


Climate Vulnerability and Sustainable Water Management in the SSRB Project

Red Deer River Basin Modelling, Final Report

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Executive Summary

Alberta faces important water challenges, including a growing economy and population and their increasing impact on the environment in the context of shifting weather and climate patterns. The South Saskatchewan River Basin (SSRB) Water Project was a collaboration with water managers and informed water users to explore practical options for adapting to environmental and climatic change, while meeting water demands and usage needs. It built on existing data, tools, capacity, and knowledge with the aim of increasing capacity for water resource management throughout the SSRB. The project had three concurrent streams of work:

1. Develop the Red Deer mass balance river system model
2. Integrate the Red Deer model with previous work from the other sub-basins and update the SSRB river system model
3. Develop land use modelling capabilities for the SSRB.

This report summarizes results from the first stream of work and part of the third: that is, modelling the Red Deer River and showing how it can be managed as an integrated ecosystem, from headwaters and tributaries to the Alberta-Saskatchewan border, including consideration of climate variability and land use changes.

Unlike other sub-basins in the SSRB, the Red Deer River Basin is not closed to new water allocations and thus diverse economic development opportunities are available. The landscape and the broader environment in the region are valued for the cultural, aesthetic, and recreational benefits they provide, and there is a strong social desire to ensure these aspects are protected. A Water Conservation Objective (WCO) is already in place to support protection of the aquatic environment during low flow periods. The modelling suggests there is likely enough water to grow, but growth and demands should be managed carefully in order to avoid degrading environmental health. Environmental health in the context of strategies, in some cases, would need to be better understood and evaluated.

Climate variability projections developed for this project suggest that average annual streamflow in the basin will increase due to future climatic change. Although this would make more water in the watershed available overall, the basin will still be prone to droughts, and needs to build resilience to both wet and dry conditions. High streamflow variability, as seen in the recent past, is likely to continue. Land use plays an important role in watershed health and river management. Increases in water withdrawals and consumption due to predicted settlement patterns and other development activities will have a major land use impact on future streamflow.

Several types of strategies were explored and identified to meet the goal of balancing economic growth with maintaining environmental health in the basin. Strategies that enabled both growth and environmental protection were preferred by participants, but strategies that supported one and were neutral to the other were also supported, as reflected in the following list of most promising strategies:

- Implementation of functional flows when appropriate could improve environmental conditions like fish and riparian habitat.
- Consideration should be given to reviewing Dickson Dam operations in light of changing weather conditions, growing instream demands and existing operational priorities. Currently,

Dickson Dam does not have the resiliency or capacity to influence significant change to current outflow regimes without impacting current water management priorities.

- As demand for water grows, it may be necessary to consider additional storage. Mid-basin on-stream storage appeared to show promise for addressing water shortages and mitigating downstream flooding.
- Local flood mitigation options were favoured over dry dams. Working Group discussions indicated that there are limited benefits to the upstream dry dams. Local mitigation measures (berms, etc.) appear to provide the "biggest bang for the buck."
- Conservation makes a measureable difference in water availability and should be considered as part of the solution, supported by policy and regulatory requirements such as best practices conditions on new licences and public education programs.
- Application of land use best management practices (BMPs) to reduce impact on streamflow. The modelling work conducted here did not focus on implementing BMPs, rather it looked at impacts of higher or lower rates of development. However, multiple BMPs can be applied to help minimize impacts of land use change on water resources. Working Group discussions acknowledged that BMPs are an important part of water management.
- Provincial regulator and basin water users will need to develop a better understanding and process about how shortages could be managed during periods of drought. This could mean sharing shortages as was done between water users in the Oldman Basin; negotiations to develop a plan could be facilitated by Alberta Environment and Sustainable Resource Development (ESRD), the Red Deer River Watershed Alliance or the Coordinating Committee: the Intrabasin Water Coordinating Committee for the SSRB[1].
- Effective implementation of Alberta's Wetland Policy should help protect existing wetlands and restore those that have been lost to development. The footprint on the land should be managed to avoid creating new negative impacts to streamflow; one example is to enforce conditions of no change in net discharge from new development, meaning that there is no increase to runoff from pre and post development.

To build resilience and sustainability in the face of climatic and environmental change and increased growth, a layered approach will be needed, as no single solution can meet every need. The work completed for this project provides a solid foundation on which to determine appropriate actions, build more detailed plans and invest in the science needed so the basin's water management system is better prepared to respond when expected growth and climate variability demands arise. However, this work did identify a need for more and better data to enhance understanding and support water management decisions; examples include improved groundwater, meteorological, and naturalized flow data, as well as more streamflow monitoring stations.

All strategies and combinations modelled for the project are briefly described in this report. Modelling assumptions and input data will be documented in the publicly available files accessible through the University of Lethbridge servers at http://www.uleth.ca/research-services/node/432/.

With the completion of this project, all sub-basins in the SSRB now have a refined mass balance river system model with specific performance measures for each system. This innovative and integrated approach recognizes that land use along with climate variability and change are important factors

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[1] http://ssrb.environment.alberta.ca/partnerships.html

affecting the environmental, social, and economic future of the SSRB. The modelling work has enabled water users and managers in the basin to better understand climate variability impacts and risk and to enhance adaptive capacity by identifying implementable strategies that build system resiliency. This provides a solid base and framework upon which future water planning and management can occur, so basin water users and decision makers are clear on the facts, the unknowns, and the degree of acceptable risk related to future decisions about water resources.

The expectation is that the management strategies developed through this collaborative work might be used as a sound basis for water managers to apply as they anticipate and respond to future changes in water supply, water demand, and climate.

Acronyms and Abbreviations

AI-EES	Alberta Innovates – Energy and Environment Solutions
ALCES	A Landscape Cumulative Effects Simulator
ARD	(Alberta) Agriculture and Rural Development
BAU	Business as Usual
CDF	Cumulative Distribution Function
dam^3	cubic decametre (1,000 cubic metres or .81 of an acre foot)
ESRD	(Alberta) Environment and Sustainable Resource Development
GCM	General Circulation Model
GLS	Generalized-least-squares (describing regression models)
HUC	Hydrologic Unit Code
IDM	Irrigation Demand Model
m^3/s	cubic metres per second ($1\ m^3/s$ = 35.3 cubic feet per second)
NARCCAP	North American Regional Climate Change Assessment Program
OASIS	Operational Analysis and Simulation of Integrated Systems
PARC	Prairie Adaptation Research Collaborative
PFRA	Prairie Farm Rehabilitation Administration
PM	Performance Measure
RCM	Regional Climate Model
RDROM	Red Deer River Operational Model
RDRWA	Red Deer River Watershed Alliance
SAWSP	Special Areas Water Supply Project
SSRB	South Saskatchewan River Basin
TDL	Temporary Diversion Licence
WCO	Water Conservation Objective
WRMM	Water Resources Management Model

Contents

List of Tables

List of Figures

1. Introduction

Alberta's environmental, social, and economic vitality depends, in large part, on how Alberta's natural resources are managed – especially water. With an expanding population, accelerating economic growth, the impact of this growth on the environment, and continuing climate variability and change, Alberta needs to better understand its water resources and increase its capacity to adaptively manage its river basins. Proactive and informed management decisions, made in collaboration with knowledgeable water stakeholders in each basin, will require a clearer understanding of how future growth and climatic change could affect water resources, the users who depend on them, and Alberta's ability to respond and adapt.

Tree-ring data correlated with river flow show extreme climate variability in past centuries for flows in the Bow and Oldman Rivers (Figure 1). These data suggest that future flood and drought events could be much more serious than those experienced in recent years. The same variability in river flow can also be observed in the Red Deer River.

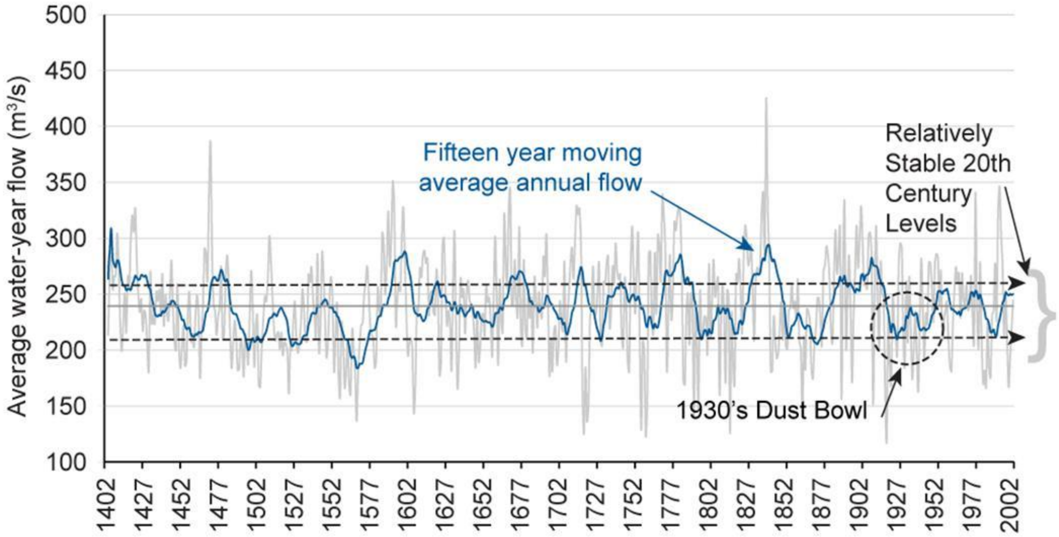

Figure 1: South Saskatchewan River Basin flows (Bow + Oldman)

Source: Axelson et al., 2009

Future challenges from growth and climatic changes present an 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 appropriately addressed by any single initiative or sector; fortunately, Alberta has a history of successfully meeting challenges through multi-sector collaboration and engagement. The project described in this report – "Climate Vulnerability and Sustainable Water Management in the South Saskatchewan River Basin (SSRB)" project, referred to as the "SSRB Water Project" – was funded by Alberta Innovates-Energy and Environment Solutions and executed by Alberta WaterSMART. This phase of the project was a collaborative effort to explore practical options for adapting to environmental and climatic change. It built on existing data, tools, capacity, and knowledge with the aim of increasing capacity for water resource management throughout the SSRB. The project had three concurrent streams of work:

1. Develop the Red Deer mass balance river system model
2. Integrate the Red Deer model with previous work from the other sub-basins and update the SSRB river system model
3. Develop and integrate land use modelling capabilities for the SSRB.

The SSRB Water Project capitalized on the interests and experience of seasoned water stakeholders in the region. In the first stream of activity, these individuals actively collaborated to develop and test an interactive mass balance streamflow model for the Red Deer River Basin with environmental and other performance measures. The results are being integrated with similar work from the Bow, Oldman, and South Saskatchewan River sub-basins to complete an integrated suite of such tools for the entire SSRB (stream two). Participants also explored the application of a land use model to better understand how future climatic and environmental change in the SSRB might affect water resources and water users (stream three).

This report summarizes results from the first stream of work and part of the third: that is, modelling the Red Deer River and showing how it can be managed as an integrated system, from headwaters and tributaries to the Alberta-Saskatchewan border, including consideration of climate variability and land use changes.

With the completion of this project, all sub-basins in the SSRB now have a mass balance river system model refined and tested by participants, with specific performance measures. Each sub-basin also has established a collaborative process and working group of knowledgeable and engaged stakeholders who are keen to be part of future collaborative work to support sustainable and proactive management of their water resources. This innovative and integrated approach recognizes that water management, climate variability and land use are important factors affecting the environmental, social, and economic future of southern Alberta. This modelling work has enabled water users, managers and experts in the basin to better understand potential impacts and risks to enhance adaptive capacity by identifying implementable strategies that build system resiliency.

2. The Red Deer River Basin

The Red Deer River Basin (Figure 2) is one of four sub-basins in the SSRB, along with the Bow, Oldman, and South Saskatchewan sub-basins. Like the other major rivers in the SSRB, the Red Deer originates in the Rocky Mountains, specifically in the northern part of Banff National Park. The Red Deer River Basin comprises 41% of the total SSRB area, or just under 50,000 square kilometres. Fed largely by snowmelt, the Red Deer River is 724 km long and flows over and through a very diverse landscape, including mountains, foothills, rangeland, forests, parkland, cropland, coal and oil deposits, and cities and towns. It crosses the Alberta-Saskatchewan border near the Town of Empress and joins the South Saskatchewan River about eight kilometres east of the border.[2]

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[2] Much of the information in this section was adapted from content on the Red Deer River Watershed Alliance website at www.rdrwa.ca.

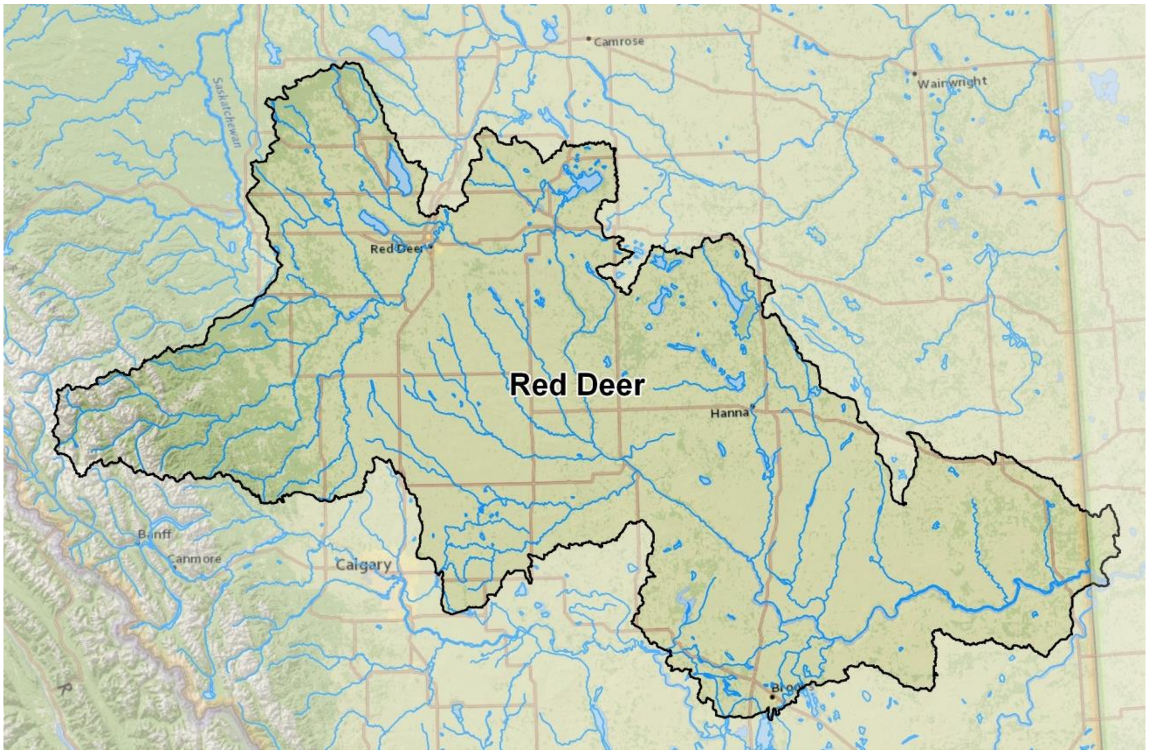

Figure 2: The Red Deer River Basin

The Red Deer River watershed contains 55 urban centres and 18 rural or regional municipalities. Its population grew steadily at a rate of about 2% per year from 1996-2001, increasing to more than 9% per year from 2001-2006; in 2006, the urban population comprised just over two-thirds of the basin's total (69% urban, 31% rural). Forecasts are that the watershed will see a 40% increase in population over the next 25 years and a further 10% increase in the following 25 years, with most of this growth in the Calgary-Edmonton corridor. Agriculture is a major land use, with 43% of the land in cropping (mainly grains, forage, and canola) and a further 48% in pasture; some private irrigation occurs in the watershed. Beef production is an important activity, especially in the southern region, but the watershed has a higher proportion of dairy, hog, and poultry farms than the rest of the province. The oil and gas sector is a significant industrial player in the region, with a substantial land base devoted to drilling and refining operations. Forestry is also an important activity in the upper watershed. Diverse industrial and commercial activities, ranging from food processing to manufacturing facilities and construction, are located within the watershed, and the basin is also known for the archeological and paleontological resources it contains.[3]

This project looked at the actual area taken up by five categories of land use in the basin and how changes in these uses might influence the volume and timing of flow to the Red Deer River system over the next 50 years. The five land use categories are: settlements, energy development, agriculture, forestry and fire, and wetland restoration. The ALCES[4] model was used for this analysis; the model and

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[3] Information in this paragraph was obtained from the *Red Deer River State of the Watershed Report,* prepared in 2009 for the Red Deer River Watershed Alliance by Aquality Environmental Consulting Limited.

[4] ALCES is "A Landscape Cumulative Effects Simulator."

its parameters are described more fully in Section 3.4.In the context of providing a historical perspective of land use activity in the basin, Table 1 shows the changes in land base area over the last 50 years for each category.

Table 1: Historical land use changes over 50 years (1960-2010) in the Red Deer River Basin

Land use category	Historical change	Source
Settlements	Area of towns and residences has increased 550%	ABMI Human Footprint Map, 2010 Version 1.1
Energy development	Energy footprints have increased by more than 1000%	ABMI Human Footprint Map, 2010 Version 1.1
Agriculture	Farmland expansion has been negligible (5%)	ABMI Wall-to-Wall Land Cover Map, 2010 Version 1.0
Forestry and fire	Timber harvest has replaced fire as the dominant disturbance in recent decades, during which suppression reduced the average fire rate to less than 0.1% per year	ALCES Timber Production layer Historical Wildfires by Decade
Wetland restoration	Approximately 60% of the basin's wetlands have been drained.	ABMI Wall-to-Wall Land Cover Map, 2010 Version 1.0

In much of the SSRB, the focus of water management has been to mitigate drought, but the floods of 1995, 2005, and 2013 reminded everyone of the diverse hydrological conditions experienced in the region – and of the need to be resilient and adaptable in responding to a wide range of future climate variability and its associated impacts. In seeking the best solutions to sustain Alberta's prosperity and quality of life, water management issues must be top-of-mind for residents, elected officials, and other decision makers. Several specific parameters provide a backdrop against which water is managed in the SSRB as a whole:

- *Water for Life* strategy and action plan that reaffirms Alberta's commitment to the *Water for Life* approach: the wise management of the province's water resources for the benefit of all Albertans
- Alberta remains committed to its existing priority system of water allocation based on licence seniority, commonly known as first-in-time, first-in-right (FITFIR).
- Since 2006 when the South Saskatchewan River Basin Water Management Plan was approved by the Lieutenant Governor in Council, no applications for new water allocations have been accepted in the Bow, Oldman, and South Saskatchewan River sub-basins. The Red Deer is the only sub-basin in the SSRB that is still open for new applications.
- The Master Agreement on Apportionment (1969) requires that 50% of the flow by volume of eastward-flowing provincial watercourses must be passed from Alberta to Saskatchewan annually.
- Alberta Environment and Sustainable Resource Development (ESRD) is the body responsible for the regulatory decision making component, for non-energy related development, of water management in the Province of Alberta.

The geography of Alberta has made it necessary to work with other jurisdictions. Within Canada, the Master Agreement on Apportionment (1969)[5] between the governments of Alberta, Saskatchewan, Manitoba, and Canada describes the process and conditions for sharing the waters of eastward-flowing interprovincial streams. Under this agreement, 50% of the annual flow by volume must be passed from Alberta to Saskatchewan. Historically, the average flow to Saskatchewan has typically been more than 75% because Alberta lacks sufficient storage to take its full entitlement. Fifty percent is a minimum and reflects choices and trade-offs of water use, but the river ecosystem benefits from these higher, closer-to-natural flows. The proportion passed on to Saskatchewan, while meeting Apportionment obligations, was much lower during low-flow years such as 1988, 2000, and especially 2001 when it was 54%.

Both urban and rural municipalities continue to grow in the Red Deer River region. They require a safe, secure supply of drinking water as well as water to meet wastewater treatment and dilution needs and other municipal demands. A growing population can also create new demands for recreational opportunities. Like many other rivers in Alberta, the Red Deer is already being managed for environmental and economic benefits (Figure 3). Infrastructure on the Red Deer system is less complex compared to others in the SSRB in that it has only one on-stream dam; the Dickson Dam, owned and operated by the Government of Alberta. It was completed in 1983 and created Gleniffer Reservoir. This reservoir, approximately 11 kilometres long and 2 kilometres wide, operates differently from more southerly reservoirs as its primary function is to store water to supplement natural flows in the winter. Storage and flow regulation provide a number of benefits including an assured water supply for municipal and environmental protection (e.g., effluent dilution) purposes, flood and erosion control, recreational opportunities, and hydroelectric power generation. This regulation of flow and the relatively low level of water use in the watershed have had little effect on annual flow volumes (AMEC, 2009). Thus the Red Deer River has so far been able to support regional growth without compromising environmental quality and without experiencing constrained supplies, which is not the case for other river systems in the SSRB.

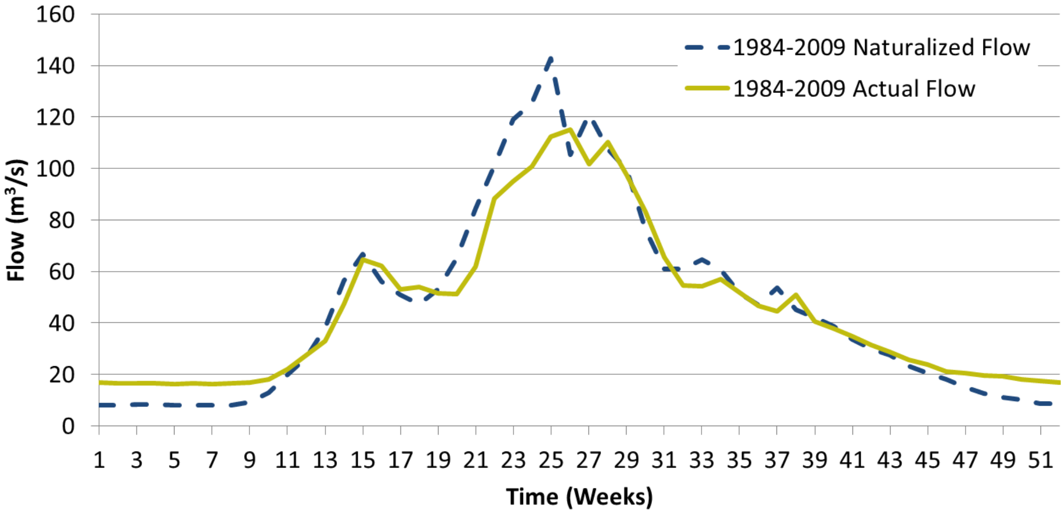

Figure 3: Natural vs. managed flows, Red Deer River at Red Deer

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[5] See http://environment.alberta.ca/01706.html

University of Lethbridge researchers are studying how river systems are adapted to a natural flow regime in the Oldman and Red Deer basins. This AI-EES funder project has collaborated with the SSRB Water Project to build into the model a set of operating criteria that can be used to enhance riparian growth downstream of major on-stream infrastructure. The Red Deer system, despite its management, still displays a relatively natural flow regime, including high spring flows, which are an essential component of natural systems as they move materials and develop channels. Cottonwood recruitment occurs in the post-flood period as flows recede in the summer. Enough flow is also needed in the fall and winter to maintain aquatic habitat and dissolved oxygen levels, and regulate water temperature in the summer. To recruit cottonwoods and willows, gradually receding water levels are needed to allow them to quickly develop roots. The 2013 flood event created new sand and gravel bars available for colonization and ideally, native species such as willows and cottonwoods would become established rather than invasive species. Winters with high snowpack present opportunities to deliver a ramping flow regime that can aid cottonwood colonization and survival, while providing higher and much more consistent winter flows for fish and assimilation of treated effluent from municipal and other sources.

3. SSRB Water Project: Process and Methodology

3.1 The Collaborative Modelling Process

HydroLogics, Inc. the consultant who was involved with previous modelling activity for the Bow, Oldman, and South Saskatchewan basins, led the modelling for the Red Deer River Basin, using the sophisticated simulation software they developed for modelling water systems throughout the US and internationally. HydroLogics' modelling software—called OASIS (Operational Analysis and Simulation of Integrated Systems)—is flexible, transparent, completely data-driven, and effectively simulates water facility operations.

The project team and some participants had been involved in prior SSRB work and were very familiar with the OASIS software used to develop the Red Deer River model, described in more detail in Section 3.2. Although operations and priority water allocations differed from basin to basin, the core of the mass balance OASIS model was essentially the same for all SSRB sub-basins.

Coupled with the modelling tool, the project used a collaborative modelling process that enabled parties with disparate goals to collaboratively develop operating policies and solutions that mutually satisfied their diverse objectives, and to assess and address challenges and opportunities.

Developing performance measures (PMs) is one of the first steps in the process to help parties scope the issues. PMs reflect the objectives and desired outcomes for the project and indicate whether one result is better or worse than an alternative. They define the functional aspects that the model needs to have, and thus they inform and influence how the model is constructed. Participants identified and developed specific PMs based on their individual and collective water outcome needs for this project.

For the collaborative modelling process, once PMs are in place, the model can be run and the results tested and vetted using the PMs to determine if the outcomes are reasonable and realistic, based on participants' deep knowledge and experience. Exploring and modelling alternative operations is what most often results in model improvements and updates, and strengthens model results. When the model is refined and ready to be tested, participants then spend a number of hours working collaboratively in small groups to identify and test opportunities and potential scenarios or strategies to achieve the PMs. Based on these outcomes and the results of the PMs, collaborators can then seek agreement on the alternatives that are most beneficial to the basins and meet as many user needs as possible.

Project participants met in Red Deer four times between May and November 2014; a list of participants appears in Appendix A. A one-day live modelling session was held in June to explore future demand scenarios, balancing water supplies and demands with environmental protection, and flood mitigation options. This was followed by a two-day live modelling session in September to identify opportunities in the basin to enhance water management and resiliency with a focus on changes to streamflow due to potential climate variability and land use changes. The first day looked at climate impacts and potential effects on streamflow and participants developed strategies to adapt to these changes and to increases in demand. Climate scenarios developed by Dr. David Sauchyn and his team specifically for the project (see Section 3.3) were used in this modelling session. The second day was spent applying the ALCES model to examine land use impacts on the Red Deer River (see Section 3.4 for a detailed discussion). The final meeting in November was spent reviewing and refining the most promising individual options and combinations.

Throughout the project, participants worked collaboratively, providing advice and insight based on their knowledge and experience. Project terms of reference were approved by the group and appear in Appendix B. Participants actively offered ideas and comments to advance the discussion, while respecting the views and opinions of others. This process was not designed to seek or achieve total consensus; rather, it was designed to explore practical water management strategies and ideas, based on the best data and knowledge in the basin. The results are presented as a solid foundation for discussion and further analysis by those who use, manage, and make decisions about water in the Red Deer Basin as they consider adaptations to climate variability and change. The expectation is that the ideas and strategies developed through this collaboration would serve as a sound basis for water managers to start from as they anticipate and respond to future changes in water supply, water demand, and climate.

3.2 The Red Deer River Operational Model

The Red Deer River Operational Model (RDROM) is a daily mass balance model that reflects the streamflows and operations of the river system involved (Figure 4). The RDROM allows users to understand today’s integrated demands and infrastructure operations through 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.

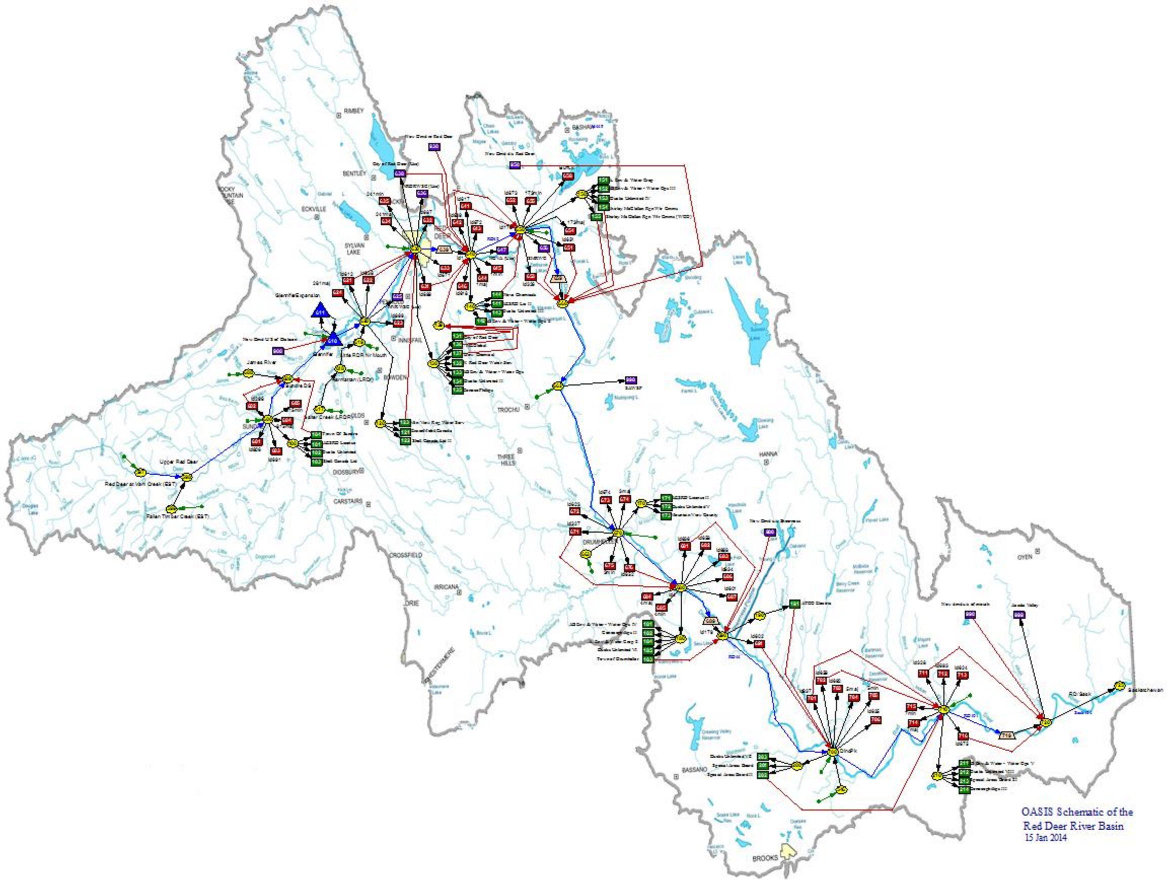

Figure 4: Schematic of the RDROM

Once the RDROM was developed, a "base case" was established upon which scenarios of change in the system could be modelled and differences between the base case and a given scenario could be evaluated. The base case applies how the river is currently operated, which includes "current operations", for which the model simulates current operating practices based on a set of modelling rules, and demands within the context of licensed priorities and water management plans. The base case is applied to the naturalized historical flows from 1928 to 2009. The base case RDROM implies that all current infrastructure and demands were present in the basin for the entire period of record (i.e., infrastructure, operations, and developed land remain constant). The exception was the irrigation requirements calculated by Alberta Agriculture and Rural Development's (ARD) Irrigation Demand Model (IDM). The IDM utilizes 2011 crop mix, on-farm efficiency, and district infrastructure to calculate irrigation demands based on historical weather records. Area irrigated remains constant, but water demands vary based on historical precipitation and conditions.

Base case results were validated against historical records and were seen to generally match outflows and reservoir levels for the post-Dickson Dam period. Some deviation from the historical record is to be expected, and while there is a modest overestimation of optimum crop water requirements in the IDM, these deviations were not seen as being unreasonable or out-of-scope for the modelling activities that have taken place.

3.2.1 General RDROM Assumptions and Model Overview

OASIS models operate under a few basic assumptions. Mass balance is always preserved by having water enter the model only at nodes with inflows, and exit only through demands, evaporation, or a terminal junction node. Water is also, in the general sense, allocated to each "use" (minimum flows, demands, reservoir storage, etc.) through a weighting system; that is, higher weighted uses get water first. In the Red Deer system this is slightly modified to account for time of travel (addressed more fully in the detailed model description in Appendix C), but in any discrete stretch of the Red Deer River this still holds true. These weights can be modified in various alternatives to increase the priority of one use over another, but the fundamental concept is applied regardless.

The RDROM was developed for the Red Deer system (Figure 4) to run on a daily timestep. Primary inputs include naturalized flows, evaporation and precipitation, licensed allocation for the whole system or consumptive use (in some cases actual use numbers were provided by users), return flows, and physical data for diversions and reservoirs, with associated operations. For detailed information on input data sets and model validation, see Appendix C.

3.2.2 Performance Measures

Performance measures (PMs) were developed and used to assess and demonstrate the impact and benefits of changes made in the RDROM. Various PMs were developed with a subset being used regularly in the modelling; the six key PMs in this subset are:

1. Flows at the Mouth of the Red Deer River (Weekly)

This PM identifies periods of low flows that might be of concern for environmental, economic, and social objectives as well as noting violations of the Water Conservation Objective (WCO). The WCO is an important PM as it represents an agreed upon water use threshold in an approved Water Management Plan under the Alberta Water Act. WCO requirements at the mouth of the river are a minimum of 10 m^3/s in the summer and 16 m^3/s in the winter. Weekly (rather than daily) flows were analyzed as operations in the model were targeted towards meeting the WCO on a weekly basis.

2. Elevation of Gleniffer Reservoir (Daily/Annual)

As Gleniffer Reservoir is the only on-stream storage in the Red Deer system, remaining storage in the reservoir is of critical importance, in particular during drought periods. Gleniffer Reservoir serves to maintain the WCO in the winter. Monitoring its storage helps to identify years where both the WCO and junior demands would be at risk.

