwater. Groundwater contribution to base flow is implicitly part of the naturalized flow data obtained from the WRMM model, and implicitly a part of the hydrology derived from future climate scenarios. The model also does not include aspects of water quality, although it can assess water quality parameters as a function of

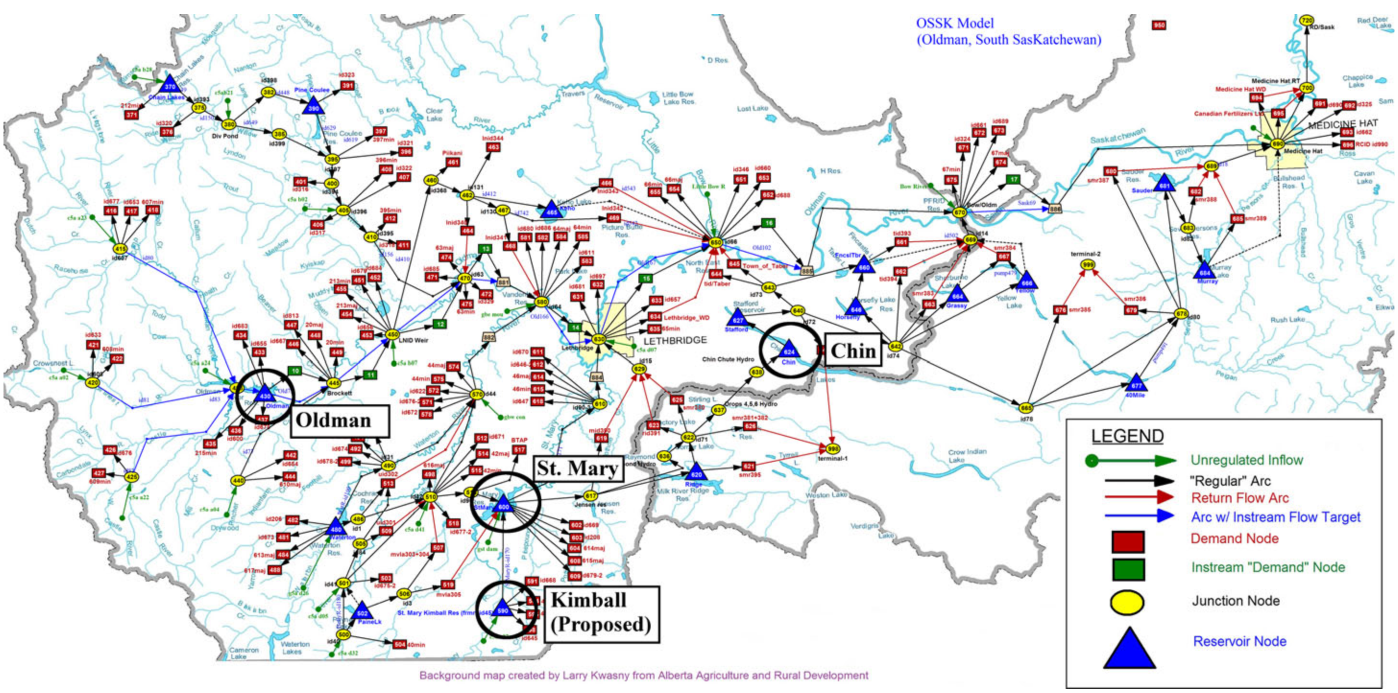

FIGURE 2. Schematic Showing the Area Represented by the Oldman and South Saskatchewan River Basins (OSSK) Model and the Model's Complexity with Certain Reservoirs Circled for Reference to Modelled Scenarios.

streamflow at particular river reaches of interest. The primary inputs are naturalized streamflows (m^3/s), lake evaporation (mm) and precipitation (mm), consumptive uses (m^3/s), return flows (m^3/s), physical infrastructure data, and facility operations. Most of these data were derived from the WRMM, with the exception of agricultural consumptive use data, which were provided directly by Alberta Agriculture and Rural Development. As currently configured, time step by time step, the model meets as many existing water needs defined by stakeholders in the basin as possible, given physical constraints and operating rules. It simulates the balancing of reservoirs, and the outcomes from changes in operations or storage. The model base case was compared to historical streamflow records and reservoir levels, and the validity of the operating policies was validated by stakeholder review. Demand data at each model node, including all existing licensed allocations, were reviewed and modified by the working group participants to reflect current demands and operations.

Performance measures (PMs) were developed to assess the impacts and benefits of proposed changes for various scenario runs of the OSSK model. Stakeholders, working collaboratively at group meetings, identified specific PMs based on their water needs and desired project outcomes. The models were run with results tested using appropriate PMs to determine if the outcomes were reasonable and realistic, based on local knowledge and experience. Participants then worked collaboratively to identify and test opportunities and potential scenarios or strategies to achieve specific outcomes illustrated by the PMs. Twenty-four PMs were processed for each strategy (Table S1), but for the purposes of this paper, a short list of four PMs was selected.

Daily Storage in AESRD and Chin Reservoirs

This PM depicts the total daily storage in dam^3 for all three AESRD (Alberta Environment and Sustainable Resource Development) reservoirs (Waterton, St. Mary, and Oldman), and Chin Reservoir, operated by an irrigation district (see Figure 2). This PM indicates how balancing of storage supports adaptive water management options in the basins.

Cumulative Irrigation Shortage Days for All Districts

This PM examines the effects of operational schemes on irrigation districts by assessing shortage days cumulatively for all districts. Shortage is defined as a full or partial shortfall in delivery to a water request (demand).

Cumulative Irrigation Shortage Days per District

This PM examines the effects of operational schemes on irrigation districts by assessing shortage days cumulatively for individual districts. Shortage is defined as a full or partial shortfall in delivery to a water request (demand). The individual district shortages were of particular interest to participants, many of whom represented individual districts. Comparison of the changes in shortages by district allowed the participants to evaluate the equitable allocation of benefits.

Weighted Usable Area

This PM was designed to capture the effects of operations on fish habitat in selected stream reaches (the St. Mary River below St. Mary Reservoir and the Oldman River near Lethbridge) for selected indicator species. Weighted usable area (WUA) is the wetted area of a stream weighted by its suitability for use by aquatic organisms or recreational activity (Clipperton *et al.*, 2003). This PM is expressed as a proportion of total usable area.

DEVELOPING HYDROCLIMATIC SCENARIOS

In the mid-latitude continental climate regime of the OSSK basins, streamflow is highly variable over a range of scales. Current water management is well adapted to the extreme seasonality and deals effectively with water deficits that persist for up to approximately two years (the typical reservoir capacity). Our goal was to present water users and managers with scenarios outside this familiar operating mode of variability, i.e., hydroclimatic variability at interannual to decadal scales, which is evident in the Oldman River annual hydrograph (Figure 3a). The annual flow has a large range, 159% of the average, and the extreme flows are not randomly distributed over time but rather tend to cluster in periods of 2-3 decades as highlighted in Figure 3.

