Chin Reservoir expanded, and expansion balanced

Several strategies were considered that involved Chin Reservoir, some of which had more potential than others. The most promising option (d) was described in Section 4.1. Option (b) was described in the immediately preceding section, and option (c) is discussed here as also showing some promise when modelled.

a) Expanding Chin Reservoir storage by 74,000 cdm (60,000 AF) to reduce the risk of downstream municipal and irrigation shortages.
b) Adding Chin Reservoir at its current capacity to the balancing system.
c) Expanding Chin Reservoir by 74,000 cdm (60,000 AF) and balancing only the new storage (that is, balancing only the 74,000 cdm).
d) Expanding Chin Reservoir by 74,000 cdm (60,000 AF) and fully balancing (that is, the entire amount of existing and new storage was added to the balancing system).

Many irrigators felt that expanding Chin Reservoir by 74,000 cdm (60,000 AF) and balancing only the new storage was a more likely scenario than balancing the whole of this reservoir. Allowing ESRD to balance the additional storage might be considered a reasonable trade-off for expanding the reservoir.

Model results and impacts

Figure 45 shows that expanding Chin Reservoir and balancing only the new storage of 74,000 cdm (the fourth bar in the chart) offer a modest reduction in shortage days during the 82-year period of record when compared with current operations: 303 days, or a reduction of about 8%.

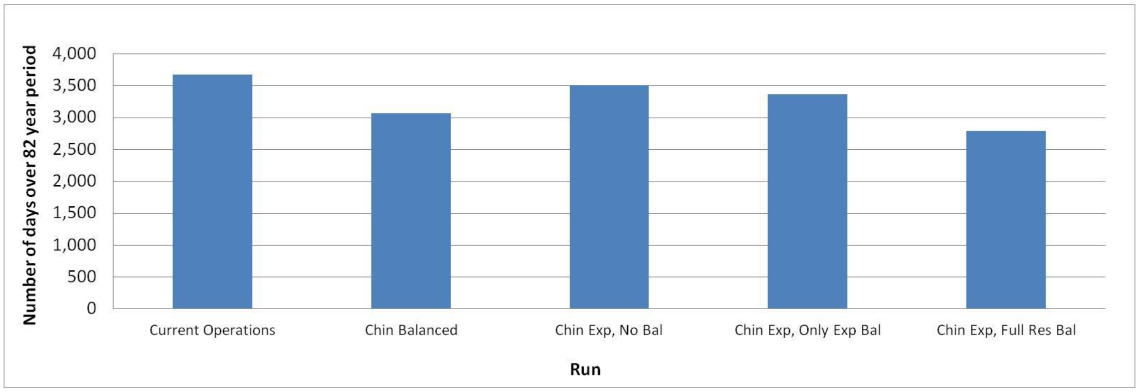


Figure 45: Total number of days in 82-year period with shortages across all irrigation districts

As shown in Figure 46, the effects of this strategy (the purple bar) vary by irrigation district; TID, for example, sees a 45% reduction in shortage days during the 82 years, while MVLA increases very slightly and others see very small reductions. SMRID, for example, has a large, fairly junior licence (1991) so it benefits only after more senior licences have benefitted.

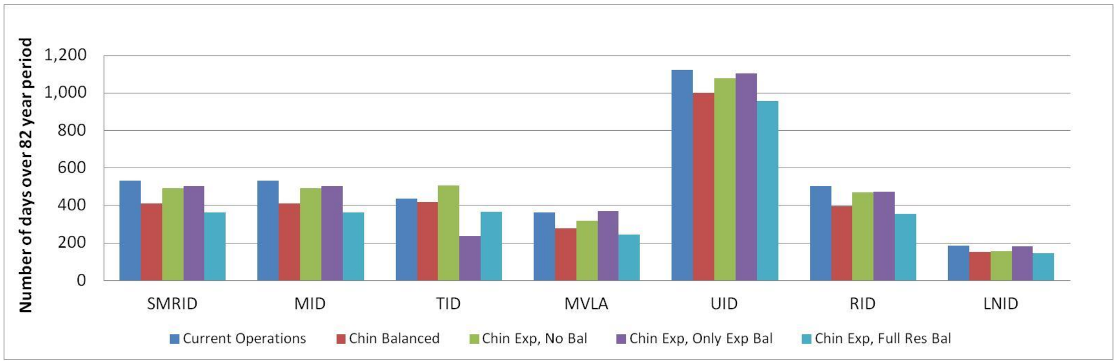


Figure 46: Total number of days in 82-year period with shortages by irrigation district

Relevant OSSK Model run name

CB6.9_ChinBalanced+60kJust60Bal

Drought-modified Fish Rule Curves

This strategy was suggested as a way to improve Fish Rule Curve (FRC) flow reliability by:

- Reducing FRC flow requirements in years where storage did not fill,
- Banking the water thus saved, and
- Releasing that water once storage is otherwise empty to continue meeting the reduced FRC requirements.

This strategy, which could be applied across the OSSK basins, would see the flows needed to meet FRCs reduced during times of drought to make the stored water last longer than it otherwise would. It was recognized that the FRCs are already written in a flexible manner to reflect flow conditions and this strategy aimed to increase that flexibility. If reservoirs are emptied to meet the full FRC, the result could have a greater impact on fisheries than a reduced flow. In drought conditions, factors such as dissolved oxygen and water temperature have a critical influence on fish. It was noted that fish have adapted to stressful conditions, and can handle “natural” low flow infrequently, but the third or fourth year of a drought would be problematic.

In years where the snowpack or soil moisture point to a potentially dry summer, some of the stored water released for instream flow support in the spring could instead be conserved in a storage bank to supplement the required instream flows in the summer. Water that is banked when flows are higher, and later released, would be used only for FRCs, which would help mitigate the effects of higher summer water temperatures and lower dissolved oxygen levels. The bank’s release thresholds could be adjusted as well as how fast and how often it releases water. If reservoirs refilled, this does not become an issue as releases can return to the normal FRC obligations.

