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.

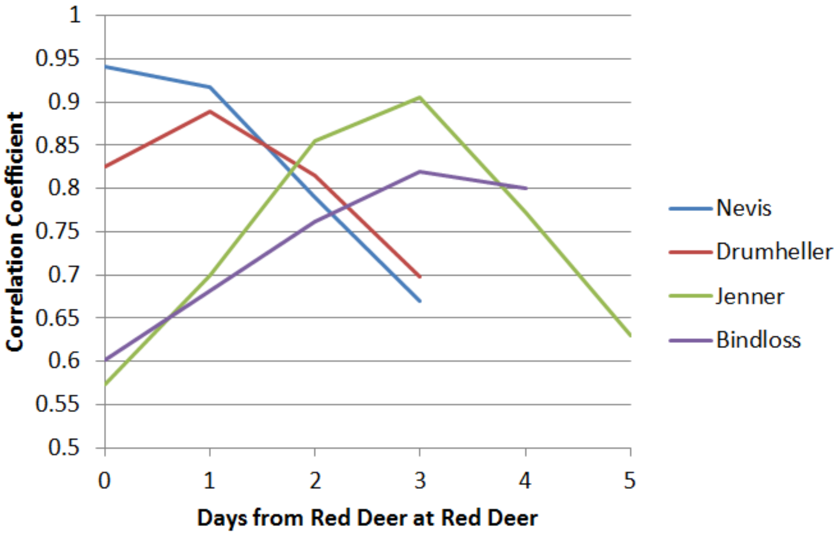


Figure C1: Correlation between flow at Red Deer and flow downstream on subsequent days

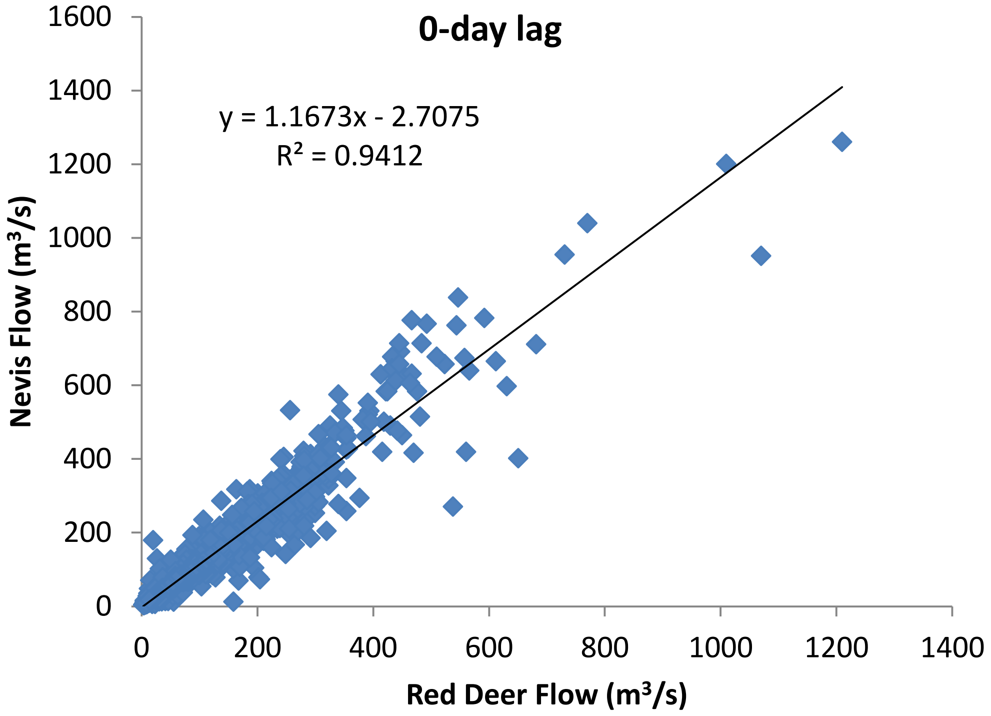


Figure C2: Correlation between flow at Red Deer and flow at Nevis (no lag)