3. Outflow from Gleniffer Reservoir

Gleniffer Reservoir releases are primarily of interest in terms of the functional flow alternatives looking at environmental flows below the dam and correlating those with reservoir storage targets and operational priorities. Outflow from the reservoir is shown to establish the effect of ramping on flows immediately downstream of the reservoir.

4. Cottonwood Recruitment

This PM estimates the likelihood of successful cottonwood recruitment and captures the quality of successful recruitment events. It shows the number of years when optimal recruitment can be expected and the number of years when partial recruitment can be expected.

5. Shortages to New Demands (Annual/Daily)
Since existing demands in the system are nearly all senior to the WCO and never saw shortage in any scenario or alternative, shortages in the system were analyzed as how many occurred in demands junior to the WCO (i.e., demands introduced in basin scenarios). Although presented primarily in annual terms in the report, they were often examined on a daily basis in the Working Group sessions.

6. Mid-stream Storage
This PM tracks the drawdown in the hypothetical mid-stream storage and operations proposed by the participants to estimate the additional volume of storage needed to remedy shortages to users and occasional deficits in Gleniffer Reservoir storage. It is presented where appropriate based on alternatives.

It is important to note with the PMs used to illustrate the results of this work, while water quality is certainly one aspect of the ecosystem, other environmental performance measures (e.g., biological, geomorphological, connectivity) need to be evaluated to assess all environmental risks.

The full list of PMs for the Red Deer River system (Appendix D) was processed for each strategy described in Section 4. Charts for specific PMs are included as appropriate in that section to illustrate a particular result, and the full set of PMs is available in the electronic RDROM files. Some graphics in this report have dates along the horizontal axis. Unless otherwise indicated, these dates indicate years in the future basin scenarios, as shown in the model runs; for example, 08/18/41 is August 18, 2041. Figures using the historical data set are included where appropriate and dated accordingly.

3.3 Development of Climate Scenarios for the Red Deer Basin

One objective of the SSRB Water Project was to propose adaptive and robust water management strategies that take into account the regional impacts of climate variability and 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. Thus, developing climate scenarios that could be used in the RDROM was the first step in contemplating potential water management strategies.

The innovative approach to developing the climate scenarios is described in detail in Appendix E and is summarized here. This aspect of the work was led by the Prairie Adaptation Research Collaborative (PARC), which has been developing climate scenarios for ESRD for some time, and developed the climate scenarios used in previous SSRB modelling work in the Oldman, South Saskatchewan, and Bow basins. The approach to developing the scenarios for the Red Deer River Basin differed from that used for the other three river basins because the previously-used, generalized-least-squares (GLS) regression models did not explain a sufficiently large amount of the variance (a 50% threshold) for flows in the Red Deer Basin. This may be because the hydroclimatology of Red Deer Basin is transitional between the North and South Saskatchewan River basins which behave quite differently.

For the Red Deer Basin, 10 Regional Climate Model (RCM) runs from the North American Regional Climate Change Assessment Program (NARCCAP) were selected to provide a range of future climate conditions. NARCCAP modellers from around the world have run a set of RCMs driven by a collection of General Circulation Models (GCMs) over an area spanning the United States and most of Canada. The RCMs simulate the climate of a region at a high resolution, whereas the GCMs simulate the climate of the entire world at a lower resolution. The RCMs are nested within the GCMs.

To simulate realistically regional hydrology, raw RCM results were bias-corrected, meaning outputs from the RCM were adjusted to match regional hydrometeorological conditions. From this procedure, biased-corrected projected mean daily flows for each year and for each of the 10 RCM runs for both the projected future and simulation periods were obtained. Further processing of the projected and historical streamflow data produced time series of plausible projected daily flows. From those, average cumulative distribution functions (CDFs) were derived of all the bias-corrected projected mean daily flows for the period 2041–2070. An empirical CDF from the historical (1912–2009) naturalized mean daily flows of the Red Deer River at Bindloss was also derived. By matching flows of equal probability, the two closest historical analogues for each RCM and each future year were identified. To arrive at daily flows for a projected year, the daily observations from a weighted average of its two analogue years were lognormal scaled by the projected values of the mean and standard deviation. By using a randomly (uniform distribution) weighted average of the two closest analogue years, the problem of exact repeats of streamflow from repeatedly chosen analogue years was avoided.

An approach was adapted to adjust the timing of the projected mean daily flows to include an advance in the timing of peak snowmelt runoff as is projected for western North America. On average our analysis suggests, there could be an advance of 10.5 days by 2041–2070. The worst case scenario showed an advance of more than a month (38 days) with the CRCM4 RCM for the year 2067. This advance of the spring peak will prove challenging, since at the end of summer there will be less water in the river when it might be particularly needed, depending on what crops are grown. These changes in flow are also important for aquatic ecosystem function, as low flow periods are typically the most sensitive for aquatic organisms.

The results found that streamflow on average either stayed the same or was projected to increase for the Red Deer River. Student's t-tests of the differences between the bias-corrected simulated runoff for 1971–2000 and the bias-corrected projected runoff for 2041–2070 for each RCM showed significant ($p < 0.05$) future increases for four RCMs, and no change for the other six RCM runs. The historical naturalized mean daily flow of the Red Deer at Bindloss is 62.7 m^3/s for 1912–2009. The simulated mean daily flow averaged over all the RCMs for the Red Deer River for 1971–2000 is 62.1 m^3/s. The projected mean flow averaged over all the RCMs for the Red Deer River for 2041–2070 is 70.2 m^3/s. The projected flows should only be compared to the simulated mean flows, and not to the actual historic flows. These results are different from those found in the Bow, Oldman, and South Saskatchewan river basins by earlier WaterSMART projects (Sauchyn *et al.,* submitted). This could be due to the change in methods (i.e., using a GLS statistical downscaling technique versus using the total run-off term out of the RCMs directly). More likely, however, these RCMs are showing that the expected transition between the drier south and the wetter north will occur in the Red Deer River Basin (IPCC, 2013). Further research on this subject is being conducted by the group at PARC.

Six scenarios were chosen for use in the SSRB Water Project to show a spread of potential future streamflow from changes in climate (Table 2) from the available 10 annual flow projections (Climate Scenarios) of 30 years (2041–2070). Taking annual flows to daily flows does not capture peak high flows since they must be calculated hourly; rather, it captures the high volumes in a given year. Therefore, a "synthetic flood" year was also created to help in the evaluation of impacts of a large peak flood event. Flood flows were scaled based on 2005 data and future climate projections for the single largest event (HRM3gfdl in 2049) at a daily timestep. The other scenarios were derived from a combination of one RCM and one emission scenario (one potential future climate) and provided annual average flows, downscaled to daily streamflow. This methodology shows a generally wetter system, with severe and extended events, and an earlier shift in the hydrograph.

Table 2: Selected climate scenarios for the Red Deer River Basin

Selection Criteria	Scenario Run (GCM, Run, Emission Scenario)	Representative Period	Scenario Name
Single lowest annual flow year	HRM3gfdl	2061	1yr Min
Second lowest annual flow year	ECP2gfdl	2067	2nd 1yr Min
Lowest 3-year consecutive annual flow	MM5Iccsm	2060-2062	3yr Min
Max Average 1 year Flow	CRCM4	N/A	1yr Max
2yr Median Flow- **Historical Analogue**	RCM3gfdl	N/A	2yr Median
Wettest year from all climate scenarios	HRM3gfdl	2049	Synthetic Flood

Since direct statistical comparison between historical and future scenarios can be misleading, a historical analogue was chosen to serve in that role. The two-year median average scenario (2yr Median) is meant to indicate a future climate scenario similar to current conditions. Even with this analogue, however, climate scenarios should be carefully compared, as the effects of operations can be concealed by differences in hydrological conditions. In these scenarios, three show varying levels of drought (1yr Min, 2nd 1yr Min, and 3yr Min) while one represents a "wet" scenario (1yr Max). The synthetic flood year is to provide a scaled-up flood year based on the highest annual flow of all the years from all the scenarios. While all these scenarios were available, for the most part, collaborative modelling done by the Working Group focused on the historic record, the 1yr Min, and 3yr Min scenarios as they emphasized drought.

These potential future streamflows present challenges in the Red Deer Basin to the environment, regional economy, and society, but they also present an opportunity to identify adaptation options and build resiliency to respond to future climatic changes.

3.4 Land Use Modelling Using ALCES

The ALCES model simulates spatial and temporal variance in hydrological indicators (e.g., water quantity and water quality) and the user can choose to aggregate or disaggregate space and time based on the nature of the catchment being examined and the resolution of input data or desired output indicators. ALCES uses runoff coefficients to simulate water yields from different landscapes and the model accounts for many variables that affect hydrology including (ALCES Group, 2014), but not limited to:

- Landscape Type

- Cropland Types
- Footprint Type
- Footprint Type Age (10-year increments)
- Elevation
- Slope (percent or fraction)
- Soil Type
- Precipitation by Landscape or Footprint Type (annual or monthly)
- Potential Evapotranspiration by Landscape or Footprint Type (annual or monthly)

Hydrological metrics can be summarized by Hydrologic Unit Codes (HUCs). HUCs are used because they represent contributing watersheds to the Red Deer River and enabled inflows to OASIS to be represented spatially.

ALCES is also able to simulate the following natural and anthropogenic disturbance regimes:

- Fire
- Avalanches (mountainous terrain)
- Transportation
- Agriculture
- Mining
- Hydrocarbon exploration and extraction
- Forestry
- Settlements (urban and rural)

ALCES was chosen for this project because it is widely applied in Alberta and offers a cost-effective and credible means of addressing a key focus of this study: to support understanding and management of changes on land and how they affect streamflow. The ALCES model was not used to simulate hydrologic response to climate change for this project.

Annual, monthly, and daily streamflows were calculated for five watersheds within the Red Deer River Basin. These five watersheds were delineated based on sub-regions from the HUC watersheds of Alberta (Figure 5). Annual streamflows associated with the simulated landscape composition of each watershed were calculated using relationships derived from historical naturalized flow data. Annual streamflows were then disaggregated into daily flows based on historical hydrographs, but modified to reflect a relationship between natural land cover and peak flow. The relationships and their application are described in Appendix F.

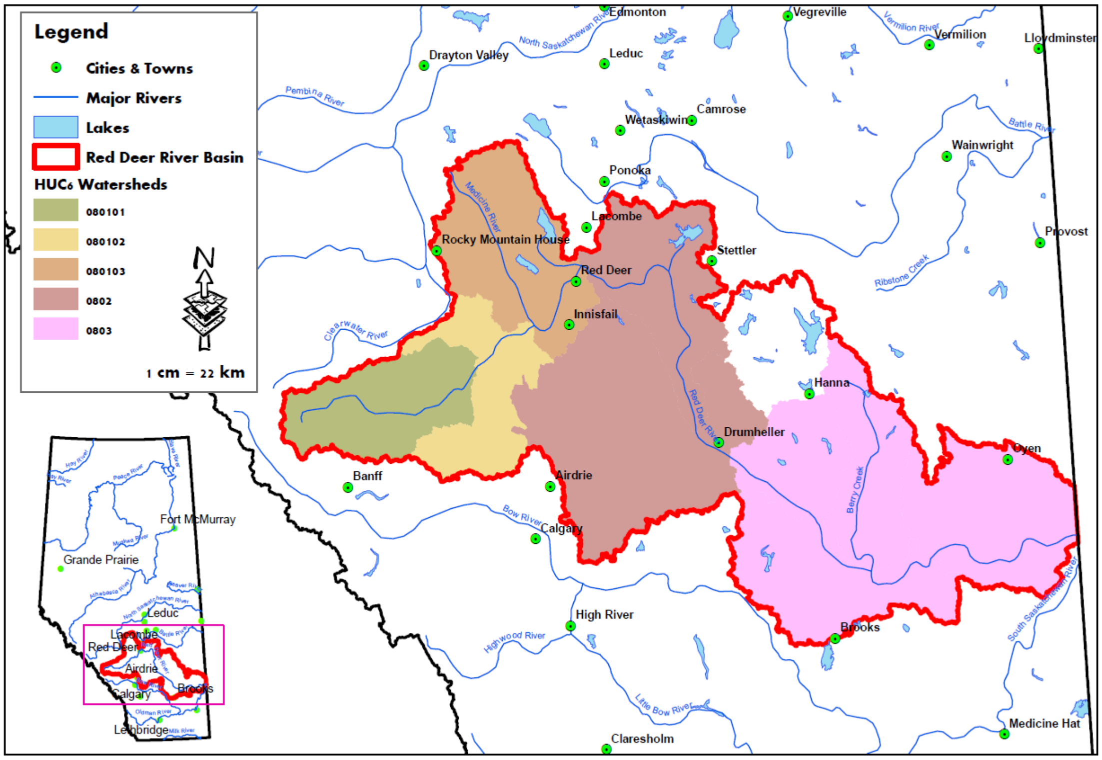

Figure 5: Red Deer River Basin and delineated HUCs used in land use modelling with ALCES. The white portion of the basin is non-contributing to flow in the Red Deer River.

3.4.1 ALCES Analysis for the Red Deer Basin

ALCES modelling provided project participants with five land uses that could be assessed. The five land uses can be combined to create a very large number of scenarios, the exploration of which can be overwhelming. The land uses that were evaluated are: settlements, energy development, agriculture, logging and fire, and wetland restoration.

3.4.1.1 Settlements

Settlements include cities such as Red Deer, smaller communities such as Sundre, and residences in rural areas. Combined, they cover 677 km^2 (1.4%) of the Red Deer Basin. In addition, major and minor roads cover over 1,200 km^2 of the basin, some of which are used to access towns and rural residences. Roads are tightly coupled to growth and can be expected to expand as settlement increases.

Over the past 50 years, the area of towns and rural residences increased 550% to accommodate a growing population. Extrapolation of recent population growth rates suggests that the towns and rural residences will expand by almost 200% over the next 50 years. The effect of these buildings, sewers, and hard surfaces such as roads tends to accelerate the rate at which precipitation flows off land into streams, rivers, and lakes, thereby decreasing infiltration. As a result, settlements and their associated infrastructure increase both total streamflow and peak flow.

3.4.1.2 Energy Development

Energy development is associated with a number of footprints, including well sites, pipelines, and seismic lines. Combined, they cover 386 km^2 (0.8%) of the Red Deer Basin. In addition, minor roads, some of which are used by the energy sector, cover over 800 km^2. Roads are tightly coupled to growth and can be expected to expand with energy development.

Over the past 50 years, rapid expansion of the energy sector caused energy footprints to increase by more than 1000%. Extrapolation of projections made by the Alberta Energy Regulator suggests that energy footprints may expand by almost 300% over the next 50 years. Energy footprints can accelerate the rate at which precipitation flows off land into streams, rivers, and lakes. However, these footprints also hold water back and evaporate more of the precipitation that falls on the ground due to ditches and diversions. As a result, the net effect of the energy footprint in these simulations is both positive (higher) and negative (lower) in terms of streamflow changes.

3.4.1.3 Agriculture

Cropland and pasture cover 25,492 km^2 (51.0%) of the Red Deer Basin. Over the past 50 years, farmland expansion has been negligible (5%). Farmland may decline over the next 50 years due to encroachment by other land uses such as settlements and energy development. Offsetting the decline in farmland due to encroachment by projected settlement expansion and energy development would require the creation of new farmland accounting for 6% of today's extent. Farmland was not found to strongly influence streamflow, in large part because farmland is located in the eastern portion of the basin where low rainfall results in negligible streamflow and changes from grassland to crop land has a relatively small effect on runoff generation.

3.4.1.4 Forestry and Fire

Forestry and fire alter the age-class composition of forests in the basin, with higher rates of these disturbances creating more young forest. With much of the basin's forest allocated to the forestry sector, timber harvest has replaced fire as the dominant disturbance in recent decades. During that time, suppression reduced the average disturbance due to fire to less than 0.1% of the land base per year. If timber harvest follows a 100-year rotation, and fire continues to be negligible, an average of 1% of the forest will be disturbed each year.

Generally, more water is transmitted to streams from forested areas when forests are young or non-existent. Based on current literature, this simulation assumed that disturbances that cause a large proportion of the forest to be younger than 40 years of age can increase annual streamflow and peak flow.

3.4.1.5 Wetland Restoration

Many wetlands in the agricultural portion of the Red Deer Basin were drained years ago to increase arable land. Restoration of drained wetlands recovers the ecosystem services they provide, including regulating water flow, filtering water, recharging groundwater, and providing wildlife habitat.

Wetlands can intercept runoff before it enters streams, rivers, and lakes, especially during the high flow period in spring and early summer. A portion of the water entering wetlands can evaporate and recharge aquifers, thereby reducing annual flow to streams, rivers, and lakes and lowering peak flow during the spring freshet. Wetlands provide natural water storage in the basin, lowering peak flows during flood events, and help alleviate drought conditions. Approximately 60% of the Red Deer Basin's original wetlands have been drained. If land uses such as agriculture and settlement continue to expand, more wetlands are likely to be lost although at a reduced rate relative to what happened in the 20th century. Alternatively, wetland area can expand through increased restoration. Returning wetland area to its pre-settlement level would require wetland area to grow by 150% relative to today, with much of that restoration focused in the prairie portion of the basin.

In these simulations, the effect of wetlands was modelled using research conducted in the Smith Creek Research Basin, Saskatchewan (Pomeroy *et al*., 2014). The study found total streamflow volume to be sensitive to wetland loss, and that streamflow volumes increased with increased wetland loss. A relationship between wetland area and percent change in annual flow was used to derive wetland scenarios.

4. Project Results and Findings

This section describes the results of modelling done to examine the impacts of climate variability and land use on streamflow, and to identify suitable strategies for building resilience in the Red Deer Basin to allow for growth while dealing with emerging water management challenges. A number of the charts in this section have dates along the horizontal axis. Unless otherwise indicated, these dates indicate years in the future basin scenarios, as shown in the model runs. Figures using the historical data set are included where appropriate and dated accordingly.

It is important to understand the WCO for the Red Deer and how it is modelled in the RDROM. The WCO comes from the Approved Water Management Plan for the SSRB (Alberta Environment, 2006). For the Red Deer River Sub-basin, any licences issued after May 1, 2005 are subject to the following WCOs:

Upstream of the confluence with the Blindman River, to Dickson Dam:

- For new licences or existing licences with a retrofit provision, a rate of flow that is 45% of the natural rate of flow, or 16 m^3/s, whichever is greater at any point in time.

Downstream of the confluence with the Blindman River:

- For future licences that withdraw from November to March inclusive, a rate of flow that is 45% of the natural rate of flow, or 16 m^3/s, whichever is greater at any point in time.
- For future licences that withdraw from April to October inclusive, a rate of flow that is 45% of the natural rate of flow, or 10 m^3/s, whichever is greater at any point in time.
- For existing licences with a retrofit provision, a rate of flow that is 45% of the natural rate of flow, or 10 m^3/s, whichever is greater at any point in time.

Based on this information, in the RDROM, and as referred to in this report, the WCO is modelled as a minimum winter (November – March) WCO of 16 m^3/s, and a minimum summer (April – October) WCO of 10 m^3/s. For modelling purposed this is the targeted WCO at the mouth of the Red Deer River. A WCO of 16 m^3/s also exists immediately below Dickson Dam (mirroring their operational policy of a 16 m^3/s minimum release). All licences in the model prior to 2005 are senior to the WCO, thus it is possible for the WCO to be violated.

4.1 Impacts of Climate Variability in the Red Deer Basin

The climate variability scenarios developed for this project provide a range of plausible future streamflows to assess the impacts of potential climatic change on streamflow in the Red Deer River (as described in Section 3.3). Natural streamflows shown in the six selected climate variability scenarios reflect conditions that have been seen throughout the historical record and are well within the recent range of variability in terms of magnitude and duration (Figure 6). Figure 6 compares the 30-year average flow at a weekly timestep produced from five of the chosen climate scenarios with the 30-year average flow from the historical record in the model; it also shows the 2000–2001 drought and the 2005 flood for reference. It should be noted that the 2005 flood peak is much larger than any of the climate scenarios because it is only one year instead of a 30 year average like the scenarios.
The “synthetic flood” scenario is not shown explicitly, but the annual flow from which is was derived falls within the 1yr Min scenario in terms of annual flow volume. The plotted historical time series provides context for the streamflow produced by the climate scenarios.

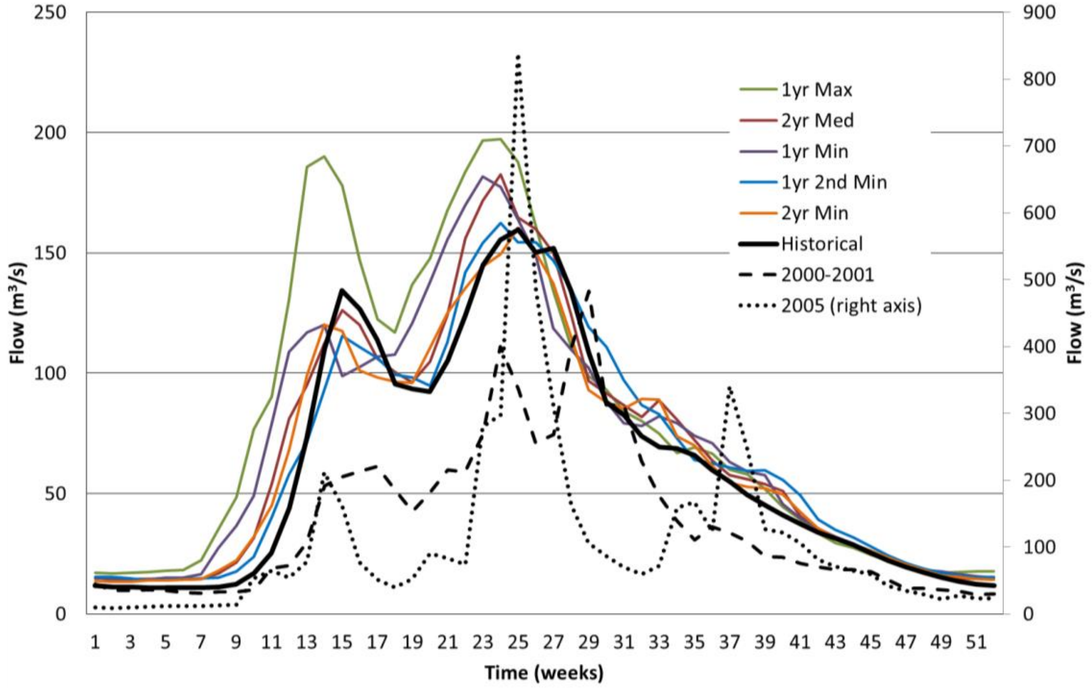

Figure 6: Average weekly modelled natural flow in the Red Deer River at Bindloss compared to the 2000–2001 drought

The climate variability scenarios in Figure 6 show a shift in the peak flows with peaks occurring up to a month earlier than the historical record. The first peak is frequently smaller than historical whereas the second peak is consistently at or above the historic flows. Figure 6 also shows that, in the climate variability scenarios, there is more water in the system as a whole and the winter base flows are consistently higher than the historic winter base flows.

Due to the projected increases in streamflow and annual water yields in the Red Deer River the climate variability runs did not put a great deal of additional pressure on the system at current demand levels, thereby allowing some additional growth without the need for more storage infrastructure.

The current demand is discussed at three levels – actual use, rational use, and full licensed use (Appendix C). When growth is discussed in climate variability scenarios land use is not currently incorporated; growth is simply an increase in demand proportionate to the current demand.

Three climate variability scenarios were of particular interest during the live modelling session: the single lowest annual flow year (1yr Min), the lowest three-year consecutive annual flow (3yr Min), and the wettest year synthetic flood scenario. It is important to note that the single lowest annual flow year and the single wettest annual flow year from all climate scenarios occur in the same 30-year climate scenario run, illustrating the increased variability projected for the system.

Figure 7 compares the 2000–2001 historical drought to the single lowest annual flow year (2062) in the 1yr Min scenario. The drought in this scenario shows 950 dam^3 less inflow the 2000–2001 drought over the course of the year. During the 2000–2001 drought, in contrast to the 2062 scenario, a late rainfall helped to fill Gleniffer Reservoir. This peak in the 2062 1yr Min hydrograph allowed for the refill of the reservoir from critical levels. Despite this drought, however, on average over the entire 30-year 1yr Min scenario there is more water on average annually than over the annual average of the historical 82-year record.

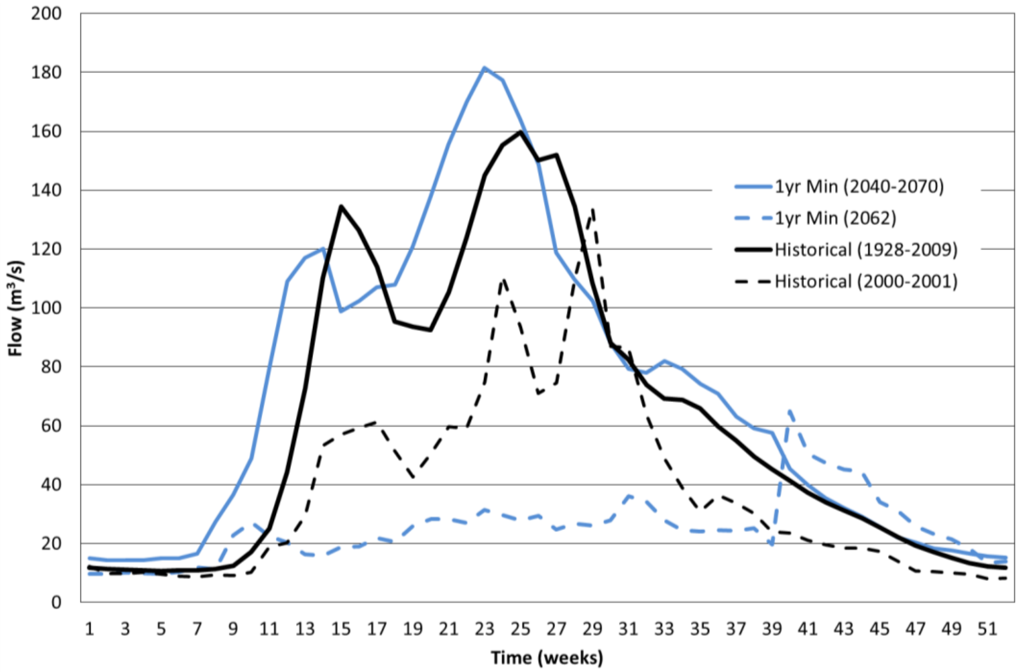

Figure 7: Average weekly modelled natural flow in the Red Deer River at Bindloss during historical and projected future droughts

At rational and actual use levels, the lowest annual flow year (1yr Min) scenario does not cause any WCO violations nor does it create shortages within the system, as the flow does not drop below the WCO and demands are all met throughout the system. At licensed use there are small WCO violations (less than 2.0 m^3/s) and relatively small volumes of shortages (less than 475 dam^3/day or 10% in total during the worst drought year). Figure 8 shows the flow of the Red Deer River at the mouth for 2061–2062 of the 1yr Min scenario, where the WCO would be measured. In the actual and rational use scenarios the flow in the river remains slightly over the WCO. In the full licensed demand scenario the flow rate is at or below the minimum 10 m^3/s for most of the summer. It is important to remember that the WCO is not an environmental flow recommendation but rather the trade-off among the three competing interests; environment, economy and society.

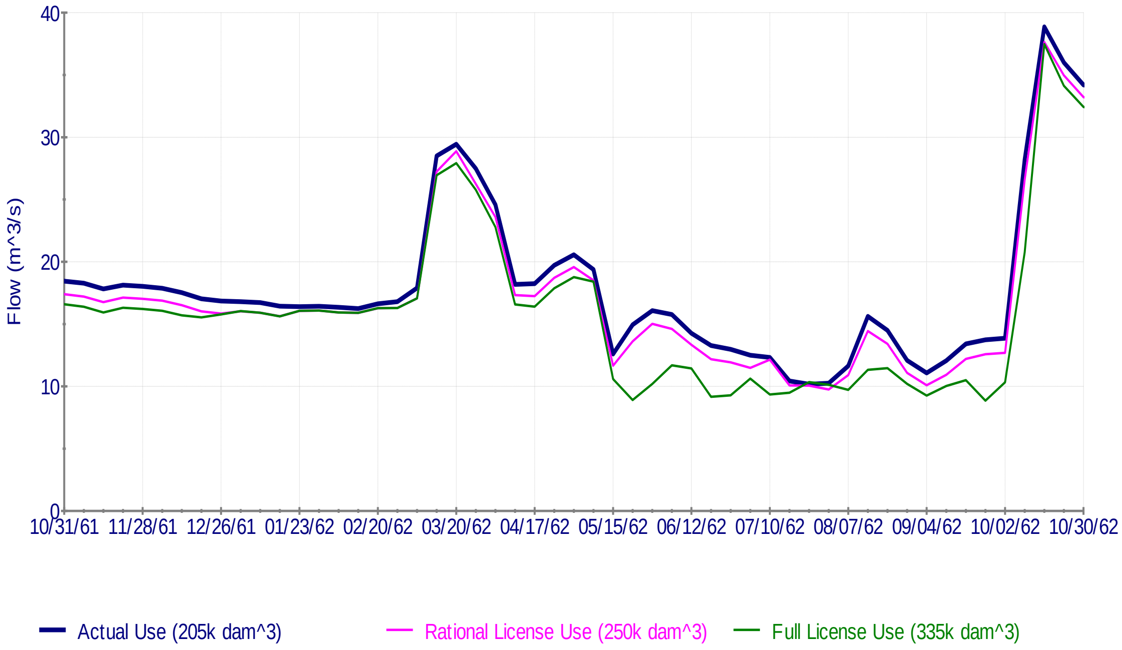

Figure 8: Flow at the mouth of the Red Deer River (1yr Min scenario), 2061-2062

Figure 9 shows the level of Gleniffer Reservoir for actual, rational, and licensed demands during the 2062 drought in the 1yr Min scenario. Because there is so little flow into the reservoir and the dam is supplementing summer flows to meet the WCO, the reservoir does not fill and water levels fall below the lowest permissible elevation.

At current demand levels the single lowest annual flow year (2062 in the 1yr Min) is the only year in the climate variability scenarios where Gleniffer Reservoir does not refill. However, because there is projected to be generally more water in the system based on the climate variability scenarios, changes to infrastructure operation (see Section 4.4) could avoid many of the shortages and WCO violations.

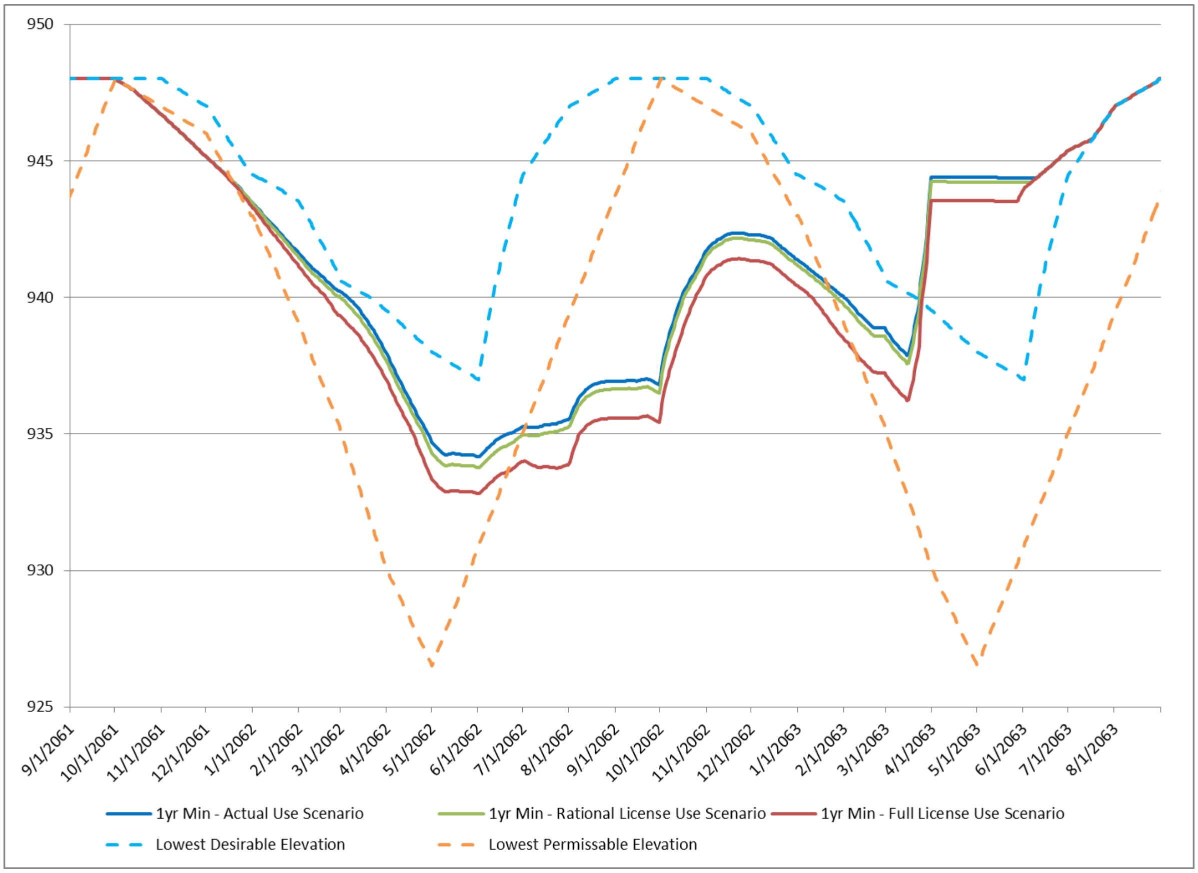

Figure 9: Gleniffer Reservoir elevation during 1yr Min scenario, 2062–2063

The lowest three-year consecutive annual flow (3yr Min) scenario is on par with the historic drought from 2000–2001 in terms of total annual flow. This scenario presents far less stress to the system than the single lowest annual flow year scenario (1yr Min). One reason that the 3yr Min scenario does not stress the system is because the climate scenarios produced higher winter base flows than seen historically, which increases the water in the system as a whole.