Lower-frequency hydroclimatic variability, beyond the familiar one to two years of wetter or drier conditions, has important implications for water management. In Figure 3a, few years had below average water levels during the 30-year period 1947-1976 (a negative phase of the Pacific Decadal Oscillation — PDO; St. Jacques *et al.*, 2010, 2014), while these low flow years were common in the prior and subsequent few decades when the PDO was in a positive state. The much longer proxy record for the Oldman River

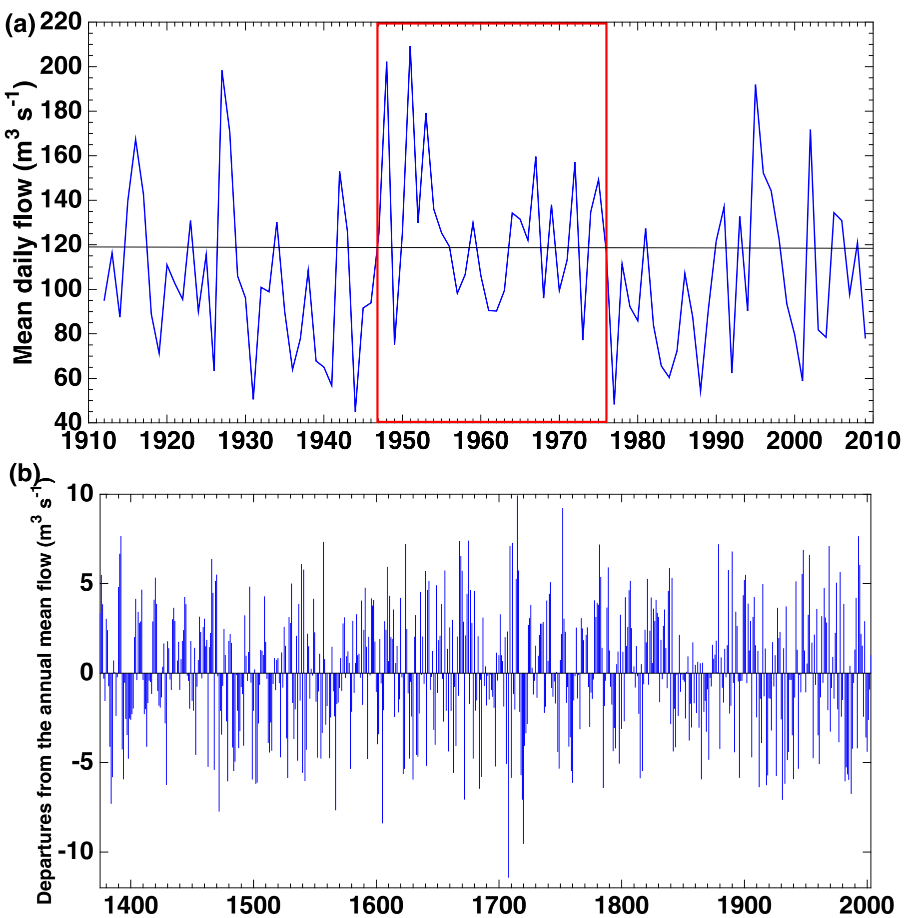

FIGURE 3. (a) Annual Naturalized Flow (m^3/s) of the Oldman River at Lethbridge from 1912 to 2009, Based upon the Instrumental Record. The red box highlights a period of consistently higher annual flow. The black line shows the mean flow for 1912-2009 of 109.7 m^3/s. (b) Departures from the annual mean flow (m^3/s) of the Oldman River at Lethbridge, Alberta, from AD 1375 to AD 2003. This reconstruction was derived from a network of tree-ring chronologies in the upper reaches of the river basin (updated from Axelson *et al.*, 2009).

extending from 1375 to 2003 (Figure 3b) shows that this river basin is prone to far more variability than recently recorded in the naturalized record for 1912-2009. Prior to the instrumental period, departures from mean water levels exceeded the recorded extremes in terms of both magnitude and duration. The most severe environmental and social (on the Indigenous populations) impacts would have been associated with sustained low water levels such as those during the 16th and 18th Centuries, and the 1840s through 1860s. In the current warming climate, the reoccurrence of drought of these durations would have substantial economic consequences.

Global climate models (GCMs) are “the only credible tools for simulating the response of the global climate system to increasing greenhouse gas concentrations” (IPCC-TGICA, 2007). Using output from a climate model to force a statistical hydrological model is a scientifically rigorous approach compatible with common engineering practices (Wilby *et al.*, 2004; EBNFLO Environmental AquaResource Inc., 2010; Kienzle *et al.*, 2011; Larson *et al.*, 2011; MacDonald *et al.*, 2011). Whereas hydrological models are typically calibrated to replicate measured daily flows and seasonal fluctuations over a relatively short period of 10 to 30 years, the approach taken here accounts for the interannual to decadal modes of hydroclimatic variability evident in the annual hydrograph for the entire period of record (1912-2009) (Figure 3a) and clearly demonstrated by 629 years of inferred annual flows (Figure 3b). To achieve this, we modelled naturalized streamflow at a network of gauges as a function of the ocean-atmosphere oscillations that drive the low-frequency variability of the regional hydroclimatic regime (St. Jacques *et al.*, 2010, 2013). The teleconnections between the PDO, El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) and the hydroclimate of western Canada are well documented (e.g., Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997, 2011; Bonsal and Lawford, 1999; Bonsal *et al.*, 2001; Shabbar and Skinner, 2004; Bonsal and Shabbar, 2008;

St. Jacques *et al.*, 2014). We developed streamflow projections by regressing historical river flows against climate oscillation indices and then running these statistical models using outputs from climate models. For each generalized least squares (GLS) regression model, the predictand was mean daily streamflow over the water year (October 1-September 30), while the predictors were the linear historical trend, and the PDO, Southern Oscillation (SOI), and NAO indices for the current year, and lagged with the climate index leading streamflow by one and two years, and also with the climate index lagging streamflow by one year (because of antecedent conditions). The error term followed an ARMA residual model. The GLS models captured a large proportion of the variance in naturalized streamflow ($R^2_{\text{reg}} \geq 0.50$, $R^2_{\text{innov}} = {\sim}0.60$) over the period 1912-2009.

We assumed that since the teleconnection indices could account for much of the interannual variance in historical streamflow (St. Jacques *et al.*, 2010, 2013), we could create scenarios of future annual flows from climate model projections of the future status of the ENSO, PDO, and NAO. This approach, unlike those that feed hydrological models with changes in mean monthly or annual precipitation and air temperature, takes advantage of the capacity of GCMs to simulate the internal variability of the climate system. We chose ten GCMs from Phase 3 of the Coupled Model Intercomparison Project (CMIP3), according to how well they simulate the spectral and geographic characteristics of the ENSO and PDO (Furtado *et al.*, 2011; Lapp *et al.*, 2012) (Table 2). We drove the GLS models of annual streamflow using output from an ensemble of 50 runs of the ten GCMs externally forced according to the three commonly used SRES greenhouse gas emission scenarios: A2 (high emissions), A1B (medium emissions), and B1 (low emissions). The projected PDO, SOI, and NAO indices were computed using model output for sea surface temperature and pressure, and then corrected for systematic bias using the method of variance scaling recommended by Teutschbein and Seibert (2012).

For example, the GLS model for the Oldman River near Lethbridge gauge is

$$Q_t = -0.32 - 6.13\,\text{trend}_t - 9.15\,\text{PDO}_t - 8.63\,\text{SOI}_{t-1} - 9.85\,\text{PDO}_{t-2} - 4.03\,\text{SOI}_{t-2} + \varepsilon_t \quad (1)$$

for $t = 1\ldots L$, with an ARMA(2,1) residual error model ε_t, where Q_t is centered mean daily streamflow (annualized) and the climate variables are standardized. The simulated and projected results for this gauge, and all three SRES emission scenarios, are plotted in Figure 4. These simulations and projections of mean daily flow over the water year (October 1-September 30) were slightly smoothed using a 5-point binomial filter. The high-frequency residual variance removed by this low-pass filter was characterized using the historical flows from 1912-2009. It followed a Gaussian distribution ($\mu = -0.02$, $\sigma = 16.74$), which was randomly sampled in order to add back the missing high frequency variance. The downward trajectory of the all-model mean (heavy magenta line) is consistent with the historical trend and future projections identified elsewhere (e.g., Schindler and Donahue, 2006; Rood *et al.*, 2008; Sauchyn *et al.*, 2009; Shepherd *et al.*, 2010; Kienzle *et al.*, 2011; Larson *et al.*, 2011; MacDonald *et al.*, 2011; St. Jacques *et al.*, 2013). What is novel about the results in Figure 4 are the modeled shifts in variability, and in particular, the projection of a larger range of flows in the future. For the historical period (1912-2009), the statistical model, driven with output from historical runs of the GCMs, emulates the range of flows in the gauge record (red line). Into the future, low flows frequently exceed historical minimums.