Model results and impacts

This strategy has not yet been tested in the OSSK model. Instead, to assess the potential of this approach, the model was used to calculate the volume of storage in St. Mary and Waterton reservoirs used for instream flow support from February 1 to April 30 (Table 3). This calculation was done by running the OSSK model with and without the instream flow requirements and comparing drawdown in the reservoirs. Twenty percent of this volume (as an example of the amount that could be conserved) is shown for the years with the lowest 20% of natural flow at Lethbridge from June 1 to August 31. The next two columns show the daily supplementation level of this banked storage for 60 or 20 days during the summer. More than half of these years could provide more than four cms of supplementation for 20 days under these assumptions.

Table 3: Potential benefits of drought-modified FRCs in selected years

	20% of storage used to meet FRCs from Feb 1 to April 30	Daily supplement available for 60 days in the summer		Daily supplement available for 20 days in the summer	
Year	**cdm**	**cdm/day**	**cms**	**cdm/day**	**cms**
1931	6942	116	1.34	347	4.02
1936	12902	215	2.49	645	7.47
1939	4527	75	0.87	226	2.62
1940	10042	167	1.94	502	5.81
1941	4577	76	0.88	229	2.65
1944	7504	125	1.45	375	4.34
1949	6243	104	1.20	312	3.61
1973	4040	67	0.78	202	2.34
1977	6018	100	1.16	301	3.48
1984	8821	147	1.70	441	5.10
1985	15592	260	3.01	780	9.02
1987	0	0	0.00	0	0.00
1988	11050	184	2.13	553	6.39
1992	7054	118	1.36	353	4.08
1994	0	0	0.00	0	0.00
2000	796	13	0.15	40	0.46
2001	11848	197	2.29	592	6.86

FRCs are written to vary with the climate and water supply and are a surrogate indicator for the full aquatic environment, not just fisheries health. FRC licence conditions have various policy and regulatory implications, and it is important to ensure that others (e.g., junior licence holders) are not being affected if FRCs are not met for part of the year. It could also be a challenge to ensure that when water is released for FRCs, it is not diverted for other uses.

This strategy shows some promise, but would require additional monitoring and more information to determine what the potential benefits might be in terms of meeting dissolved oxygen and water temperature criteria. Time of travel would also need to be factored in and the success of the strategy would depend on accurate forecasting.

Opportunities to adjust minimum flows in the Southern Tributaries to meet FRCs during part of the year (e.g., 10% or 20% adjustment) were also examined. However, there is so much demand already in this region that there appears to be little room for adjustments, and realistic opportunities would be limited in water short years.

Relevant OSSK Model run name

N/A

4.3 Strategies with Limited Promise

The strategies in this third category were shown to have limited promise and could not provide many benefits under conditions of climate variability, in particular drought, compared to the strategies in Sections 4.1 and 4.2. Of the six strategies in this section, the first three pertain to specific geographic locations, while the last three apply more generally across the OSSK basins.

Full strategy title	Short title for PM charts
Category 3: Strategies with limited promise	
1m additional storage in existing St. Mary Reservoir	N/A
Chin Reservoir expanded without balancing	Chin exp, no bal
Downstream dry dam for flood control	N/A
Simple triggered shared shortages	N/A
Lower FSL in all ESRD reservoirs by 2m when needed until July 1	N/A
Developing a storage reserve	N/A

1 metre additional storage in existing St. Mary Reservoir

Since Kimball Reservoir seemed to have substantial downstream benefit, but also required substantial cost, the question was asked whether it might be possible to gain some of that benefit with much less cost by expanding St. Mary Reservoir. It is not known if the current dam infrastructure could accommodate this expansion; as well, there could be significant land impact trade-offs, and the maximum possible increase would be only about one metre. This 1-metre increase in storage was modelled, assuming that the additional 1 metre would have the same storage-elevation relationship as the preceding 1 metre. Preliminary modelling indicated this increase would add only approximately 24,600 cdm (20,000 AF) of storage, which was not enough to substantially improve performance in the system. This strategy could be re-examined in future, but perhaps only in combination with other alternatives.

Chin Reservoir expanded without balancing

Several strategies were considered that involved Chin Reservoir, some of which had more potential than others. The most promising option (d) was described in Section 4.1 and those with some promise (b and c) were described in Section 4.2. Option a) was considered to have limited promise.

a) **Expanding Chin Reservoir storage by 74,000 cdm (60,000 AF) to reduce the risk of downstream municipal and irrigation shortages,**
b) Adding Chin Reservoir at its current capacity to the balancing system,
c) Expanding Chin Reservoir by 74,000 cdm (60,000 AF) and balancing only the new storage (that is, balancing only the 74,000 cdm), and
d) Expanding Chin Reservoir by 74,000 cdm (60,000 AF) and fully balancing (that is, the entire amount of existing and new storage was added to the balancing system).

Expanding Chin Reservoir by 74,000 cdm (60,000 AF) but not balancing any of the storage showed limited promise when modelled, and is discussed below.

Model results and impacts

The number of irrigation shortage days during the 82-year period of record (Figure 47) shows that simply expanding Chin Reservoir without adding any of the storage to the balancing system (the third bar in the chart) provides very few improvements in performance. During the 82-year historical record, this strategy results in just 158 fewer shortage days (a 4% reduction) compared with current operations.