In the 3yr Min scenario, the WCO is met at all of the current water use levels (Figure 10). The flow at the mouth of the river drops to the 10 m^3/s minimum flow for two weeks – this could adversely affect fish populations during warm or oxygen depleted periods. However, flow does recover quickly. Negligible shortages occur in this scenario.

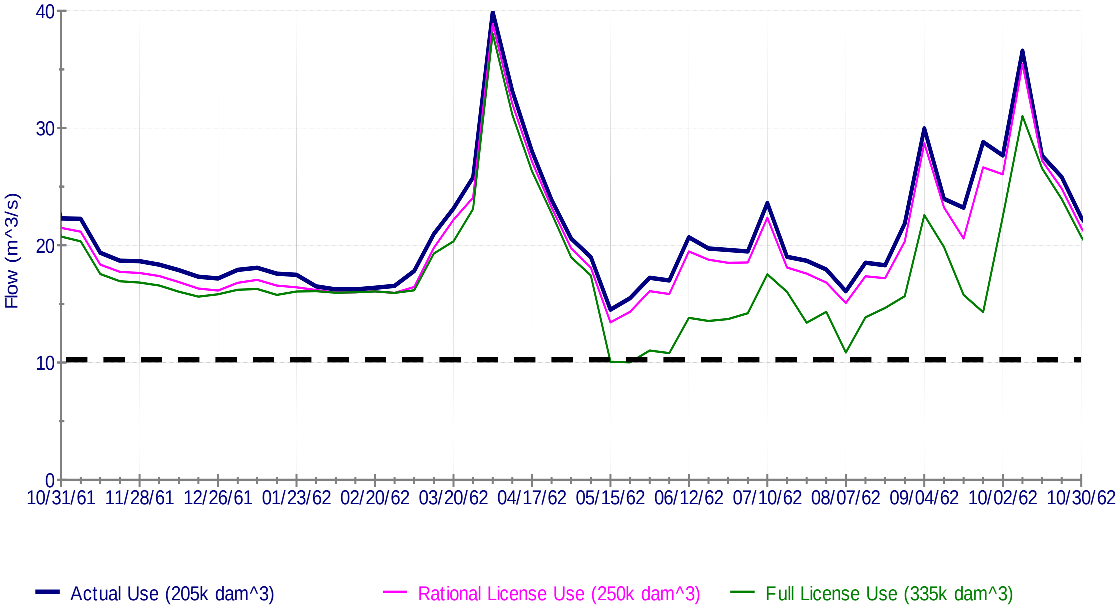

Figure 10: Flow at the mouth of the Red Deer River (3yr Min scenario), 2062–2063

Gleniffer Reservoir refills during all three years of the drought in the 3yr Min scenario, as shown in Figure 11. The reservoir never drops below the lowest permissible level in this scenario as it does in the single lowest annual flow run (1yr Min), and generally does not drop a significant amount below the lowest desirable level.

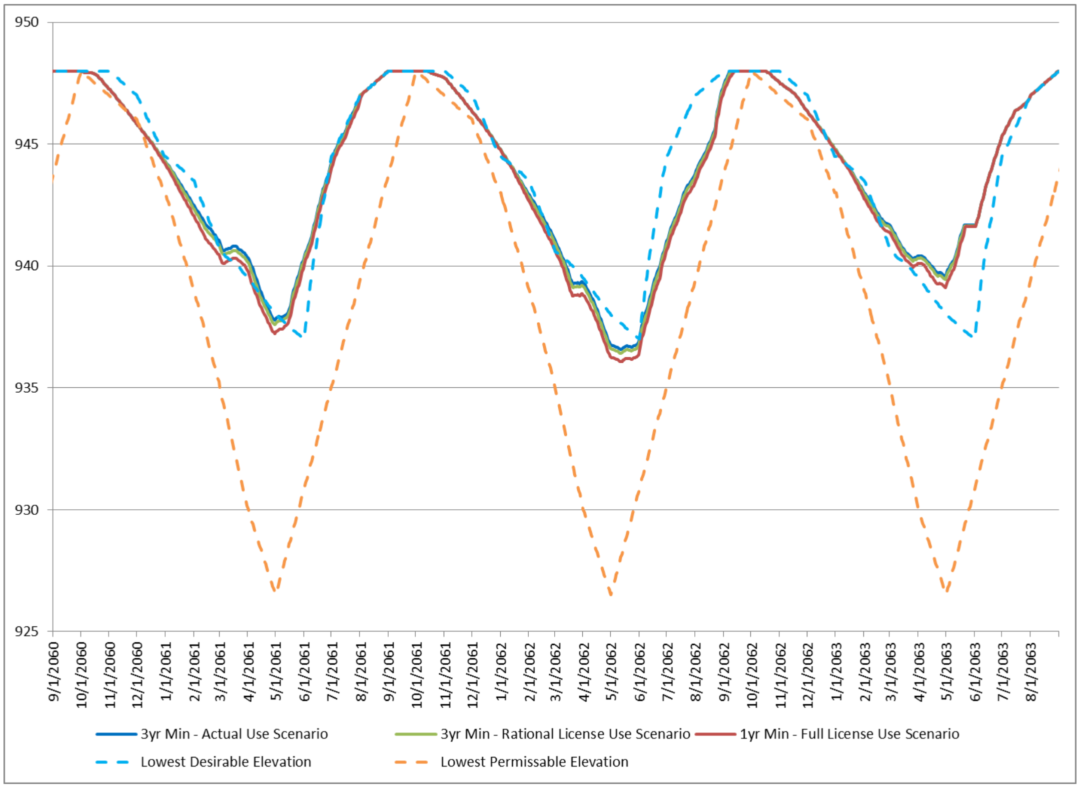

Figure 11: Gleniffer Reservoir elevation during 3yr Min scenario, 2060-2063

Neither the single lowest annual flow year (1yr Min) nor the lowest three-year consecutive annual flow (3yr Min) has negative impacts on water quality thresholds defined as the instream flow requirement for water temperature and dissolved oxygen, as measured by the model's PMs. Figure 12 shows the percentage of days across the 30-year climate variability period where water quality thresholds are met or exceeded at Bindloss. This performance measure does not focus exclusively on the year(s) of drought. It shows that water quality thresholds for fisheries are not met most of the time during the winter, and are generally consistent between model runs for the spring, summer, and fall. Figure 12 demonstrates that winter is in fact a sensitive period that is likely to be affected by future changes in streamflow.

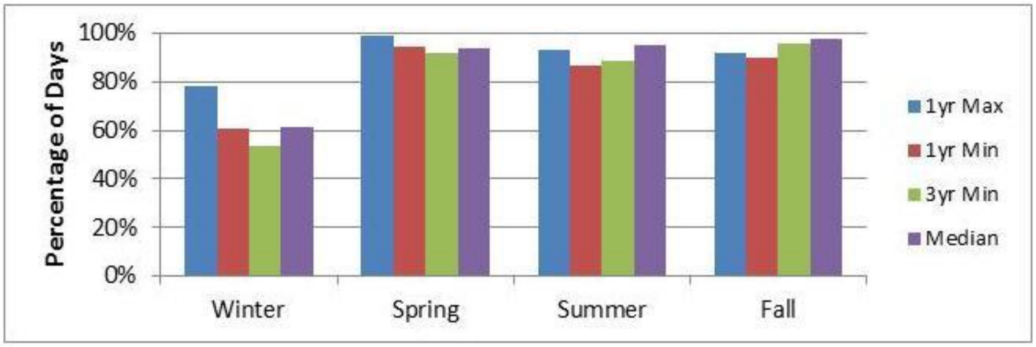

Figure 12: Percentage of days in 30 years when water quality thresholds are met or exceeded at Bindloss (median being the historical analogue)

Figure 13 shows the years of partial and optimal cottonwood recruitment in the Red Deer River at Red Deer. Historically cottonwood recruitment would take place approximately one in every ten years. The 1yr Min scenario shows partial or optimal recruitment for six years over the 30-year period, while the 3yr Min scenario shows only partial recruitment in one year and no optimal recruitment. The differences between runs are a function of the flow magnitudes in the Red Deer River: higher flows offer more opportunity for recruitment, while lower flows do not provide adequate scouring of gravel bars.

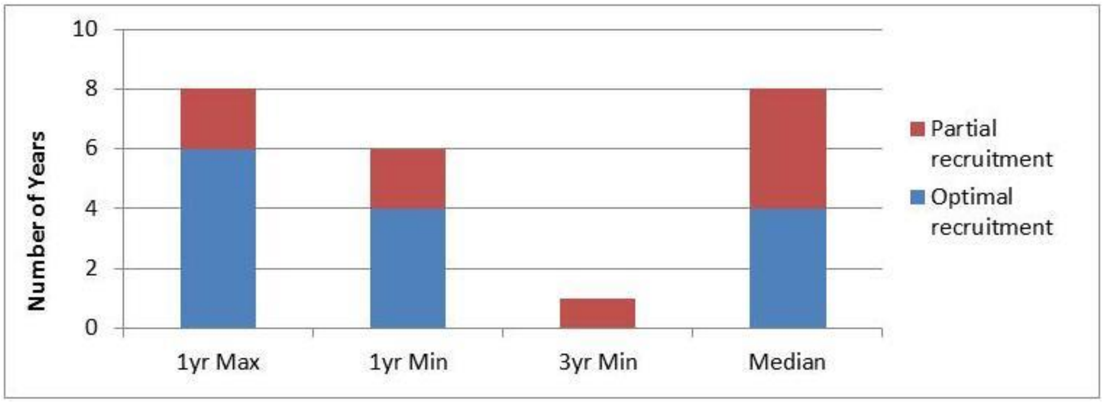

Figure 13: Years of cottonwood recruitment success for the Red Deer River near Red Deer over 30-year period

The synthetic flood scenario, which was simulated based on the 2005 hydrograph and scaled up to the annual flow from the wettest year in the climate variability scenarios (see Section 3.3) causes some stress to the system but does not create a high flood peak or flow situation that cannot be mitigated by the Dickson Dam.

During this flood the modelled daily average peak flow at Drumheller was approximately 1,300 m^3/s, as seen in Figure 14. This daily average peak flow translates roughly into an instantaneous peak flow of 1,444 m^3/s, which is below the flooding level for Drumheller but is still uncomfortably high.

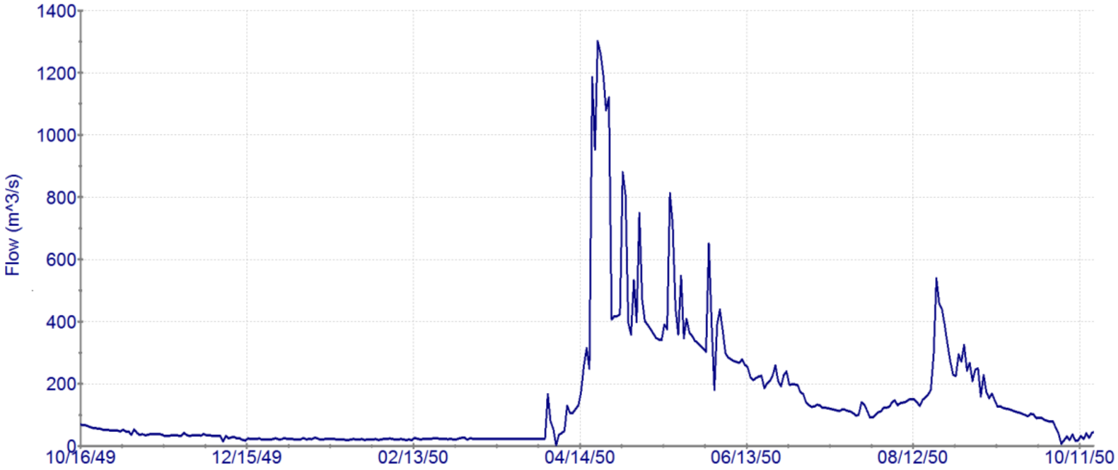

Figure 14: Daily peak flood flows at Drumheller during synthetic flood scenario, 2049–2050

4.2 Impacts of Land Use in the Red Deer Basin

The base case for the land use simulations is a future 50-year time series from 2011 to 2061 that assumes there is no land use change relative to 2010. Land use change scenarios were implemented based on business as usual (BAU) growth rates, which assume that the growth trajectory over the past 50 years remains the same into the future. For this work, BAU has been termed medium growth rates, and both high and low growth variations from BAU. For example, settlement footprint has increased 550% to accommodate a growing population. Extrapolation of recent population growth rates suggests that settlements will expand by approximately 200% over the next 50 years; this projected growth rate is considered to be medium growth (BAU). Growth rates for energy and agriculture are described in Section 3.4. Low growth scenarios assume that the growth trajectory is 50% of medium growth, and high growth scenarios assume growth is 150% of medium growth.

Forest disturbance changes (fire or logging) are not based on growth but on disturbance level. The low scenario assumed a 1% removal of forest cover per year, which is similar to current timber harvest practices. The medium scenario had 50% forest disturbance in decade 1 and decade 2 and the high scenario had 100% forest disturbance in decade 3. These disturbances represent large catastrophic events such as forest fire, not timber harvest. Vegetation was allowed to grow back at natural growing rates for conifers and deciduous trees following disturbance.

Wetland restoration scenarios assume that a percentage of wetlands would be restored relative to the number that was present in 2010. The “no restoration” scenario assumes there would be no wetland restoration, and wetland area could actually be lost under this scenario if development in settlements, energy, and agriculture occurs on historic wetland areas. The “low wetland restoration” scenario assumes 15% of wetlands would be restored at the onset of the simulation. The low wetland restoration scenario assumes that there would be no other land use changes and restored wetlands would be maintained. However, under combination scenarios, land use change is allowed to occur, so the restored wetlands can be subsequently lost to new development.

Crop scenarios included expanding irrigated area by increasing demands. The Special Areas Water Supply Project (SAWSP)/Acadia Valley scenario was considered to be low crop growth, with an increased water demand of 80,000 dam^3. A number of other crop scenarios were developed during the Working Group session, incrementally increasing the water demand. The medium crop scenario was an increased irrigation demand of 100,000 dam^3. As explained in Section 3.4, irrigated crop expansion did not have a significant effect on changing streamflow; therefore, these scenarios are reflected solely by changes in the demands and are not included in the simulation analysis below.

4.2.1 Individual Land Use Simulation Results

4.2.1.1 Settlement

As modelled, settlement expansion in the Red Deer River Basin resulted in increased streamflow overall, with increases of 0.5%, 1.3%, and 2.8% over the entire 50-year simulation as a function of low, medium, and high development respectively. Settlement effects were most noticeable toward the end of the 50-year simulation because the amount of settlement was assumed to increase over time. The last 10 years of the simulation are illustrated in Figure 15A; these results demonstrate the effect of land use and do not include operations or changes in demand.

4.2.1.2 Energy Development

The effect of energy sector development (roads, mines, seismic lines, transmission lines, pipelines, non-productive well sites, and exposed soil or non-vegetated surfaces) was a reduction of 1% in flow over the entire simulation period for both medium and low development scenarios (Figure 15B).The Working Group suggested that high energy development would not substantially increase water demands for the whole Red Deer Basin given that efficiencies can be made with this type of resource extraction (e.g., directional drilling). However, it is expected that Temporary Diversion Licenses (TDL's) will increase under future development, thereby increasing the demand on tributaries. As with Figure 15A, these results demonstrate the effect of land use and thus do not include operations or changes in demand.

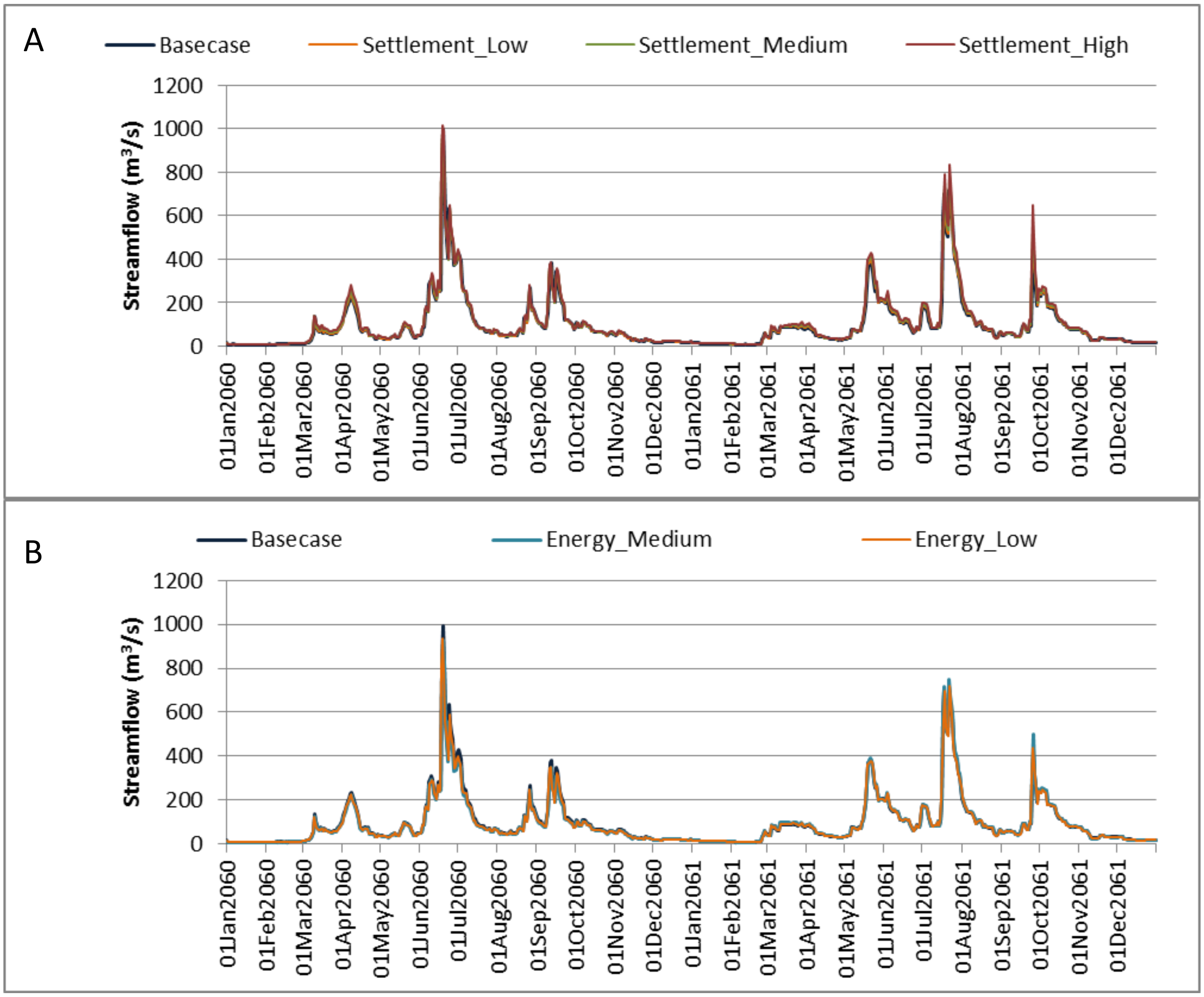

Figure 15: Effect of settlement (A) and energy development (B) on total daily inflow (natural streamflow) at Bindloss from January 1, 2060 to December 31, 2061

4.2.1.3 Forest Disturbance

Forest disturbance (fire or logging) resulted in increased streamflow overall except for the low development scenario, which assumed a 1% change in forest cover per year (Figure 16A). The medium scenario had 50% disturbance in decade 1 and decade 2, resulting in an average increase in streamflow of 3.6% over the entire simulation. The high scenario was 100% disturbance in decade 3, and led to an average increase in streamflow of 6.4% over the entire simulation, similar to results found by Pomeroy *et al*. (2012) and MacDonald *et al*. (2014). These results are shown for Bindloss; effects of harvest on hydrology at smaller spatial scales in the upstream basins where logging occurs are larger than those simulated downstream at Bindloss, particularly for peak flow. For example, the farthest upstream HUC had a daily mean peak flow of 876 m^3/s in the basecase. This increased to 1,058 m^3/s in the high scenario, an increase of 20% above basecase.

4.2.1.4 Wetland Restoration

Without wetland restoration the streamflow did not change. However, low wetland restoration resulted in a 1.7% reduction in streamflow over the entire simulation. Low wetland restoration also reduced peak flow by approximately 8% on average at Bindloss near the end of the simulation period (Figure 16B). All results in Figure 16 demonstrate the effect of land use and do not include operations or changes in demand.

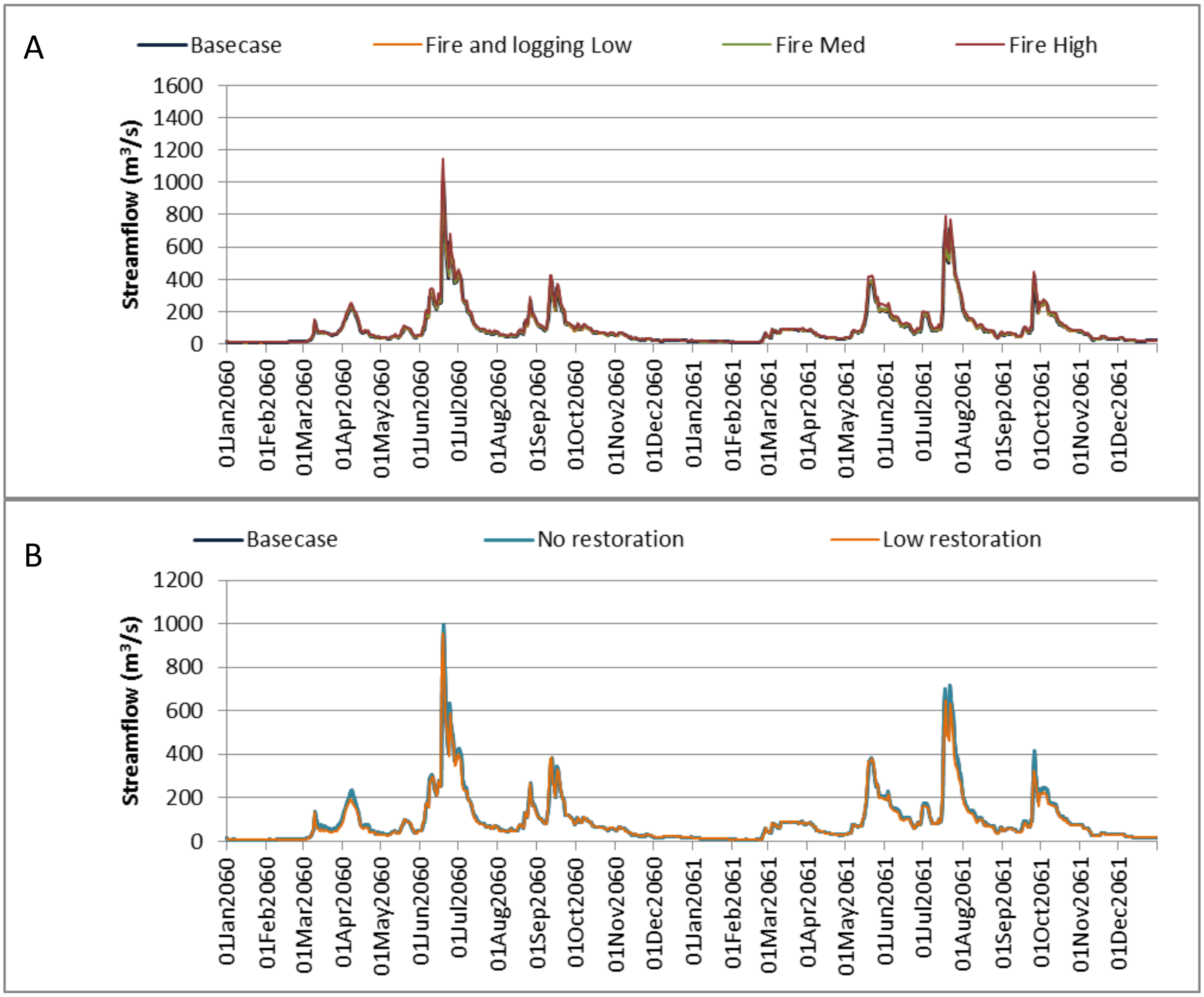

Figure 16: Effect of forest disturbance (A) and wetland restoration (B) on total daily inflow (natural streamflow) at Bindloss from January 1, 2060 to December 31, 2061

4.2.2 Land Use Simulated Results in Combination

Fourteen combinations of land use changes were assessed by Working Group participants. Some of the specific combinations were given colloquial names at the working session and these are reflected in the list and Table 3 below:

1. General changes in settlements and energy
2. Full medium scenario
3. Full medium scenario without wetland restoration
4. “Bill’s Run”: medium settlement and energy, low for crop development (SAWSP/Acadia at 140,000 dam^3), medium fire/logging, and no wetland restoration
5. Full medium, but with low SAWSP/Acadia Valley crop development
6. Full low
7. “Worst case”: crops (SAWSP/Acadia), high settlement, high energy development, and high fire or logging, and no wetland restoration

8. “Pretty”: low settlement, low energy development, low crop development, medium fire or logging, and high wetland restoration
9. “Ugly”: high settlement, high energy development, high fire or logging, medium crops, and no wetland restoration
10. No wetland restoration and medium settlement
11. Medium settlement and crops
12. Medium settlement and energy
13. All high except for medium fire or logging, and no wetland restoration
14. Medium settlement and crops, low energy, medium fire or logging, and low wetland restoration

Table 3: Land use change scenarios explored with the Working Group

Land Use Change					
Scenario	**Energy**	**Settlement**	**Crops**	**Fire and logging**	**Wetland restoration**
1	Discussion	Discussion	-	-	-
2	Medium	Medium	Medium	Medium	Medium
3	Medium	Medium	Medium	Medium	None
4	Medium	Medium	SAWSP/Acadia	Medium	None
5	Medium	Medium	Low	Medium	Medium
6	Low	Low	Low	Low	Low
7	High	High	SAWSP/Acadia	High	None
8	Low	Low	Low	Low	High
9	High	High	Medium	High	None
10	-	Medium	-	-	None
11	-	Medium	Medium	-	-
12	Medium	Medium	-	-	-
13	High	High	High	Medium	None
14	Low	Medium	Medium	Medium	Low

Looking across the results from all the combinations, the settlement growth scenarios increased total water demand but also resulted in increased peak streamflow as a function of hardened, less permeable surfaces. Modelling results suggest that without conservation or mitigation strategies (further details in Section 4.3), future new demands, which are junior to the WCO, associated with settlement growth may not be consistently met under any scenario. These shortages were reduced under the high and low settlement growth scenarios using water conservation strategies, which assumed there would be a reduction in water demand as a function of increased efficiencies. Working Group participants also acknowledged that it is imperative to consider new storage as part of any strategy to mitigate shortages that would occur as a result of growth.

Model outputs suggest that growth in energy development results in higher shortages to new licences than residential growth, and that energy and settlement impacts start to overlap as growth occurs. For example, substantial energy development is expected in the Sundre area, which is where most wetlands in the basin are found, and conflicts between sectors could emerge there. Conservation and planning for when to withdraw water will be key in terms of mitigating shortages to new licences that result from energy sector growth.

Scenarios that follow medium growth in energy development and settlements generally resulted in lower flows at the mouth of the Red Deer River, largely due to increased demands. At the same time, an increase in streamflow occurs under these scenarios due to settlement expansion (e.g., more pavement and less permeable surfaces), which results in higher runoff. Although there was an increase in peak daily streamflow of approximately 40% under full medium scenarios, Gleniffer Reservoir was able to capture the upstream portion of this increase.

In each combination of land use changes, individual land use effects were expressed in different ways. Overall, however, the increased streamflow in the Red Deer River that resulted from a larger, more intensive land use footprint was outweighed by increased water demands from expansion of agriculture, settlements, and energy development.

The net effect of expansion in irrigated crop land was an increase in shortages for new demands. This increase in shortages could be offset somewhat by increased growth in energy development and settlement due to higher runoff contribution to streamflow. As well, expanding irrigation agriculture will drain some wetland areas, which would likely not have an immediate effect on water yield or directly affect annual streamflow but would have ecological impacts on groundwater recharge and ecosystems. Generally, results of this work suggest that wetlands can play a role in offsetting increased peak streamflow from growth in runoff due to changing land uses or forest disturbance in the headwaters.

“Bill’s Run” was a scenario developed initially to look at potentially likely growth in the Red Deer Basin. This scenario resulted in higher peak streamflows as well as slightly higher variance in streamflows during normal periods. Observed shortages to SAWSP and Acadia Valley were viewed as manageable.

The “Ugly Scenario” resulted in large increases in high streamflow events as a function of 100% forest disturbance, similar to the large fire of 1910 (Arthur, 2013). However, shortages also increased due to higher demands. The Ugly Scenario contrasts with the “Pretty Scenario,” which looked logically at what would happen if low growth rates occurred and wetlands were restored. The model results suggest there would be decreased peak flows and fewer shortages to new demands relative to the Ugly Scenario. These two contrasting scenarios demonstrate the importance of considering the cumulative effect of multiple overlapping land uses in terms of water supply and water demand.

4.3 Plausible Basin Scenarios

Information from and discussion by participants throughout the project led to general agreement that the basin has enough water to support a range of growth opportunities through new allocations. However, the key questions are: a) How can water management evolve and adapt as the basin grows and the climate varies to ensure risk to users is acceptable and there is a balance between growth and environmental interests, and b) How can both growth and environmental impacts be measured?

At the final Working Group modelling session, three plausible scenarios for growth in the basin (basin scenarios) were presented. Based on feedback and comments, slight modifications were made and a fourth scenario was added. Table 3 compares the four basin scenarios based on modelling work done during the project, and includes changes in land use footprint and corresponding growth and change in water withdrawals. In the basin today there is approximately 335,000 dam^3 of water allocated in the

Red Deer River basin, with an active annual withdrawal of roughly 275,000 dam^3 (O2 Planning + Design Inc. et al., 2013). Scenario 1 is a conservative view of today as it shows more active withdrawals than now, but is roughly equivalent to current allocations. Scenario 2 is a medium growth scenario, and Scenario 3 is a high growth scenario that is still in the upper bounds of the recommended allocation volume for the basin.[6] Scenario 4 provides insight into what might happen when the upper bounds of the recommendations from the 2006 SSRB Water Management Plan are pushed. It is important to remember that increased demands from Red Deer are offset by increased return flows, so net demand is relatively low. For the modelling work, return flows are increased proportionally relative to historical numbers.

While these scenarios reflect growth, they are not intended to reflect the timing of growth nor are they intended to be predictive. Rather their intent is to provide a basis for water management considerations and trade-offs if and when the need arises.

Table 3: Four plausible basin scenarios for the Red Deer River Basin

	Scenario 1 Current Conditions	Scenario 2 Medium Growth	Scenario 3 High Growth	Scenario 4 Extremely High Growth
Active Withdrawal (dam^3)	250,000	350,000	440,000	575,000
Total Allocation (dam^3)	335,000	435,000	525,000	655,000
Return Flows (m^3/s)	Current rates of return flow	Return flows scaled up with demands	Return flows scaled up with demands	Return flows scaled up with demands
TDLs (dam^3)	10,000	10,000	10,000	10,000
Wetlands	No change	10% more than today	10% more than today	10% more than today
Crops	No change	SAWSP + Acadia (85,000 dam^3)	SAWSP + Acadia (85,000 dam^3)	SAWSP + Acadia + 15,000 dam^3
Settlement	No change	4% of total growth in the BAU Scenario	Medium (100% BAU)	High (150% BAU)
Energy Development	No change	4% of total growth in the BAU Scenario	Low (50% BAU)	Medium (100% BAU)
Fire / Logging	No change	No change	No change	No change

As seen in Table 3, each scenario includes a modelled active withdrawal and return flows, as well as a total allocation for each scenario. The differences between active withdrawals and total allocation are what would be considered non-consumptive licences (e.g., water management, flood control, and some of the licences for Ducks Unlimited). Temporary Diversion Licences (TDLs) are included in each scenario to account for active withdrawals that can occur each year in addition to permanent licensed withdrawals. Volumes for TDL withdrawals in the model are based on a 10-year annual average (2003–2012) of actual TDLs issued during that period of time. All of the active withdrawals are scaled up based on growth projections from the ALCES land use modelling. Land use footprint changes simulated in ALCES correspond with active withdrawals for each scenario. Questions were raised in the final

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[6] It is recommended that an allocation volume of approximately 600,000 dam^3 be considered the initial total allocation target. When allocations reach 550,000 dam^3, a temporary closure to applications to permit a review of the aquatic environment and allocations should be undertaken. Source: Alberta Environment, 2006.

Working Group session about whether water conservation can achieve a 15% reduction even if new technology is considered. It became evident that modelling water conservation was more of a strategy and not a parameter that would be included in the basin scenarios. Cities and industry should keep doing what they can (e.g., continuous improvement), and during times of drought, cut back where possible and as appropriate (e.g., watering golf courses). Based on the feedback, a water conservation strategy was implemented in the model with 5% total water conservation in the winter (October 1–March 31), and 15% total water conservation in the summer (April 1–September 30, irrigation season).

4.4 Strategies to Build the Resilience of the Red Deer Basin

Over the course of the project, various individual water management strategies were suggested, modelled, and tested in live modelling sessions. These strategies were then layered as appropriate to build combinations of strategies, which were also modelled and tested with Working Group participants. Individual and combination strategies were used in conjunction with the basin scenarios described in Section 4.3 to examine a range of opportunities to build resilience and capacity for water management in response to growth demands and a more variable climate, while balancing growth and environmental protection.