TABLE 2. Metadata for the Ten Chosen CMIP3 Global Climate Models.

No.	IPCC4 Model ID	Country	Atmospheric Resolution	Oceanic Resolution	Number 21st Century Runs B1	A1B	A2
1	CGCM3.1(T47)	Canada	3.7° × 3.7° L31	1.84 × 1.85° L29	3	3	3
2	CGCM3.1(T63)	Canada	2.8° × 2.8° L31	1.4 × 0.9° L29	1	1	0
3	ECHAM5/MPI-OM	Germany	1.875° × 1.865° L31	1.5 × 1.5° L40	2	2	1
4	GDFL-CM2.1	USA	2.5° × 2.0° L24	1.0 × 1.0° L50	1	1	1
5	MIROC3.2(hires)	Japan	1.125° × 1.12° L56	0.28 × 0.188° L47	1	1	0
6	MIROC3.2(medres)	Japan	2.8° × 2.8° L20	(0.5-1.4°) × 1.4° L43	1	1	1
7	MRI-CGCM2.3.2	Japan	2.8° × 2.8° L31	(0.5-2.5°) × 2.0° L23	5	5	5
8	NCAR-CCSM3	USA	1.4° × 1.4° L26	(0.3-1.0°) × 1.0° L40	1	1	1
9	NCAR-PCM	USA	2.8° × 2.8° L18	(0.5-0.7°) × 0.7° L32	2	2	2
10	UKMO-HadCM3	UK	3.75° × 2.5° L15	1.25 × 1.25° L20	1	1	1

The ensemble of streamflow projections for each gauge was processed to derive exceedence probabilities, and then to construct analog hydrographs of daily flows. First, the 50 projections at each gauge were resampled 20,000 times, using the PCA-based methods of Dettinger (2005, 2006) and St. Jacques *et al.* (2013), to generate additional realizations of the relatively small ensembles for the calculation of smooth cumulative distribution functions (CDFs). The CDF in Figure 5 shows a future shift to lower mean annual flows and a greater probability of extreme low flows for the Oldman River near Lethbridge gauge for the selected years 2006, 2050, and 2096. From here on, we concentrate our analysis on the period 2025-2054 given its relative immediacy for the stakeholders in the SSRB.

Further processing of the projected and historical streamflow data produced time series of plausible projected daily flows, following the approach of Woodhouse and Lukas (2006a, b) of mapping projected mean daily flows to the daily hydrographs from analog years. From the Dettinger (2005, 2006) method of resampling, we derived the average CDF of projected flows for the period 2025-2054 and an empirical CDF from the historical (1912-2009) naturalized mean daily flows (Figure 6). By matching flows of equal probability, using a QPPQ transform (or quantile translation) approach (Hughes and Smakhtin, 1996), we identified a historical analog for each simulation and each future year, i.e., 50 GCM runs × 30 years = 1,500 model years. In the example illustrated in Figure 6a, one run of the statistical model, driven with output from the GCM CGCM3.1T47_3 according to emission scenario A1B, projected a mean annual flow of 104.4 m^3/s for the year 2026. The CDF of projected flows in Figure 6a gives a probability of 0.60 that this flow will not be exceeded. The CDF of historical annual flows indicates that the closest historical analog with equal probability is 116.4 m^3/s in 1913 (Figure 6b). To arrive at daily flows for 2026, the daily observations from 1913 were lognormal scaled by the projected values of the mean and standard deviation. A strong quadratic relationship between the mean and standard deviation of the historical daily flows, shown in Figure S1, allowed scaling of both parameters.

One more transformation of the projected streamflows was required to produce plausible scenarios of hydroclimatic variability. The impacts of global warming on the hydrology of western North America include an advance in the timing of peak snowmelt runoff (Cayan *et al.*, 2001; Stewart *et al.*, 2005). We adopted the approach of Stewart *et al.* (2004) to adjust the timing of the projected mean daily flows. First the date of the center of mass flow ($CT = \Sigma\, tq_t/\Sigma q_t$, where t is the tth day of the water year and q_t is the daily discharge) was regressed against total winter (October-May) precipitation and spring (April-July) air temperature, which are the strongest controls on annual peak snowmelt runoff. Then this regression model was run using projected temperature and precipitation data for 2025-2054 from all 50 GCM experiments. For each projection, future year and gauge, we adjusted the daily hydrographs by the difference between the projected timing of the CT minus the mean date of the CT for the simulated historical period 1966-1995. Figure 7 gives one example: a 29-day advance in the 2027 spring peak of the Oldman River near Lethbridge as projected by CGCM3.1T47_1, with emissions scenario B1. The shifts in the timing of peak flow computed here are comparable to those found by Stewart *et al.* (2004)

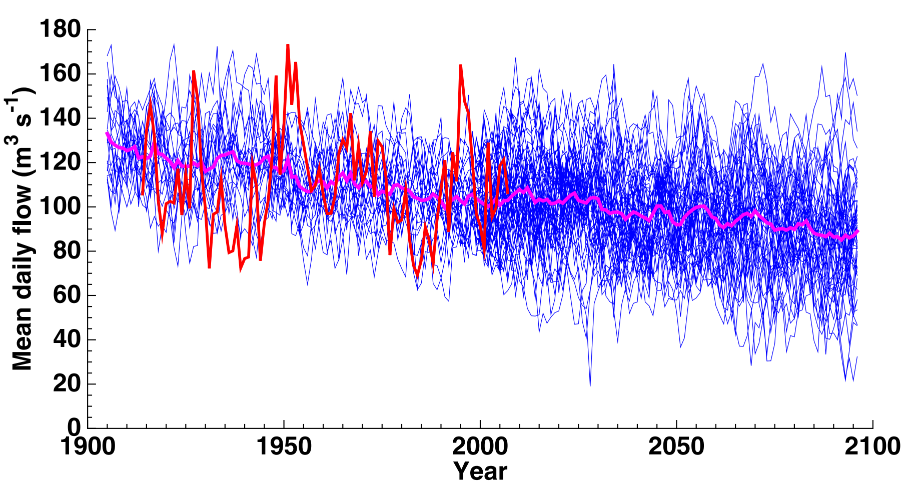

FIGURE 4. Simulated Annual Flow, from 1905 to 2096, of the Oldman River near Lethbridge. Each simulation (blue line) corresponds to 1 of 50 runs of ten CMIP3 GCMs. The observed (heavy red line) and all-model mean (heavy magenta line) flows also are plotted. Daily mean flow was smoothed using a 5-point binomial filter.

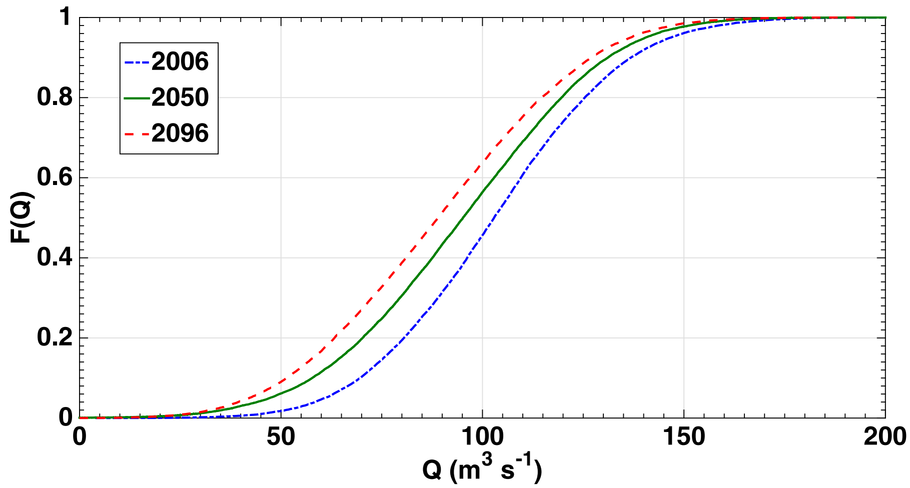

FIGURE 5. Cumulative Distribution Function of Naturalized Mean Daily Flow for the Oldman River near Lethbridge for the Selected Years 2006, 2050, and 2096.