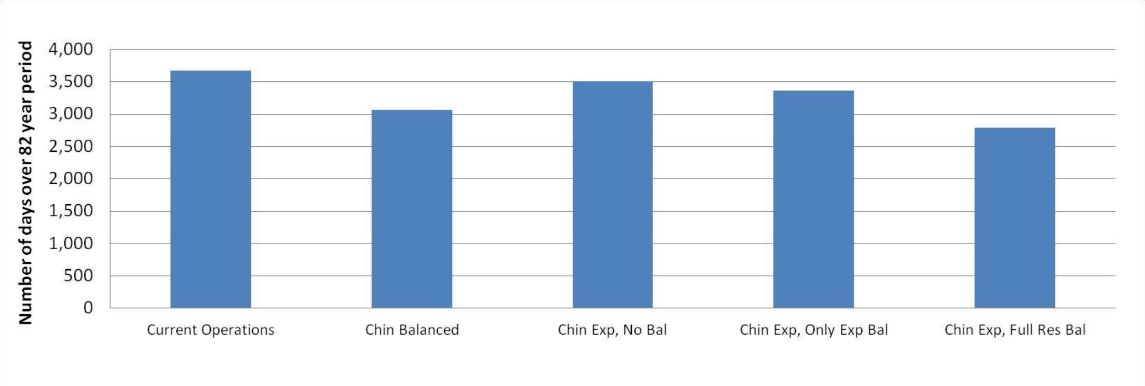


Figure 47: Total number of days in 82-year period with shortages across all irrigation districts

As shown in Figure 48, the effects of this strategy (the green bar) vary by irrigation district; TID, for example, sees a 15% increase in shortage days during the 82 years, while other districts experience very small reductions.

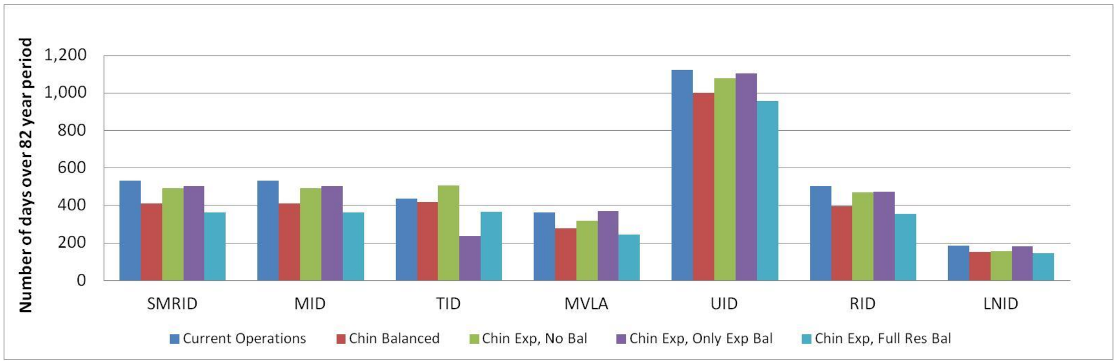


Figure 48: Total number of days in 82-year period with shortages by irrigation district

As noted earlier, strategies that involve adding Chin Reservoir to the balancing system provide more benefits to the overall system than simply expanding the reservoir.

Relevant OSSK Model run name

CB6.9_Chin+60k-NoBalance

Downstream dry dam for flood control

This strategy considered what could be done to increase flood protection for Medicine Hat. Various flood mitigation options are being actively considered, including buying out infrastructure on the Medicine Hat flood plain and/or building berms or barriers, but there is still uncertainty about appropriate mitigation targets and berm height. Some flood mitigation options for Medicine Hat are being examined by the Government of Alberta Flood Recovery Task Force. One strategy considered in this project was a dry dam in the lower basin for flood control (Figure 49, node 650). A dry dam is an onstream detention structure that temporarily detains high flows but allows normal flows to pass without hindrance and does not permanently hold water. It is built much like a full service dam and to full dam safety standards, but only stores water for short durations during and immediately following a flood event.

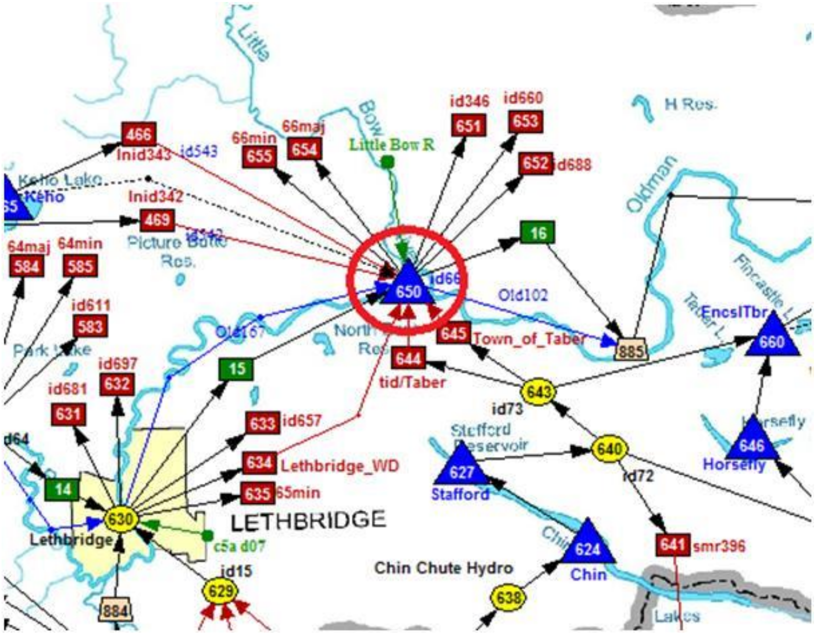


Figure 49: General location for a possible dry dam low in the basin

Model results and impacts

Preliminary work was done to examine the option of a dam that could be used for flood control and drought management, but the main intent was to consider how large such a structure might need to be. To start, stakeholders suggested a structure that could contain the flood such that flow heading to the Bow-Oldman confluence would remain under 2600 cms. Looking at the simulated record for the 1995 flood, the model suggested a large dry dam capable of storing 209,704 cdm (170,000 AF) would be required to reach this flow target (Figure 50 and Figure 51). Considering the size necessary for incomplete flood amelioration and the unlikely ability to prove the cost/benefit case for such an infrastructure investment, no additional modelling was done for this project.