Individual water management strategies were refined and documented based on feedback from participants, then combined as appropriate for each basin scenario. These combinations were presented at the final Working Group meeting and assessed. Feedback from that meeting resulted in the set of individual and combination strategies outlined in this section.

4.4.1 Individual Water Management Strategies

All of the individual water management strategy ideas and concepts that emerged over the course of the project are described briefly below in four categories. Some were modelled in detail, some were modelled superficially, and others were not pursued at all for various reasons. Further details for any of the modelled individual strategies are available from the RDROM itself.

Category 1: Strategy ideas related to managing demand

- Demand thresholds of 335,000 dam^3, 445,000 dam^3, and 550,000 dam^3 with WCO reductions

  Several demand levels and changes in the WCO were modelled to provide context for discussions around balancing growth and environmental interests.
- SAWSP and Acadia Valley demands

  New SAWSP and Acadia Valley demands of 85,000 dam^3 were modelled in addition to current allocations.
- Conservation of water through best management practices and increased efficiency.
- Effects of TDLs

  TDLs were modelled to account for active withdrawals that can occur each year in addition to permanent licence withdrawals. Volumes for TDL withdrawals were based on a 10-year annual average (2003–2012) of actual TDLs issued during that period.
- Distribution of shortages

  It was acknowledged that shortages will likely occur within the basin at some future point and agreements to share shortages and deal with licence prioritization will be needed. This situation was not modelled, but shortage sharing methods were discussed and participants concluded that more dialogue and consultation are needed with respect to potential shortage-sharing mechanisms.

- Back calculate possible growth (population and economic) that could occur without environmental degradation

  Back calculating the maximum possible growth while still protecting the environment was discussed but was not modelled. Growth without any environmental degradation seems unlikely; rather, economic development and environmental protection need to be in balance.
- Back calculate the maximum growth possible prior to construction of new infrastructure

  Possible growth in demand without the need for additional infrastructure was modelled along with various other adaptation approaches.

Category 2: Strategy ideas to enhance environmental flows

- Dynamically adjusting the WCO to provide water for environmental flows

  This management strategy is reflected in modification of Dickson Dam operations. The current operations of Dickson Dam are determined primarily by the upstream conditions, current and anticipated weather, and the requirement to meet daily reservoir elevation targets. The adapted operations are refocused to ensure that the modelled WCO at the mouth of the Red Deer River is met more often by making calculated estimates about how much water to release based on downstream conditions, weather forecasts, basin conditions and the requirement to meet daily reservoir elevation targets.
- Functional flows for riparian vegetation

  This management strategy focused on “ramping” the streamflow downstream of Dickson Dam following large flood events. These ramping operations were used to decrease the level of the Red Deer River by four centimetres per day following peak streamflow. This type of operation optimizes the recruitment capability for riparian cottonwoods and willows.
- High level of protection for aquatic ecosystems (e.g., 85% Natural Flow threshold)

  This idea was discussed as a potential management strategy to provide a high level of protection for aquatic and riparian ecosystems.
- Make the WCO the most senior priority

  This concept made the WCO senior to all demands to protect it in future basin scenarios.
- Flow stability and flow augmentation to benefit fish communities

  Flows were augmented from Dickson Dam during the summer period and maintained at stable levels during the fall-winter period. This strategy could be used during drought to ensure dissolved oxygen and water temperature conditions remain tolerable for aquatic organisms and to ensure survival of non-mobile organisms (e.g., incubating fish eggs).
- Wetland restoration (through effective policy implementation)

  This strategy was discussed as an important factor in future development in the basin. Future growth should aim to result in no net wetland loss.

Category 3: Strategy ideas related to infrastructure operations

- Dynamic operations of Dickson Dam to meet downstream demands and WCO

This management strategy to meet growth in various basin scenarios (i.e., increases of 335,000 dam^3, 435,000 dam^3, 525,000 dam^3, and 655,000 dam^3) was explored by modifying Dickson Dam operations. The current operations are determined primarily by the upstream conditions, forecasted weather and the requirement to refill. Daily downstream conditions are not used to dictate Dickson releases. The modified operations are refocused to ensure that the WCO and new downstream demands junior to the WCO are met more often by making daily calculated estimates about how much water to release to both meet the WCO and supply new junior licences. New downstream junior demands and projected WCO shortfalls are added together to form a "buffer" that is released from Dickson in addition to the releases otherwise dictated by its refill curve.

- Downstream storage for water supply

  On-stream and off-stream storage options downstream of Dickson Dam were examined for different levels of growth (i.e., 335,000 dam^3, 435,000 dam^3, 525,000 dam^3, and 655,000 dam^3). Multiple types and locations were discussed, including off-stream reservoirs within irrigation projects themselves, tank alternatives for municipalities, and large on-stream reservoirs. Consideration was given to operations in tandem with Dickson Dam, including the utilization of downstream sites for meeting WCO requirements and releasing additional upstream storage for water supply. Discussion also covered utilizing downstream storage to maintain water security, freeing up Dickson Dam for more aggressive flood operations. Size estimates were made based on modelling of an on-stream site, while off-stream storage was discussed but not directly modelled. Generally it was recognized that on-stream and up-stream storage was most valuable, but was limited by location issues.

- Dickson Dam release buffer for meeting demand

  The modified operations are refocused to ensure that the WCO and new downstream demands junior to the WCO are met more often by making daily calculated estimates about how much water to release to both meet the WCO and supply new junior licences. New downstream junior demands and projected WCO shortfalls are added together to form a "buffer" that is released from Dickson in addition to the releases otherwise dictated by its refill curve. This was not modelled on its own but was modelled in conjunction with operating Dickson Dam to meet downstream demand and to ensure that the WCO is not violated.

- Off-stream storage for irrigation

  Already under discussion as part of the potential SAWSP and Acadia Valley expansion, off-stream storage, on both a small and large scale, was raised as a robust way to ensure water supply as demand grows. Associated costs and benefits were also raised and partly discussed.

- Expanding Dickson Dam storage

  Increasing permanent storage in Dickson Dam, as examined in the Red Deer River Basin Flood Mitigation Study (Stantec, 2014), was discussed but not explicitly modelled.

- Modifications to Dickson Dam structure

  Modifications to Dickson Dam, including an alternate spillway, were discussed but not modelled.

Category 4: Strategy ideas for flood mitigation

- Increase local flood protection

  Increasing local flood protection through means such as berming, buyouts, and relocation of infrastructure was discussed but not modelled given the specific and local nature of potential local protection options.
- Dry dams

  Seven dry dam options[7] were modelled for flood mitigation and all were dismissed as having limited benefit for the associated costs. If flood flows happened directly above the particular dry dam site, some benefits would accrue; however, as the dry dam sites generally collected water from relatively small surface areas the probability of flood flows occurring above one of the dry dam sites is small. Multiple dry dams would likely be needed, the cost of which would likely outweigh the benefits.
- Upstream dams in places where dry dams have been proposed

  Upstream dams for flood protection and water storage were modelled but were thought to also have limited value. Based on the views of the participants it was discussed that the locations proposed for upstream dams were either suitable in terms of water collection potential but couldn't retain a substantial amount of water because they were too small, or they could retain a substantial amount of water but were not situated in an ideal location to collect the water because of a small upstream catchment area.

4.4.2 Most Promising Individual Water Management Strategies

Seven individual water management strategies were shown to have the most promise. They provide the most benefits under conditions of climate variability (particularly drought) and in meeting increased water demands due to growth while considering potential environmental impacts and land use. They are:

- Implementation of functional flows
- Dickson Dam operations to meet WCO (downstream focus)
- Dickson Dam operations to meet WCO and new demands (downstream focus)
- Additional storage
- Local flood protection
- Water conservation
- Application of land use best management practices
- Effective implementation of Alberta's Wetland Policy

Collectively, these strategies reflect a mix of approaches including changes in operations and management of river systems, potential new infrastructure, and conserving water through continued increases in efficiency and reduced use when needed (such as through the conservation, efficiency, and productivity plans developed by Alberta's major water-using sectors and available through the Alberta Water Council[8]). Not only are these strategies promising individually they also have many

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[7] Vam Creek (S1C), Olson Ridge (Fallen Timber Creek—S13B), James River (S14), Salter Creek (S5), Harmattan (S4), Little Red Deer Confluence (S6), and Ardley (S9)---all from Stantec, 2014.

[8] Available online at http://www.albertawatercouncil.ca/Projects/WaterConservationEfficiencyandProductivity/tabid/115/Default.aspx

benefits in combination (Section 4.4.3). The seven strategies are described more fully below, along with the modelling results; no priority is implied in the way the strategies are presented.

Implementation of Functional Flows

Functional flows work by creating a steadier drawdown along the river banks downstream of Dickson Dam following a high flow event. This steady drawdown enables cottonwood saplings to proliferate and provides favourable conditions for other types of riparian life. The effect of ramping flows on fisheries has not been assessed as part of this work. Future work will aim to account for fisheries affects as well. Functional flows are triggered by scouring flows during high flow events of250 m^3/s to 700 m^3/s. The high flows are followed by ramping down of flows to create a downstream river bank drawdown of 4 cm/day. When functional flows are incorporated into model runs over the historical record they are triggered eight times, only one of which (1929) creates a situation where Gleniffer Reservoir does not refill. In general, operating Dickson Dam for functional flows causes the reservoir to draw down steeply, but functional flows are triggered only in wet years so the reservoir will usually refill. In the one year that refilling did not occur, an operator would have the foresight to operate Dickson Dam in a manner that would likely mitigate many of the refill problems and would have chosen not to carry out functional flow operations. From an operational standpoint, functional flow releases are possible as long as another storm event is not being forecasted, in which case maximum drawdown would be employed. In this exercise functional flows were modelled consistently as part of every subsequent run regardless of combination with other strategies or in isolation. Functional flows could be implemented in other ways in future modelling work, including adaptive options such as multiple year ramping, optimizing for other values such as fisheries, or making use of forecasting. The functional flow option can be considered, post flood event, until the reservoirs seasonal target elevation is reached.

Figure 17 shows the outflows from Dickson Dam under actual current operations (blue) and when functional flows are implemented (red); the ramping down of streamflow, which benefits riparian health, is clearly demonstrated.

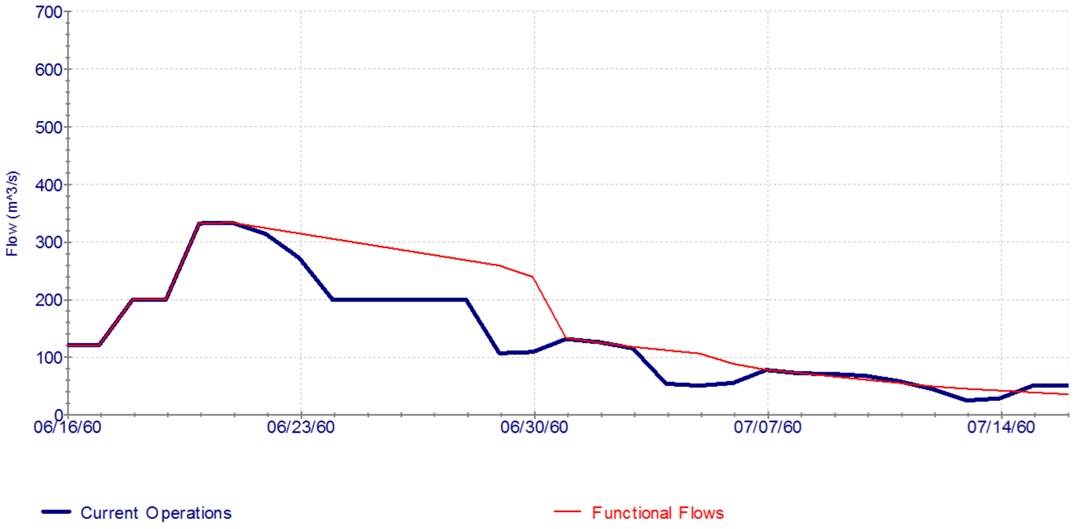

Figure 17: Dickson Dam outflows with and without functional flows, 2060

Dickson Dam Operations to Meet WCO (Downstream Focus)

The current operations of Dickson Dam are determined primarily by upstream conditions, meeting reservoir target elevations and ensuring the reservoir fills by late fall. While WCO violations are already few (Figure 19), they can be further decreased by modifying Dickson Dam operations to make calculated estimates based on downstream conditions for how much water to release to ensure the WCO is met. At present, a buffer volume is released based on upstream conditions, while proposed new Dickson Dam operations would calculate the buffer based on downstream conditions. If the reservoir falls below the lowest permissible level, the buffer reverts to the minimum 16 m^3/s release. The WCO is modelled as a calculated flow (roughly 45% of natural flow, dashed green line in Figure 18), with a hard minimum of 10 m^3/s in the summer, and a hard minimum of 16 m^3/s in the winter.

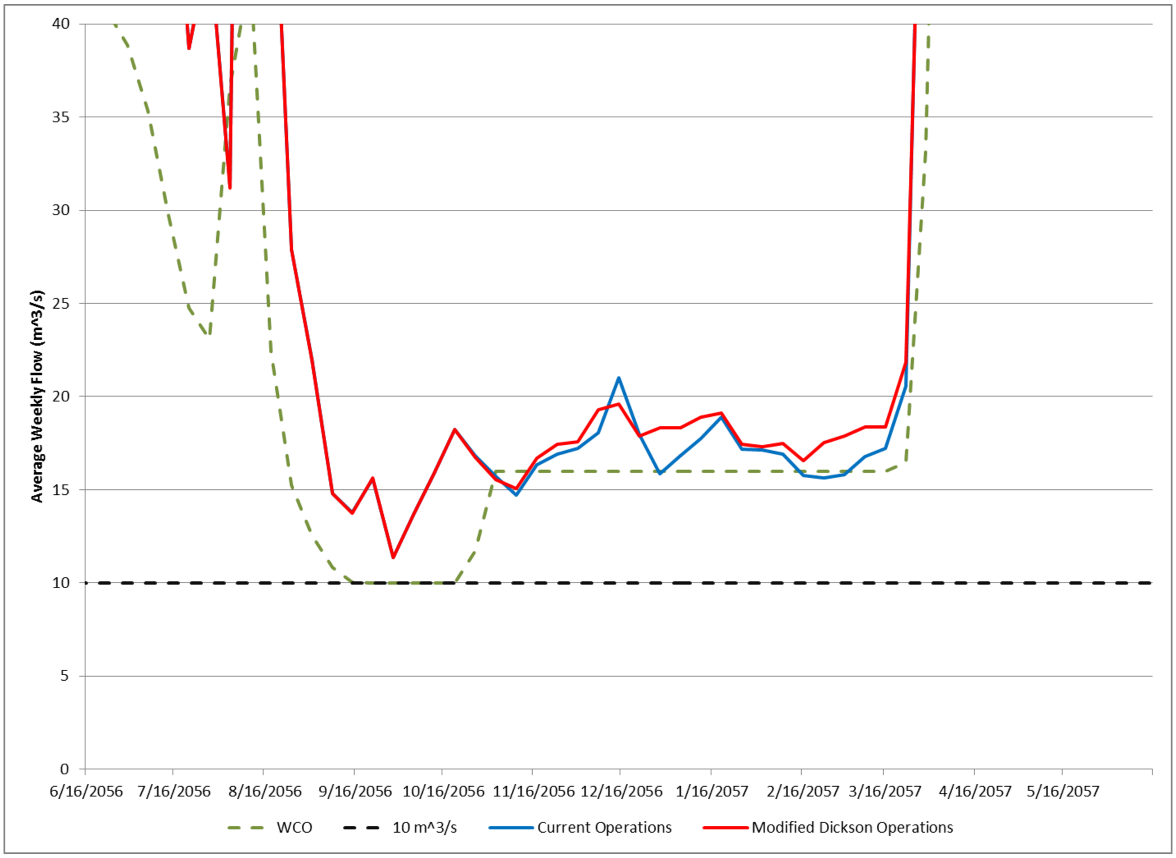

Figure 18: Comparison of WCO violations under current and modified Dickson Dam operations, 2056–2057

Figure 18 shows that four WCO violations occur in the model under current Dickson Dam operations (blue) versus two violations with modified operations (red). The blue curve and the red curve are identical for the first part of the graph and the red line overlays the blue one. The dam could be operated in this way now to ensure that the WCO is met more frequently, but because many licences are senior to the WCO, it is important to remember that the WCO could still be violated even with modified operations.

Figure 19 shows the elevation of Gleniffer Reservoir over the same time period as Figure 18 under current Dickson Dam operations (blue) and modified operations (red). Although the modified operations draw the reservoir down more to meet the WCO, the reservoir still refills at the end of the year.

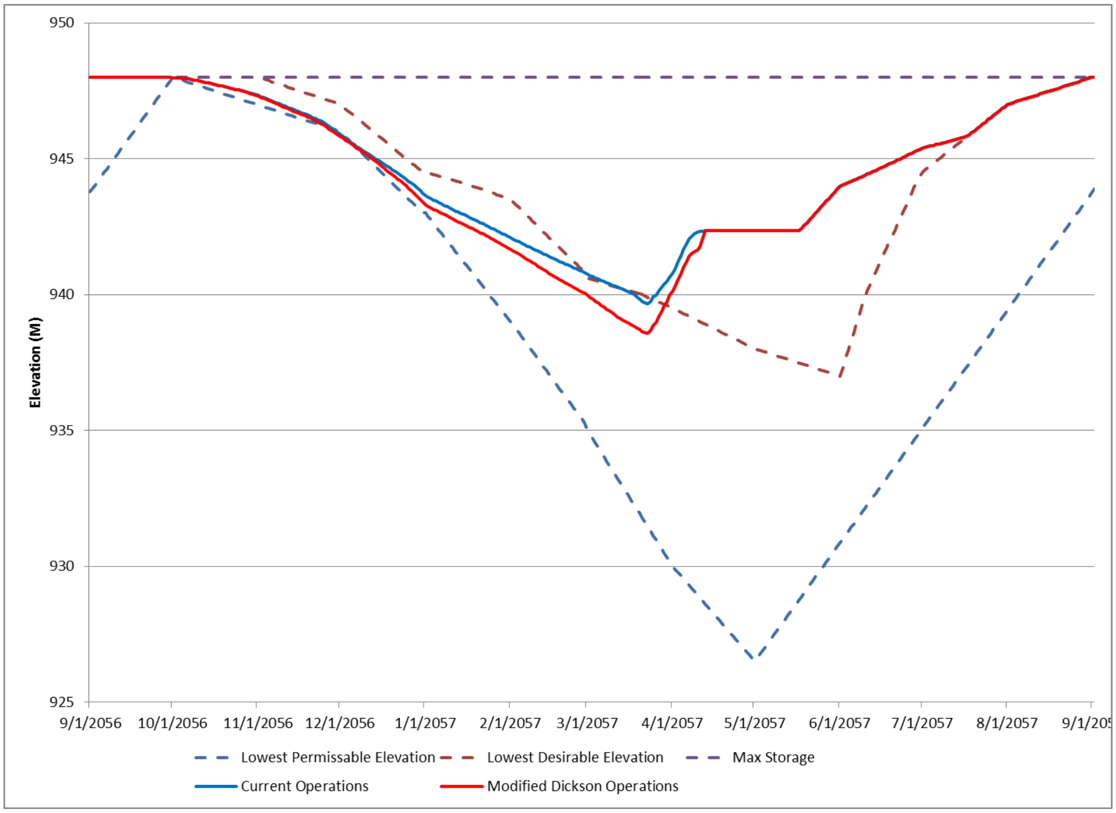

Figure 19: Gleniffer Reservoir elevation for current Dickson Dam operations and modified Dickson Dam operations, 2056–2057

Dickson Dam Operations to Meet WCO and New Demands (Downstream Focus)

This management strategy is similar to Dickson Dam operations to meet the WCO. Dickson Dam operations would be further modified to ensure that the WCO and new downstream demands are met. With the new operations the WCO is still met before junior licences can withdraw water, but releases are intended to minimize shortages to junior licences. As all demands are being met currently, Dickson Dam operations to meet the WCO and meet new demands would apply only to scenarios with increased demand.

Figure 20 shows the annual shortages seen in the Red Deer system in Basin Scenario 2 (medium-growth, Table 3) with current and modified Dickson Dam operations. Modifying the Dickson Dam operations almost eliminates the shortages in the system.

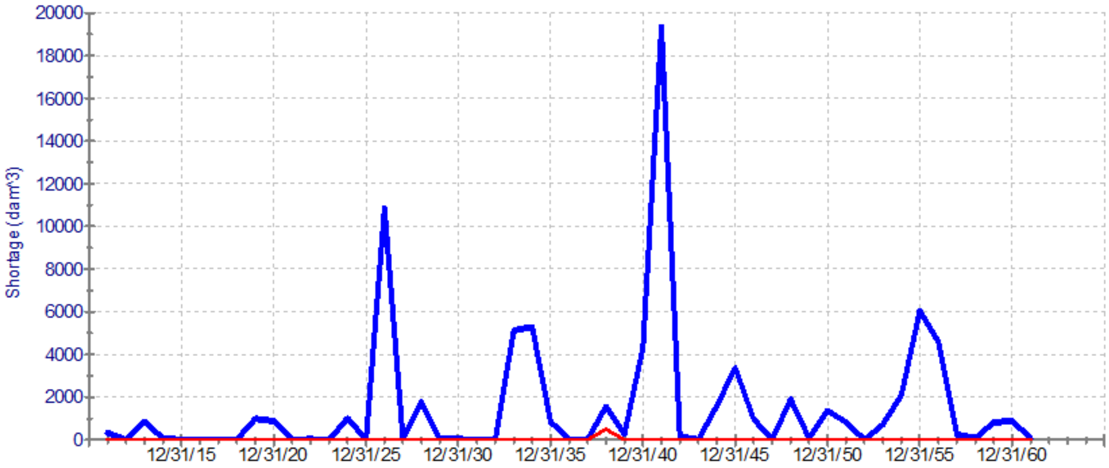

Figure 20: Annual shortages in Scenario 2 with current and modified Dickson Dam operations, 2015–2060

Figure 21 shows Gleniffer Reservoir elevation for 2057, a dry year in the model, with both current and modified Dickson Dam operations. Although the reservoir has a larger drawdown to meet new demands, even with modified operations the reservoir still refills at the end of the year.

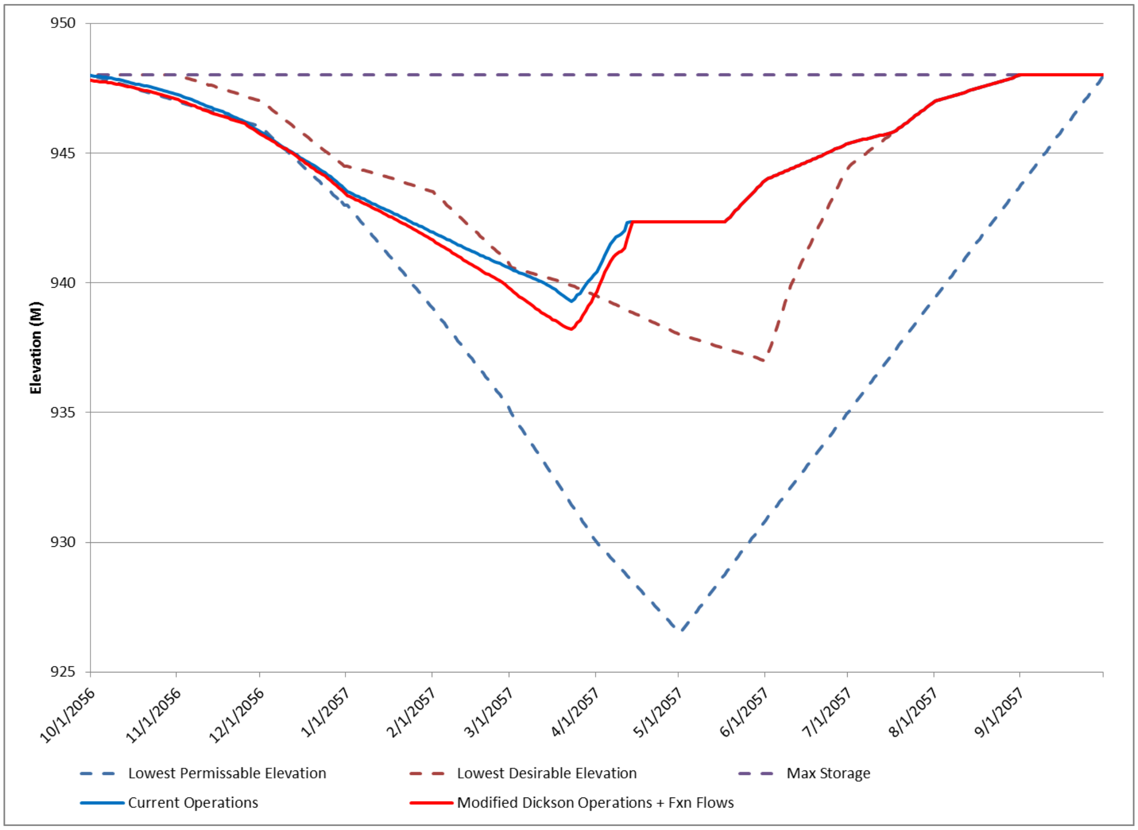

Figure 21: Gleniffer Reservoir elevations for Scenario 2 with current and modified Dickson Dam operations, 2056–2057

Additional Storage

Additional storage, either on-stream or off-stream, is examined as a combined strategy to adapt to increased water demands due to growth in the system. Additional storage is a promising strategy on its own; however, it was felt that additional storage would likely only be considered once growth outstripped the ability for current storage and infrastructure to meet demands and all possible conservation efforts had been applied. Therefore, additional storage was only assessed in combination with operational changes and conservation.

Additional storage was examined mainly in the mid-stream portion of the system, just downstream of Red Deer. An example often used for mid-stream storage is Ardley Reservoir, storage proposed downstream of the city of Red Deer, but upstream of the Buffalo Lake diversion. The Ardley Reservoir was modelled with a maximum storage of 700,000 dam^3 (based on Alberta Environment, 2008), with 300,000 dam^3 reserved as empty storage for flood mitigation. The impacts of such storage will be shown in Section 4.3.3.

Local Flood Protection

Several flood mitigation structures were modelled over the course of the project. Pre-releases from Dickson Dam could make more space available in advance of a flood when storage downstream is available to maintain the WCO in case Gleniffer Reservoir has difficulty refilling later in the season. The Working Group also discussed various aspects of natural system functions, such as wetlands, and how they can play a role in moderating peak streamflow by capturing water on the landscape. Dry dams have ecological impacts because they store large flows that typically move material, affect fish corridors, deposit material above the structure, affect vegetation, and create issues with debris management. Working Group discussion indicated that there are limited benefits of the upstream dry dams and it might be cheaper to do local mitigation, such as put in a long-span bridge or create a berm that is designed to fail and give room back to the river. Local mitigation measures (berms, etc.) appear to provide the "biggest bang for the buck," which suggests a high priority should be enhancing dykes in Drumheller. Several local mitigation measures were presented for several municipalities and counties in the Red Deer River Basin, and can be found in a recent flood mitigation report (Stantec, 2014).

Water Conservation

A water conservation strategy was implemented in the model with 5% total water conservation in the winter (October 1–March 31), and 15% total water conservation in the summer (April 1–September 30, which is irrigation season). Conservation by sector (i.e., Municipal vs. Industrial vs. Agricultural) was considered, leading to the 5% winter vs. 15% summer conservation was used as slight gains may be had in the irrigation sector, and municipalities and some industrial would be able to reduce some consumption if needed (e.g., lawn, garden, and golf course watering). The 5% winter reduction represents possible efficiencies gained in municipal and industrial use. The actual conservation percentages were applied basin-wide, recognizing that winter conservation will not apply to agricultural demands (since there is no winter agricultural demand) while the 15% summer target would, in reality, not be applied uniformly across sectors. That said, for the project's modelling efforts and basin-wide analysis, this abstraction was considered reasonable.

Figure 22 illustrates the decrease in shortages seen when conservation measures are implemented in Basin Scenario 2 (Table 3). Conservation represents a total decrease in water use in the system; it can decrease the shortages but does not eliminate them as an individual water management strategy.

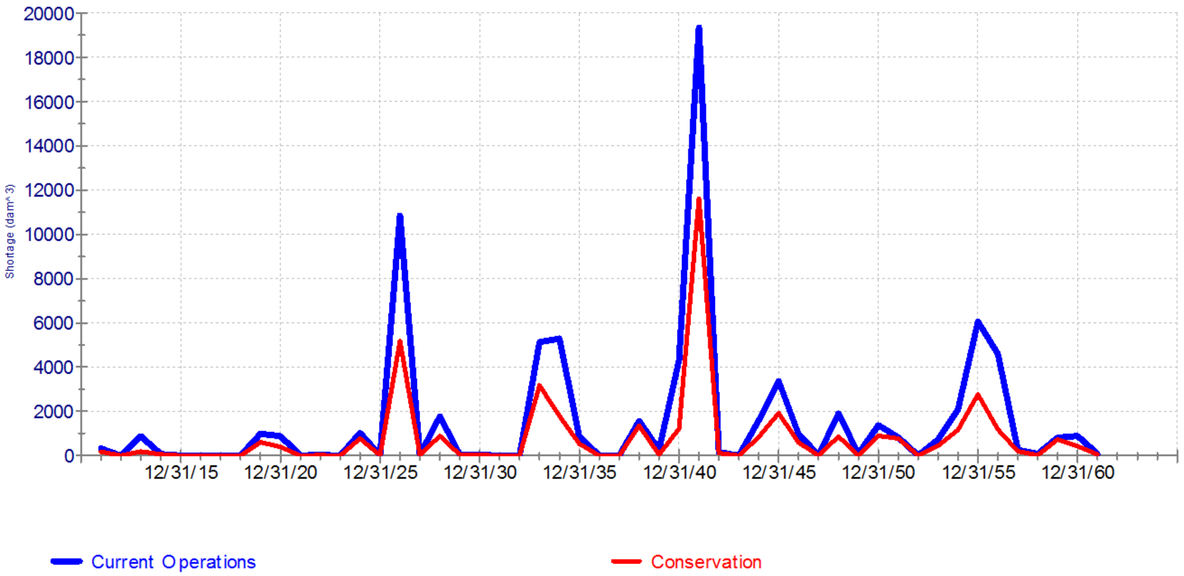

Figure 22: Annual shortages in Scenario 2 with and without conservation, 2015–2060

Application of land use best management practices

The modelling work conducted here did not focus on implementing best management practices (BMPs), rather it looked at impacts of higher or lower rates of development. However, multiple BMPs can be applied to help minimize impacts of land use change on water resources. Below is information based on literature reviews of BMPs that can inform some modelling assumptions in ALCES.

Two management practices in the municipal sector that can be improved are intensification of urban and rural residential footprints, and water conservation. A common standard for management of urban and rural residential footprint is the maintenance of current population density. This management practice could be improved by decreasing the footprint expansion required by population growth by 25%, a goal of the City of Edmonton. Optimistically, this percentage could go as far as 50%, which is Calgary's goal. Similarly, maintaining current per capita water use would be the basic practice for water conservation. This could be improved by reducing per capita water use by 25%, or optimistically, 50%. For example, Calgary's Metropolitan Plan has set a goal of reducing per capita water use by 30% in the Calgary metro region (ALCES Group, 2014). It is important when setting these goals to consider what proportion of the municipal licence is used for basic domestic water use versus water use for industrial activities within the city. Depending on the breakdown, a 30% reduction in domestic water use may or may not have an impact on overall municipal water use.

The natural resource extraction sector has land use management practices for reclaiming semi-permanent energy sector infrastructure, accelerated reclamation of transitory footprint, efficient footprint layout, and water conservation. Presently it is expected that semi-permanent energy sector infrastructure would remain over a 50-year period. There are several ways in which this could be managed differently. Reclamation of a well site 20 years after production would be a better land use management practice, while immediate reclamation would be the best management practice. Reclamation of the transitory footprint could be accelerated as a best management practice. A standard cutline has a life of 60 years. If the cutline only had a life of 40 years that would be an improved land use management practice, while a cutline life of 20 years would be the best management practice (ALCES Group, 2014).

Energy sector footprints have been shown through this project to affect water yield and could become more efficient if planned appropriately. It is good practice to include 10 wells for every in situ well pad through directional drilling. An improvement would be installing 15 wells for each in situ well pad, or as many as 20 wells.

The historical rates of road growth to access new resource developments could be reduced to give land use footprints a more efficient layout. Coordinated planning can achieve a 25% reduction in road required to access new wells and cutblocks. For example, in block roads can have a life of 40 years in regions with steep slopes, and a life of only 25 years in regions with moderate or flat slopes. In each region the lifespan could be reduced by 25%, regardless of steepness of slope. This lifespan could be further reduced by as much as 50%, or completely removed (ALCES Group, 2014). A study in northeastern Alberta concluded that road access could be reduced by 34% when energy and forestry companies coordinated their road planning (Schneider and Dyer, 2006).

Effective implementation of Alberta's Wetland Policy

The modelling work conducted here did not focus on the potential effects of Alberta's wetland policy implementation; rather it looked at impacts of higher or lower rates of development, as well as rates of wetland restoration. Effective implementation of Alberta's wetland policy will involve various measures, designed to protect existing wetlands in the face of new development, and facilitate wetland restoration in areas where they have been lost and their benefits can provide the most value.

4.4.3 Combination Water Management Strategies

It was expected that potential adaptation strategies would be implemented in combination, reflecting the needs of the basin and the intended degree of risk management. The project modelled combinations under four different basin scenarios to demonstrate how adaptation strategies might be layered to produce cumulative and offsetting impacts for each scenario shown in Table 4. These four basin scenarios are the same as those first presented and described in Table 3 (Section 4.3). Many of the strategies used in the combinations were also modelled individually as described in Section 4.4.2.