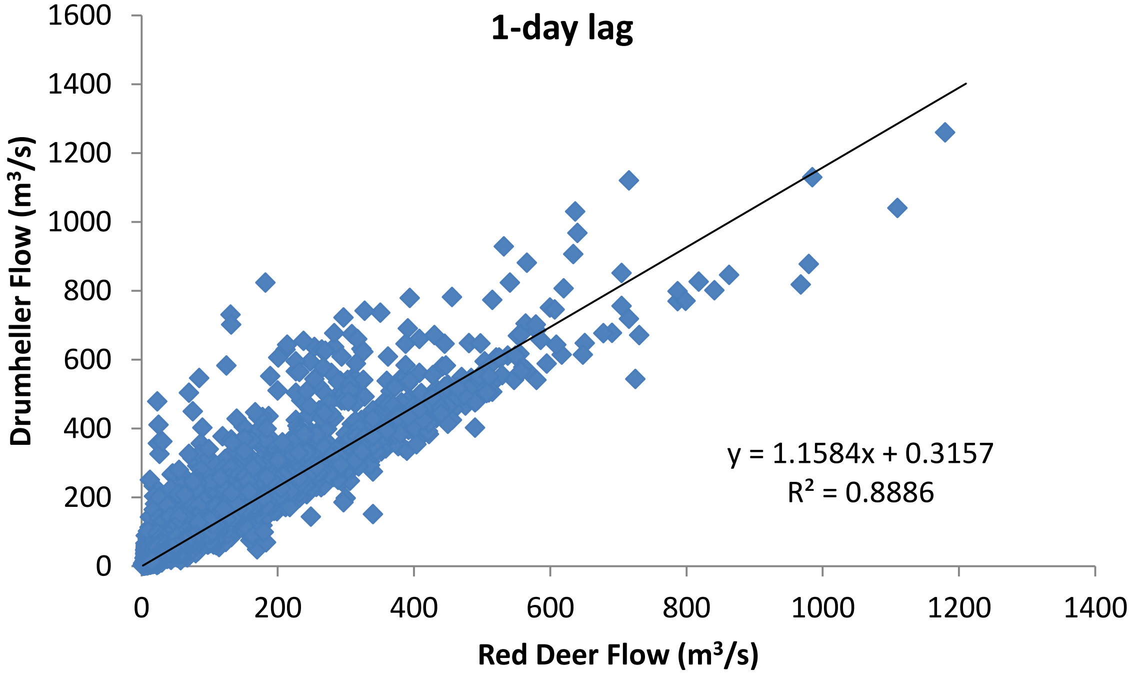


Figure C3: Correlation between flow at Red Deer and flow at Drumheller (1-day lag)

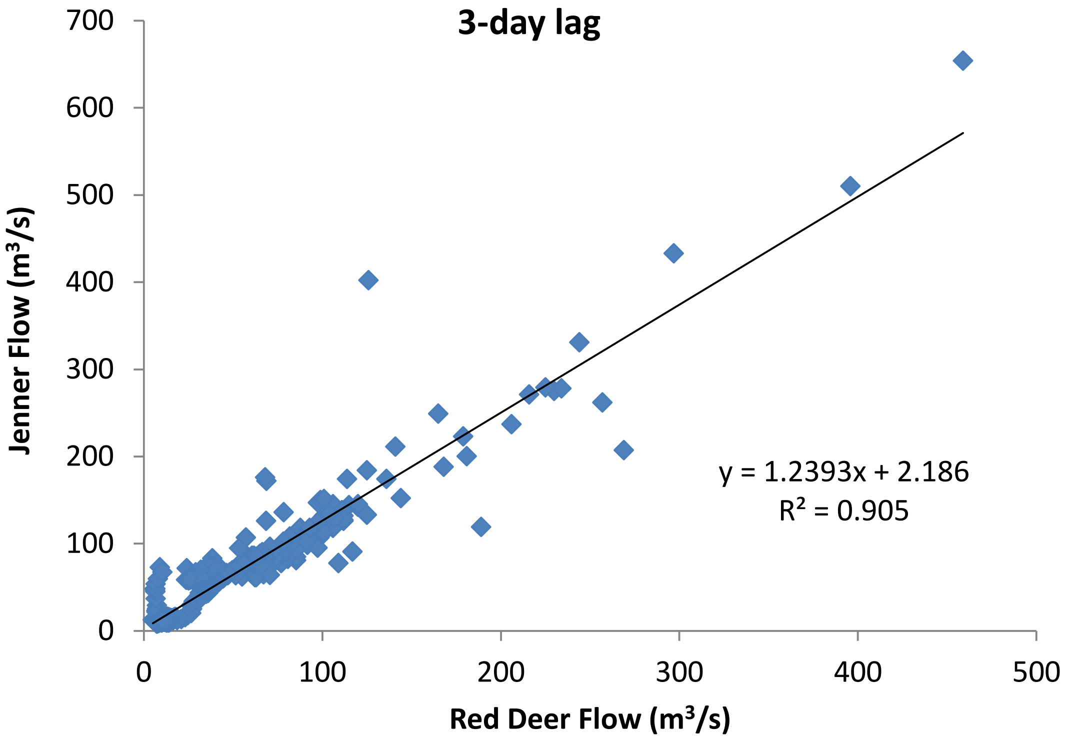


Figure C4: Correlation between flow at Red Deer and flow at Jenner (3-day lag)