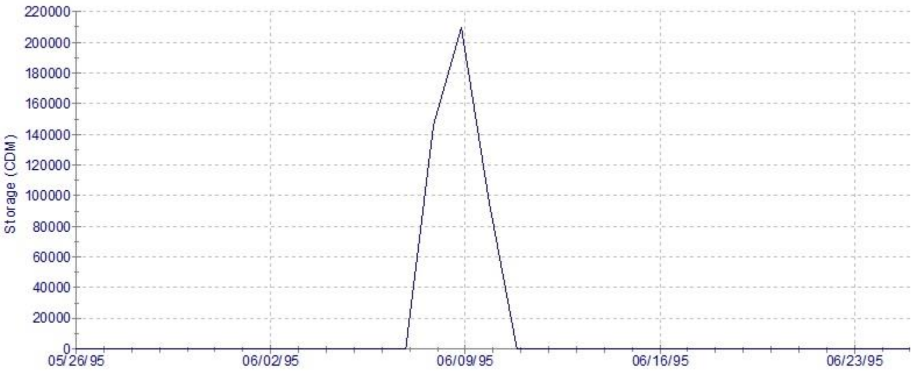


Figure 50: Storage needed in dry dam to protect Medicine Hat (1995)

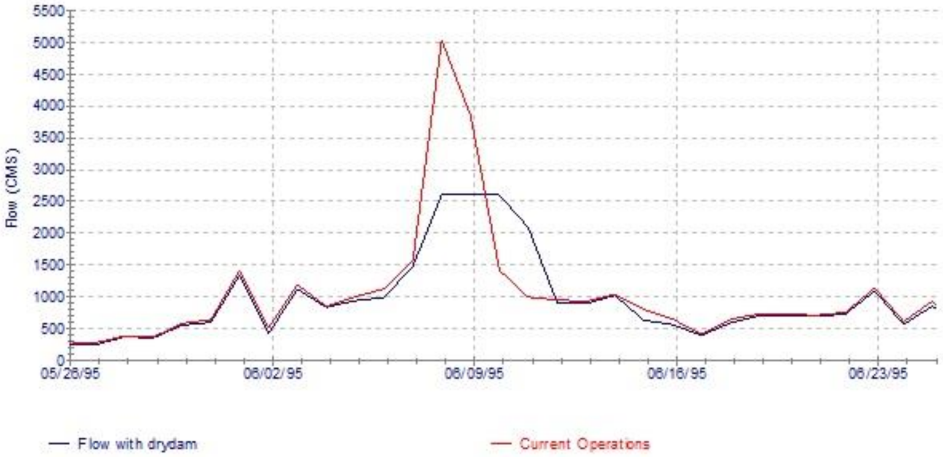


Figure 51: Flow to Oldman Mouth with dry dam in place (1995)

Many factors would influence a decision to build a dry dam, including impacts on aquatic ecosystems. Such a dam would affect access to much of the Oldman River for lake sturgeon, which is a threatened species. Some lake sturgeon are known to undertake extensive movements, thought to be related to spawning, from the South Saskatchewan River into the Oldman River. They have moved at times to sites above Lethbridge and may spawn just downstream of the Lethbridge Weir. OSSK participants were skeptical that a dry dam in this location would ever be built.

Relevant OSSK Model run name

CB6.9_OM_Flood-drydam

Simple triggered shared shortages

This strategy took a similar approach to that actually used with water users in the Southern Tributaries in 2001, but with different triggers. It arose from an early discussion with the OSSK working group that explored different approaches to sharing shortages during the climate variability CAN session. The intent was to reduce demand across all water users in the basins to prevent or delay emptying of reservoirs. Two approaches were modelled because two different groups worked on a similar strategy:

1. Reduce all demand by 25% from July to October in years when low flows are expected. In this case the model is able to look ahead to actual low flow data ("perfect forecasts"); in reality this approach would rely on forecasts.
2. Reduce all demand by 10% if reservoir is not full on July 1, until reservoir refills to rule curve. This was applied separately to the St. Mary and Oldman sub-basins.

The strategy aimed to ensure that the IO on the St. Mary River and instream flow requirements on the Oldman River were met. This discussion evolved into the development of forecast-based rationing, presented in Section 4.1.

Model results and impacts

Modelling was done using climate variable hydrology (2yr Min, Scenario CGCM3T6_3A1B, 30-year record) so that operations would be needed more frequently than under historical hydrological conditions (see Section 3.4 for a discussion of climate scenarios). Figure 52 shows the distribution of annual natural flows through Lethbridge for the climate variability historic analogue and the 2yrMin, which extends forward into the future. Flow in the median year is about 13% lower for the 2yrMin.

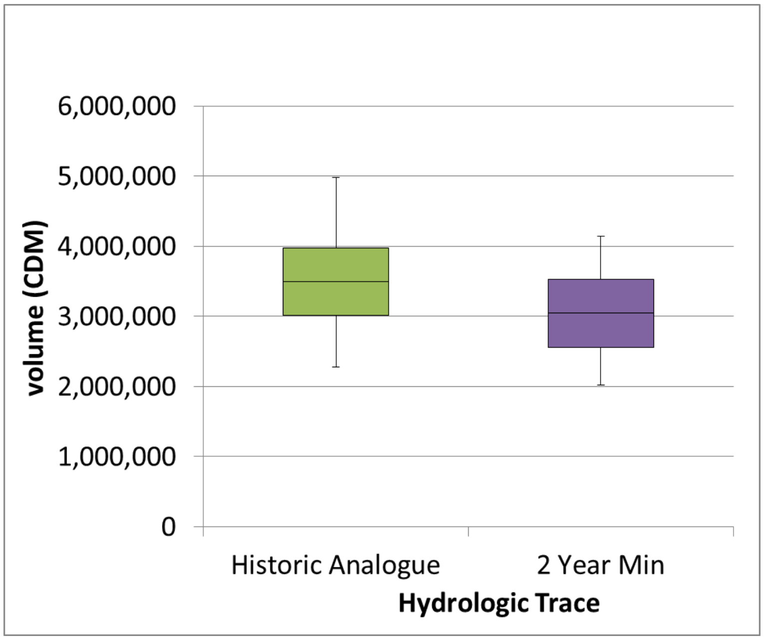


Figure 52: Yearly natural flow downstream of Lethbridge for the historical analogue and 2yr Min climate variability scenarios