Table 4: Basin Scenarios and Combination Water Management Strategies

	Scenario 1 Current Conditions	Scenario 2 Medium Growth	Scenario 3 High Growth	Scenario 4 Extremely High Growth
Active Withdrawal	250,000 dam^3	350,000 dam^3	440,000 dam^3	575,000 dam^3

Total Allocation	335,000 dam^3	435,000 dam^3	525,000 dam^3	655,000 dam^3
Combination Water Management Strategies	Current base + WCO met through Dickson operations + Functional flows	Current base + Conservation + Functional flows + Dickson operations to meet WCO and meet new demands AND/OR + Wetland Policy implementation + Execution of licence priorities and shortage sharing in extreme events	Current base + Conservation + Functional flows + Dickson operations to meet WCO and new demands + Additional storage (needed); e.g., Ardley (small) AND/OR + Wetland Policy implementation + Execution of licence priorities and shortage sharing in extreme events	Current base + Conservation + Functional flows + Dickson operations to meet WCO and new demands + Additional storage (needed); e.g., Ardley (large) AND/OR + Wetland Policy implementation + Execution of licence priorities and shortage sharing in extreme events

Water management strategies were combined in ways that would allow various levels of future economic growth in the basin. All of the basin scenarios draw on the land use modelling and the ALCES inflow simulations. Climate variability was not considered in the basin scenarios because the simulated inflows do not stress the system compared to the historic record. All modelled combination strategies are briefly described below, along with the modelling results, impacts, and associated observations. The most pertinent PMs are illustrated for each strategy.

In scenarios 2 to 4, to reflect reality, growth occurs incrementally over the modelled time frame. This is important to note when reviewing shortages in the scenarios—shortages seen near the end of the time frame are representative of the shortages seen at the total allocated demand for each scenario. Table 5 summarizes the WCO and allocation violations (i.e., times when the WCO is not met). As growth increases, shortages and WCO violations increase under current infrastructure. The bottom row shows the additional storage that would be needed to eliminate shortages and WCO violations as well as retain reasonable storage in Gleniffer Reservoir.

Also in scenarios 2 to 4, wetland restoration through effective policy implementation was discussed as an additional management strategy in the live modelling sessions. Overall the group recognized that wetlands do play an important role in helping to regulate the quantity and quality of streamflow, and was an important factor in future development in the basin and should aim to result in no net wetland loss. The concept of sharing shortages between water users was also discussed for these scenarios as it is an important part in basin resilience. An effective approach would be to have a common understanding about how it would take place and who would need to be involved in such discussions, based on licences modelled in the system.

Table 5: Summary of modelled percentage of time where the WCO and active withdrawals in the basin scenarios are not met, as well as additional storage required to eliminate shortages while operating Dickson Dam within preferred operating conditions

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	
Problem	% time WCO not met	5.0%	6.2%	9.3%	11.0%	Current Infrastructure
	% time active withdrawals not met (Shortages)	5.3%	6.62%	12.1%	15.7%	
Solution Through Storage	Storage (dam^3)	0	0	58,000 dam^3	72,500 dam^3	Additional Storage

Basin Scenario 1

Scenario 1 represents current conditions in the Red Deer system with respect to demand and infrastructure, as noted in Table 4. Under current conditions four small violations to the WCO occur in the modelled years 2056–2057, which is a dry year (Figure 23).

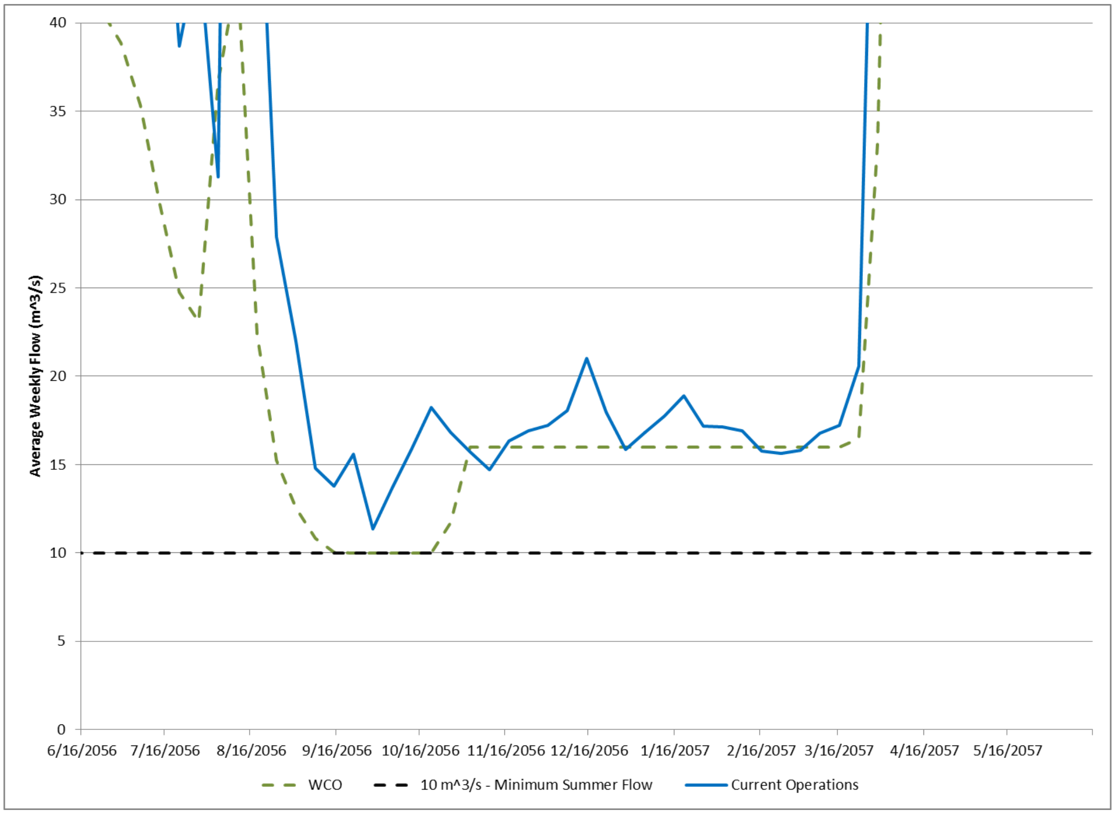

Figure 23: Violations to the WCO in Scenario 1, 2056–2057

Modifying Dickson Dam operations to meet the WCO, as described under “most promising individual water management strategies,” decreases the number of WCO violations from four to two (Figure 24). Although operations have changed, many licences are senior to the WCO so the WCO can still be violated.

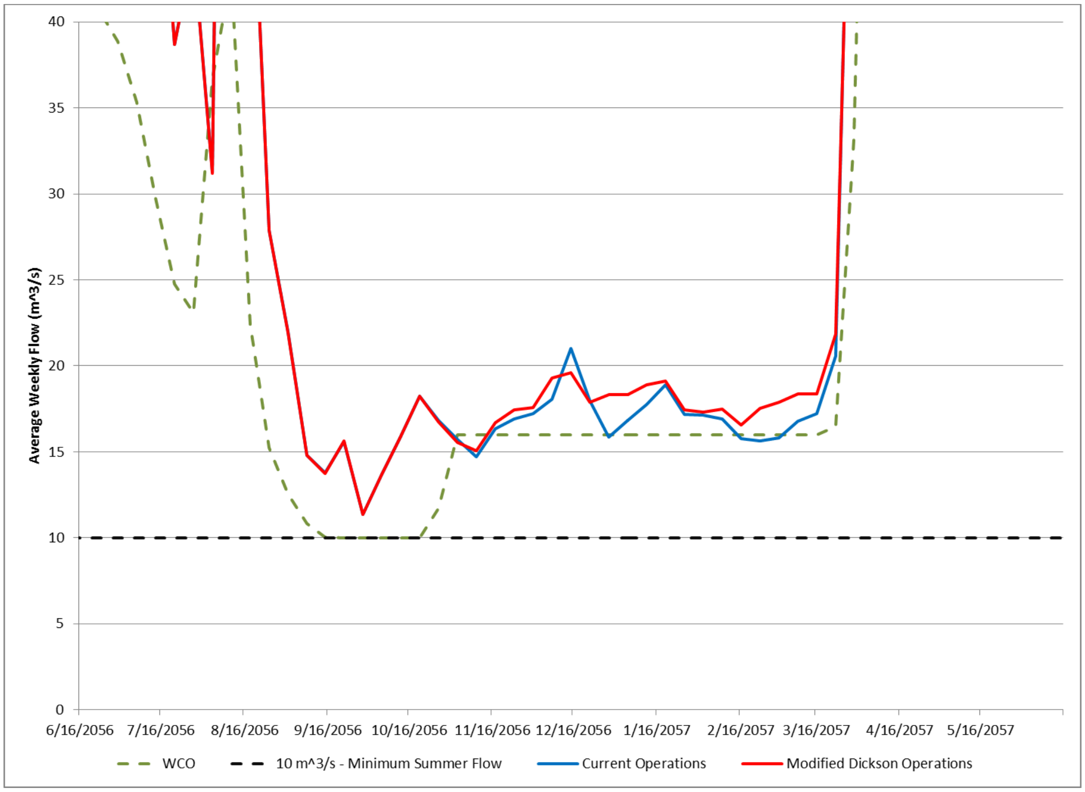

Figure 24: Violations to the WCO in Scenario 1 with modified Dickson Dam operations, 2056–2057

These changes in the operation of Dickson Dam come at a slight cost to the reservoir level during drought years as more water is released to meet the downstream WCO. The modified operations that were modelled have a greater degree of precision and efficiency than historical operations because the model perfect knowledge (i.e. it knows exactly what inflows and demands will be with no uncertainty); it can calculate downstream demands at any given time and release only the amount of water that is needed. The logic behind the modified operations could be applied in real-life operations with similar outcomes. It should also be noted that daily operational decisions also factor in many intangibles that cannot be incorporated into a model such as current and forecasted weather, antecedent basin conditions, and operator experience.

Functional flows were described in Section 4.4.2 as a promising water management strategy. When functional flows are layered onto modified Dickson Dam operations in Scenario 1 they are triggered four times, in the years 2016, 2038, 2052, and 2060. Figure 25 shows the flow rate out of Dickson Dam in 2038; after the flow hits its peak of approximately 340 m^3/s, the flow is slowly reduced as a consequence of the ramping functional flow operations, if the weather forecast permits.

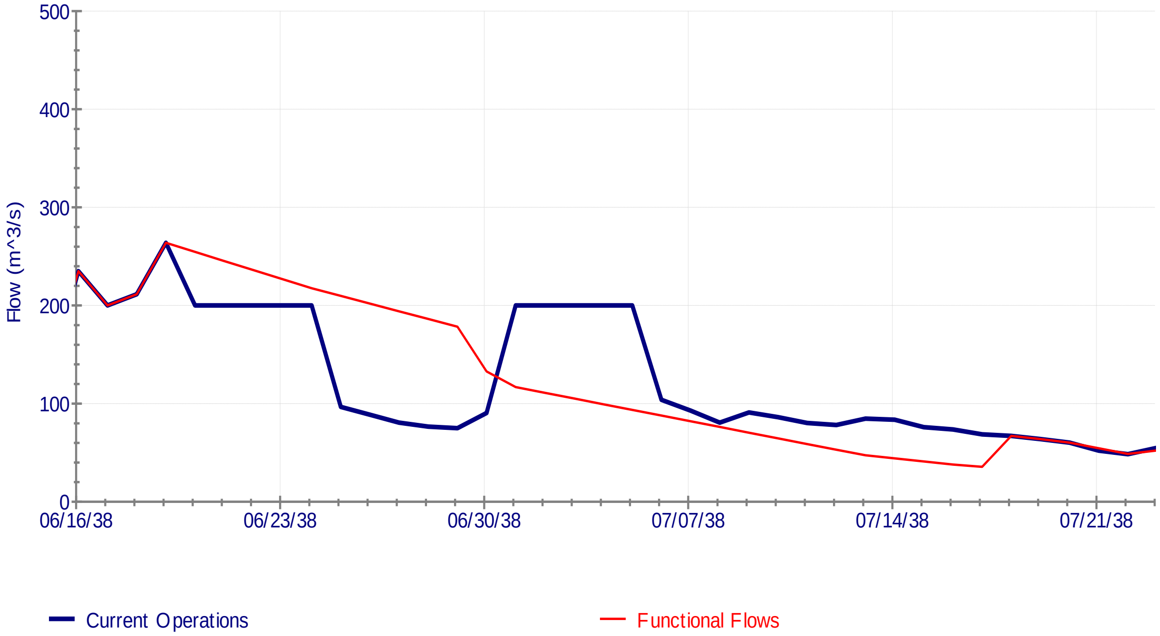

Figure 25: Dickson Dam outflow for Scenario 1 with modified Dickson Dam operations and functional flows, 2038

Operating Dickson Dam for functional flows does come at a price to reservoir storage, as it increases the risk of not being able to refill to meet the WCO throughout the winter. Operations must consider more than just flows when considering ramping of flows (e.g., reservoir target elevations. Operators can ramp flows, if conditions warrant, however, they will only drawdown to the seasonal target elevation then match inflows. Figure 26 shows the elevation of Gleniffer Reservoir in 2038 when functional flows are triggered. A greater volume of water is needed from the reservoir to maintain functional flows (green line) because the flows start high and are slowly ramped down, causing the reservoir to draw down steeply to below the lowest desirable elevation (red dotted line). Because functional flows are generally only triggered in high flow years the reservoir refills every year that functional flows are triggered, but this increases the risk of the reservoir not refilling as it is possible to have drought like conditions after a high flow event. This risk would need to be carefully managed by the experienced operators.

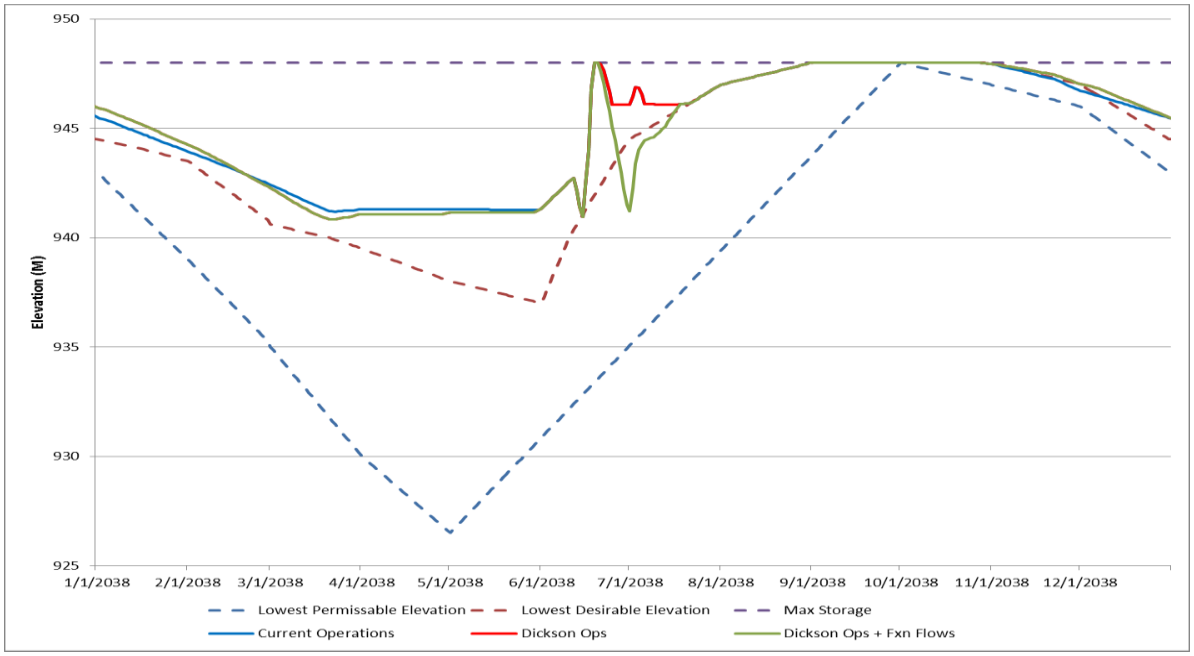

Figure 26: Gleniffer Reservoir elevation for Scenario 1 with modified Dickson Dam operations and functional flows, 2038

Functional flows are thought to be beneficial to the environment and not detrimental to water supply security as seen by the fact that Gleniffer Reservoir always refills. As such, functional flows are included in all subsequent runs and scenarios.

Basin Scenario 2

In Basin Scenario 2 (medium growth in Table 4) there are many years with substantial shortages to new licences under current Dickson Dam operations. New licences are junior to the WCO so the WCO must be met prior to new licences getting water. Modifying Dickson Dam operations to meet both the WCO and new demands is described in Section 4.4.2 as a promising strategy. Figure 27 compares the shortages that occur in Scenario 2 with current operations and with modified Dickson Dam operations. These results suggest that changes to Dickson Dam operations can help supply the needs of new users in the system and can effectively eliminate almost all shortages (red line vs. blue line) at this level of growth. Small shortages remain in the year 2038. This scenario also contains functional flows from Dickson Dam.

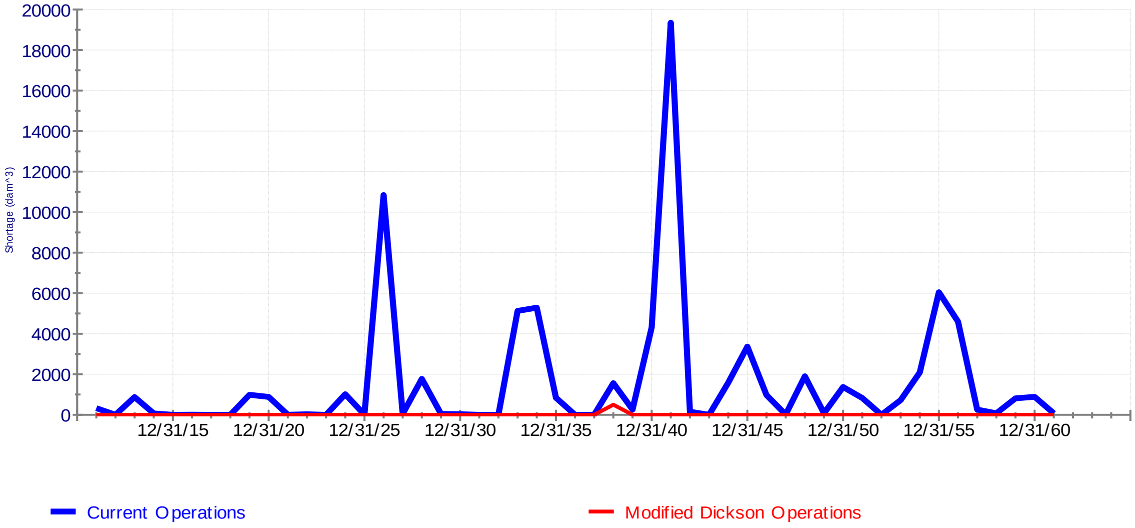

Figure 27: Shortages in Scenario 2 with current Dickson Dam operations (blue) and with modified Dickson Dam operations (red), 2015–2060

Operating Dickson Dam in this manner has some costs to reservoir storage (Figure 28) as elevation falls approximately one metre lower than with current operations. Although Gleniffer Reservoir does refill every year, this change in operations increases the risk of the reservoir not being able to refill as the level is sometimes below the lowest desirable elevation in dry years. Modified Dickson Dam operations (red line) result in greater drops in reservoir storage because of meeting new downstream demands. Figure 28 shows a dry year, so functional flow releases would not be made in that year. This is because functional flows are applied as a rule over a full model run, and are only triggered in the run when it is a wet year, but they still remain as part of the combination. This could represent substantial risk related to multiple dry years and the re-filling of the reservoir.

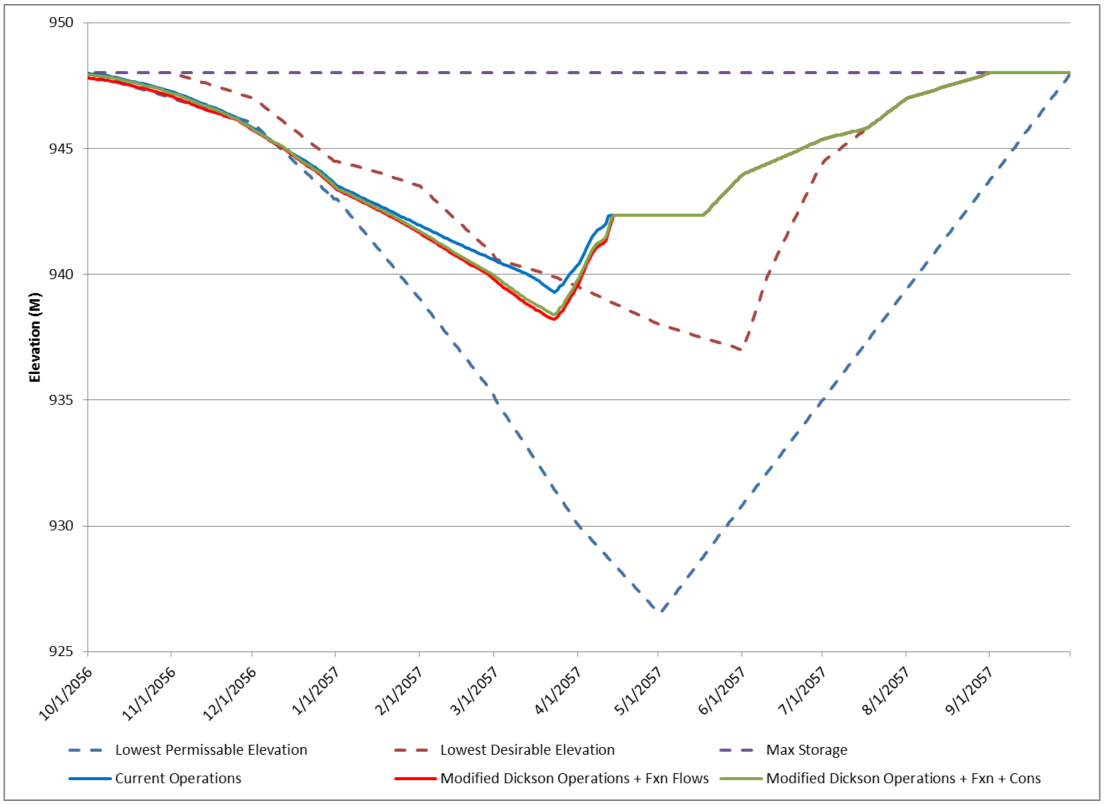

Figure 28: Gleniffer Reservoir elevation for Scenario 2 with modified Dickson Dam operations and functional flows, 2056-2057

Conservation was discussed as another management strategy in the live modelling sessions. In Scenario 2, modified Dickson Dam operations are responsible for the reduction in shortages relative to current operations. To accomplish this, Gleniffer storage falls further than it otherwise would under current operations. Applying conservation on top of modified dam operations can reduce the additional drawdown, but only very slightly (about 0.2 m).

It appears that the medium level of growth, as set out in Scenario 2, can be handled by the current system without the need for any additional infrastructure.

Basin Scenario 3

With growth and added demand as set out in Basin Scenario 3 (high growth, Table 4) there are far more shortages to new licences junior to the WCO than in Scenario 2. Under current operations, the peak shortage in Scenario 3 is 45,000 dam^3 as compared with 19,000 dam^3 in Scenario 2.

The shortages seen in Scenario 3 can be reduced by modifying the operations of Dickson Dam, as was done in Scenario 2. By modifying the operations, shortages can be reduced to almost nothing. Shortages seen in Scenario 3 with current and modified Dickson Dam operations are shown in Figure 29.

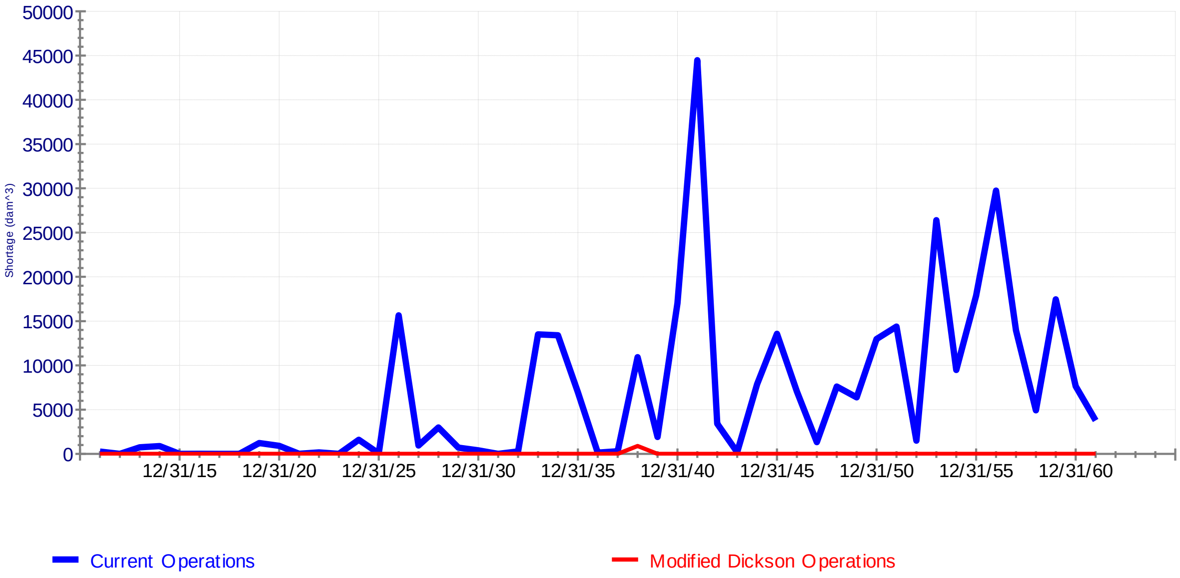

Figure 29: Annual shortages in Scenario 3 with current Dickson Dam operations and with modified Dickson Dam operations, 2015–2060

Due to the larger demand in Scenario 3, the reduction in shortages from modifying Dickson Dam operations comes at a high cost with respect to reservoir elevation. The extra water that is released from the dam to meet new downstream demands would draw the reservoir down to below the lowest permissible elevation, jeopardizing water security and reliability of supply. Figure 30 shows the elevation of Gleniffer Reservoir with current and modified operations.

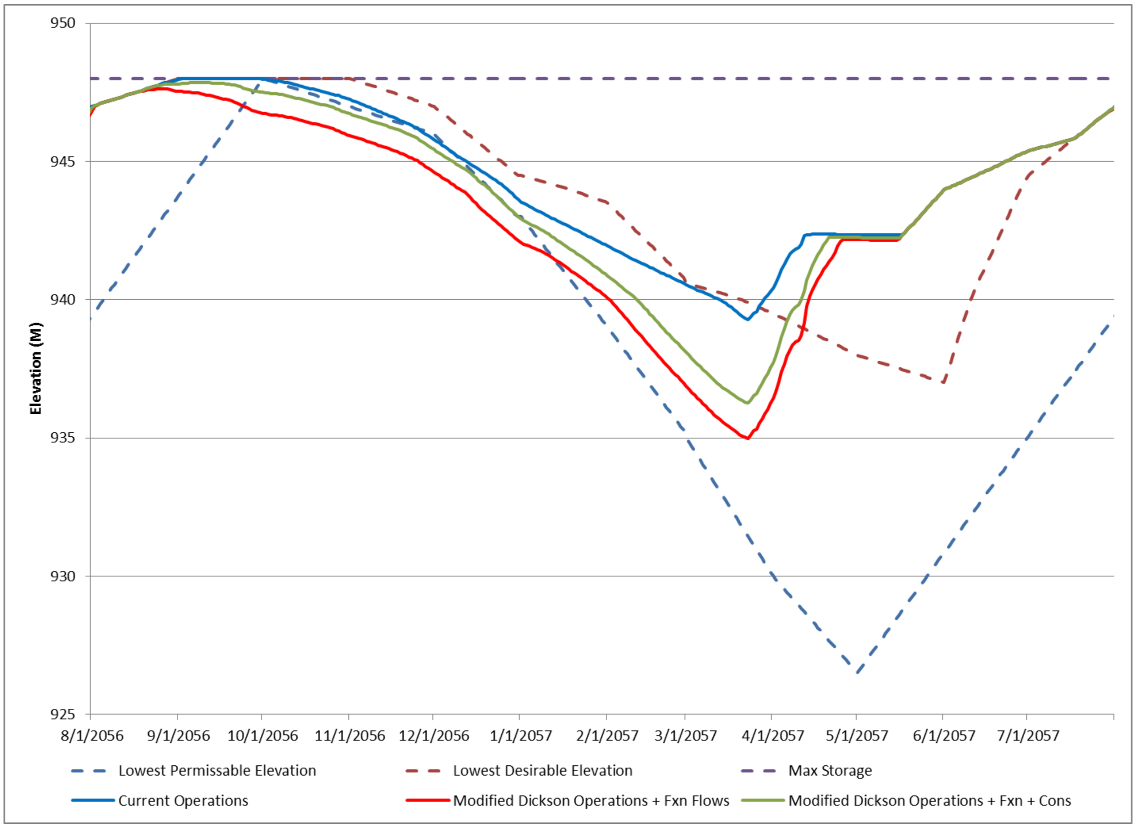

Figure 30: Gleniffer Reservoir elevations under Scenario 3, 2056–2057

Modified Dickson Dam operations (red line) result in greater drops in reservoir storage because of meeting new downstream demands. Water conservation measures of 5% in the winter and 15% in the summer, in addition to modified Dickson Dam operations (green line), ameliorate some of the extensive reservoir drawdown that occurs in the absence of conservation. Conservation allows for an additional 1-1.5 metres of reservoir elevation. However, conservation is not enough to completely remedy the situation as the reservoir elevation still falls below the lowest permissible level. Figure 30 illustrates elevations for 2056–2057, which is a particularly dry period; in other years there is typically enough water in the system to meet the demands. Because this is a dry year, functional flow releases would not be made, so the difference between the red and green lines is due strictly to conservation.

In the live modelling sessions there was discussion about adding storage (on-stream or off-stream) to the system. Additional storage was modelled in Scenario 3 and it was found that approximately 58,000 dam^3 of extra storage would be needed in the driest future year to relieve the burden on Dickson Dam (i.e., restore Gleniffer storage to its refill curves) and to meet the growth associated with Scenario 3.

Basin Scenario 4

Extremely high growth in Basin Scenario 4 (see Table 4) leads to increases in volume and frequency of annual shortages of up to 70,000 dam^3.

As with the other basin scenarios, modifying the operations of Dickson Dam can ameliorate the shortages to a certain extent, although it cannot completely eliminate them. In Scenario 4, due to extremely high demands, when Dickson Dam operations are modified to make releases to reduce downstream shortages the costs to reservoir storage are high as the risk to reservoir refill are substantially increased. In dry years, as seen in Figure 31, the reservoir often falls below the lowest desirable elevation.

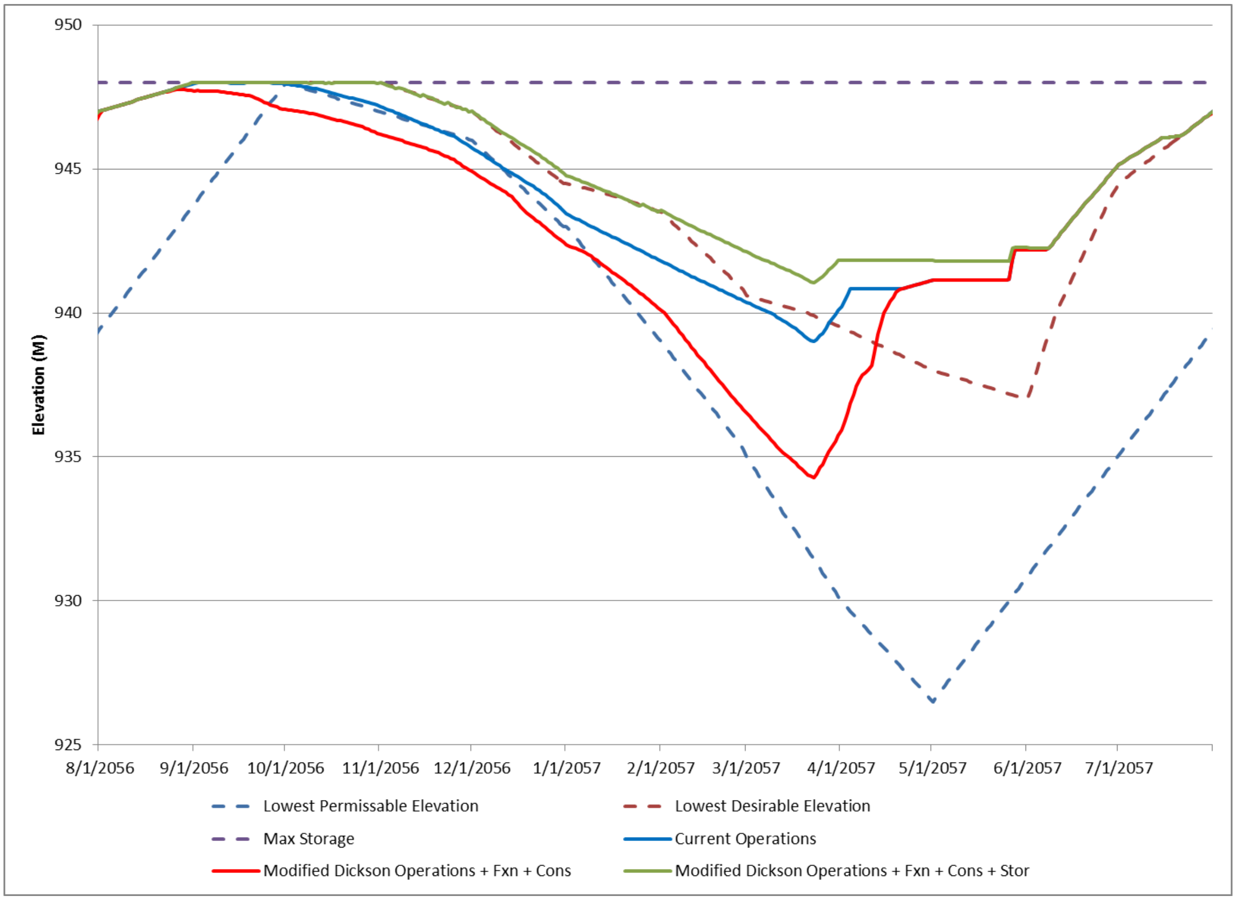

Figure 31: Gleniffer Reservoir elevation in Scenario 4, 2056–2057

Modifying Dickson operations (red line) results in greater drops in reservoir storage because of meeting new downstream demands. Figure 31 shows a dry year, so functional flow releases would not be made. As previously discussed, adding storage to the system (e.g., 72,500 dam^3, green line in Figure 31) can reduce the stress on Dickson Dam and increase water security for junior licence holders. In Figure 32, the storage needed to reduce the stress on the system and effectively manage water in a dry year such as 2056 for both Scenarios 3 and 4 is the difference between the dashed line and the drawdowns shown in blue (Scenario 3) or red (Scenario 4)in Figure 32.