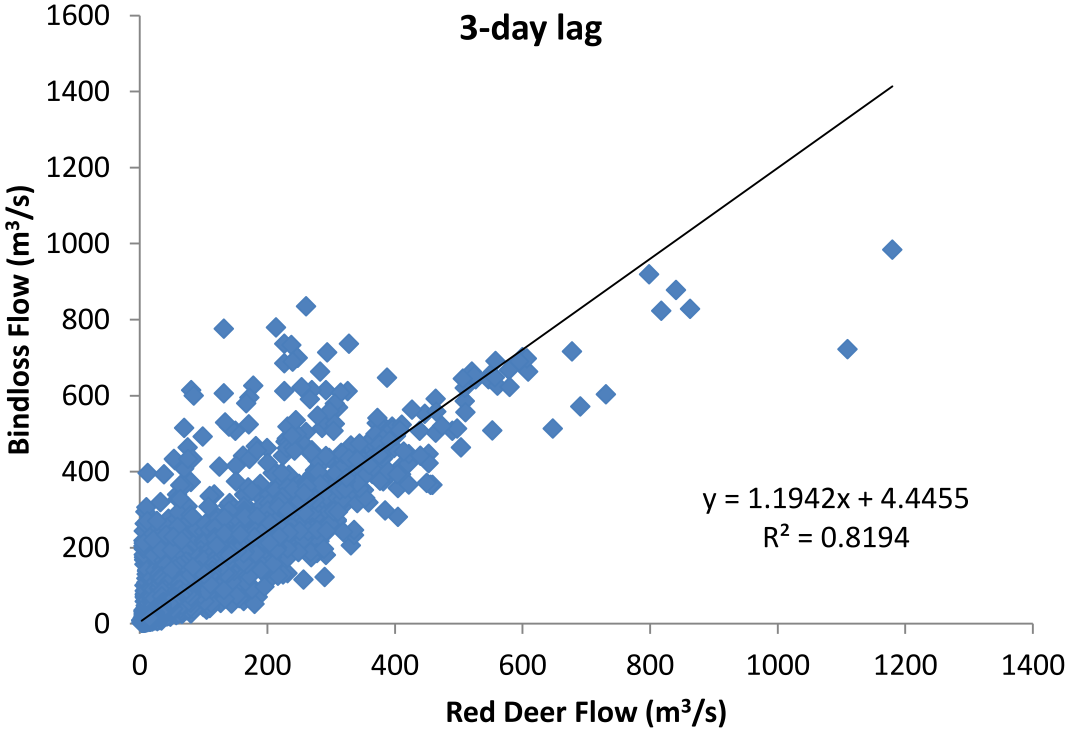


Figure C5: Correlation between flow at Red Deer and flow at Bindloss (3-day lag)

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.

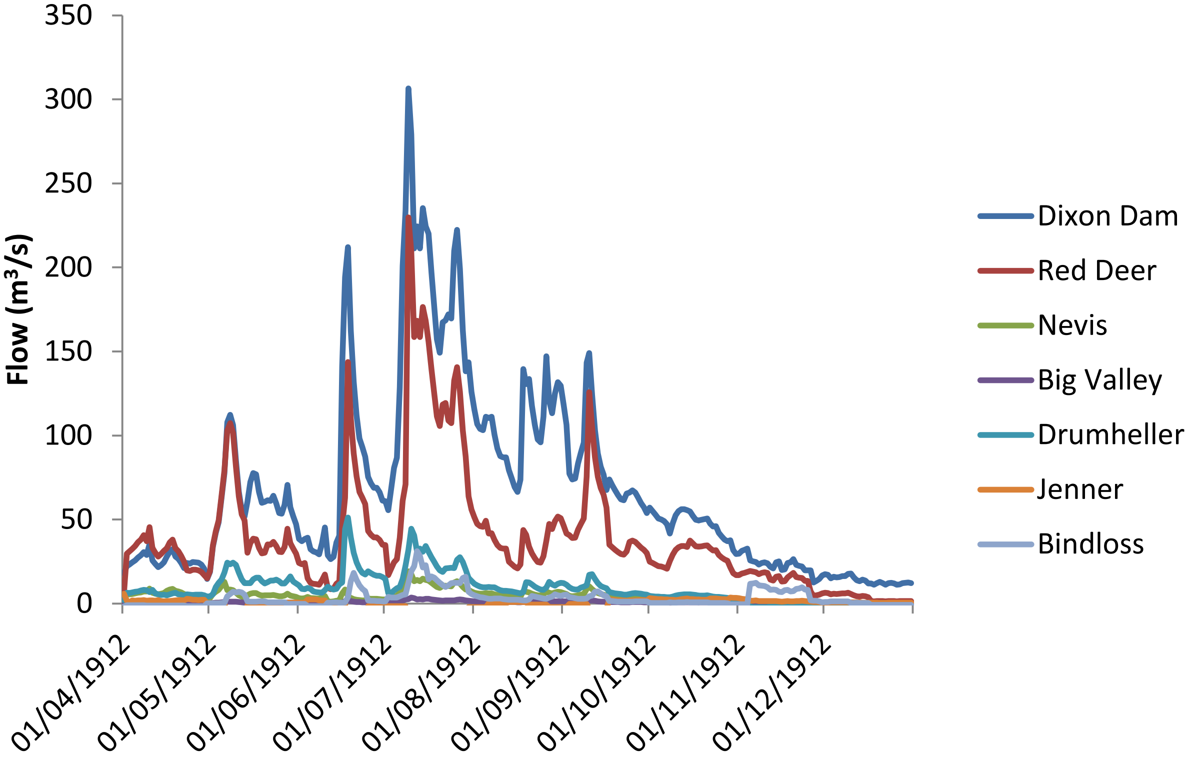


Figure C6: Example of disaggregated flows from April to December, 1912

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.