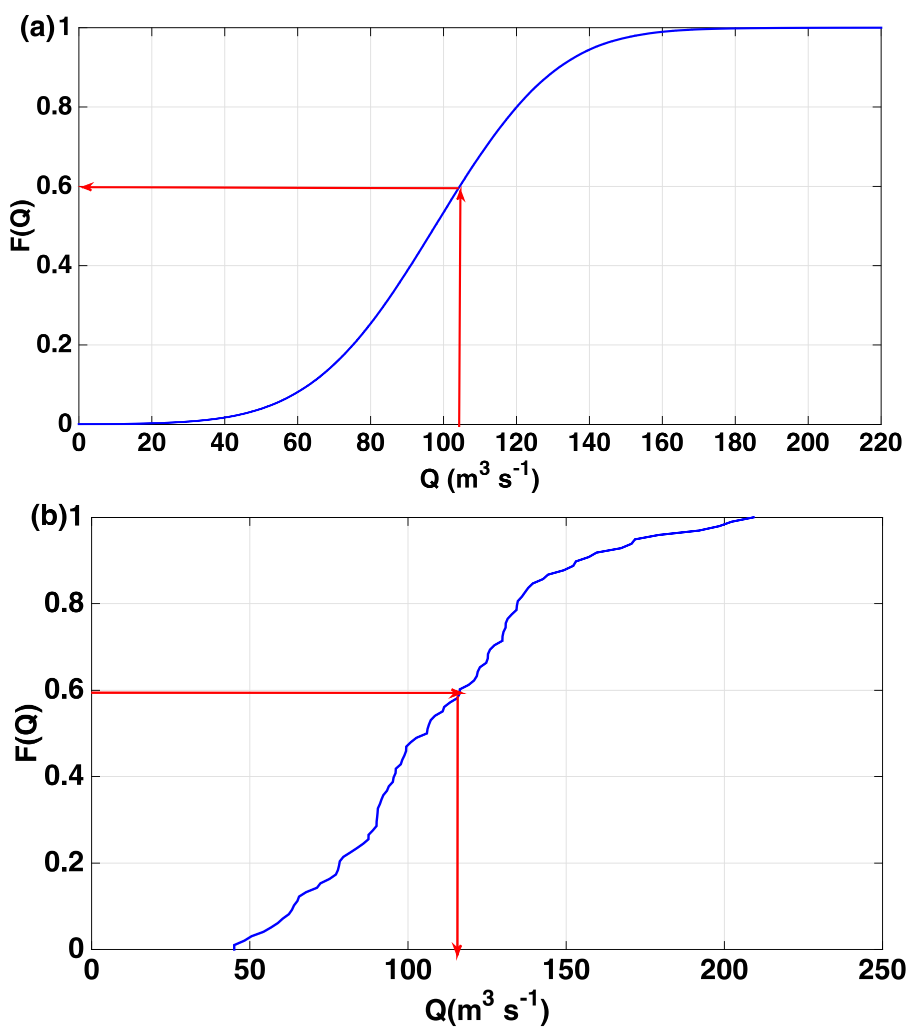

FIGURE 6. The CDFs of the (a) Projected and (b) Historical Naturalized Mean Daily Flows of the Oldman River near Lethbridge. The red arrows depict (a) a probability of 0.60 that mean daily flow will not exceed 104.4 m^3/s during 2025-2054 and (b) did not exceed 116.4 m^3/s at a probability of 0.60 during 1912-2009.

who included a few southern Alberta headwater gauges in their study.

Finally the overall objectives of the SSRB Adaptation Project were met by applying the large ensemble of streamflow projections to the OASIS water management model described above for the Oldman River subbasin and South Saskatchewan River subbasin. To maintain consistent analog years among gauges, and to provide stakeholders with scenarios under rigid time constraints, the projections for a single gauge were chosen in each river subbasin (e.g., the Oldman River at Lethbridge gauge) and then projected flows were disaggregated according to historical monthly patterns at each upstream location (e.g., Pincher Creek in January typically contributes 1.5% of the total natural flow of the Oldman River at Lethbridge). The watershed stakeholders participating in the project were presented with the full range of 50 hydroclimatic scenarios; however, for the purpose of testing the resiliency of current water infrastructure and management practices, only five scenarios were chosen to convey a plausible range of future water supplies (Table 3).

1. The 1-year Min scenario has a key year of interest —2033. This drought is much worse than that of the worst observed historical drought of 2000-2001. The following years (2034 and 2035) are also dry.
2. The 2-year Min scenario has two consecutive severe drought years (2034-2035) with other low years as well. The antecedent years 2032 and 2033 are also dry.
3. The 3-year Min is the worst scenario of the five with two severe dry periods, one at the beginning of the time period and one later. The key years are 2027-2029.
4. The 1-year Max scenario is generally wetter and puts almost no drought pressure on the system. The overall intent is to ensure that no alternatives have negative impacts if the actual future ends up not being dire in terms of drought. Flood impacts cannot be properly assessed due to methodology limitations.
5. The 2-year Median scenario has some drought periods and some wet periods, but its purpose is to assess alternatives under historical-like conditions.

While all these scenarios were available, for the most part, collaborative modeling done by the working group focused on the 2-year Min scenario, as it emphasized prolonged drought.

APPLICATION OF HYDROCLIMATIC SCENARIOS

Participants developed and explored a wide range of adaptation strategies in response to projected