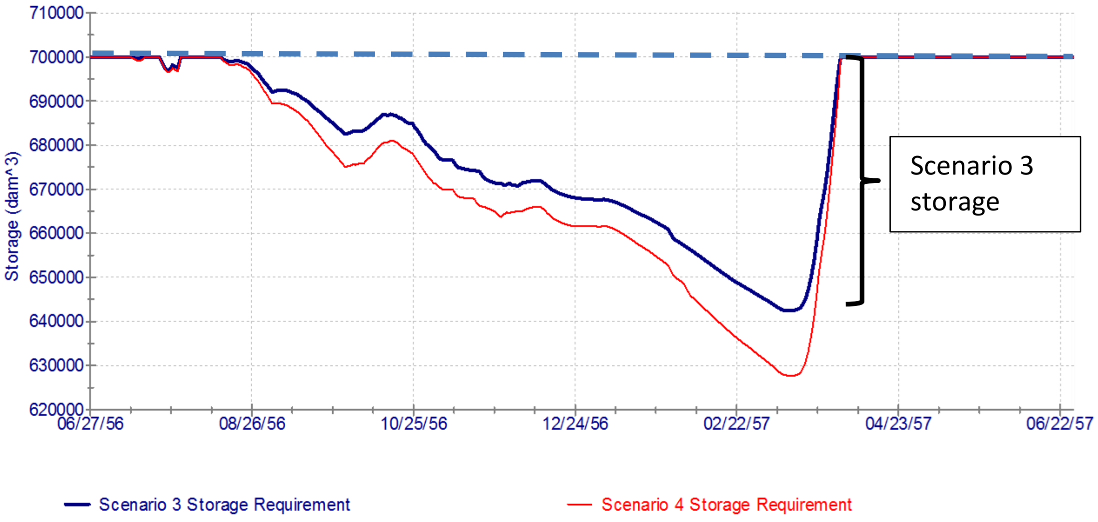

Figure 32: Storage needed to support modelled growth in Scenarios 3 and 4, 2056–2057

Stress Test

There have been multi-year historical droughts worse than those seen in the ALCES model runs or in the climate variability model runs. The basin scenarios imply that modifications to the operation of the Dickson Dam could meet high demand conditions, sometimes in a way that presents risks to water security. Testing the operations against the more severe droughts seen in the historical record shows that modifying Dickson Dam operations may not be the preferred strategy to cope with severe droughts.

In the basin scenarios (Table 4) the minimum annual inflow to the system is on the order of 1,250,000 dam^3; this inflow occurs twice in the 50-year projected record. In contrast, the historical record is either at or below this flow rate for 15 years out of the full 81-year historical timeframe. The historical minimum inflow is around 905,000 dam^3, which is 345,000 dam^3 less than any of the modelled future scenarios.

Figure 33 shows more aggressive water use (from Scenario 3) and modified Dickson Dam operations under a severe drought, as seen in the historical record (2001–2002). These conditions can cause Gleniffer Reservoir to drain completely (red line).

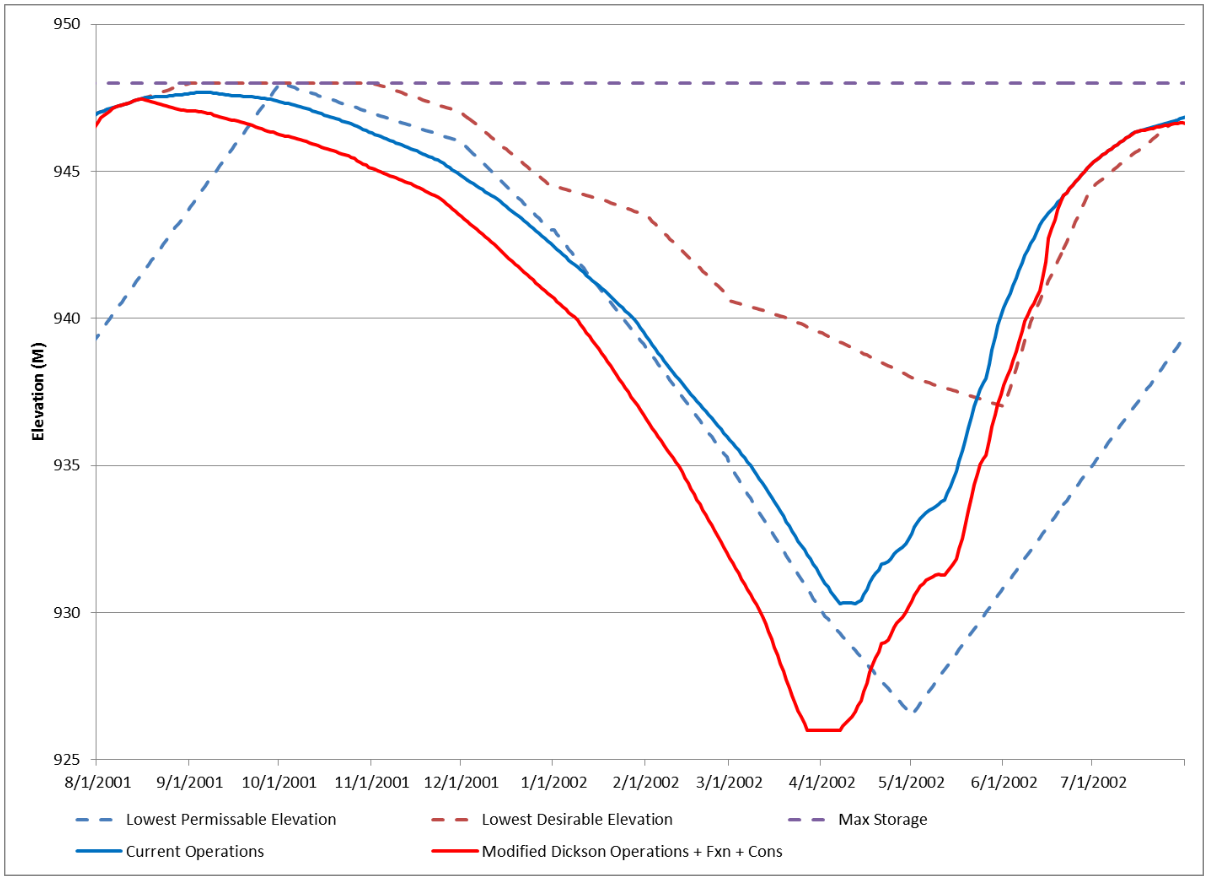

Figure 33: Gleniffer Reservoir elevation in a historic drought with 440,000 dam^3 demand, 2001–2002

When the historical record is modelled with increased demand from Scenario 3 and modified Dickson Dam operations, Gleniffer Reservoir drains completely six times over the 81 year record (in 1930, 1935, 1937, 1950, 1985, and 2001-2002). Figure 33 illustrates that currently available storage in the reservoir can provide some of the water needed to ameliorate extreme droughts, but there is not enough current storage to provide water through a severe drought under a higher growth scenario. To deal with increased water demand due to growth and the potential for extreme or extended droughts, it is necessary to add storage to the system. Even with increased storage there will be times when there is not enough water and shortage sharing will be necessary. Shortage sharing was discussed in the live modelling sessions, and it was noted that a formal shortage sharing arrangement could be negotiated and actual shortage implementation practices better understood.

5. Next Steps

In addition to building a comprehensive mass balance model of the Red Deer River system and applying it to 81 years of historic data with current and projected demands, this project developed climate variability and land use scenarios, and explored options for meeting future water demands in response to economic growth in the region. Equally important is the collaborative process and group of knowledgeable water stakeholders that have been actively involved and are keen to engage in future collaborative work to support sustainable and proactive management of their water resources for the Red Deer River Basin.

This basin differs from the others in the SSRB for which modelling has been done (the Bow and the Oldman-South Saskatchewan) in several important ways. Thus, any decisions on next steps for water management in the Red Deer system need to consider the specific context of this region:

- The Red Deer Basin is not closed to new allocations and thus has a range of growth opportunities.
- Like other basins, the landscape and the broader environment in the Red Deer region are valued for the cultural, aesthetic, and recreational benefits they provide, and there is a strong desire to ensure these aspects are protected.
- Climate variability projections from this work suggest that streamflow in the basin will increase due to future climatic change. Although this would suggest more available water, the timing and magnitude of changes in streamflow may dictate whether additional water yields are indeed available to meet increased demand. The basin will still be prone to droughts, and needs to build resilience to both wet and dry conditions. High streamflow variability, as seen in the recent past, is likely to continue.
- Land use plays an important role in watershed health and river management. Increases in withdrawals and consumption due to settlement patterns and other development activities impact streamflow.
- Although there appears to be enough water and existing infrastructure to support substantial growth with consideration for maintaining environmental health, high-growth scenarios would require additional water storage to meet increased demands and maintain environmental integrity. However, there are also trade-offs with creating additional storage with respect to environmental integrity. Indeed, a key finding of this study was that a medium level of growth (Basin Scenario 2- 350,000 dam^3 of active withdrawal, and 435,000 dam^3 of allocation) can be handled by the current system without the need for any additional infrastructure.

With the regional context in mind, the water management strategies discussed and modelled as part of this project offer a valuable continuation of the important discussion raised through the approved Water Management Plan for the South Saskatchewan River Basin (Alberta Environment, 2006). The strategies align with this plan as well as the *Water for Life* strategy and *Our Water, Our Future: A Plan for Action* based on the 2012 Water Conversation (Government of Alberta, 2014). They should help support discussions about building resilience in the basin while enabling growth and protecting the environment in the face of expected climate variability.

As demand for water grows, water users will need to further develop a common understanding about how shortages could be managed during periods of drought. This could mean sharing shortages as was done in the Oldman Basin. In discussion with the working group participants, a preliminary list of water users who would need to be involved in such discussions, based on licences modelled in the system. The Red Deer River Watershed Alliance could facilitate such negotiations by:

- Collaboratively drafting water shortage response plans for each water user or for each sub basin.
- Convening water licence holders and users to consider how the basin as a whole might manage and implement effective responses to specific water shortages.
- Working with stakeholders and ESRD to develop reasonable regulatory requirements for new water licences.

At the same time, it is prudent to further local flood protection measures as the value of major on-stream infrastructure for flood mitigation in the headwaters is relatively small. Local flood mitigation was discussed during the working group sessions, but specific local flood mitigation options were not modelled. Mid-basin on-stream storage appeared to show promise for addressing water shortages and mitigating downstream flooding by relieving pressure on Gleniffer Reservoir later in the year under high growth basin scenarios. However, new on-stream storage involves trade-offs with respect to environment and aquatic life. Off-stream storage in this area might also be considered to support irrigation expansion. It appears that the medium level of growth, as set out in Scenario 2, can be handled by the current system without the need for any additional infrastructure.

Water strategies to address regional growth and climate variability must include aspects of water conservation through reductions in consumption, as well as improvements in water efficiency and productivity. Improvements in conservation, efficiency, and productivity will protect ecosystems, allow jurisdictions to be better prepared in times of water shortage, provide a safety margin that may help avert water shortages, and promote best management practices to address an uncertain water future.

Several types of strategies were explored and identified to meet the goal of balancing economic growth with environmental health. Strategies that enabled growth and maintained environmental health were preferred but strategies that supported one and were neutral to the other were also supported, as reflected in the following list of most promising strategies:

- Implementation of functional flows - A steady drawdown of Dickson Dam releases after a high flood flow would enable cottonwood saplings to proliferate and provide favourable conditions for other types of riparian life, and was clearly demonstrated in the modelling work as achievable.
- Dickson Dam operations to meet WCO (downstream focus) - Modified operations would ensure that the WCO could be met at all times, compared to modelled current operations. It should be noted that even with modified operations the WCO could still be violated because many licences are senior to the WCO.
- Dickson Dam operations to meet WCO and new demands (downstream focus) - Operations would be further modified to ensure that the WCO and new downstream demands are met. Although the reservoir would have a larger drawdown to meet new demands, even with modified operations the reservoir should still refill at the end of every year, based on modelling of 81 years of historic data with current and some future demands.
- Additional storage - Additional storage would be a means to adapt to increased water demands due to growth in the system. Additional storage is a promising strategy on its own; however, it was felt that additional storage would likely only be considered once growth outstripped the ability for current storage and infrastructure to meet demands and all feasible

conservation efforts had been applied. Therefore, additional storage was only assessed in combination with operational changes and conservation.

- Local flood protection- Several flood mitigation structures were modelled over the course of the project. Discussion indicated that there are limited flood benefits of the upstream dams and it would likely be more effective to focus on do local mitigation and protection.
- Water conservation - Conservation would offer a total decrease in water use in the system from what it would otherwise be; it can decrease some shortages in the system but would need to be coupled with other water management strategies to ensure long term water supply. Conservation by sector (i.e., Municipal vs. Industrial vs. Agricultural) was explored, for example, the suggestion of 5% winter vs. 15% summer conservation as slight gains may be had in the irrigation sector, and municipalities and some industrial use would be able to reduce consumption if needed (e.g., lawn, garden, and golf course watering).
- Application of land use best management practices - The modelling work focused on the impacts of higher or lower rates of development on flows into the river system and demands on the river system. Land use best management practices, while not explicitly modelled, were identified as being vital in minimizing impacts of land use change on water resources.
- Effective implementation of Alberta’s Wetland Policy - Effective implementation would incorporate various measures designed to protect existing wetlands in the face of new development, and facilitate wetland restoration in areas where they have been lost and their benefits can provide the most value. Wetlands help reduce flooding and soil erosion by storing runoff and slowing its downstream release, and are important areas ecologically.

The Red Deer Basin has many natural advantages and is well-positioned for future economic and population growth. Possibly because this region has generally experienced less development pressure than other sub-basins in the SSRB, it has received less attention in terms of research and data collection. This project indicates that more, and in some cases better, data are needed to adequately understand and manage water resources in the basin; examples include improved understanding of groundwater-surface water interactions, meteorological and naturalized flow data, as well as more streamflow monitoring stations. To build resilience and sustainability in the face of climatic and environmental change and increased growth, a layered approach will be needed; there are no “silver bullets.”

With the completion of this project, all sub-basins in the SSRB now have a refined mass balance river system model with specific performance measures for each system, and basin specific working groups of informed and engaged water stakeholders. This provides a solid base and framework upon which future water management planning can occur, so basin water users and decision makers are clear on the facts, the unknowns, and the degree of acceptable risk related to future decisions on water resources. The work done for this project provides a solid foundation on which to determine appropriate actions, build more detailed plans and invest in the science needed so the basin’s water management system is better prepared to respond when expected growth and climate variability demands arise. The detailed description and data for the RDROM will be available online via the University of Lethbridge servers at http://www.uleth.ca/research-services/node/432/, as well as previous SSRB sub-basin models.

The hope is that the management strategies developed through this collaborative work might be used as a starting point for water managers to consider implementing, if warranted, to be proactive in managing future changes to water supply, water demand, and climate.

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Appendix A: Project Participants

Organization	Representative(s)
Alberta Agriculture and Rural Development	Andrea Gonzalez
Alberta Environment and Sustainable Resource Development	Phil Boehme Liza Brodziak Terry Chamulak Mike Collie Jason Cooper Rick Friedl John Mahoney Lauren Makowecki Andrew Paul Carlin Soehn
Alberta Innovates – Energy and Environment Solutions	Jon Sweetman
City of Red Deer	Tom Marstaller Tom Warder
Ducks Unlimited Canada	Milana Simikian Tracy Scott
MEGlobal	Steve Quine
Mountain View County	Angela Aalbers
Natural Resources Conservation Board	Walter Cerioci
NOVA Chemicals	Andrea Brack
Red Deer River Watershed Alliance	Jeff Hanger Bill Shaw* Josée Méthot
Red Deer River Municipal Users Group	Keith Ryder
Special Areas	Jay Slemp
Sundre Petroleum Operators Group	Tracey McCrimmon
Town of Drumheller	Brad Bolduc
Town of Innisfail	Pat Churchill*
Town of Sundre	Dave Hill Erin O'Neill
West Fraser	Tom Daniels Jean Eagleson
University of Lethbridge	Laurens Philipsen Stewart Rood
Alberta WaterSMART	Claire Jackson Megan Van Ham Mike Kelly Mike Nemeth Ryan MacDonald
ALCES	Brad Stelfox Matt Carlson
HydroLogics Inc.	Dan Sheer A. Mike Sheer
Prairie Adaptation Research Collaborative	Dave Sauchyn

* indicates the individual is also affiliated with the Red Deer River Municipal Users Group

Appendix B: SSRB Water Project Vision, Principles, Goals and Benefits

Vision Statement

The Red Deer River will be modelled and managed as an integrated ecosystem, from headwaters and tributaries to the Alberta border.

Mission Statement

This project will work with fit-for-purpose models capable of providing with respect to potential future impacts of climate variability and changes in land use, key growth and change of the key users and purposes along the course of the Red Deer River. As part of the river management system, there will be open and readily available interactive, fit-for-purpose models. These models will be capable of providing information for decision-makers to assess implications of, respond to, and mitigate a wide array of user needs and climate variability forecasts, and land use change scenarios.

Overarching Project Principles

- Causing no significant, measurable environmental harm
- Meeting Alberta's annual apportionment commitments to Saskatchewan
- Maintaining minimum flow requirements for municipalities
- Supporting the long term population/economic/irrigation growth forecasts
- Addressing First Nation's needs
- Respecting Alberta's legal water priority system (FITFIR)
- Achieving Alberta's policy goals in Water for Life Strategy

Project Goals

- Develop a common understanding of river flow and the respective timing and uses of water by each large senior licence holder and other key water users, including essential environmental processes.
- Use available public data, verified by stakeholders throughout this technical research project.
- Use verified data sets applied to computer models to develop practical water demand and management scenarios to alter on-stream storage, flow rate timing, and water uses to determine an economically achievable river system management regime to better accommodate the interests of the various water uses along each reach of its main stem and tributaries while protecting, and possibly enhancing, the aquatic ecosystem.
- Evaluate regional implications for water supply and timing under historic conditions with the ability to evaluate conditions from forecast changes in climatological conditions, and scenarios of land use change.
- Based on the modelling results, assess water management alternatives and infrastructure changes to protect, and where possible enhance, the basic aquatic ecosystem while better accommodating the interests of the many water uses along each reach.
- Communicate these scenarios and operating regimes effectively to local, regional, and provincial levels of government for their purposes.
- Prepare reports and other public communication vehicles and mechanisms (as needed).
- Conduct any additional modelling that may be needed and recommend the agreed upon adaptive management model to government as the next version of the Watershed Management Plan for the SSRB System. Revisions and improvements run on model as needed.

Key Deliverables

- Project team of licensees and select key interest groups.
- Collaborative (not necessarily consensus) process to engage participants.
- Agreed upon data sets for each key component of river system management.
- Vetted and supported mass balance model of the Red Deer River system, over the available historic record.
- Vetted and supported set of Performance Measures reflecting the range of interests and needs throughout the basin.
- Practical and well considered “Scenarios” exploring improvement of various aspects of river management for climate variability and land use changes.
- Written reports and other public communication vehicles and mechanisms (as needed).
- Final report and recommendations to AI-EES and government with preliminary information on benefits, costs, and actions needed to assess adaptation strategies around changes in climate and land use, and to support decisions related to implementation.

Expected Benefits

- Improved management and mitigation options related to risk to high value and volume users from a drought or flood
- Options to improve aquatic ecosystem protection in prioritized reaches
- Improved economic development opportunities under sustainable conditions
- Improved recreational opportunities in certain reaches
- Improved data, knowledge, and management information
- A new comprehensive river system model to assess impacts of changes in climate and land use on the river system, and develop adaptation strategies
- Identify preliminary adaptation strategies on how the system could be managed to better adapt to various climate and land use change scenarios
- Note: In addition to river operations and infrastructure, there are a broad set of socioeconomic, cultural and attitude issues related to water use and adapting to climate variability. The adaptation discussions and strategies developed in this project will endeavor to identify and consider as many related issues as possible, but will not have the time nor scope to address them all thoroughly.

Project Participants

Criteria for Participant Selection

- Significant water license holder
- Significant future or current need for water
- Important knowledge and technical skills needed for project to succeed
- Managerial knowledge needed for implementation
- Every participant brings resources to the table
- Every participant brings commitment to results

Tasks

- Assemble data and QA/QC data for reasonableness
- Develop consensus on data, model, performance indicators for each participant
- Participate in Technical Teams as needed (Data and Modelling team, Environment team, etc.)

- Develop scenarios for initial model runs (revise, refine, improve)
- Environmental thresholds and assessments associated with scenarios
- Social/community implications of scenarios (recreation, assured water supply, etc.)
- Support preparation and review final report

Project Platform

WaterSMART as neutral independent party takes overall project accountability to the funding agency, Alberta Innovates - Energy and Environment Solutions, as well as project leadership, coordination/management, banker functions, contract management, and administrative processes.

Appendix C: Red Deer River Operational Model (RDROM)

Inflows

Naturalized weekly inflow data were retrieved from Alberta Environment and Sustainable Resource Development (ESRD), which was the best available data source for the purposes of this project. Unfortunately, the data suggested substantial reach losses. These reach losses were of sufficient magnitude that it was suggested some might be artifacts of the process of naturalizing historical flows. As such, the RDROM adapted the data in the same way that the Water Resources Management Model (WRMM, the model used by ESRD) did – by "zero-ing out" reach losses; that is, if a downstream gauge showed less water than an upstream gauge it was replaced with the upstream value.

Weekly naturalized flows at each location were then disaggregated to daily flow values for seven stream gauge locations on the Red Deer River using available daily streamflow data. Local naturalized inflow was calculated as the difference between the flow at a station and the flow at the next station upstream. This sometimes resulted in negative local weekly average flow. Negative inflows were replaced with a zero and retained in a separate database. These data have been retained and can be included in the model as demands. However, reach losses (negative inflows) are currently set to zero based on discussion with ESRD hydrologists.

Daily observed streamflow records are available for the Red Deer River at Red Deer for most of the period between 1912 and 2009. The observations at Red Deer and concurrent records for other sites were used to estimate the time lag between flow pulses observed at Red Deer and the arrival of those pulses downstream. Figure C1 shows the correlation coefficients for various lags at each of the gauges with daily records. The lag for a site for travel time between Red Deer and a downstream site was selected based on the maximum correlation coefficient (Figure C1). Figures C2 through C5 show scatter plots, trend lines, and correlation coefficients for the selected lag at each site for which daily data were available.

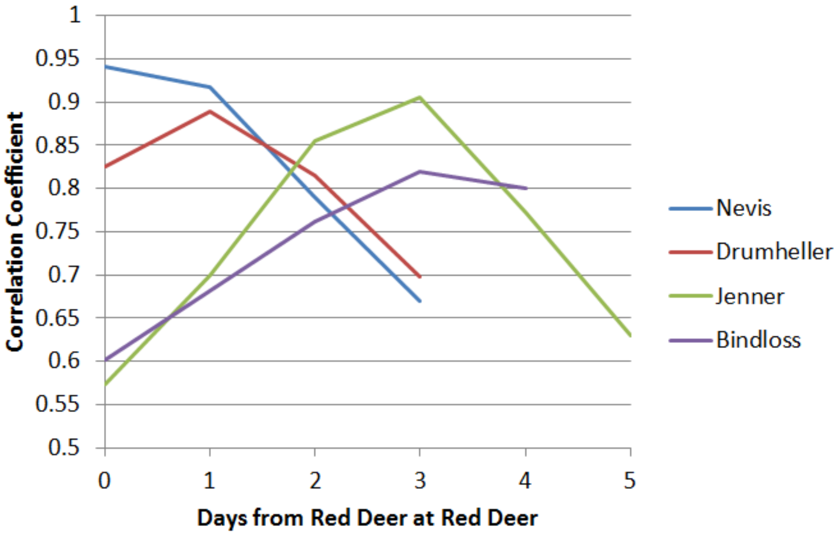


Figure C1: Correlation between flow at Red Deer and flow downstream on subsequent days

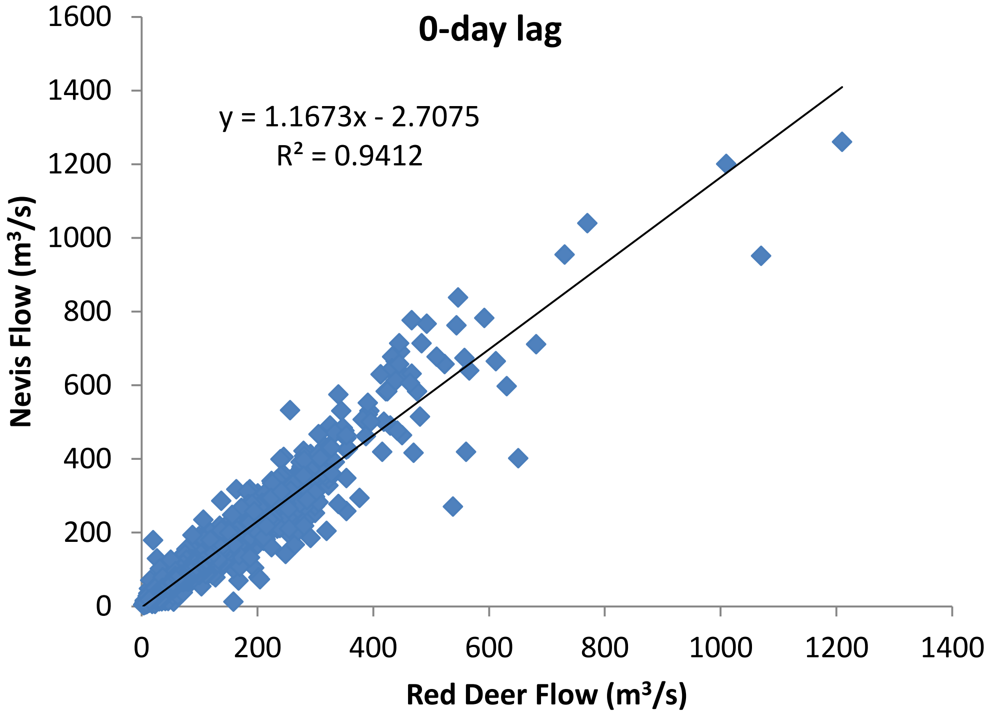


Figure C2: Correlation between flow at Red Deer and flow at Nevis (no lag)

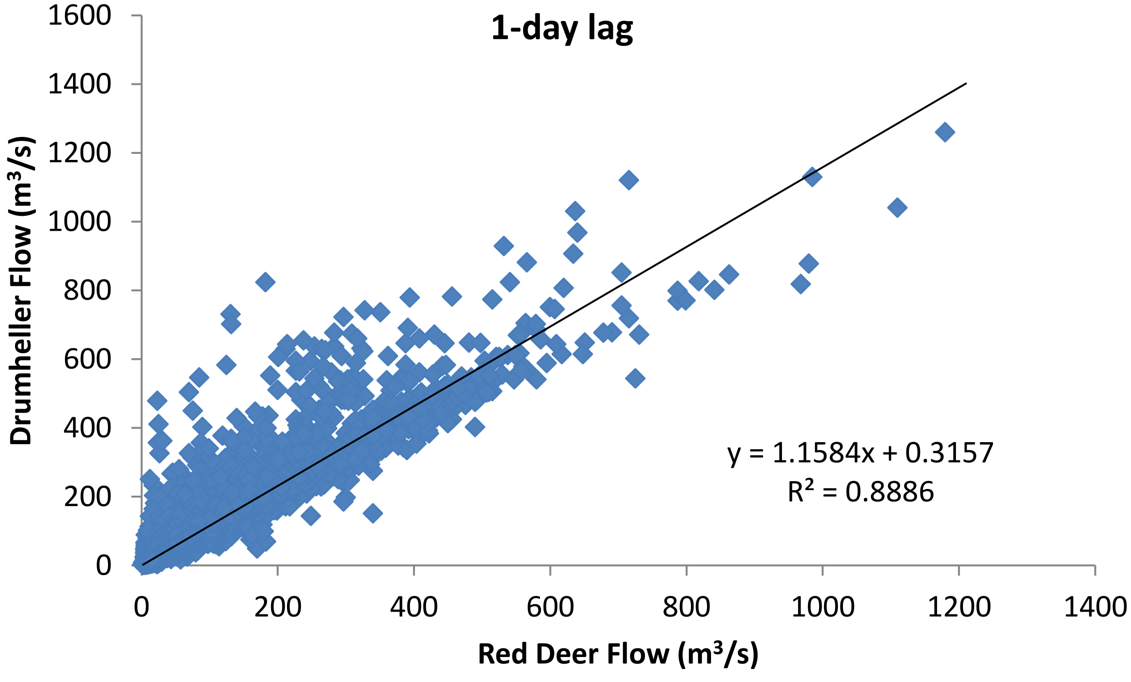


Figure C3: Correlation between flow at Red Deer and flow at Drumheller (1-day lag)

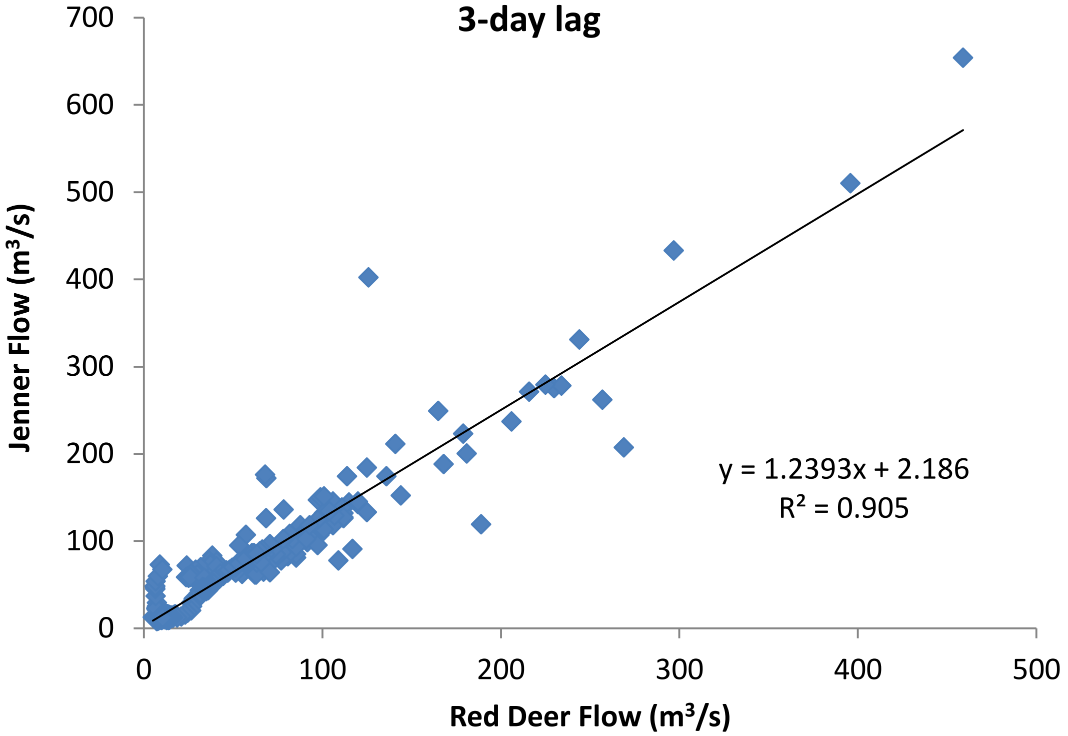


Figure C4: Correlation between flow at Red Deer and flow at Jenner (3-day lag)

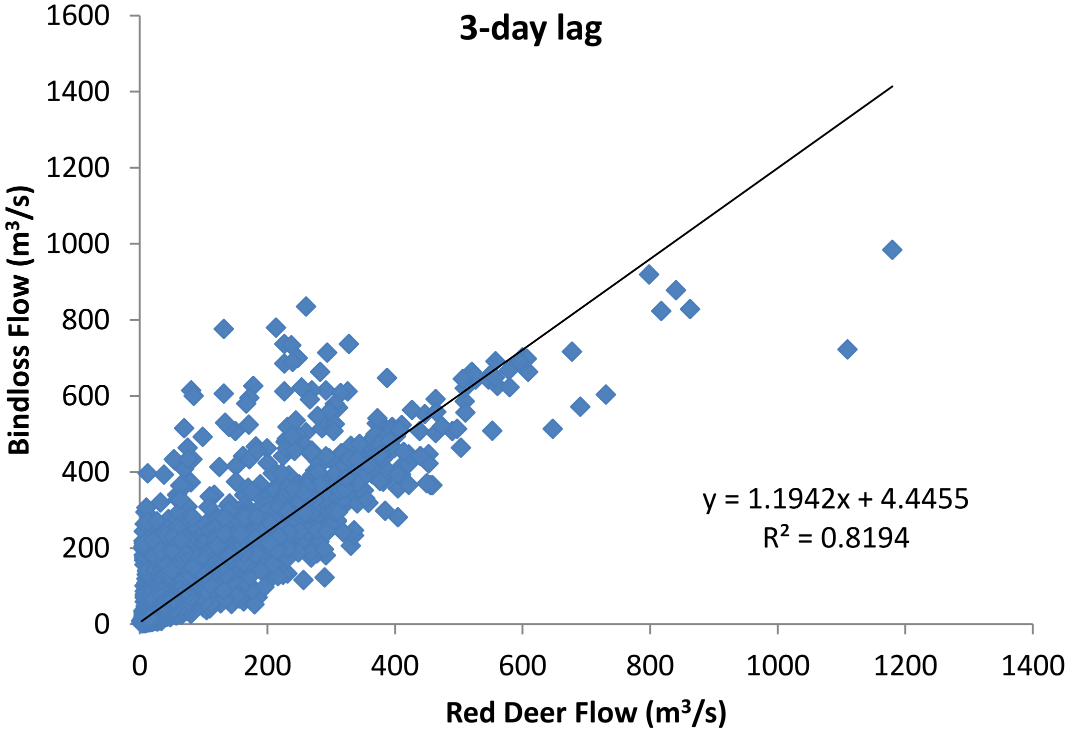


Figure C5: Correlation between flow at Red Deer and flow at Bindloss (3-day lag)

The distribution of daily observed flow occurring each week was used to disaggregate weekly flow values to daily flows. A scale factor was calculated for each day by dividing the day's flow by the sum of flow for the week. This resulted in the scale factors for each week summing to one. The weekly naturalized flow sum was then multiplied by the daily scale factor to distribute the weekly flow to each day of the week.