Modelling results are shown in Table 4. There are three possible outcomes of implementing the shared shortage operations. First, it may be that the reservoirs (St. Mary and Waterton) would not have emptied even without the shared shortage operations. This happens in 2043, for example; these years are marked as red in the table and counted as "false positives," since the operations were put into effect unnecessarily. The second possibility is that the reservoirs empty, but they empty on the same date with or without the storage reserve operations. This happens in 2035, which is marked as orange and counted as "years without change in emptying." Finally, the shared shortage operations may help in extending the time before the reservoirs empty. This happens in 2032, for example; the years are marked as green, and the dates of the extension are given so one can judge if the additional time of storage is likely to be of benefit. If the operations are triggered in one scenario, but not the other, the year is marked with grey for the untriggered scenario.

Table 4: Extension on the number of days before Waterton and St. Mary reservoirs empty as a result of shared shortage operations

Green cells indicate True positive (the operation ran with benefit); red cells indicate False positive (operation ran without substantial benefit); orange cells indicate the reservoirs emptied with or without the operation; and grey cells were "not applicable" (indicates an untriggered scenario).

	Extension on reservoirs emptying	
Years Shared Shortages Operations are Triggered in One or Both Approaches	Approach 1: 25% redux July-Oct when low flows are expected	Approach 2: 10% redux when St Mary is not full on July 1 (until refill)
2029	🟥	▨
2030	▨	🟥
2031	prevents emptying in 2031	prevents emptying in 2031
2032	44 days (8/25 to 10/7/2032)	29 days (8/25 to 9/22/2032)
2033	reductions in prior years prevents emptying in 2033	prevents emptying in 2033
2034	51 days (7/27 to 9/16/2034)	50 days (7/27 to 9/15/2034)
2035	1 day (8/4 to 8/5/2035)	1 day (8/4 to 8/5/2035)
2036	▨	10 days (9/11 to 9/20/2036)
2037	12 days (9/2 to 9/13/2037)	20 days (9/2 to 9/21/2037)
2038	reductions in prior years extends emptying 23 days (8/19 to 9/12/2038)	40 days (8/19 to 9/29/2038)
2039	▨	🟥
2043	🟥	🟥
2044	reductions in prior years prevents emptying in 2044	prevents emptying in 2044
2048	12 days (9/8 to 9/19/2048)	5 days (9/8 to 9/12/2048)
2049	reductions in prior years prevents emptying in 2049	prevents emptying in 2049
2050	🟥	▨
2051	▨	🟥
Number of years operations triggered	**9**	15
Number of false positives (no emptying)	**3**	4
Number of years without change in emptying	1	1
Number of years emptying prevented	4	4
Number of years emptying extended > 7 days	9	9
Number of years emptying extended > 27 days	7	7
Number of years emptying extended > 28 days	7	7

In addition to the storage extensions shown in Table 4, there is a moderate benefit to instream flow with the 25% reduction for four months (Approach 1), but little to no instream flow benefit from a 10% year round reduction (Approach 2). The results show potential for extending storage, but refinements would be needed to create an effective, adaptive shortage-sharing response.

The key to benefits from sharing is the ability to forecast reservoir fill, snowpack, soil moisture, and other triggers going into the crop year. Information is needed at the beginning of the season to make decisions about crop types, seeding and other aspects. The triggers would need to be further refined to make a formal shortage-sharing strategy worthwhile. Irrigators indicated this is what they do now on an informal basis.

Tools and structure would be needed to do a shortage agreement; such agreements are hard to pre-design and have to address the problem where it is occurring. A number of players would also be involved at the basin level and communications, education and awareness are keys to overall public support. Based on experience in 2001, a template exists for one year, but a longer time period of two to three years is uncharted. It would be useful if various user groups developed water shortage plans now to be in a better position for the next drought. This overall approach was refined into another strategy – Forecast-based rationing – which did show more promise (see Section 4.1).

Relevant OSSK Model run names
CB6.9_ShrdShrt_10per_min2yr
CB6.9_ShrdShrt_25per_min2yr

Lower FSL in all ESRD reservoirs by 2 m when needed until July 1

This strategy explored potential flood mitigation benefits of keeping reservoir levels two metres below full supply level (FSL) when needed until July 1, by which time the large proportion of early summer rains will typically have passed. This option would ensure reservoir storage is available to hold large volumes of water resulting from heavy rains, if necessary. All reservoirs were to be kept at two metres below FSL until July 1. This strategy would not be implemented every year, as implementation would depend on snowpack, antecedent soil moisture, and the forecasted timing and magnitude of rain events.

Model results and impacts

Preliminary work suggested that this strategy had significant detrimental environmental effects with limited flood mitigation opportunities. It was noted that big flood events will happen, and the trade-offs of drawing down water storage in anticipation of a flood event to reduce flooding impacts downstream of the dam would need to be further evaluated before being aggressively pursued. The risk of unnecessary drawdowns in a basin that is more typically concerned about drought and water shortage than flood makes the implementation of a strategy such as this quite unlikely. No detailed modelling work was done for this strategy due to data constraints, although it did lead to the creation of a synthetic flood to mimic the actual 1995 event and led in part to the development of the synthetic flood time series. Work on this option evolved into the flood mitigation strategies for the Oldman Basin.