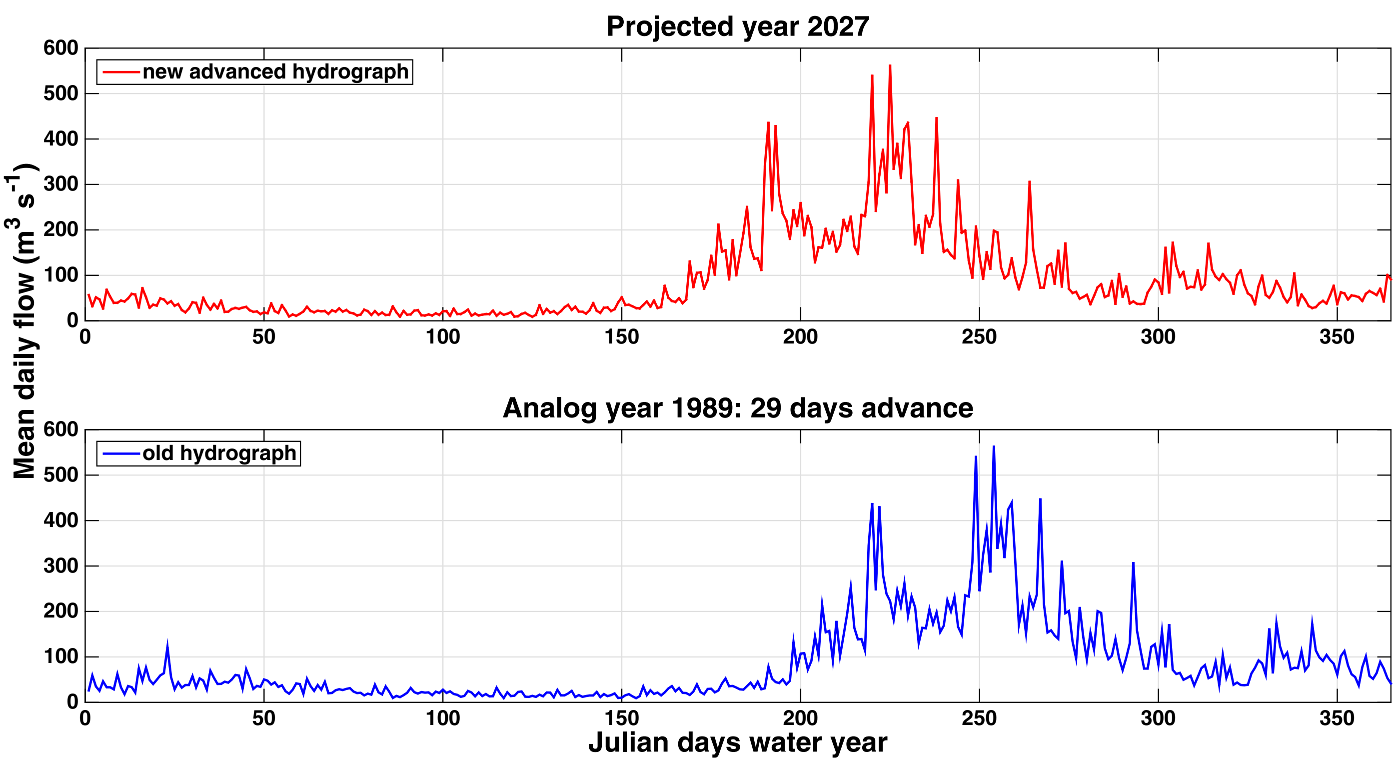

FIGURE 7. A Projected 29-Day Advance in the Center of Mass (CT) for 2027 Flows of the Oldman River near Lethbridge Using Climate Data from CGCM3.1T47_1 under the B1 Low Emissions Scenario.

TABLE 3. Five Scenarios of Hydroclimatic Variability Applied to the Simulation of Water Management and Adaptive Strategies in the Oldman River Subbasin and South Saskatchewan River Subbasin.

Selection Criteria	Scenario Run (GCM, Run, Emission Scenario)	Scenario Name
10th Percentile minimum annual single flow year	CGCM3.1T47_3A2	1-year Min
10th Percentile of 2-year consecutive minimum annual flow	CGCM3.1T6_3A1B	2-year Min
10th Percentile of 3-year consecutive minimum annual flow	PCM11_B1	3-year Min
Maximum average 1-year flow	MRI_5B1	1-year Max
Median of two years of cumulative flows	MRI_3A2	2-year Median

changes in streamflow from the OSSK model. Recognizing that the OSSK subbasins are complex and dynamic systems, individual adaptation strategies would be most likely implemented in combination, reflecting water needs in the basins and the appropriate degree of risk management. The project modelled 15 strategies (Table S2), of which we present here for brevity only the three incremental combination strategies that were the most promising (Table 4) to demonstrate how adaptation might be layered to produce cumulative benefits and to offset impacts:

1. C1: Increasing the capacity of infrastructure already in place, then improving operations to optimize the existing infrastructure,
2. C2: New infrastructure to expand storage capacity combined with existing infrastructure and operating improvements, and
3. C3: More storage and more aggressive operating changes implemented to manage water supplies through severe and prolonged drought conditions.

All of the 15 strategies were modeled individually as well (results not presented).

Complete descriptions and model results appear in the project final report (Alberta WaterSMART and AIEES, 2014b). The C3 strategy represents a set of adaptations in response to a severe multiyear drought, and includes all the components from C1 and C2. Although additional storage mitigates the effects of a single year drought, further and more aggressive water use reduction measures are needed to make subsequent drought years more manageable. The C3 strategy consists of:

1. A 74,000 dam^3 (60,000 AF) expansion of the Chin Reservoir on the existing infrastructure footprint,
2. Optimizing this storage through management changes by fully balancing storage in the expanded Chin Reservoir with storage in the other major reservoirs,
3. Augmenting low flows below St. Mary Reservoir,
4. Additional new storage with the Kimball Reservoir (125,800 dam^3 or 102,000 AF), and
5. Implementation of forecast-based rationing for irrigation districts on the premise that storage alone is not enough to survive multiyear droughts.

With forecast-based rationing, irrigation districts evaluate water availability based on winter reservoir levels and headwaters snow reports throughout the winter and early spring. This information is used to set preliminary allocations. As snowpack forecasts are not available for the OASIS model, AESRD reservoir storage on June 1 is used as a surrogate to inform rationing decisions. All strategies were compiled and tested with the OSSK model, using the International Joint Commission entitlement flows (Werner Herrera, Hydrologist, Alberta Environment and Sustainable Resource Development, November 18, 2013, personal communication), which represent minimum legal flow along the St. Mary River as it enters Canada from the U.S. Stakeholder participants made the decision to use the minimum required treaty flows after much discussion. The primary alternative was to use historical flows. The study participants considered that results derived using inflows required by the treaty would represent a "worst case" scenario. They also considered that modification of the international determinants of

TABLE 4. Combination Strategies from the OSSK Modeling Work (see text for details).

Combination	Full Strategy	Short Title for PM Charts
C1	Chin Reservoir expanded + fully balanced + St. Mary augmentation	Chin + Low Flow Aug
C2	Chin Reservoir expanded + fully balanced + Kimball Reservoir + St. Mary augmentation	Chin + Kim + Low Flow Aug
C3	Chin Reservoir expanded + fully balanced + Kimball Reservoir + St. Mary augmentation + forecast-based rationing	Chin + Kim + Aug + Frcst Rtn

flows in the OSSK subbasins was beyond their influence.

Selected OASIS Model Results Using Projected Streamflows: 2025-2054

Many combinations of the hydroclimatic scenarios, PMs, and adaptation strategies were explored by the modeling groups (see Alberta WaterSMART and AIEES, 2014b for the full range). We present here some of the most effective responses to severe droughts, the focus of our study. The 2-year Min hydroclimatic scenario (Table 3) is used to demonstrate the effects of the various adaptation strategies (Table 4). Over the entire projected period of 2025-2054 and for the 2-year Min hydroclimatic scenario, results demonstrate that the use of forecast-based rationing dramatically reduces shortage days (Figure 8). Importantly, this approach suspends the First in Time First in Right allocation system, demonstrating that collaboration (as actually occurred in 2001 with the sharing of the water deficit among users; Rood and Vandersteen, 2010) can add significant value to strategies that incorporate more storage to help meet the needs of junior water licence holders. The breakdown of these results over the seven irrigation districts in the OSSK shows that the C3 scenario reduces the number of days with shortages for all irrigation districts over the 30-year period (Figure 8c). This is achieved by delivering less water, i.e., by demands being reduced intentionally.

Next, adaptations to the extreme dry years of 2034-2035 are presented because these present such serious challenges needing a collaborative response. Drought is defined here as the 10th percentile of two year consecutive minimum annual flows. Figure 9a compares different storage and management options during the first year of the drought (2034). It shows that added storage by itself (C2 strategy, red line) has essentially the same effect as current operations (green line). However, combining rationing with extra storage (C3 strategy, blue line) allows for a nearly complete irrigation season, albeit with reduced volumes of water. In the second year of the severe drought, under the 2-year Min hydroclimatic scenario, storage alone (the C2 strategy) makes no difference to irrigation performance as supplies would have been exhausted in the previous year (2034) (Figure 9b). Figure 9b shows that extra storage combined with rationing enabled a longer irrigation period, again with substantially reduced volumes. Particularly notable in the extended drought period is the extension of irrigation to September, allowing for crops to reach a late, although reduced, harvest.