Missing flows in the Red Deer daily record (mostly in years 1931 to 1935) were filled with synthetic daily data that were generated from a log-normal distribution using the log-space mean of the flow record. The log-space variance was adjusted until a synthetic flow sequence was obtained with a real-space coefficient of variation close to the original flow record.

Measured flows (when available at each site) were used to calculate daily weighting factors. If measured flows were not available for the whole week, scale factors were derived from the Red Deer River gauge at Red Deer with the appropriate lag.

Weeks begin on 1 January of each year. An eight-day week is assumed for the last week in December such that the number of days in a year adds to 365. During leap years, an eight day week is assumed at the end of February (week 9) such that the sum of days in a leap year is 366. Figure C6 shows the disaggregated flows for a period in 1912.

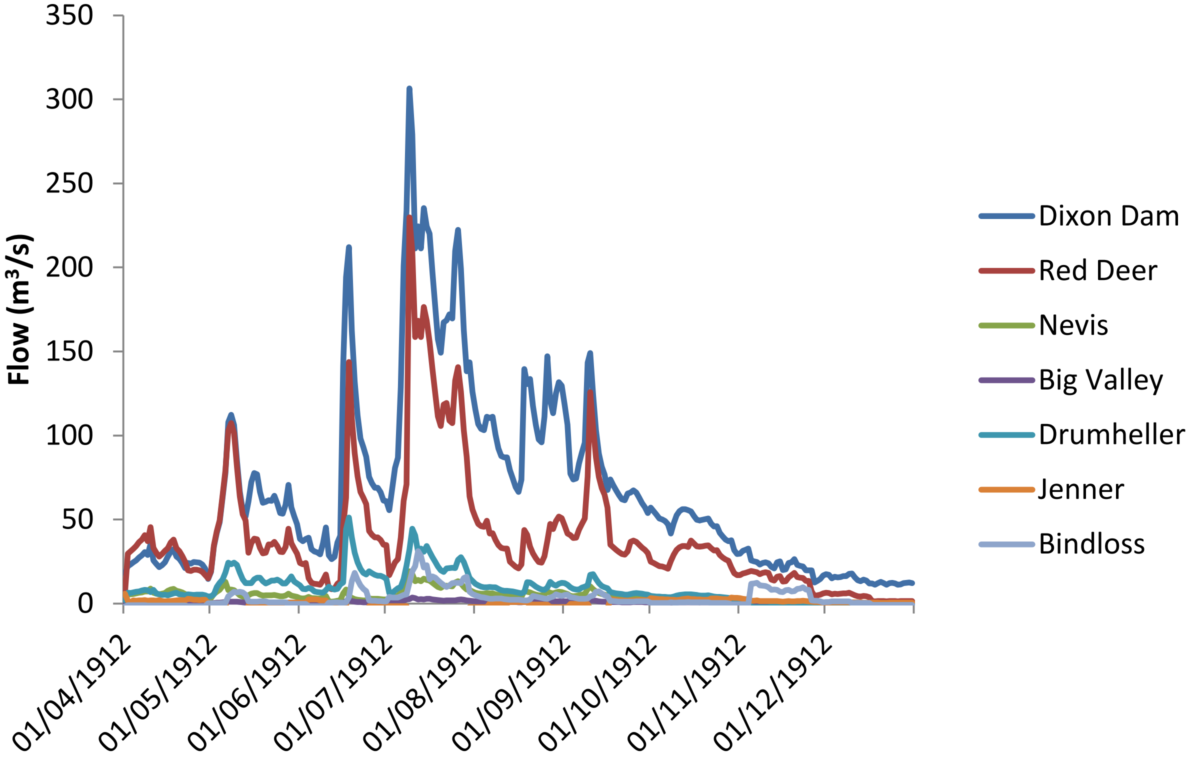


Figure C6: Example of disaggregated flows from April to December, 1912

Inflows upstream of Dickson Dam have been disaggregated relative to the original WRMM model. The RDROM currently accounts for the upper Red Deer River, Fallen Timber Creek, and the James River (disaggregated by drainage area). The upper Red Deer River inflow accounts for the total drainage area contributing to the Red Deer River at Sundre. Fallen Timber Creek and the James River are assumed to account for 15% and 12% of the total watershed area upstream of Red Deer, respectively (based on PFRA watershed delineation). The inflow at Red Deer was used to disaggregate these flows given that Fallen Timber Creek and the James River are downstream of the Red Deer River inflow to Sundre. The Little Red Deer River is also included as an inflow to the RDROM.

Inflow disaggregation

Inflow data were disaggregated for Vam Creek, Fallen Timber Creek, the James River, and the Raven River upstream of Dickson Dam. Inflow disaggregation was also done for the Little Red Deer River to represent the contributing areas to identified dry dam locations near Salter Creek, Harmattan, and the mouth of the Little Red Deer River. Inflows were derived using contributing watershed area derived from the PFRA watershed dataset and Stantec (2014), with the exception of 2005, where peak daily flows were scaled according to Water Survey Canada data for the Red Deer River below Burnt Timber Creek, James River, and Raven River.

The Vam Creek and Fallen Timber sites represented 41% and 5% respectively (Stantec, 2014) of the naturalized streamflow for the Red Deer River near Sundre. The James and Raven river sites were scaled by 15% and 12% of the area contributing to the Red Deer River at Red Deer (based on PFRA watershed delineation). The Red Deer River at Red Deer was used because this was the next downstream inflow node represented in the naturalized inflow dataset. The Salter Creek, Harmattan, and Little Red Deer River mouth sites were scaled by 8%, 34%, and 58% of the Little Red Deer River inflow (Stantec, 2014).

Peak annual streamflow was generally under-simulated for the James River, except for 2005 (Figure C7). Peak annual streamflow and baseflow were also under-simulated for the Raven River (Figure C8). These results demonstrate that streamflow estimates derived from contributing watershed area are not exact; however, the temporal patterns and relative streamflow magnitude are reasonable for both the James and Raven rivers.

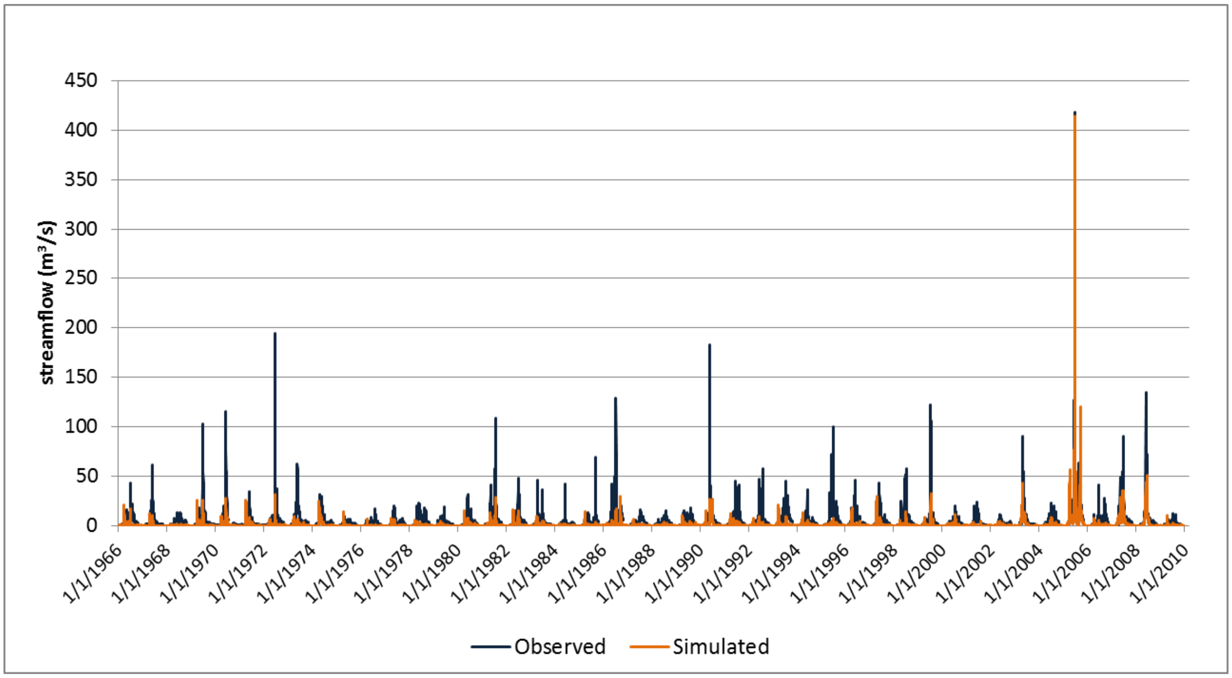


Figure C7: Observed and simulated daily mean streamflow for the James River

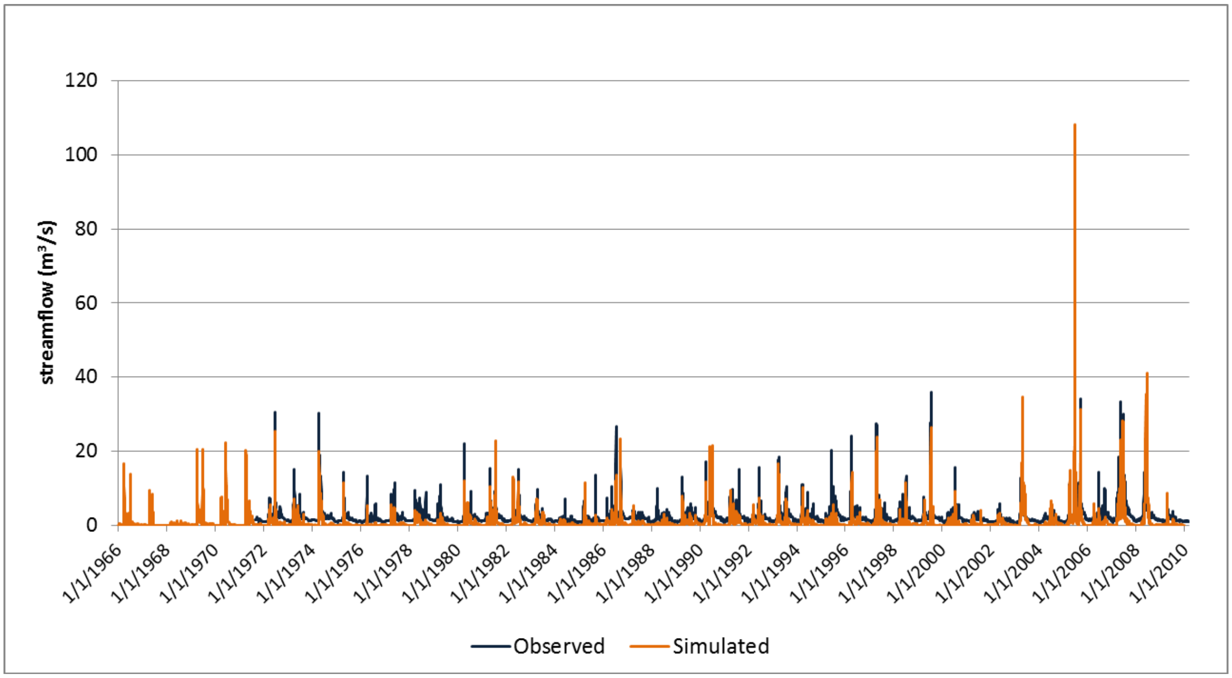


Figure C8: Observed and simulated daily mean streamflow for the Raven River

The observed and simulated streamflows for the Red Deer River at Bindloss are represented well temporally, with an under estimate of peak annual flows as well as low flows (Figure C9). This suggests that overall the scaling represented in the model is appropriate.

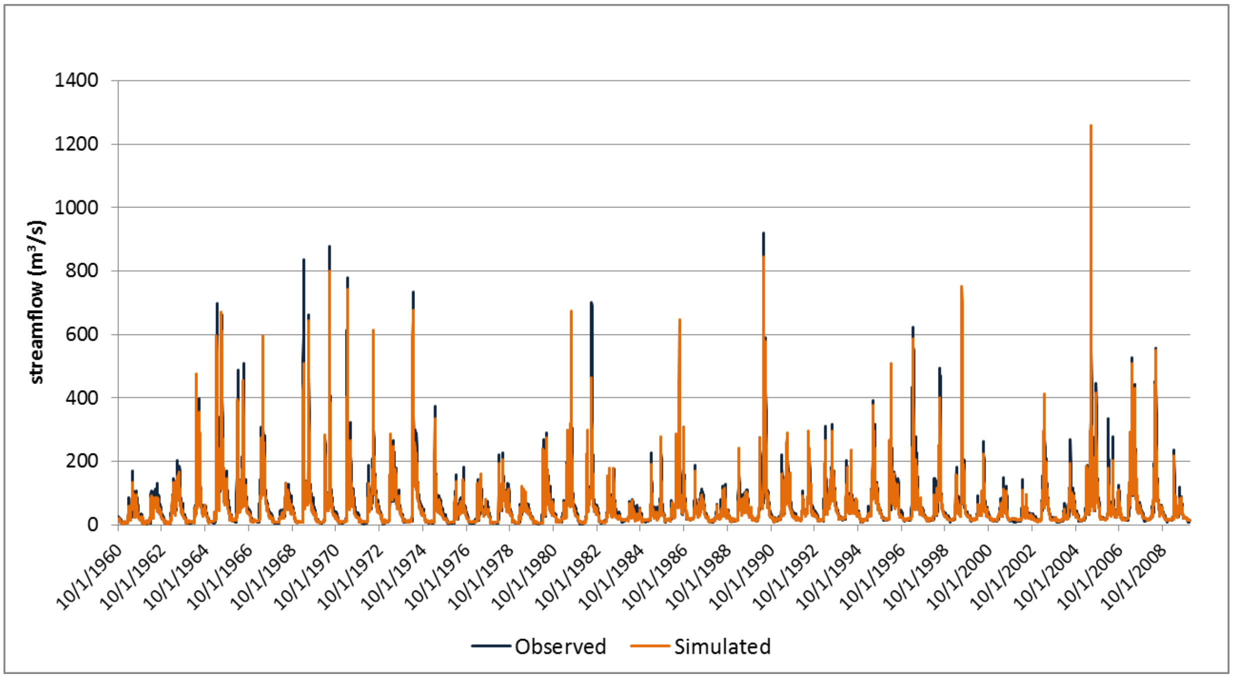


Figure C9: Observed and simulated streamflow in the Red Deer River at Bindloss for the period from October 1, 1960 to December 31, 2009

Time of Travel

The routing method used for the RDROM was invented based on the data available as shown in Table C1. Channel routing by nature is non-linear, which means that the travel time in a reach decreases as flow increases, and some non-linear routing methods do not conserve mass. Common channel routing methods, such as Muskingum, are linear, meaning the travel time in a reach is constant, regardless of flow, and mass is conserved, but these methods are unsuitable for this type of application.

Channel routing causes a lot of complications in modelling system operations. As shown in Table C1, most of the travel times are less than one day. To reduce the modelling complexity the 13 reaches were combined into four reaches, as shown in Table C2.

Table C1. Travel Time (in hours) for Red Deer River

Flow (m^3/s)	0.5	1	3	6	10	30	60	100	300	600	1000
Gleniffer Lake to blw Medicine R.	12	9	5.5	4.1	3.4	2.1	1.6	1.6	1.6	1.5	1.5
blw Medicine R. to Red Deer	69	52	33	24	20	12	9.4	9.3	9.2	8.9	8.7
Red Deer to blw Blindman R.	45	35	23	17	14	9.5	7.3	6	3.9	3	2.5
blw Blindman to Nevis	142	109	72	55	45	30	23	19	12	9.5	7.8
Nevis to Big Valley	138	106	70	53	44	29	22	18	12	9.2	7.6
Big Valley to Drumheller	117	90	59	45	38	25	19	16	10	7.8	6.5
Drumheller to blw Rosebud R.	20	15	10	7.6	6.2	4.1	3.2	2.6	1.7	1.3	1.1

Flow (m^3/s)	0.5	1	3	6	10	30	60	100	300	600	1000
blw Rosebud R. to blw Bullpound Ck.	169	129	85	65	54	35	27	22	15	11	9.3
blw Berry Ck. to blw Blood Indian Ck.	140	107	70	54	45	29	22	19	12	9.4	7.7
blw Blood Indian Ck. to blw Alkali Ck.	138	105	68	52	43	28	21	17	11	8.6	7
blw Alkali Ck. to Near Bindloss	77	59	38	29	24	16	12	9.7	6.3	4.8	3.9
Near Bindloss to Mouth	138	105	68	52	43	28	21	17	11	8.6	7

Table C2. Travel Time (in days) for Red Deer River

Flow (m^3/s)	0.5	1	3	6	10	30	60	100	300	600	1000
Gleniffer to Nevis Lag630640	10.7	8.2	5.4	4.1	3.4	2.4	1.7	1.4	0.93	0.72	0.66
Nevis to blw Rosebud Ck. Lag650660	11.7	9.0	5.9	4.5	3.7	2.6	1.9	1.6	1.0	0.78	0.65
blw Rosebud Ck. to blw Berry Ck. Lag680690	12.7	9.8	6.4	4.9	4.1	2.7	2.0	1.7	1.1	0.85	0.71
blw Berry Ck. to Mouth Lag710720	18.6	14.2	9.3	7.1	5.8	3.8	2.9	2.4	1.6	1.2	0.98

To illustrate the method, consider the reach labelled Lag680690 in Table C2 and that the flow entering the reach is 20 m^3/s. The lag time will be 3.4 days (midway between 4.1 days and 2.7 days representing 10 m^3/s and 30 m^3/s, respectively. Thus 60% of today's flow (12 m^3/s) will arrive at Berry Creek three days from now, and the remaining 40% (8 m^3/s) will arrive four days from now. Thus the travel times are approximated, and mass balance is maintained.

Demand Source Data

All demand data initially came from the original SSRB model from 2008, which was part of a pilot project to improve integrated and collaborative water management decision making in the SSRB. The data for that modelling work were provided by ESRD, and came from WRMM model output for scenario 18. The data are assumed correct in terms of demands for the basin that reflect water allocation for all licence information at the time the information was compiled for WRMM. However, after discussion with the stakeholder working group, it was decided to re-do the demand information in the nodes to show where the majority of the licences were located in the model, as well as provide assurance as to the demand data. Licensed allocations from an updated list (as of May 2014) of the current Red Deer River Basin licensed project allocations were provided by the regional hydrologist for ESRD, after being extracted from the Environmental Management System database using the GIS AWAIT tool. Demands were subsequently updated by "omitting" the registry licences above the 95% allocation mark, as was recommended by the regional hydrologist for ESRD. The registry licences account for a mere 1.2% of the total allocation volume, but represent 84% of the total licences issued in the Red Deer River Basin (see Table C3). The registry volume total allocation is relatively insignificant. The 95% of allocation by volume represents 597 and 741 licences for "without" and "with" registry licences respectively. As registry licences have never been included in natural flow computations or water use modelling, it was decided that licences with registry at 95% by volume would be used to update the model.

Table C3: Summary of number and volume of licences in the Red Deer Basin

Description	Number of Licences	Percent of Total Number	Total Allocation (dam^3)	Percent of Total Allocation	95% by Volume (dam^3)	Number of Licence at 95% by Volume
Licenses No Registry	3,037	16	332,247	99	317,274	597
Registry Only	15,456	84	3,986	1		
Licenses With Registry	18,493	100	336,233	100	321,090	741

The 741 licences were assessed in a GIS to extract each licence by sub-watershed. Sub-watersheds were obtained from the PFRA watershed shapefile (PFRA Watershed Project, Agriculture and Agri Food Canada, http://www.agr.gc.ca/eng/?id=1343313831597). Contributing sub-watersheds were determined for each OASIS demand node assuming licences from demand nodes were approximately representative spatially. Each licence was then assigned to a node based on the spatial location and contributing areas, and grouped into demand nodes based on the type of licence (e.g., irrigation, industry (seasonal and year round), urban, water management, cattle/feedlots).

It was decided that 741 licences were too many for implementation under the current scope and budget for this project. Thus, the 95% target was reduced to 70% + licences of interest target. At 70% allocation, the major licence holders are, in order:

1. ALBERTA ENVIRONMENT AND WATER - WATER OPERATIONS
2. DUCKS UNLIMITED CANADA, EDMONTON
3. CITY OF RED DEER
4. ALBERTA ENVIRONMENT AND SUSTAINABLE RESOURCE DEVELOPMENT
5. NOVA CHEMICALS CORPORATION
6. ATCO ELECTRIC LTD.
7. NORTH RED DEER RIVER WATER SERVICES COMMISSION (NRDRWSC)
8. MOUNTAIN VIEW REGIONAL WATER SERVICES COMMISSION (MVRWSC)
9. SHIRLEY MCCLELLAN REGIONAL WATER SERVICES COMMISSION (SMRWSC)
10. MEGLOBAL CANADA INC.
11. TOWN OF DRUMHELLER
12. SPECIAL AREAS BOARD

Dow Chemicals, Shell Canada, Exxon Mobil, and ConocoPhillips were also included due to interest in their operations because of involvement with the stakeholder working group. This increased direct licence modelling to approximately 72.5% of allocation.

Each licence holder was separated into its own demand node, and licence priority was applied for each licence individually. Licensed demand was then subtracted from existing WRMM demand data to reduce duplication of demand. As original licence grouping information in the WRMM model is no longer available to describe precisely which licences were in each demand “group,” this was the only feasible option for separating out individual licences.

The remaining <30% of demand maintains the weighting used in the original WRMM modelling. WRMM broke licences down into approximately five levels of seniority. Categories were broadly, and in order:

1. Senior Irrigators
2. Major Demands
3. Mid-Licence Irrigators
4. Junior Irrigators
5. Minor Demands

To incorporate licence priority data into the WRMM framework, it became necessary to break the licence data into two groups. This allows the "Mid-Licence" Irrigators to remain in the middle. Extracted licence data were thus split into two seniority groups. The two groups were split so that each contained equal licensed volume. The date of the licence that served as the dividing line between the two groups was 17-Apr-1982 #18 (i.e., the 18th licence issued on April 17, 1982). Earlier licences became the "senior" group while licences after and including 17-Apr-1982 #18 became the "junior" group. Among these, each licence still retains its individual priority, but this allowed us to maintain the remaining demand data that did not have specific licences attributed to it.

Thus the modelled RDROM demand priority became:

1. Senior Irrigators (identified by and remaining in WRMM blocks)
2. Major Demands (identified by and remaining in WRMM blocks)
3. Senior Licences (by licence date priority, pre- 17-Apr-1982)
4. Mid-Licence Irrigators (identified by and remaining in WRMM blocks)
5. Junior Licences (by licence date priority, post- 17-Apr-1982)
6. Junior Irrigators (identified by and remaining in WRMM blocks)
7. Minor Demands (identified by and remaining in WRMM blocks)

This allows us to identify which of the major licence holders are most vulnerable to shortage, noting that the model does not identify that there *will be* shortages under each scenario, only that there is increased or decreased *risk* of shortage.

After the licensed allocations were entered into the model, some of the data for larger users were updated to current demand data. Current demand data were obtained from Municipal Water Service Commissions (MVRWSC, NRDRWSC, SMRWSC), NOVA Chemicals, the City of Red Deer, and the Town of Drumheller. All irrigation demand nodes in the model were updated with recent demand estimates from the ARD IDM. Irrigation demand modelling for the Red Deer was based on 2011 current irrigated acres, crop mix, and on-farm irrigation system types. As part of the modelling work, it is assumed that every licensed acre is irrigated. Estimated irrigation demands in the Red Deer model were based on the assumption that irrigators would apply sufficient water to meet 90% of the optimum crop water requirement (Bob Riewe, personal communication).

Licence Priority Scenarios

As described above, the RDROM contains all the licences in the system, but only 70% of the allocation by volume is modelled under strict licence priority. The remaining 30% of volume is still accounted for in the model, but broken down into large general priority blocks that fall between the directly modelled licences. Average total water demand in RDROM from all licences sums to roughly 337,000 dam^3 per year. This is referred to as the **Full Licence Allocation** scenario.

During the development of this licence scheme for the model, it became apparent in discussions with stakeholders that a number of the existing licences would not, or could not, be treated as consumptive use. Examples include licences for:

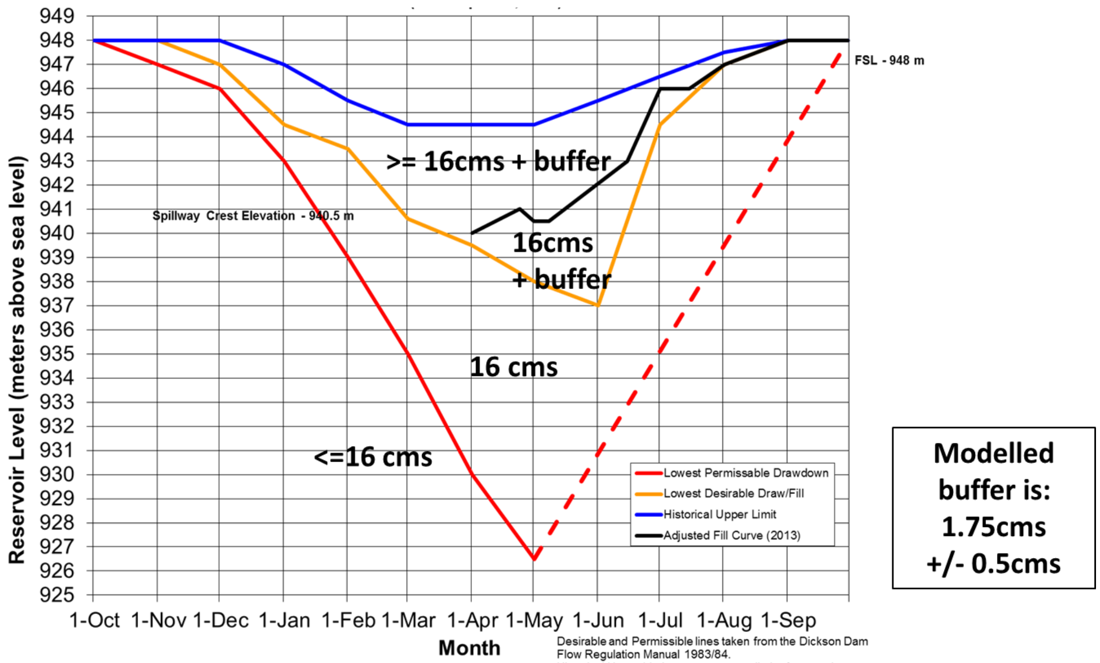
- reservoir operations (a licence is required for a reservoir to store water, but that water would not be removed from the system),
- flood operations (also would not consume water), and
- approximately 90% of the licences applied to Ducks Unlimited (licences are for loss, not consumption, and substantially overstate the day-to-day effects of operations).

Turning off these licences (i.e., removing them from the pool of demands) resulted in the **Rational Licensed Use** scenario. Average total yearly demand under this scenario is approximately 251,000 dam^3 per year. This scenario would eventually become the primary point of comparison for alternatives.

Some of the stakeholders were able to provide actual use data for their demands. To reflect the closest possible analogue to current use, we also developed a scenario that replaced their full licensed withdrawal with their recent historical withdrawals (although licence priority was maintained). Actual use was provided by MVRWSC, NOVA chemicals, City of Red Deer, NRDWSC, and SMRWC. This became known as the **Actual Use** scenario, with average total yearly demand at approximately 204,000 dam^3 per year.

Dickson Dam Operations

Physical data for all diversions and reservoirs were provided by ESRD. Figure C10 illustrates the operating curves and targeted releases for Dickson Dam. Important to note are the lowest desirable and lowest permissible drawdown curves as both are used in the modelling of water strategies in terms of thresholds for the model to trigger to stop releases or filling.



Desirable and Permissible lines taken from the Dickson Dam Flow Regulation Manual 1983/84.
Historical Upper Limit - average upper limit of reservoir

Figure C10: Dickson Dam Operating Curves and Targeted Releases

Real-life operations of Dickson Dam utilize a wide variety of factors external to the model (forecasts, snowpack, intuition, and others). The goal was to be as reflective of reality as possible while recognizing that it would not be possible to match reality exactly. In the absence of actual data for developing each year's Adjusted Fill Curve, three generic ones were created based on the top, middle, and bottom terciles, and were then smoothed (Figure C11). The reservoir tries not to fill above the curve, and will release in exceedance of the 16 m^3/s + buffer minimum to stay below it. Once below the fill curve, the reservoir will attempt to fill again, but will not release less than the 16 m^3/s +buffer minimum. Only once the reservoir falls below the Lowest Desirable fill curve will releases fall to exactly 16 m^3/s. If events draw the reservoir below the Lowest Permissible Drawdown curve, it is allowable for the reservoir to release less than 16 m^3/s. However, that has only happened once in the history of the reservoir, and the release was maintained at 16 m^3/s; in that case, releases maintaining at 16 m^3/s in the base condition were modelled. The buffer increases or decreases by +/- 0.5 m^3/s based on whether the year is considered dry, wet, or normal.

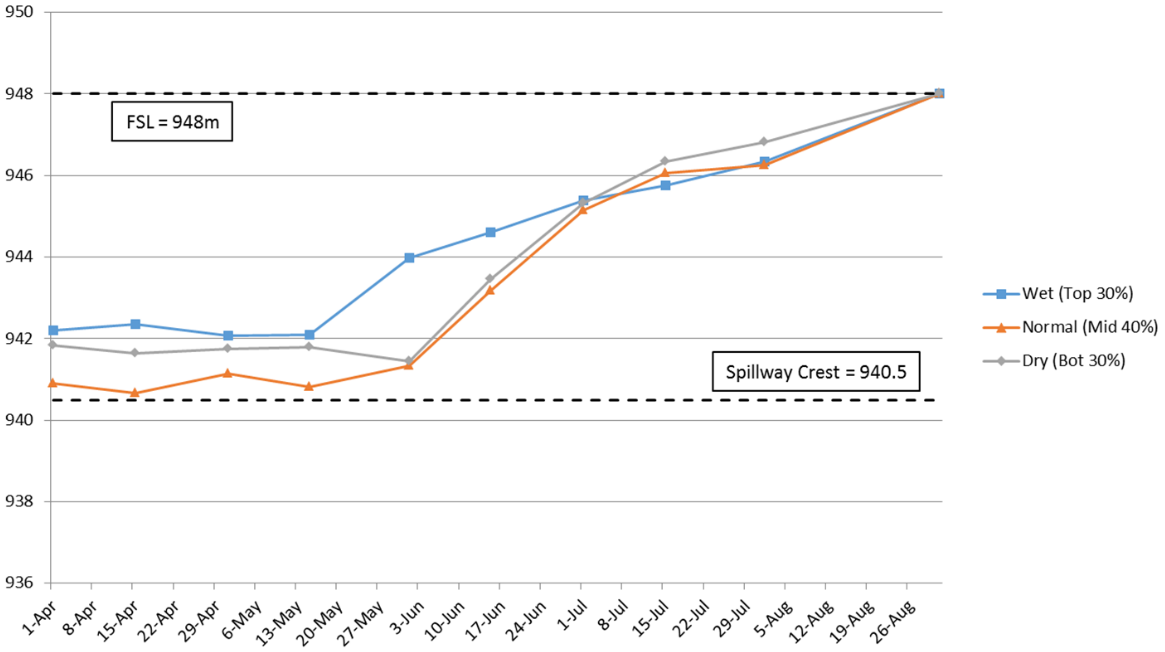


Figure C11. Average Elevation Fill Guide Curves

Flood operations for Dickson Dam utilize a pre-release schedule to ensure room is available to accommodate incoming floods. The decision to force pre-releases is based on whether the total volume of inflow over the next 1-, 2- 3-or 4-day period will cause the reservoir to exceed its maximum storage less a flood buffer. The value of the flood buffer is presently set to 10,000 dam^3. If this is the case, then a pre-release is set large enough to keep the forecast reservoir elevation below the flood buffer, or to prevent the current day volume from exceeding upper rule, whichever is less. These pre-releases are capped at 200 m^3/s to prevent pre-flooding.

Collectively, these operations resulted in modelled elevations of Gleniffer Reservoir that match historical observations fairly well (Figure C12).