Relevant OSSK Model run name

N/A

Developing a storage reserve

This strategy examined the possibility of reserving some stored water in one year to support demands the following year if a drought appeared likely. The strategy differs from the triggered shared shortages described earlier in that it applies only to irrigators. It was modelled with historical flows, with Chin Reservoir expanded and the addition of Kimball Reservoir, with the following operating rule: if storage (in St. Mary, Waterton, and Kimball reservoirs) falls below x on or after y, irrigation would cease for the year, where x = storage reserve and y = cut-off date, as shown below:

With Chin Reservoir expansion only
x = 43,155 cdm (35,000 AF), y = September 15
x = 74,000 cdm (60,000 AF), y = September 15

With Chin Reservoir expansion and Kimball Reservoir added
x = 98,640 cdm (80,000 AF), y = September 15
x = 98,640 cdm (80,000 AF), y = September 1
x = 147,960 cdm (120,000 AF), y = September 15

Model results and impacts

Table 5 shows the results for Chin Reservoir expansion only, under two scenarios: a reserve of 43,155 cdm (35,000 AF), and a reserve of 74,000 cdm (60,000 AF), both implemented on September 15.

Table 5: Extension of the number of days before Waterton and St. Mary reservoirs empty as a result of storage reserve operations

Green cells indicate True positive (the operation ran with benefit); red cells indicate False positive (operation ran without substantial benefit), and orange cells indicate reservoirs emptied the following year with or without the operation.

Year Storage Reserve Operations are Triggered	Extension on reservoirs emptying the next year Scenario 1: 35 kaf, 9/15 implementation	Scenario 2: 60 kaf, 9/15 implementation
1931	none	none
1932	🟥	🟥
1936	none	none
1937	prevents emptying in '39	prevents emptying in '39
1939	20 days (7/23 to 8/11/40)	27 days (7/23 to 8/18/40)
1940	14 days (7/19 to 8/2/41)	20 days (7/19 to 8/8/41)
1941	🟥	🟥
1944	prevents emptying in '45	prevents emptying in '45
1945	🟥	🟥
2001	🟥	🟥
Number of years with operations triggered	10	10
Number of false positives (no emptying)	4	4
Number of years without change in emptying	2	2
Number of years emptying prevented	2	2
Number of years emptying extended > 7 days	4	4
Number of years emptying extended > 21 days	2	**4**

There are three possible outcomes of implementing the storage reserve operations. First, it may be that the reservoirs (St. Mary and Waterton) would not have emptied the following year even without the storage reserve operations. This happens in 1932, 1941, 1945, and 2001; these years are marked as red in the table and counted as "false positives" since the operations were put into effect unnecessarily. The second possibility is that the reservoirs do empty the following year, but they empty on the same date with or without the storage reserve operations. This happens in 1931 and 1936; the years are marked as orange and counted as "years without change in emptying." Finally, the storage reserve operations may help in extending the time before the reservoirs empty. This happens in 1937, 1939, 1940, and 1944; the years are marked with green, and the dates of the extension are given so one can judge if the additional time of irrigation is likely to be of benefit.

For the parameters chosen, four of the ten years show some benefit the following year. Increasing the storage reserve volume extends the time to empty by a week in two of the four years.

Results for the three scenarios that include Kimball Reservoir in addition to an expanded Chin Reservoir are shown in Table 6. The grey boxes show years in which the storage reservoir operations were not triggered for that particular scenario. There were only three years with benefits out of 10 to 12 years of triggering the operations with the chosen parameters. However, the number of false positives is reduced from eight to four under historical flows in St. Mary River at the border, as opposed to IJC entitlement flows. This result is shown in Table 7, which assumes 98,640 cdm (80,000 AF) of storage reserve and a September 15 implementation date.

Table 6: Extension on the number of days before Waterton, St. Mary, and Kimball reservoirs empty as a result of storage reserve operations

Green cells indicate True positive (the operation ran with benefit); red cells indicate False positive (operation ran without substantial benefit), and grey cells were "not applicable" (indicates an untriggered scenario).

	Extension on reservoirs emptying the following year		
Year Storage Reserve Operations are Triggered	Scenario 1: 80 kaf, 9/15 implementation	Scenario 2: 80 kaf, 9/1 implementation	Scenario 3: 120 kaf, 9/15 implementation
1931	🟥	🟥	🟥
1932	🟥	🟥	🟥
1936	6 days (9/9 to 9/15/37)	prevents emptying in '37*	6 days (9/9 to 9/15/37)
1937	🟥	27 days (7/29 to 8/25/40)	🟥
1939	25 days (7/29 to 8/23/40)	▨	32 days (7/29 to 8/30/40)
1940	20 days (7/22 to 8/10/41)	26 days (7/22 to 8/16/41)	24 days (7/22 to 8/14/41)
1941	🟥	🟥	🟥
1944	🟥	🟥	🟥
1945	🟥	🟥	🟥
2001	🟥	🟥	🟥
2003	🟥	🟥	🟥
2007	▨	▨	🟥
Number of years with operations triggered	11	**10**	12
Number of false positives (no emptying)	8	7	9
Number of years emptying prevented	0	**1**	0
Number of years emptying extended > 7 days	2	**3**	2
Number of years emptying extended > 21 days	2	**3**	2
Number of years emptying extended > 28 days	0	1	1

Table 7: Extension on the number of days before Waterton, St. Mary, and Kimball reservoirs empty as a result of storage reserve operations with IJC entitlement and historical flows at the US border

Green cells indicate True positive (the operation ran with benefit); red cells indicate False positive (operation ran without substantial benefit), and grey cells were “not applicable (indicates an untriggered scenario).