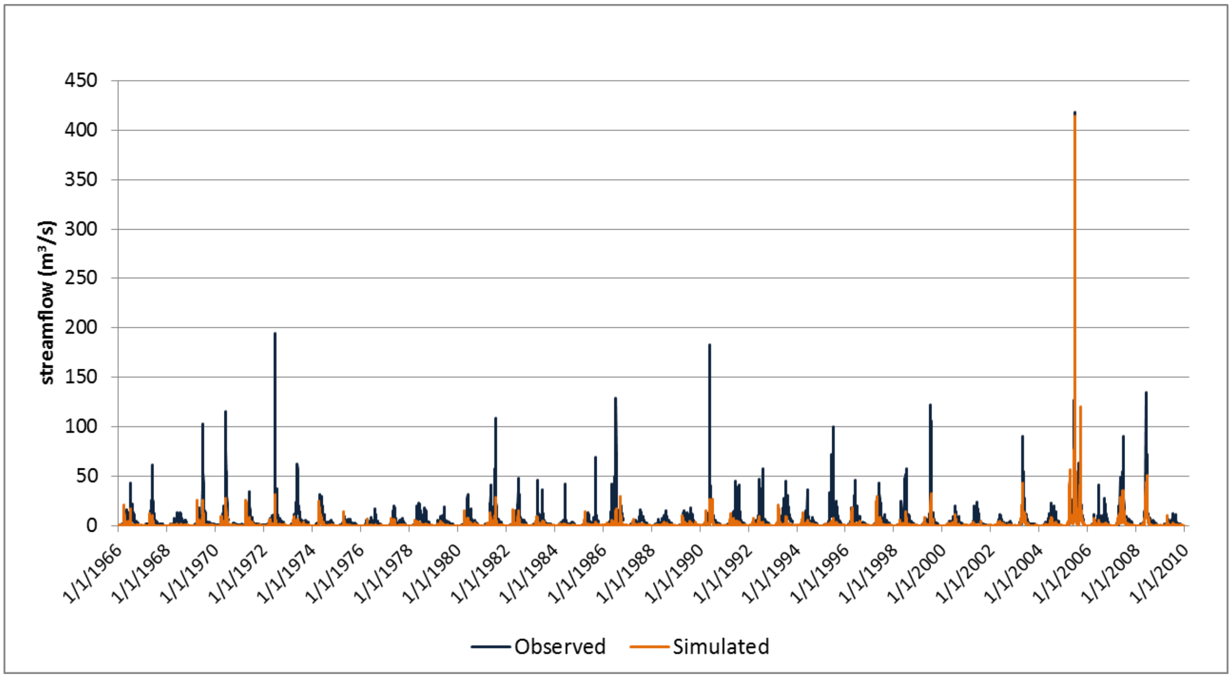


Figure C7: Observed and simulated daily mean streamflow for the James River

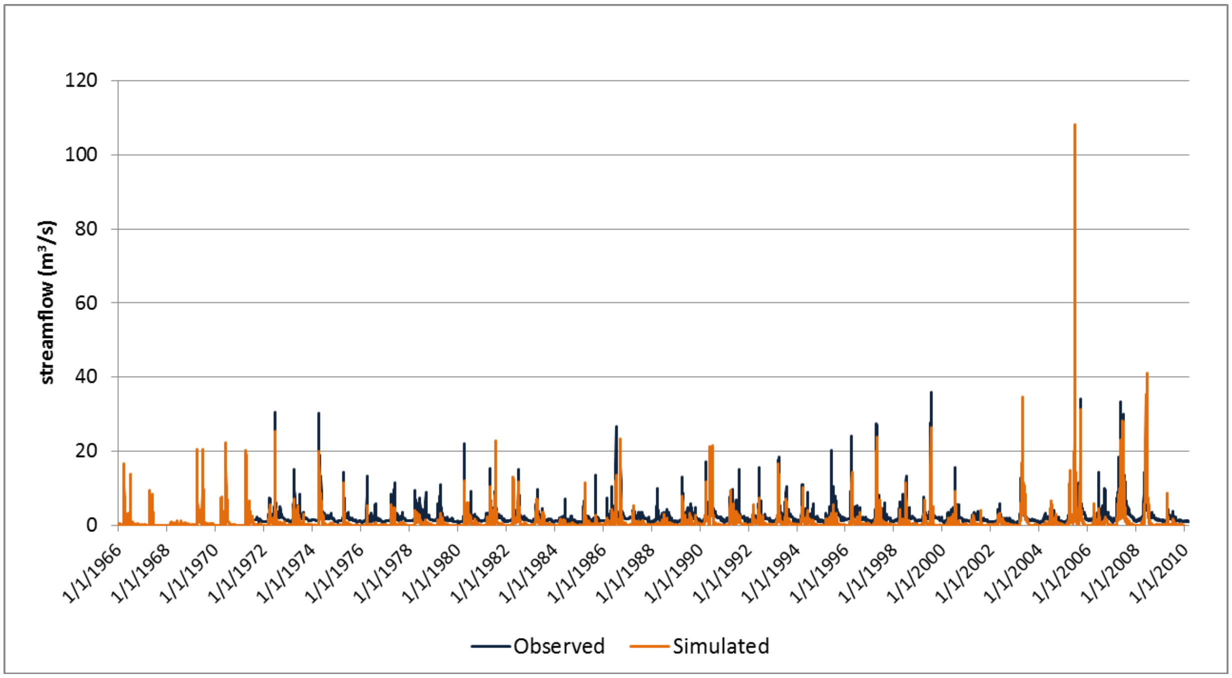


Figure C8: Observed and simulated daily mean streamflow for the Raven River

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.