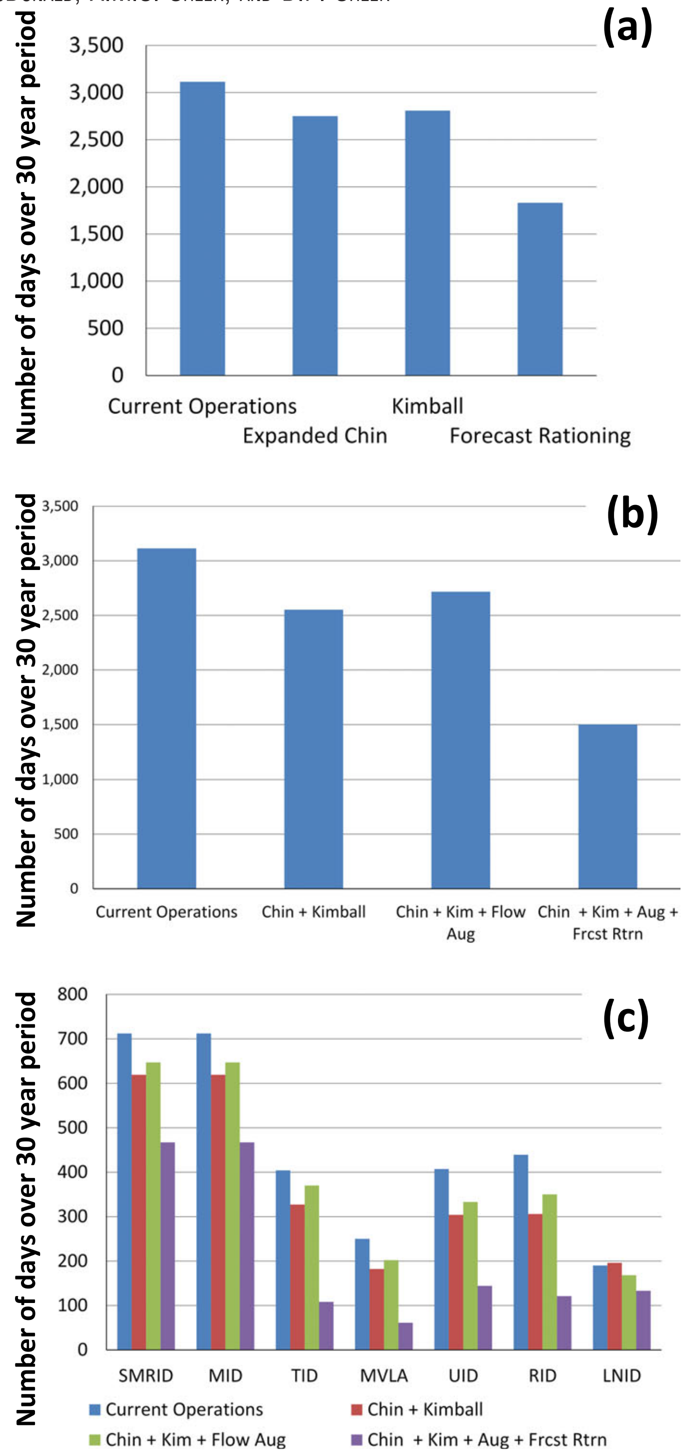

FIGURE 8. OASIS Modeling of the Total Number of Days with Shortages (out of a possible 10,950 days), Using Projected Data for 2025-2054 from 2-year Min Hydroclimatic Scenario (run 3 of the CGCM3.1T6 GCM under the A1B emissions scenario), (a) Individual Strategies Totalled across All Irrigation Districts, (b) Combined Strategies Totalled across All Irrigation Districts, and (c) Combined Strategies for Each Irrigation District in the Oldman and South Saskatchewan River (OSSK) Subbasins: SMRID (St Mary River Irrigation District), MID (Magrath Irrigation District), TID (Table Irrigation District), MVLA (Mountain View, Leavitt, and Aetna Irrigation Districts), UID (United Irrigation District), RID (Raymond Irrigation District) and LNID (Lethbridge North Irrigation District).

Selected OASIS Model Results Using Historical Data: 1912-2009

We also explored many combinations of the PMs and strategies using the available historical data for 1912-2009 (Alberta WaterSMART and AIEES, 2014b). Again we concentrate here on the most effective responses to severe droughts. Figure 10 shows the impact of the combined strategies on shortage days for the 82-year period of record (1912-2009). The addition of forecast-based rationing to C3 from C2 dramatically reduces shortage days further, but it is essential to remember that this is largely because demands are much lower. This strategy reduces shortages to zero during the 82-year period for nearly all irrigation districts (results not shown), but in most cases this is achieved mainly by intentionally reducing demands rather than from previously undelivered water. In other words, less water is being supplied to the irrigation districts even though the figure shows a reduction in shortages.

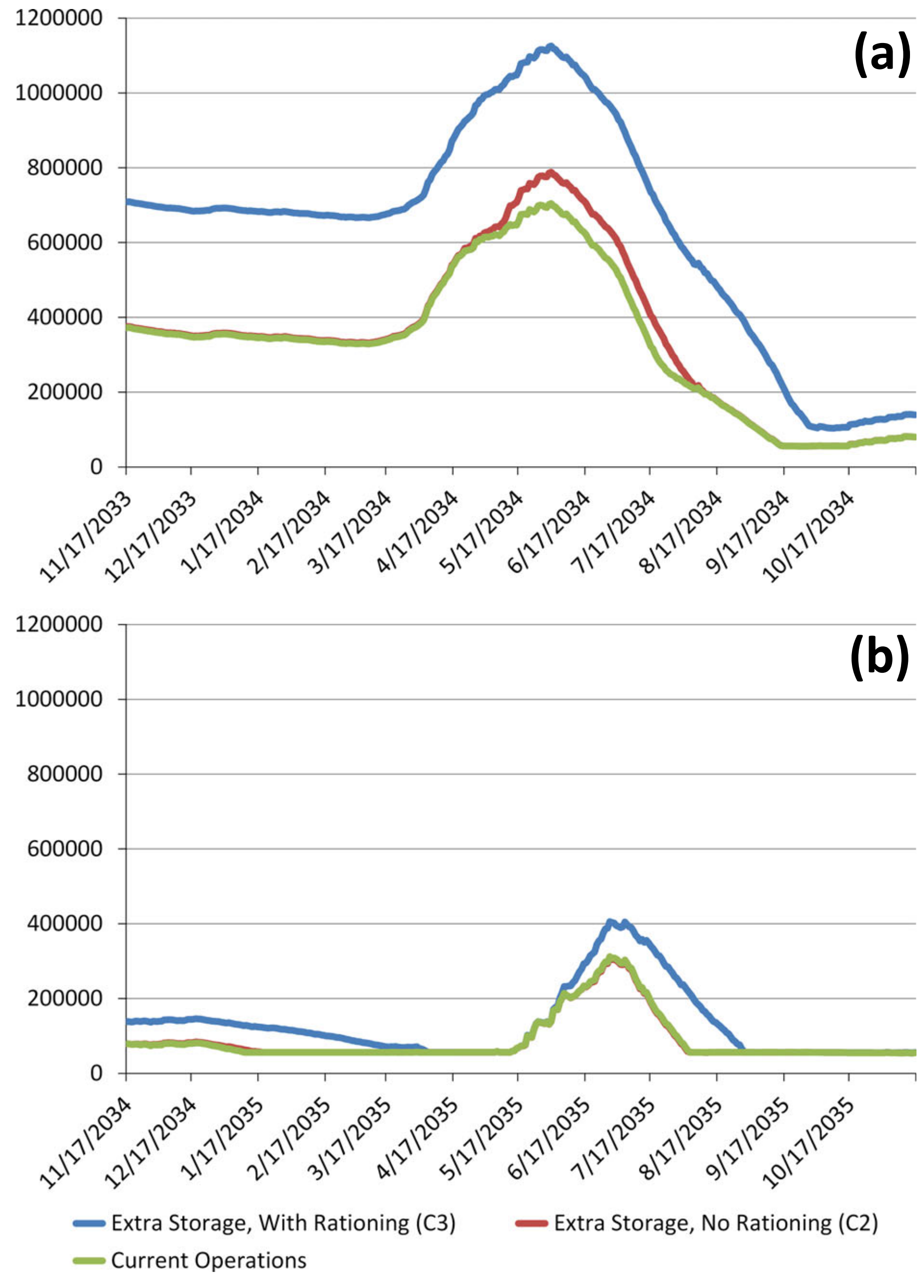

FIGURE 9. OASIS Modeled Daily Storage (dam^3) in the Three Alberta Environment and Sustainable Resource Development (AESRD) and Chin Reservoirs for the 2-year Min Hydroclimatic Scenario for the (a) First Year and (b) Second Year of the Projected 2033-2034 Drought, Using the C2 and C3 Adaptation Strategies.