Year Storage Reserve Operations are Triggered	Extension on reservoirs emptying the next year Entitlement flows at the border	Extension on reservoirs emptying the next year Historical flows at the border
1931	🟥	🟥
1932	🟥	▨
1936	6 days (9/9 to 9/15/37)	prevents emptying in '37*
1937	🟥	prevents emptying in '40**
1939	25 days (7/29 to 8/23/40)	▨
1940	20 days (7/22 to 8/10/41)	18 days (8/10 to 8/28/41)
1941	🟥	🟥
1944	🟥	🟥
1945	🟥	▨
2001	🟥	🟥
2003	🟥	▨

* Without operations, reservoirs empty on 9/22/1937

**Without operations, reservoirs empty on 9/6/1940

In essence, out of the 82 years simulated, a benefit was seen in only a few years, assuming the strategy was perfectly implemented. Irrigators indicated that this strategy was very unlikely to be considered or supported. If the water is there and the crops need it now, irrigators would continue to use it. That said, any irrigation affected by this strategy would likely be fall irrigation since little crop irrigation occurs after September 1.

Other sharing approaches that enable decisions earlier in the year would be preferable to being required to store water later in the season. This strategy also has a number of policy implications, including crop insurance eligibility.

Relevant OSSK Model run names

CB6.9_CarryO_ChinBal+60k_35k_May29
CB6.9_CarryO_ChinBal+60k_35k_Sept15
CB6.9_CarryO_ChinBal+60k_60k_May29
CB6.9_CarryO_ChinBal+60k_60k_Sept15
CB6.9_CarryO_ChinBal+60k+Kim_80k_Sep15-IJC_Hist
CB6.9_CarryO_ChinBal+60k+Kim_80k_Sept01
CB6.9_CarryO_ChinBal+60k+Kim_80k_Sept15
CB6.9_CarryO_ChinBal+60k+Kim_120k_Sept15

4.4 Other Strategies

A number of other ideas were suggested, some of which were modelled in very limited detail. Others were not pursued at all for various reasons. This section of the report lists all of the other ideas that came forward; if they were modelled, the results and impacts are noted. Those that received some modelling attention are presented first, in alphabetical order, followed by the rest of the suggestions, also in alphabetical order.

Some of these strategies might offer valuable resiliency for local areas in the OSSK basins. While the working group discussion tended to focus on basin-wide opportunities, these local opportunities should not be lost or overlooked.

Allocate water for increased urban growth and development
Castle River (Canyon Site) Reservoir
Expand LNID acreage by 30%, reduce return flows from 18% to 5%
Expand RID acreage by 20%, reduce return flows from 15% to 5%
Expansions to Ridge
Further use of Irrigation District licence amendments
Increase canal capacity on diversion from Belly to St. Mary
Kenex site in LNID
Oldman Dam case study
Plug and play demands
Stafford spillway to Oldman River
Upper Belly Reservoir
Upper Oldman (Gap) Reservoir
West Raymond Reservoir
Dam upstream of Cardston/Lee Creek
Double municipal licence demands and double return flows
Headwaters tourism opportunities
Hydro development opportunities
Increase flow at Lethbridge
Increase on-farm efficiencies in IDs
Possible flooding of non-urban land
Regional impacts of oil and gas
Reservoir at Taylorville site (SMRID)
Restore and improve river flows on Southern Tributaries
Risk management for expansion
Several small reservoirs
Spillway on St. Mary main canal
Surcharge canals for short periods under high demand conditions
Transfer from BRID canal
Use all reservoirs for original purposes
Water reuse opportunities

Allocate water for increased urban growth and development

Three potential growth scenarios were considered for this option: full build at 1.5, two, and three times current demand for Lethbridge, Medicine Hat, and Taber. These options were briefly examined to determine the potential impact of population and economic growth in the three municipalities. The first two expansion scenarios had little impact, while the "three times current demand" scenario created a 55,500 cdm shortage for the SMRID over the full 82 year period. Even at three times current demand, water levels at Lethbridge were very similar to the present. The three expansion scenarios had no effect on cottonwood recruitment, but there were some FRC violations on the Oldman between where Lethbridge withdraws and returns water. One way to implement this strategy is by making use of Irrigation District licence amendments, described below.

Castle River (Canyon Site) Reservoir

A reservoir was suggested in the Castle River Canyon area on the Castle River, upstream of the existing Oldman Dam. This would provide on-stream storage of about 49,339 cdm (40,000 AF). Although this option was modelled, the dam is unlikely to be built, recognizing the environmental sensitivities in the headwaters region. The results and impacts are approximately the same as those for the Upper Oldman (Gap) reservoir.

Expand LNID acreage by 30%, reduce return flows from 18% to 5%

In this scenario, the LNID area was expanded by 30% (just over 20,000 ha) with the same diversion, and return flows were reduced from 18% to 5%. Over the 82 years of the model, there was one year with shortage less than 22,200 cdm (18,000 AF) and four years with less than 18,500 cdm (15,000 AF). These results indicate the LNID could expand its acreage with little negative internal impact. The few years of observed shortages indicate that a repeat of the historical hydrology would be able to support this expansion through most (but not all) years.

Expand RID by 20%, reduce return flows from 15% to 5% (RID 'pipe dream')

In this scenario, the RID area was expanded by 20% (about 3,755 ha) and return flows were reduced from 15% to 5%. This is essentially modelling the pipe dream, where a pipe from the main canal would be used to replace the current works. The current works would limit expansion to about 7%. This expansion scenario, or the pipe dream, would increase RID ability to use more allocation. Model results showed that these changes could occur with a small impact on the SMRID only.

Expansions to Ridge

This alternative was modelled, but the analysis was the same as the West Raymond site; it was too small and did not provide enough benefit so was not examined further.

Further use of Irrigation District licence amendments

At present, irrigation districts each have a relatively small amount of water in their licences that could be used for non-irrigation purposes. This water could be used in ways that break the traditional seasonality of existing irrigation district demands. For modelling purposes, these seasonal demands were assigned as year-round demand for new uses not previously in the model. The new demands were added in places that were considered to be reasonable in each irrigation district. To fully explore this option, it was assumed that the water to meet these new uses was removed from the system and there were no returns, which is not completely realistic. The additional demands were modelled as entirely dependent on local reservoir storage. The table below shows the volume of modelled licence amendments for the major irrigation districts in cubic decametres (cdm), with the volume in acre-feet in parentheses.