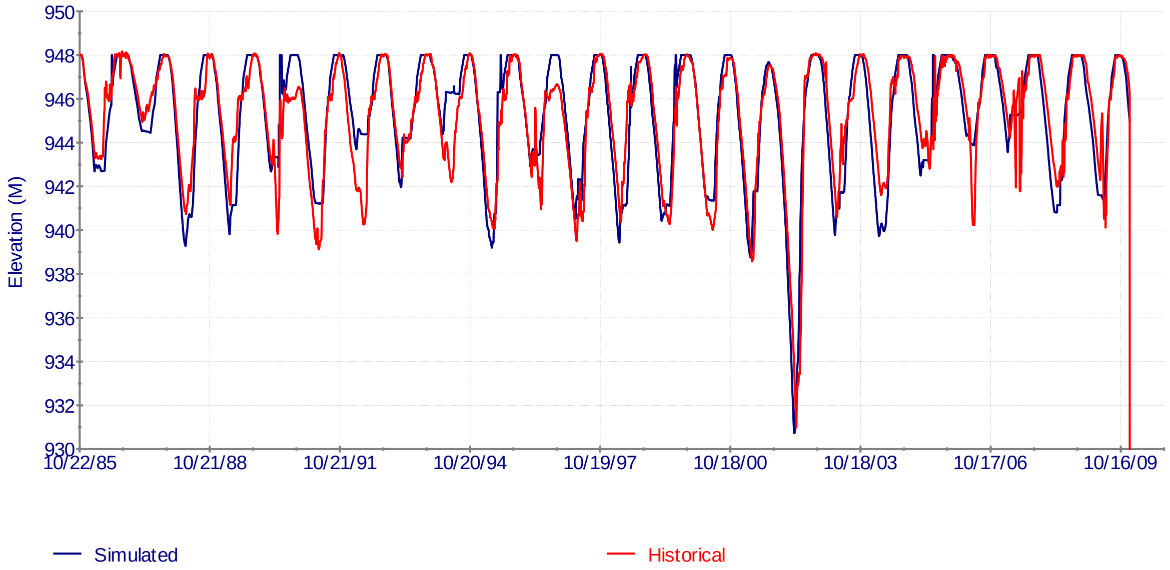


Figure C12. Elevation of Gleniffer Reservoir

Buffalo Lake Operations

Buffalo Lake generally operates only to receive water from the Red Deer system, and is not used as a water supply. As such, Buffalo Lake was modelled as a demand rather than a reservoir. To ensure conservative assumptions consistent with the rest of the project, it was modelled as pumping 1.268 m^3/s continuously during its operation period (May 1 to Oct 31). This is below the maximum pump capacity (1.4 m^3/s) but uses the full licence (20,000 dam^3) each year. Buffalo Lake was also operated under the assumption that, in a shortage situation, other water uses would take priority (i.e., it is weighted lowest).

Sheerness and Deadfish Diversions

The Sheerness and Deadfish diversions were originally simulated based on information from WRMM. Sheerness and Deadfish Diversion information was also provided by Derek Lovlin (personal communication). The Sheerness diversion is essentially an ATCO pumphouse that pumps water for ATCO and ESRD. ATCO pumps water into their cooling pond for their Sheerness coal-fired power generation station. Water pumped from the river by ATCO is also used for irrigation; it is pumped into a series of small reservoirs or holding ponds (e.g., Carolside). A few kilometres downstream from the Sheerness Diversion is the Deadfish Diversion, which is an ESRD pumphouse that pumps water for irrigation and stock watering.

The Sheerness diversion is regulated by two different licences. The ESRD licence is a diversion of 22,200 dam^3 from the Red Deer River (13,800 dam^3 directly from the river and 8,400 dam^3 return from ATCO's pond). ATCO has a licence for a 22,000 dam^3 diversion from the Red Deer River (8,400 dam^3 return flow). The rate of diversion is 2.5 m^3/s and the actual pump-limited diversion rate is 2.14 m^3/s.

The Deadfish diversion is regulated by a single ESRD licence of 1.70 m^3/s. ATCO supplies 36.5% from its Sheerness pipeline, with a return flow of 0.14 m^3/s to Red Deer River.

At present, the only diversions modelled on the Sheerness Pipeline are ATCO and one irrigation block, both of which are consistently well below the maximum diversion limitation.

A Note on Groundwater and Water Quality

The RDROM does not explicitly calculate or account for groundwater or include water quality aspects. That said, groundwater contribution to streamflow is inherently part of the naturalized flow data used as inflows to the model. Implications for water quality as it relates to flows at points in the river can be assessed using the RDROM when relationships between water quality and quantity at a particular point in the system are known.

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Personal Communications

Bob Riewe, Alberta Agriculture and Rural Development; emails dated June 13, 2013 and November 7, 2013.

Derek Lovlin, Alberta Environment and Sustainable Resource Development; email dated June 11, 2013.

Other Data Sources

Evaporation data received December 5, 2013 from Carlin Soehn, ESRD. This included updated evaporation data from 2001 to 2009 for Deep Lake near Lacombe.

Background map for model schematic produced by Larry Kwasny of ARD in an email June 25, 2013.

Appendix D: Performance Measures for the Red Deer Basin

The full list of PMs for the Red Deer System, shown below, was processed for each strategy. Charts for specific PMs are included as appropriate in the body of this report to illustrate a particular result, and the full set of PMs is available in the electronic Red Deer model files.

- Flows at the Mouth of the Red Deer River (Weekly)
- Elevation of Gleniffer Reservoir (Daily/Annual)
- Outflow from Gleniffer Reservoir
- Cottonwood recruitment
- Shortages to New Demands (Annual/Daily)
- Mid-stream Reservoir
- Annual weekly minimum flows
    - Fish specific: Minimum weekly flow at Red Deer River at Bindloss – no water, no fish, accompanied by a bar chart that shows percent of years with zero flow as the annual minimum at Bindloss
- Fish Water Quality Thresholds
- Flow Stability During Fall Spawning Season
- Natural Flow Thresholds by Proportion
- Gleniffer refill by September 1
- Municipality Shortages (by days & volume)
- Industry Shortages (by days & volume)
- Irrigation Shortages (by days & volume)
- Irrigation Summer Shortages (by days & volume)
- Number of Flooding Events
- Annual Volume of Red Deer Outflow as a Percentage of Natural Flow
- Recreation days on Gleniffer Reservoir
- Average Annual Number of Instream Recreation "Points" assigned for the Upper Red Deer and Lower Red Deer
- Low Flows at the Mouth of the Red Deer (Daily/Weekly)
- Apportionment Contribution by Source (i.e., Red Deer vs. Oldman vs. Bow)
- Consecutive Ramping Weeks at Red Deer to Support Cottonwood Recruitment
- Number of High Flow Events at Multiple Reaches

Appendix E: Development of Climate Scenarios

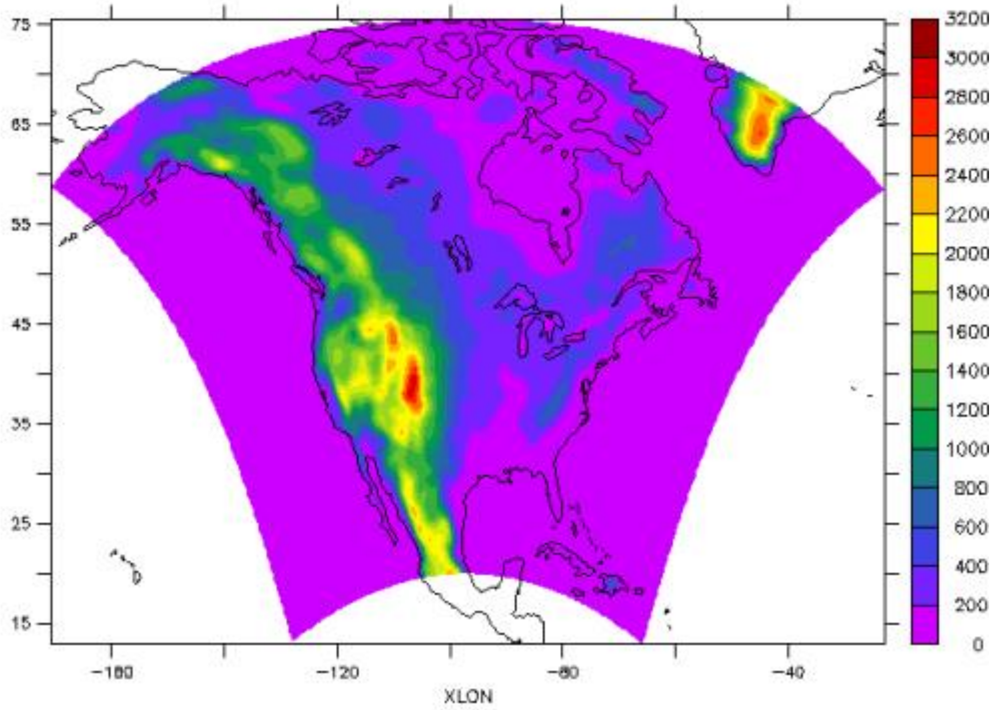
A different approach from our previous collaborative projects with WaterSMART and HydroLogics was used for producing projected extremes for the Red Deer River Basin than for the Bow, Oldman and South Saskatchewan River Basins. This was because the previously-used GLS modelling, using the climate indices as inputs (St. Jacques *et al*., 2010; 2013; Sheer *et al.*, 2013; Sauchyn *et al., in prep*.), did not explain a sufficiently large amount of the variance (a 50% threshold was used). Perhaps this was because the hydroclimatology of the Red Deer Basin is transitional in between the North and South Saskatchewan River Basins which behave quite differently, or perhaps there is a large groundwater component to the Red Deer's flow.

Certainly the Red Deer River Basin has a much smaller amount of Rocky Mountain headwaters in comparison to the southern Alberta rivers that were previously modelled. For the Red Deer Basin, surface and subsurface run-off term (mrro) was used from regional climate models (RCMs), following the approach of González-Zeas *et al*. (2012). Because it is unknown which RCM will best model future climate, a set of nine RCM runs was used from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns *et al*., 2007; 2009), together with one RCM run from the Canadian Centre for Climate Modelling and Analysis.

NARCCAP is an international co-operative program aiming to produce high-resolution climate change simulations to examine uncertainties in regional-scale projections of future climate and to generate climate change scenarios for use in impacts and adaptation research (http://www.narccap.ucar.edu/about/index.html). NARCCAP modellers from around the world have run a set of RCMs driven by a collection of general circulation models (GCMs) over a domain spanning the United States and most of Canada (Figure E1, Tables E1 and E2). The RCMs simulate the climate of a region at a high resolution, whereas the GCMs simulate the climate of the entire world at a lower resolution. The RCMs are nested within the GCMs, *i.e*., a limited area RCM is forced with inputs such as winds, temperature and geopotential height, at the RCM's boundaries by output from a GCM. Nine RCM/GCM combinations were used (Table E3). NARCCAP produced only runs for the current period (1971-2000) and for the future period 2041-2070. The GCMs have been forced for the 21st century by the SRES A2 emissions scenario (a high emissions scenario). Given recent emissions of GHGs at a rising rate (WMO 2014), A2 is increasingly a relevant and reasonable emission scenario. Control simulations with these GCMs were also produced for the current (historical) period. All the NARCCAP RCMs are run at a spatial resolution of 50 km.

Table E1: NARCCAP regional climate models (RCMs) used in this project

Model	Modelling Group	Full Name
CRCM	OURANOS / UQAM	Canadian Regional Climate Model
ECPC	UC San Diego / Scripps	Experimental Climate Prediction Center Regional Spectral Model
HRM3	Hadley Centre	Hadley Regional Model 3
MM5I	Iowa State University	MM5 - PSU/NCAR mesoscale model
RCM3	UC Santa Cruz	Regional Climate Model version 3



FigureE1: Domain spanned by NARCCAP, together with topography (m). Figure courtesy of NARCCAP (http://www.narccap.ucar.edu/about/index.html)

Table E2: NARCCAP global climate models (GCMs) used in this project

GCM	Modelling Group	Full Name
CCSM	National Center for Atmospheric Research	Community Climate System Model
CGCM3	Canadian Centre for *Climate Modelling* and Analysis	Third Generation Coupled Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory	Geophysical Fluid Dynamics Laboratory GCM
HadCM3	Hadley Centre	Hadley Centre Coupled Model, version 3

Table E3: The nine NARCCAP RCM/GCM combinations used in this project

RCM/GCM	GFDL	CGCM3	HADCM3	CCSM
CRCM		x		x
ECPC	x			
HRM3	x		x	
MM5I			x	x
RCM3	x	x		

A run of the CanRCM4 RCM covering the North American region at a spatial resolution of approximately 25 km was also included. It was nested within the CCCma-CanESM2 GCM from by the Canadian Centre for Climate Modelling and Analysis (http://www.cccma.ec.gc.ca/data/canrcm/CanRCM4/index_cordex.shtml). This gives 10 RCM runs in all. The CCCma-CanESM2 GCM was forced for the 21st century by RCP8.5 (a later generation high emissions scenario comparable to the SRES A2 emissions scenario).

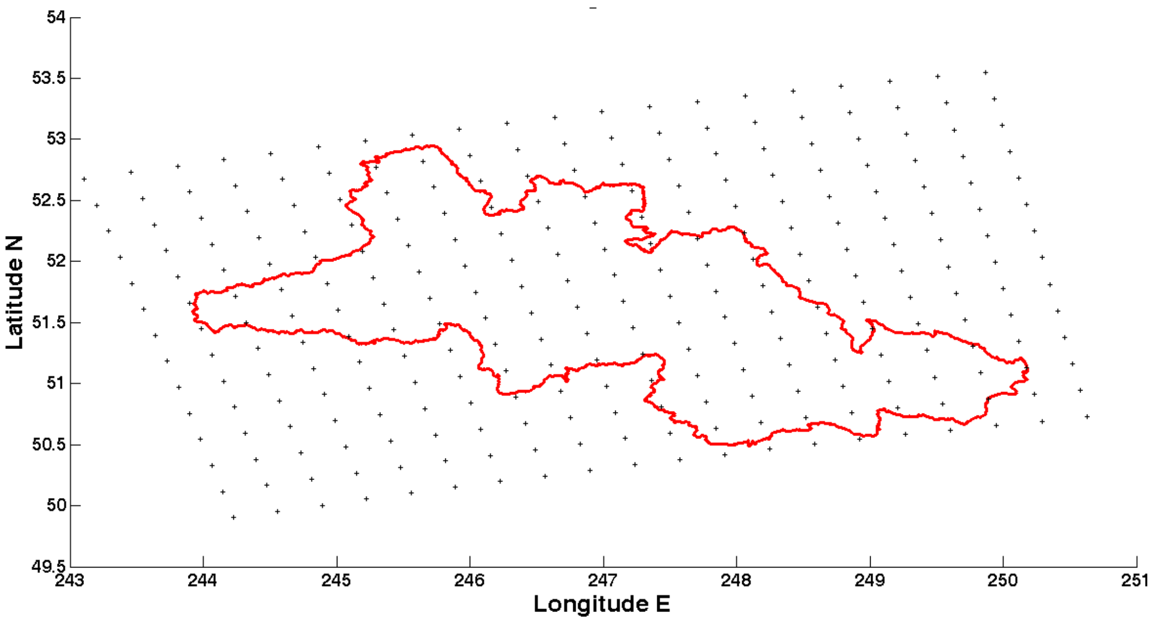


Figure E2: Red Deer River Basin boundaries with the superimposed grid cell centers from CRCM4

Each RCM or GCM partitions its domain into regular grid cells. Each RCM and GCM has its own grid cell pattern. For each of the 10 RCM runs, the grid cells centered within the Red Deer River Basin were identified. For example, Figure E2 shows the boundaries of Red Deer River Basin with the superimposed grid cell centers from CRCM4, 84 of which lie within the boundaries. To estimate the annual run-off from the entire Red Deer River Basin, the 3-hourly mrro data were summed for each water year (October-September) over all the RCM grid cells within the basin. This total summed output over the basin is equivalent to the naturalized river flow from the most downstream gauge at Bindloss, Alberta, just before the Red Deer joins the South Saskatchewan.

To simulate realistically regional hydrology, raw RCM model results have to be bias corrected (Wood *et al*., 2004; Christensen *et al*., 2008; Ashfaq *et al*., 2010; Teutschbein and Seibert, 2012). There are a wide number of different bias correction techniques. The widely-used quantile–quantile (QPPQ) mapping approach was used (Hughes and Smakhtin, 1996; Boé *et al.,* 2007), which is currently considered among the best practices. For a given variable, the cumulative density function (CDF) of a control simulation is first matched with the CDF of the observations, generating a correction function depending on the quantile. Then, this correction function is used to unbias the projected variable from the climate scenario quantile by quantile. From this procedure, the biased-corrected projected mean daily flows for each year were obtained and for each of the 10 RCM runs for both the projected future and simulation periods.

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, 2006b) and Zorita and von Storch (1999) for mapping projected mean daily flows to the daily hydrographs from analog years. Using a kernel density smoother, the average CDF of all the bias-corrected projected mean daily flows for the period 2041-2070 was derived, as well as an empirical CDF from the historical (1912-2009) naturalized mean daily flows of the Red Deer River at Bindloss (Figure E3). By matching flows of equal probability, using a QPPQ transform approach again (Hughes and Smakhtin, 1996), the two closest historical analogs for each RCM and each future year were identified. To arrive at daily flows for projected year, the daily observations from a weighted average of its two analog years were lognormal scaled by the projected values of the mean and standard deviation. A strong quadratic relationship between the mean (μ) and standard deviation (σ) of the historical daily flows ($\sigma = -15.44 + 1.21\mu + 0.0025\mu^2$), permitted scaling of both parameters. By using a randomly (uniform distribution) weighted average of the two closest analog years, we avoided the problem of exact repeats of streamflows from repeatedly chosen analog years.

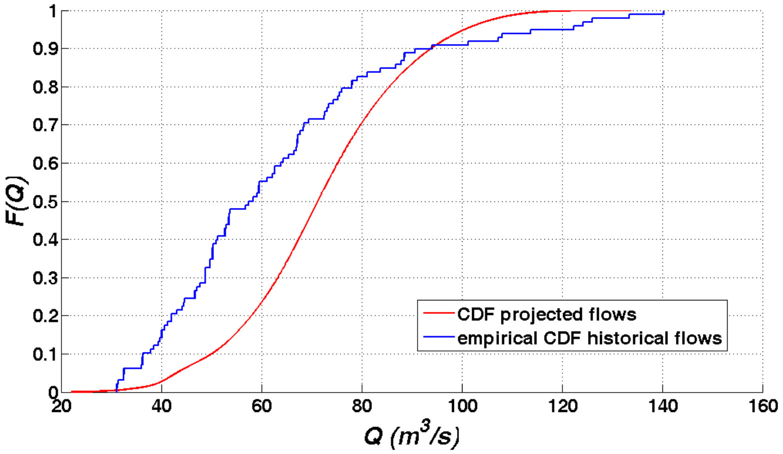


Figure E3: Smoothed average CDF of the bias-corrected projected mean daily flows for 2041-2070 and the empirical CDF of the historical (1912–2009) naturalized mean daily flows of the Red Deer River at Bindloss, Alberta

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). The approach of Stewart *et al.* (2004) was adopted to adjust the timing of the projected mean daily flows. First the date of the center of mass flow (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) was regressed against spring (May-August) air temperature from Olds, Alberta, in the center of the Red Deer Basin. Then this regression model (CT = *294.5 - 4.636 temperature*) was run using bias-corrected projected temperature data for 2041-2070 from all 10 RCM experiments. For each RCM and future year, the daily hydrographs were adjusted by the difference between the projected timing of the CT minus the mean date of the CT for the simulated historical period 1971–2000. On average, there could be an advance of 10.5 days by 2041–2070. The worst case scenario showed an advance of 38 days, more than a month, with the CRCM4 RCM for the year 2067 (Figure E4). This advance of the spring peak may prove challenging to stakeholders, since at the end of summer there will be less water in the river, when it might be particularly needed, depending on what crops are grown.

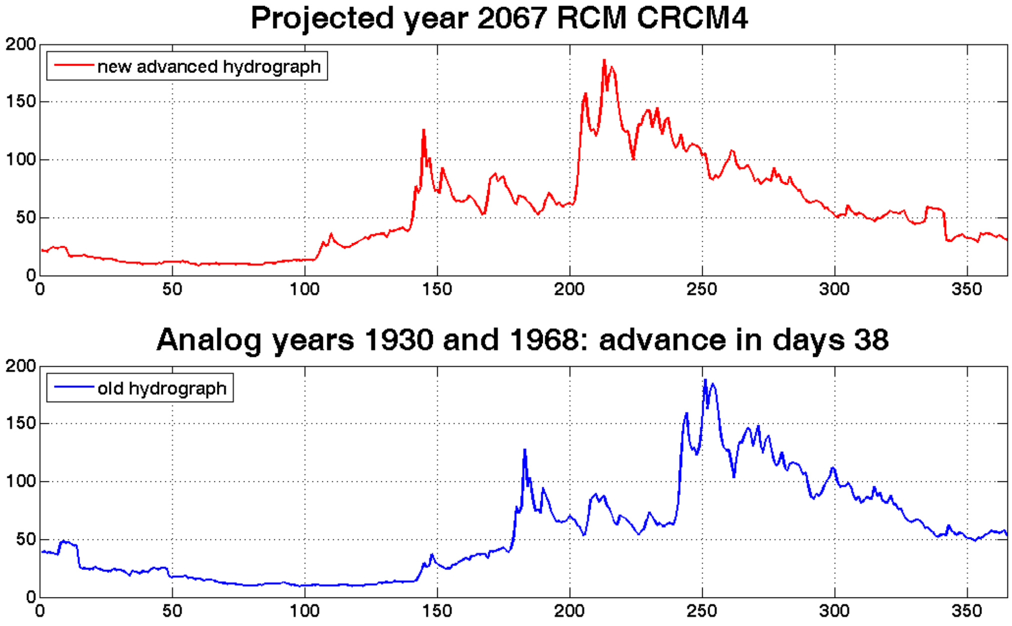


Figure E4: Worst case advance in projected flows: advance of 38 days for the year 2067 from the CRCM4 RCM

Unlike our results further south in Alberta, we found that streamflow on average either stayed the same or was projected to increase for the Red Deer River (Figure E5). Student's *t*-tests of the differences between the bias-corrected simulated runoff for 1971–2000 and the bias-corrected projected runoff for 2041-2070 for each RCM showed significant ($p < 0.05$) future increases for 4 RCMs, and no change for the other 6 RCM runs. The historical naturalized mean daily flow of the Red Deer at Bindloss is 62.7 m^3/s for 1912–2009. The simulated mean daily flow averaged over all the

RCMs for the Red Deer River for 1971–2000 is 62.1 m^3/s. The projected mean flow averaged over all the RCMs for the Red Deer River for 2041–2070 is 70.2 m^3/s. The projected flows should only be compared to the simulated mean flows, and not to the actual flows. The actual flows can be compared to the simulated control flows. These results are different from those found in the Bow, Oldman and South Saskatchewan River Basins in previous SSRB modelling work (Sauchyn *et al., in prep*.). This could be due to the change in methods (*i.e.,* using a GLS statistical downscaling technique versus using the total run-off term out of the RCMs directly). More likely, however, these RCMs are showing that the expected transition between the drier south and the wetter north will occur in the Red Deer River Basin (IPCC, 2013). Further research on this subject is being conducted by PARC.

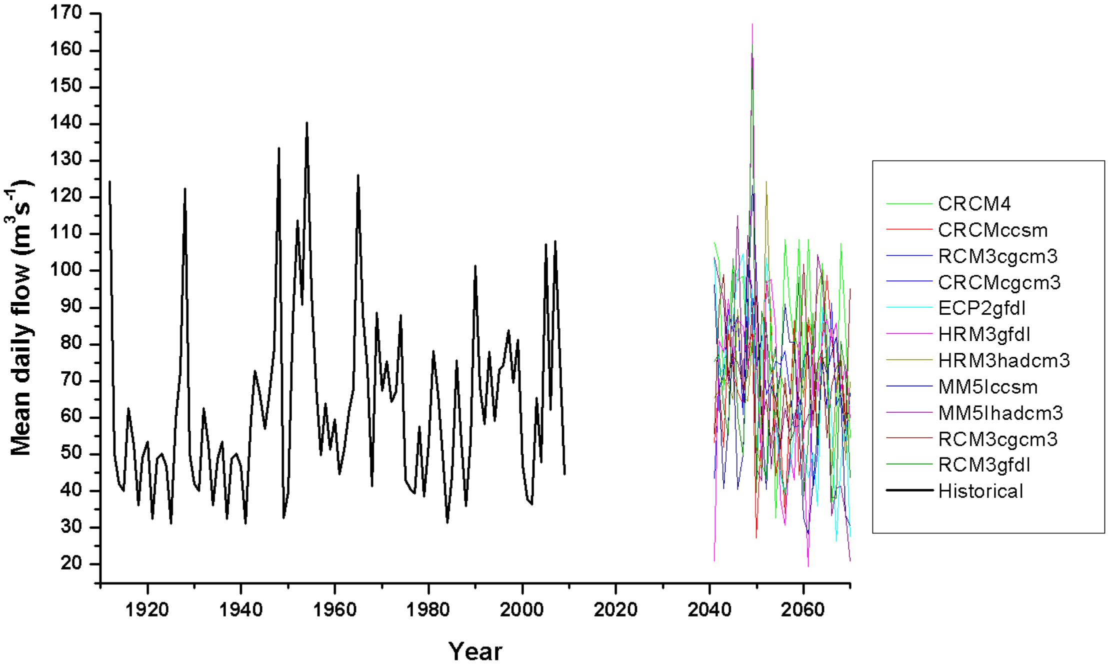


Figure E5: Historical naturalized flows of the Red Deer River at Bindloss (black) and the bias-corrected projected flows from the 10 RCMs for 2041–2070 (colors)

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Appendix F: Land Use Modelling Using ALCES

Described in greater detail by Donahue (2014), predictive predictive models of areal water yield were estimated through regression of data from 53 sub-catchments within the South Saskatchewan River Basin. The response variable was naturalized monthly yield, calculated from Alberta Environment and Sustainable Resource Development's naturalized flow database (2002 to 2009; based on Water Survey of Canada's HYDAT database) and corrected to remove streamflow from upstream sub-catchments. Candidate explanatory variables included attributes related to climate, land cover, and topography, summarized to the sub-catchment scale. Candidate climate variables were monthly and seasonal air temperature and precipitation from the current year. Monthly and seasonal climate from the previous year were also considered, but removed due to low statistical significance. Candidate land cover variables included: water (including wetlands), rock, and ice; forest; grass- and shrub-lands; agriculture; linear disturbance (roads, mines, seismic lines, transmission lines, pipelines, non-productive well sites, and exposed soil or non-vegetated surfaces); and recreational, residential, and industrial footprints. Candidate topographic variables included slope and elevation. Monthly models relating areal water yield to the candidate explanatory variables were created via step-wise multiple linear regression (Table F1).

Table F1. Monthly water yield (mm) relationships calculated from HYDAT sub-catchments within the South Saskatchewan River Basin

Equation	R^2
January water yield = 0.277*slope + 0.07*January_precip + 0.309*January_temp + 16.52*Rec_res_ind – 0.724	0.61
February water yield = 0.242*slope + 0.035*January_precip + 0.249*February_temp – 0.071	0.55
March water yield = 0.029*winter_precip + 40.19*rec_res_ind + 0.616*March_temp + 0.189*slope – 3.962	0.35
April water yield = 0.061*winter_precip = 258.249*lin_dist + 51.012*rec_res_ind + 0.084*April_precip – 11.046	0.36
May water yield = 0.22*winter_precip + 0.348*May_precip – 65.301*water_rock + 25.205*forest – 28.769	0.64
June water yield = 0.258*spring_precip + 0.179*winter_precip – 797.08*lin_dist + 27.124*forest – 20.478	0.66
July water yield = 76.194*water_rock + 0.073*winter_precip – 289.735*lin_dist – 1.32*July_temp + 15.426	0.62
August water yield = 68.103*water_rock + 0.017*elevation + 0.096*July_precip + 0.027*winter_precip - 24.98	0.68
September water yield = 0.609*slope + 0.148*August_precip + 0.166*September_precip – 12.362	0.52
October water yield = 0.071*summer_precip + 0.034*spring_precip + 0.753*slope – 23.54*water_rock – 0.011*elevation – 12.28	0.64
November water yield = 0.136*November_precip + 0.3*slope + 0.012*spring_precip + 0.455*November_temp + 23.152*rec_res_ind + 0.011*summer_precip – 7.767	0.59
December water yield = 0.212*slope + 0.009*spring_precip + 0.039*November_precip + 0.012*summer_precip – 4.042	0.53

Note: Explanatory variables include the watershed's average slope and elevation, monthly and seasonal precipitation (i.e., precip) in mm, monthly and seasonal average temperature (i.e., temp), and proportion of watershed that is recreation/residential/industrial footprint (rec_res_ind), linear disturbance (lin_dist), water/rock/ice (water_rock), or forest.

The yield models were tested by comparing estimated yields for the five watersheds within the Red Deer Basin to yields calculated from naturalized flow data, for the years 2005 to 2009. The models tended to over-estimate yield in high-flow months and under-estimate yield in low-flow months. However, estimated annual yields (i.e., sum of monthly yields) agreed well with annual yields calculated from naturalized flow data. As a result, application of the yield models was limited to calculation of simulated annual, as opposed to monthly, streamflows.

For each watershed in the Red Deer Basin, the predictive yield models were applied to estimate monthly yield associated with simulated future landscape composition, and the absolute values of monthly yields were summed to calculate annual yield. Fifty years of historical climate data (1959 to 2009) were used when calculating yield for a 50-year forecast, such that each simulation year utilized a different year of historical climate data. The sequence of the historical years was randomized prior to application for calculating yield, with the same randomized sequence used for each simulation. The sequence of years was randomized because the intent in using the historical data was to apply appropriate climate values when estimating future yield, rather than replicate historical trends in climate and yield.

Wetlands can moderate streamflow by storing surface water. The statistical modelling that was applied to estimate relationships between yield and climate, land cover, and topography was not suited for estimating the effect on wetlands on streamflow. Instead, results from a detailed study on the hydrology of wetland complexes were applied. The research was conducted to develop the wetland module for the Prairie Hydrological Model using hydrological data from Smith Creek Research Basin in Saskatchewan (Pomeroy et al., 2014). The study found total flow volume to be sensitive to wetland loss, and derived a relationship between wetland area and percent change in annual flow. For the purposes of the Red Deer Basin study, the relationship was summarized as $y = 54.36 - 6.20x + 0.12x^2$ ($R^2 = 0.999$), where y is percent change in annual flow and x is percent of watershed existing as wetland. The relationship was applied to calculate proportional change in flow based on reduction in wetland cover between 2010 and future simulated years for each watershed. Proportional change in flow was then applied as a modifier to adjust simulated annual flow as calculated from the predictive models of areal yield described previously.

Forest age was another aspect of land cover not addressed by the predictive yield models. Using relationships between yield and coniferous forest age (Jones and Post, 2004) and deciduous forest age (Hornbeck et al. 1997), annual yield modifiers were derived (Table F2) to incorporate the effect of future changes in each watershed’s forest age as simulated by ALCES. For each watershed, eight scenarios of forest disturbance (i.e., combined effect of forestry and fire) were simulated to explore the consequences of low (100 year return interval; 1%) versus high (50 year return interval; 2%) disturbance rate and various temporal distributions of disturbance (equally across years, or concentrated into large disturbance events occurring every decade or every other decade). The modifiers were combined with the predictive yield models to incorporate the influence of forest age into yield estimates. The modifiers were only applied to forested portions of watersheds.

Table F2. Multipliers applied to annual yield to incorporate the effect of forest age

Forest age	Coniferous forest yield multiplier	Deciduous forest yield multiplier
1-20	1.201	1.055
21-40	1.103	0.994
41-60	1.041	0.994
61-80	1.002	0.994
81-100	0.977	0.994
101-120	0.935	0.994
121-140	0.935	0.994
141-160	0.935	0.994
161-180	0.935	0.994
181-200	0.935	0.994

Simulated annual streamflows were disaggregated into daily streamflows based on the distribution of annual streamflow across days in historical naturalized daily hydrographs for each watershed. Hydrographs from 1959 to 2009 were used for the disaggregation, in the same randomized sequence as used for the climate data. A limitation of using historical hydrographs to disaggregate annual flow is that the distribution of flow across days is not only affected by climate but also by landscape composition. In particular, loss of natural vegetation due to conversion to farmland or other anthropogenic land use is likely to cause more responsive runoff resulting in higher peak flows. To incorporate this dynamic, peak flows (as calculated from simulated annual flow and historical hydrographs) were adjusted to reflect a relationship between natural land cover and peak flow calculated from a selection of watersheds in eastern and central United States that differed with respect to the proportion of forest converted to agriculture (Holland, 1969). The relationship is linear, with every percent reduction in natural land cover resulting in a 3.3% increase in peak flow. For a given simulation year, percent decline in natural land cover relative to 2010 for forested watersheds was multiplied by 3.3 to determine the percentage increase that should be applied to peak flow. This approach may under-represent the extent to which peak flows should be increased relative to older hydrographs (e.g., from the 1960s) because natural land cover declined from approximately 50% to 45% from 1960 to 2010. It was assumed that any effect of natural land cover on annual flow was already represented by the predictive yield models described previously. As such, flow in the 30 days following peak was reduced to produce no net change in annual flow.

The disaggregated daily flows were coupled with OASIS using a partially-automated system developed specifically for this project. Daily flow from each HUC was incorporated into the OASIS model by scaling the total HUC streamflow by the proportion of historical streamflow represented by each of the OASIS streamflow nodes.

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