For comparison to the most severe projected drought (Figure 9), we also present selected results from the observed historical drought conditions of 2001-2002, the most severe two-year drought on record. The superior benefits of the C3 scenario are again shown (Figure 11). The red line, which denotes the C3 strategy and includes forecast-based rationing, shows how much the rationing component of this combination extends the irrigable season compared with current operations and the C1 and C2 strategies.

The C3 strategy produces ecological benefits, as well as advantages for direct human use. The benefits of the C3 scenario according to the fisheries PM of weighted usable area are shown when applied to the observed 1912-2009 data (Figure 12). The fisheries PM demonstrates that the C3 scenario either slightly improves mountain whitefish (*Prosopium williamsoni*) habitat or does not change rainbow trout (*Oncorhynchus mykiss*) habitat downstream of major reservoirs relative to that resulting from natural undisturbed flow (Figure 2). However, improvements of available habitat on the St. Mary River were at the cost of reduced habitat upstream of the St. Mary reservoir, where native trans-boundary fish populations reside, including the endangered (in Montana) bull trout (*Salvelinus confluentus*) and other threatened and endangered species including the Rocky Mountain sculpin (*Cottus* sp.), which does not do well in reservoirs (DFO, 2013). The PMs chosen by the participants did not include the evaluation of the environmental changes caused by the flooding of the streambed under the reservoir. This work was designed to identify, examine, and assess the intended and unintended consequences and tradeoffs of potential water management tools (including new storage), and therefore the study was much more focused on operations rather than structures. Evaluation of a new structure and its potential environmental, economic, or social consequences (good and bad) were outside the scope of this work. The results and conclusions in this paper should be interpreted in light of the potential detrimental and beneficial physical impacts of new reservoirs.

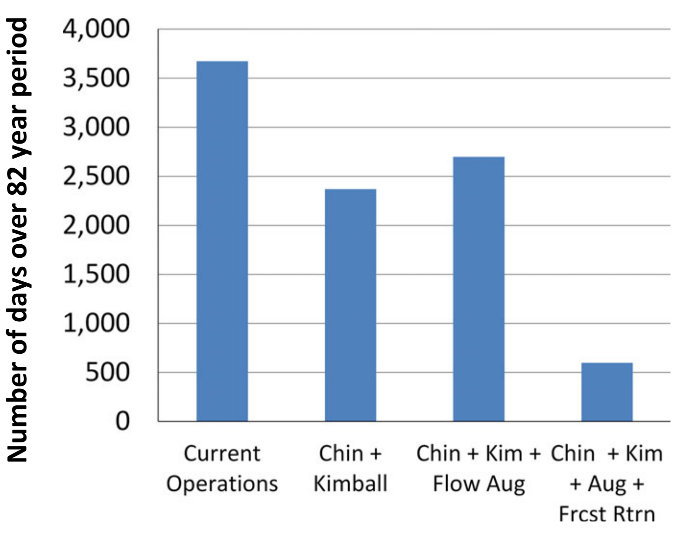

FIGURE 10. OASIS Modeling of the Total Number of Days with Shortages (out of a possible 29,930), Using Historical Data from 1912-2009 with Results Totaled across All Irrigation Districts.

The OASIS modeling groups extensively explored many combinations of PMs and adaptation strategies (Tables S1 and S2), using both the projected hydroclimatic scenarios for 2025-2054 and the historical data from 1912-2009. For brevity, we have presented a synopsis here and refer the reader to Alberta WaterSMART and AIEES (2014b) for the full exploration. We found that the C3 strategy performs better than any of the other alternatives with regard to most of the PMs, and at least as well as the other strategies with regard to the rest of the performance measures. Hence, we conclude that C3 is superior, but it must be noted that it has its costs outside of the purview of the modeling exercise.

CONCLUSIONS

Water management and engineering in southern Alberta generally does not account for low-frequency climatic variability at decadal time scales, nor the potential for unprecedented extremes in a warming climate. It relies instead on recent (i.e., roughly the past 30 years) recorded water levels and weather, which assumes that these observations adequately represent the long-term trends and variability in climate and water variables. This approach is conventional engineering practice and is consistent with the foundational concept of stationarity, the assumption that climate and hydrology fluctuate within a constant range of variability (Milly *et al.*, 2008). The approach described in this paper explicitly models climate forcing of the interannual to decadal variability of the hydrological regime (St. Jacques *et al.*, 2010, 2013). Our 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 the climate forcing, we are able to reevaluate the teleconnections between climate and hydrology for future years using output from GCMs that have the capacity to simulate the internal variability of the climate system that emerges under greenhouse gas forcing (Furtado *et al.*, 2011; Lapp

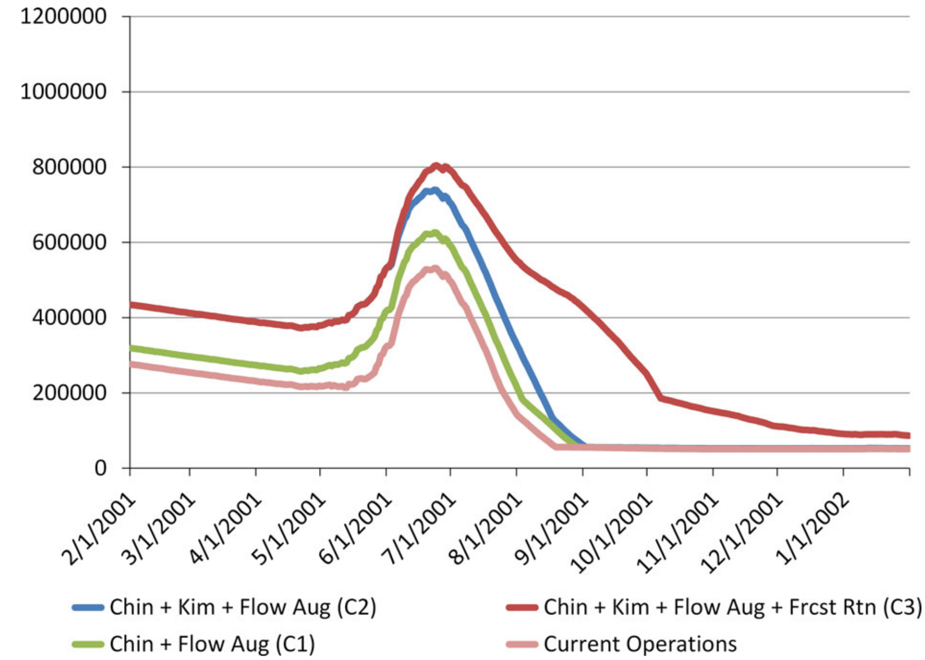

FIGURE 11. OASIS Modelled Daily Storage (dam^3) in the Three Alberta Environment and Sustainable Resource Development (AESRD) and Chin Reservoirs for the Observed Drought of 2001-2002, Using the C3, C2, and C1 Adaptation Strategies and Current Operations.