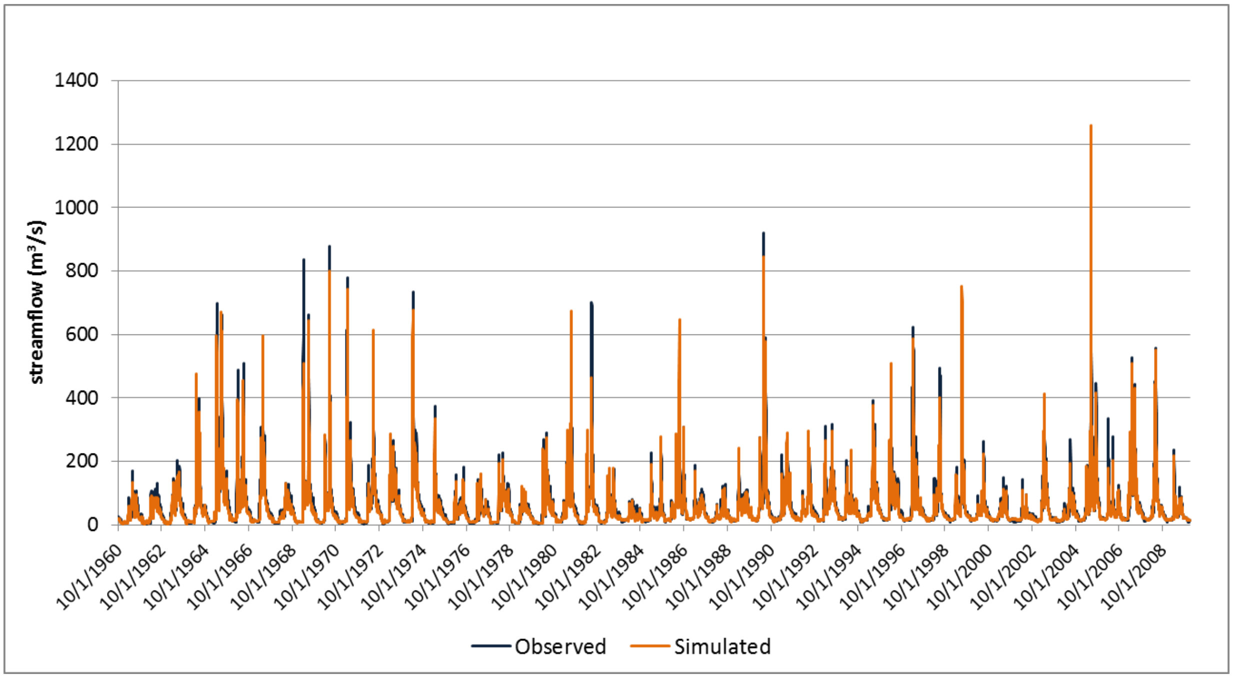


Figure C9: Observed and simulated streamflow in the Red Deer River at Bindloss for the period from October 1, 1960 to December 31, 2009

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:

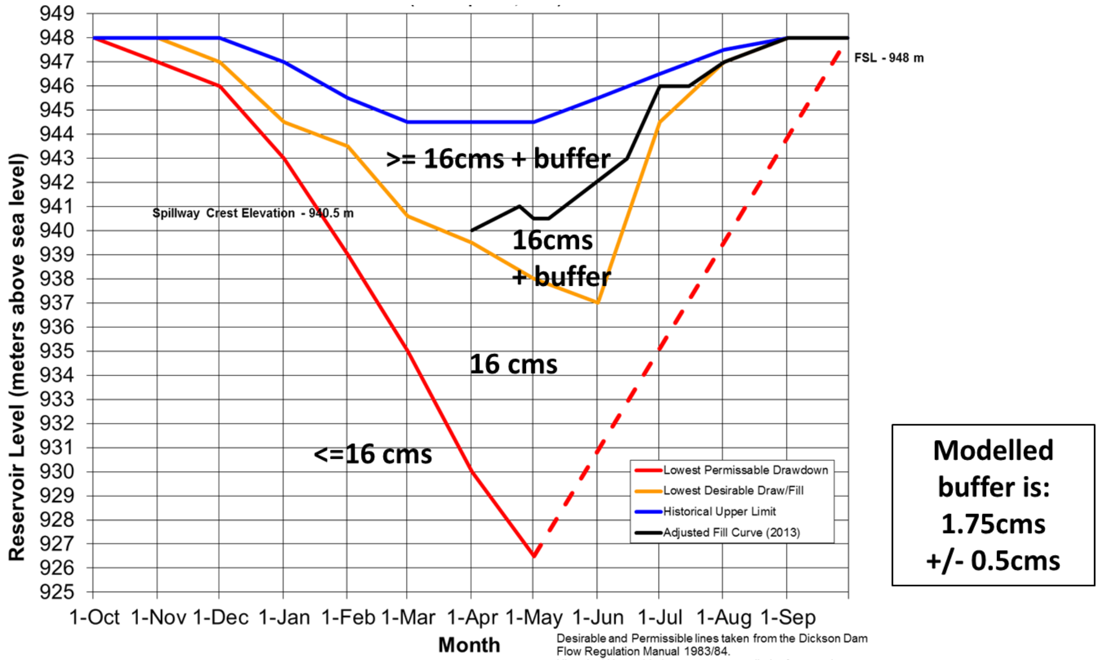
- reservoir operations (a licence is required for a reservoir to store water, but that water would not be removed from the system),
- flood operations (also would not consume water), and
- approximately 90% of the licences applied to Ducks Unlimited (licences are for loss, not consumption, and substantially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