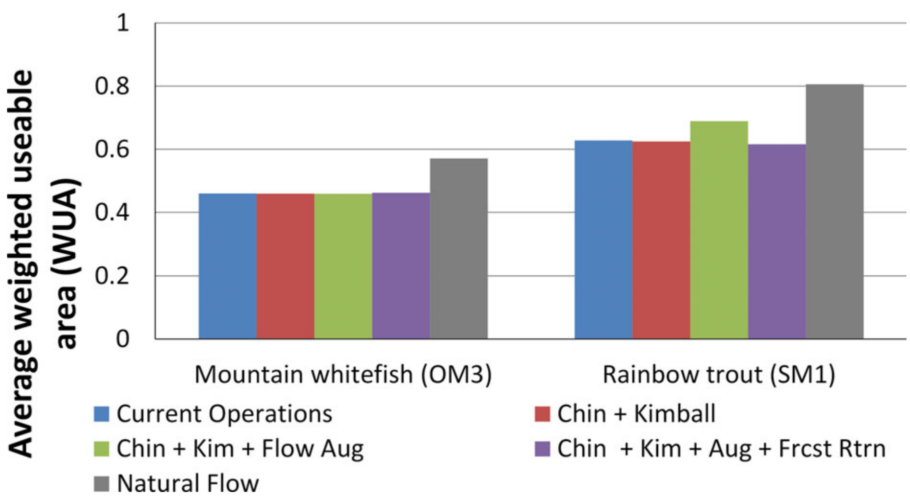

FIGURE 12. Weighted Useable Area for Mountain Whitefish (*Prosopium williamsoni*) in the Oldman River and Rainbow Trout (*Oncorhynchus mykiss*) in the St. Mary River, Using the OASIS Model Run According to the C3, C2, and C1 Adaptation Strategies and Current Operations with Observed 1912-2009 Data.

et al., 2012). The limitation of this novel approach is that we do not attempt to dynamically simulate watershed hydrology. For example, we are unable to represent processes such as mid-winter melting of snow over frozen soils in a warmer climate, or extreme flood peaks. Whereas the conventional (engineering) approach has advanced hydrology and simple climate (e.g., Christensen *et al.*, 2004; EBNFLO Environmental AquaResource Inc., 2010; Forbes *et al.*, 2011; Kienzle *et al.*, 2011; Larson *et al.*, 2011; MacDonald *et al.*, 2011; Islam and Gan, 2014), our novel (scientific) approach has advanced representation of climate and a simple hydrological regime (St. Jacques *et al.*, 2013). Compromising the modeling of watershed hydrology is justified by the nature and purpose of the research, which was to develop plausible scenarios of hydroclimatic variability and apply these to watershed-scale adaptation planning.

Our OASIS modeling consistently showed that the C3 strategy, consisting of forecast-based rationing and new expanded storage, was best able to address severe and extended droughts. However, all three adaptation strategies, C1 (improved existing storage), C2 (new expanded storage), and C3 (a combination of C1 and C2), improved basin water management according to the stakeholder-chosen performance measures as compared to current operations in the base case. Our OASIS modeling also demonstrated the vulnerability of the system in the face of extended multiyear droughts. Our river modeling revealed that the use of stored water provided benefits throughout the system. It further demonstrated that balancing reservoir use in an integrated manner (between private and provincially owned reservoirs) can ensure municipal and irrigation supply from current and potential storage reservoirs and provide environmental benefits. Additional storage could meet multiple objectives, including a modest increase in the security of supply under adverse drought conditions; potential benefits for junior licence holders by reducing the impact on irrigation districts from participating in water sharing agreements through rationing within their senior licences; some possible flood mitigation for downstream infrastructure depending on the location; and meeting environment flow needs. The added value of expanded storage capacity should be further evaluated for a few select locations. When this is done, the impacts of flooding on stream reaches, and the *in situ* benefits of newly created reservoirs, need to be included in the analysis. In conclusion, the C1, C2, and C3 strategies (particularly the C3 strategy) are very promising and should be further investigated relative to the broader range of considerations including environmental impact assessments, cost-benefit analysis, engineering feasibility studies, consideration of impacts on landowners and First Nations, etc.

Expanding Chin Reservoir and an appropriately sized Kimball Reservoir shows potential benefits if additional storage is warranted in the system, and especially in the event of a permanent reduction in supply should the U.S. take advantage of its full allocation in the St. Mary system. Model results also suggest that expanding off-stream storage at Chin Reservoir in the St. Mary River Irrigation District, and adding the entire storage of the expanded reservoir to the AESRD balancing system, would offer a number of benefits to the basins, including adaptation to dry or low flow conditions. However, Alberta Agriculture and Rural Development produced a concurrent storage study with separate modeling (although we all exchanged information) which resulted in different conclusions because of modeling assumptions (AMEC, 2014).

Policy Implications and Next Steps

The integrated OASIS river modeling tools and the associated collaborative process are now available to inform policy and capital decisions as needed. The discussion of potential new storage in the Oldman system raised questions about the effectiveness of current policies regarding Water Conservation Objectives and In-stream Objectives, in particular with respect to new infrastructure, and it raises the opportunity to compare the environmental benefits of more assured downstream flows against the net impacts and benefits imposed by the construction of a new reservoir. Many stakeholders apparently would welcome a discussion of whether the current Water Conservation and In-stream Objectives regime yields the intended benefits and whether they might be refined. This collaborative process effectively demonstrated its value and potential for informing river management policy, and decisions about operations and capital allocation. This collaborative power can be transitioned from a project-based initiative into an ongoing function. This ongoing function would require definition of who is involved (e.g., major licence holders, resident water experts, watershed groups, academic organizations), what it informs or influences (e.g., policy development, governance, operationalizing adaptive water management), how the collaborative function would operate (e.g., annual workshops, targeted working groups, data maintenance, development of suitable tools, appropriate support, funding), and where it resides (e.g., within the Government of Alberta, arm's length from the Government of Alberta, or with independent bodies).

This work reinforced the importance of building system-wide adaptive resiliency now, before the system is unduly stressed since the projections and history of drought in the SSRB region suggest it would be prudent to develop and test procedures, agreements, and practices required to mitigate the impacts of a prolonged drought (Schindler and Donahue, 2006; Axelson *et al.*, 2009; St. Jacques *et al.*, 2010, 2013). Water managers in virtually all river basins are working on these same types of considerations (*e.g.*, Christensen *et al.*, 2004; Grafton and Hussey, 2011; Luce *et al.*, 2012; De Stefano *et al.*, 2012; Green *et al.*, 2013; Wang *et al.*, 2015). There are practical steps that can be taken now in each SSRB subbasin, and further options that should be implemented if the risk warrants it. These include legal agreements, operational details, forecast-based triggers for action, and other processes for monitoring and managing drought. This process began with a discussion about the impact of climate change and variability on the SSRB's water resources, which led naturally to the identification and assessment of potential adaptation strategies. In each basin, specific strategies were identified that could be virtually tested on the river, as a step towards full implementation, e.g., working on a flexible long-term water management agreement with TransAlta Utilities in the Bow River Basin for re-management of flows to support basin resiliency to flood and drought (Sheer *et al.*, 2013), piloting the potential of balancing current and future private and public storage in the OSSK subbasins, and exploring and testing governing principles for shortage sharing for use during severe drought. There is general agreement that the successful collaborative arrangements that emerged in the 2001 drought (Rood and Vandersteen, 2010) are a good starting point but many SSRB project participants suggested that had the 2000-2001 drought continued for one or more additional years, the agreement would not have been practical as an effective response for the water users. Further resiliency will come from strategies and solutions that build on the current most effective management practices. Many of these proposed strategies for adaptation are easier to achieve than large new infrastructure projects, and can be implemented under noncrisis conditions. Nevertheless, in the face of prolonged drought, more aggressive strategies warrant due consideration. The work described in this paper is currently being applied in the Red Deer River Basin, and will then see the integration of the Bow, Oldman, South Saskatchewan, and Red Deer models into a single SSRB model to assess adaptation and management options in the context of an entire SSRB river system (Alberta WaterSMART, 2014).

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article: a graph of the strong quadratic relationship between the means and standard deviations of naturalized historical daily flows of the Oldman River near Lethbridge and tables of all 24 Performance measures (PMs) and all 15 strategies examined.

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