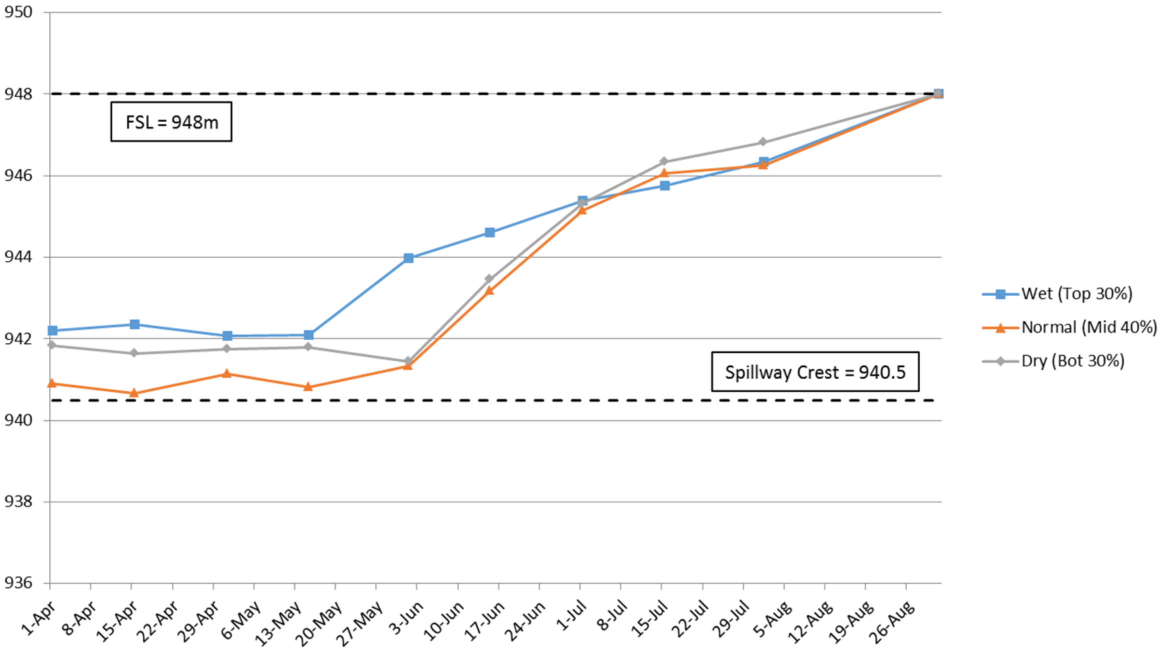


Figure C11. Average Elevation Fill Guide Curves

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).

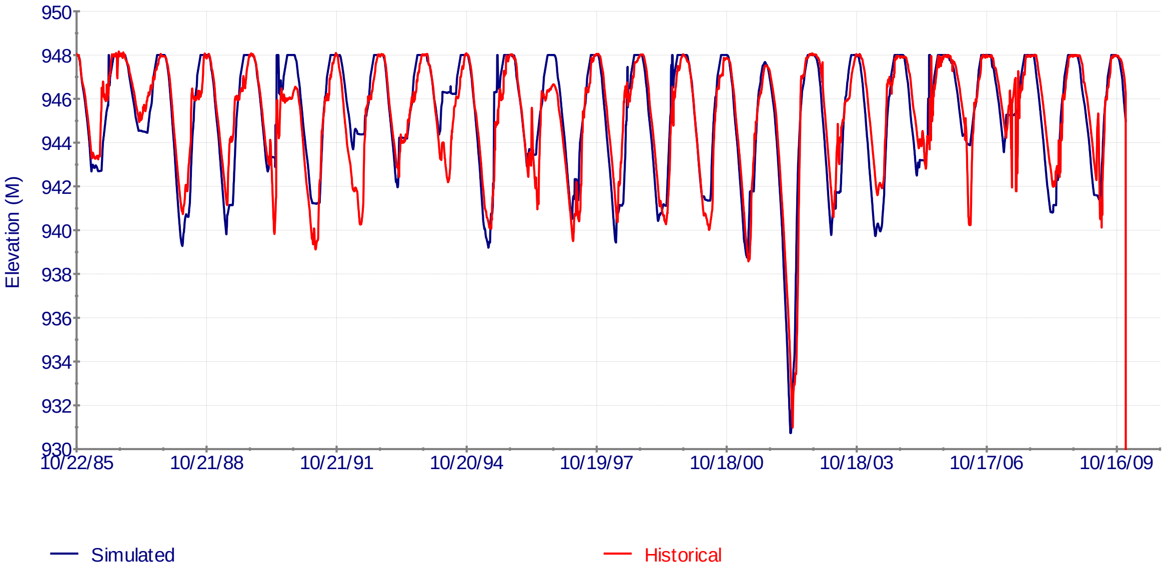


Figure C12. Elevation of Gleniffer Reservoir

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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Stantec Consulting Inc., March 31, 2014. Red Deer River Basin Flood Mitigation Study. PP 4.1-4.16, 5.7-5.31, Appendix H.

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

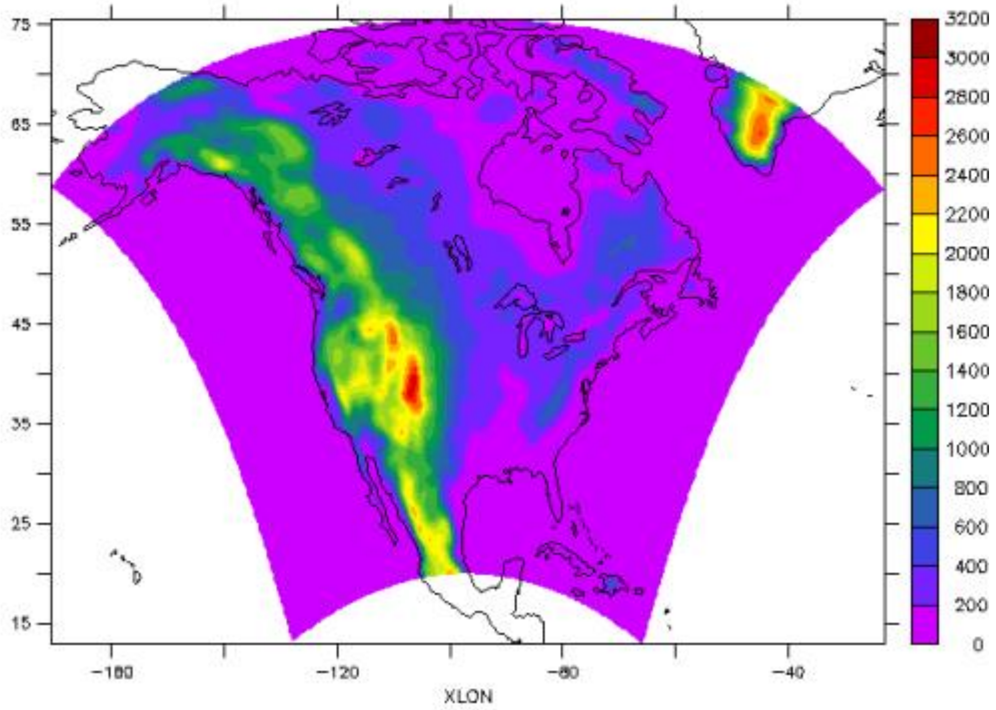
A different approach from our previous collaborative projects with WaterSMART and HydroLogics was used for producing projected extremes for the Red Deer River Basin than for the Bow, Oldman and South Saskatchewan River Basins. This was because the previously-used GLS modelling, using the climate indices 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).

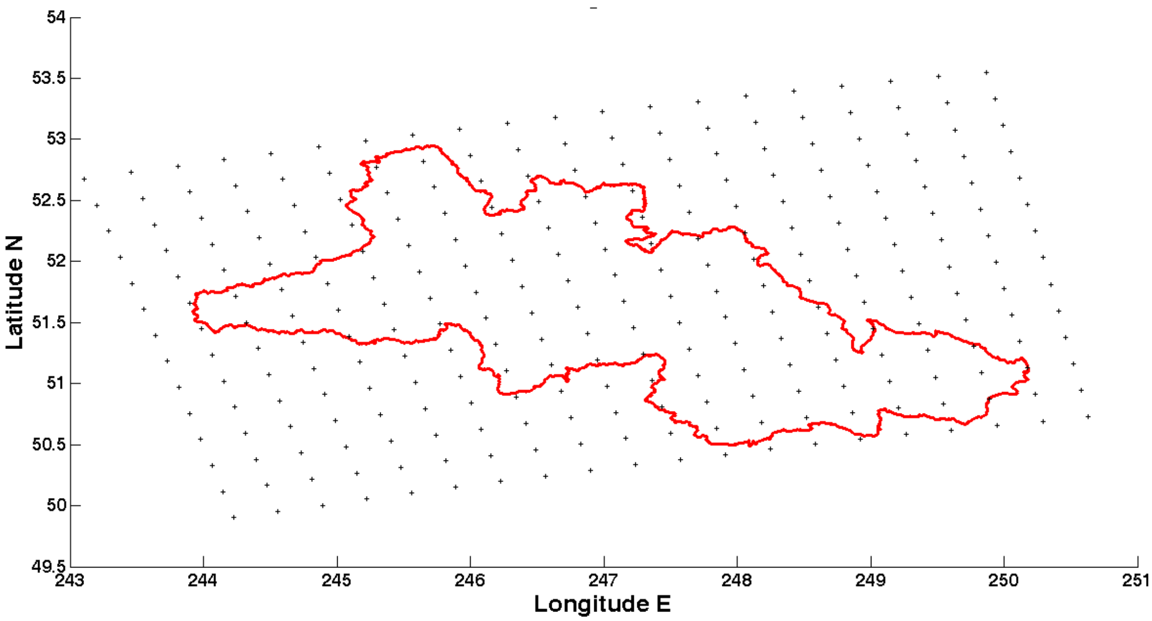


Figure E2: Red Deer River Basin boundaries with the superimposed grid cell centers from CRCM4

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.

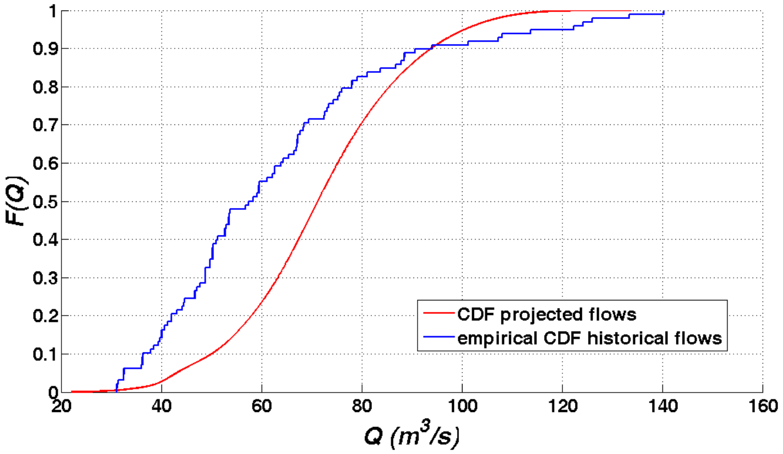


Figure E3: Smoothed average CDF of the bias-corrected projected mean daily flows for 2041-2070 and the empirical CDF of the historical (1912–2009) naturalized mean daily flows of the Red Deer River at Bindloss, Alberta

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.

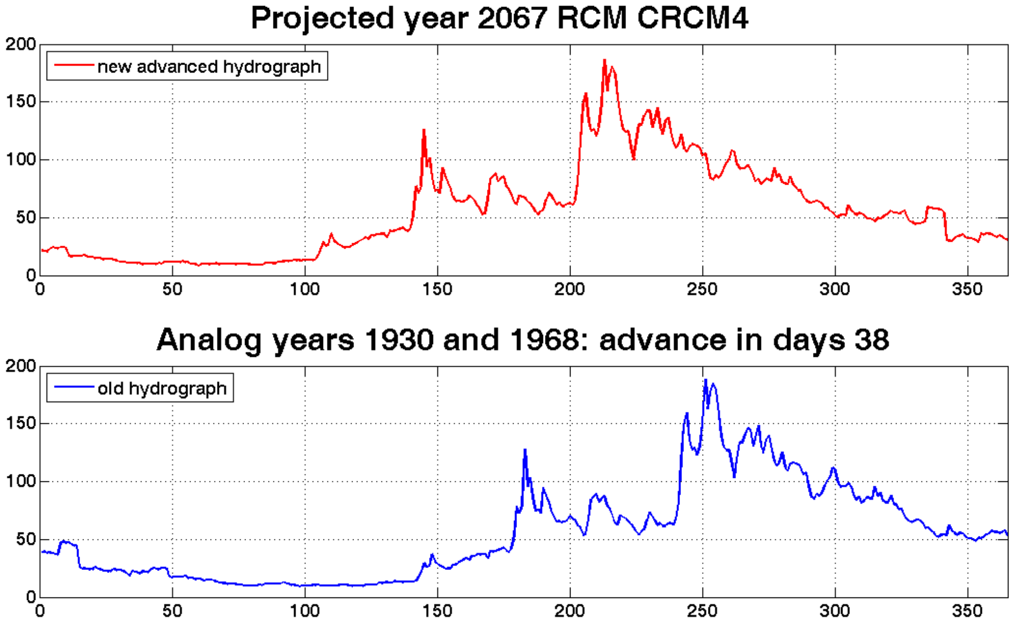


Figure E4: Worst case advance in projected flows: advance of 38 days for the year 2067 from the CRCM4 RCM

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.

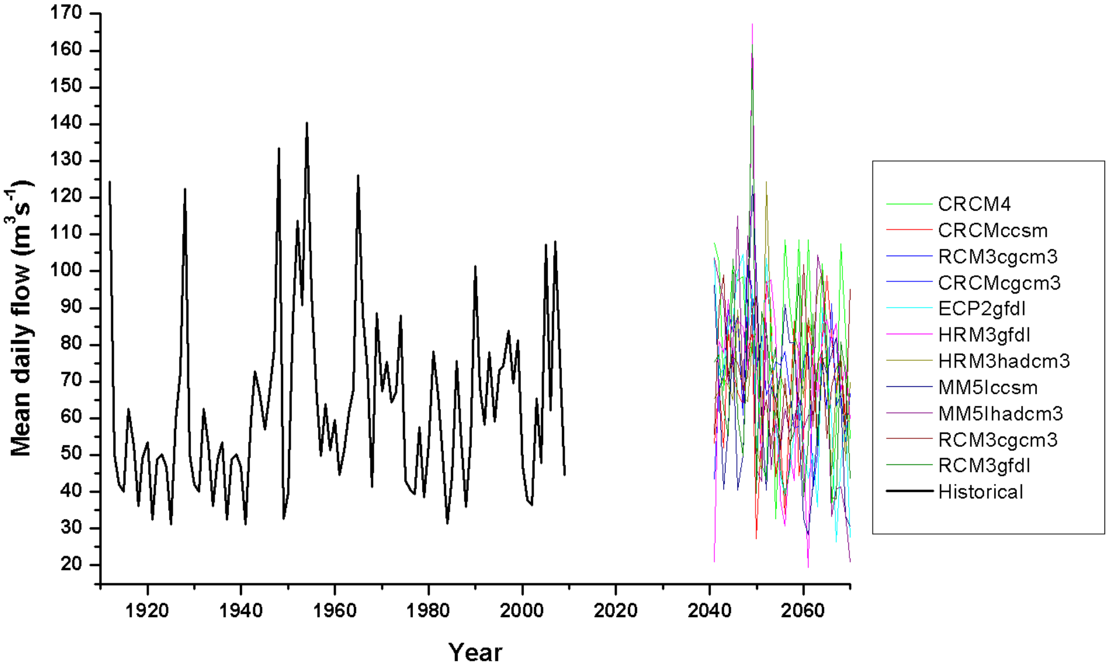


Figure E5: Historical naturalized flows of the Red Deer River at Bindloss (black) and the bias-corrected projected flows from the 10 RCMs for 2041–2070 (colors)

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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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