Irrigation District	Amended volume (cdm)	Amended volume still available (cdm)
SMRID	14,796 (12,000 AF)	7,398 (6,000 AF)
LNID	48,171 (39,068 AF)	6165 (5,000 AF)*
TID	9,864 (8,000 AF)	9,494 (7,700 AF)
RID	5,548(4,500 AF)	4,069 (3,300 AF)
MID	912 (740 AF)	912 (740 AF)
MVLA	2,096 (1,700 AF)	2,096 (1,700 AF)
UID	1,233 (1,000 AF)	1,208 (980 AF)

*5,000 AF was immediately approved for other use purposes, as some of that 39,068 AF can be used for expansion of irrigation acres as is currently the plan within the LNID. If more water for other use purposes were needed, more of the 39,068 AF could be allocated to other use purposes as needed.

Increase canal capacity on the diversion from Belly to St. Mary

This alternative (also referred to as “Improvements to Waterton-St. Mary-Ridge Canal”) would change the diversion limits from the St. Mary and Belly to ensure Chin can be filled early and often. Deliveries to Chin were ramped up as Chin fell. The size of the main canal from the Belly to St. Mary would need to be increased for this alternative. This was modelled in combination with expanding Chin, but turned out to not be necessary because the Belly-St. Mary stretch was not in fact a bottleneck. Although the maximum flow is reached and maintained regularly, the actual bottleneck that affected performance was at Drops 4, 5, and 6 which were changed as part of the strategy to expand and balance Chin.

Kenex site in LNID

Another site considered for storage was Kenex, near the LNID diversion. This has obvious benefit to the LNID, but provided minimal benefit to other users. Because of its location, caution will be needed, as Kenex could interfere with the operations of the Oldman Dam if it re-fills using Oldman releases intended for other purposes. Because this dam is only able to provide water to the LNID and Piikani Nation, it was limited as a potential strategy. In the small amount of modelling that was done, it was found that if Kenex were operated aggressively (i.e., reaches full and empty in most years) it could potentially benefit downstream users and flows, though some time would be necessary to find operations to actualize this benefit. As stakeholders were more interested in investigating other options, Kenex did not receive substantial attention.

Oldman Dam case study

It was suggested that modelling be done to see what the impact would be if the Oldman Dam were removed from the system. Model results showed a large drop in storage at the end of the irrigation season. The minimum weekly flow of the Oldman River at Lethbridge was lower most of the time, and the annual minimum weekly flow drops. Without this dam, St. Mary and Waterton would try to meet the system needs. The total volume of shortages for irrigation is much greater. Other reservoirs try to meet the downstream FRC, but this is very difficult. Much more water is also being sent onto Saskatchewan as it can no longer be stored. It was noted that taking this water away is not the same as not building the dam, and that the dam was built irrigation so water was allocated accordingly. It was suggested that if the dam had not been built, the basin would probably have been closed earlier and some processors and other economic activity may not have moved in.

Plug and play demands (add a demand anywhere in the model, three were pre-modelled: corn chip factory @120,000m^3/yr; potato chip factory @300,000m^3/yr, and food processing plant at 1.8Mm^3/yr)

These options were not a high priority for stakeholders to model and explore. They will, however, be included in the model documentation and are available for future examination.

Stafford spillway to Oldman River

This spillway would be put in place on the St. Mary main canal downstream of Stafford to:

- Handle flood flows to Ridge and the main canal,
- Enable storage of more water upstream without raising the risk of overtopping, and
- Enable some flows to run through the spillway to provide more power generation.

This strategy was modelled but input data do not contain the circumstances that would merit its use (that is, no floods). This strategy is essentially flood risk prevention, but was outside the scope of this modelling exercise.

Upper Belly Reservoir

The Upper Belly Reservoir was the second storage site proposed on the Belly River at the Belly-Waterton confluence. A range of sizes was considered, with capacity between 19,100 and 55,500 cdm (15,500 to 45,000 AF). Storage at the upper end of the contemplated range could mitigate low levels on Waterton and St. Mary Reservoirs but has a marginal benefit to the Oldman Reservoir. Shortages were less to the UID and overall irrigation delivery shortages were reduced, but this could come at a disproportionate environmental cost, as this is a sensitive area. Opportunities to promote cottonwood regeneration were minimal and FRC violations increased on the Oldman mainstem, likely due to a lower contribution from the Belly River. A new set of operating tables for fish rule curves may be needed if such a dam were built. This alternative was subjected only to preliminary analysis because other reservoir sites showed much more promise. Further refinement of operations for the site could increase benefits and mitigate costs, but the maximum possible gain from this site did not seem to merit extra investigation.

Upper Oldman (Gap) Reservoir

A reservoir was suggested in the Gap area on the Upper Oldman, upstream of the existing dam. This would provide on-stream storage of about 283,600 cdm (230,000 AF). Although this option was modelled, it is unlikely to be built, recognizing the environmental sensitivities in the headwaters region. This reservoir was balanced with all other reservoirs and provided benefit for cottonwoods. It was then given priority in holding water and helped fill the Oldman Reservoir in low flow years, but with minimal benefit to flows below Lethbridge. The location of the reservoir had neither the ability to capture substantial inflows (relative to sites on the Belly and/or St. Mary), nor could it provide water to the Southern Tributaries where the vast majority of irrigation occurs. Its primary benefit was to provide extra flows for environmental purposes (reduce FRC violations and/or increase minimum flows). This option was quickly set aside by stakeholders as the environmental damage from building the dam was considered excessive relative to possible downstream environmental gains.

West Raymond Reservoir

A potential reservoir at this site would provide off-stream storage of 19,800 cdm (16,000 AF) below Ridge Reservoir. The West Raymond Reservoir would be located directly west of the existing Raymond Reservoir, approximately three miles south and west of the Town of Raymond. Water would be supplied through a minor canal or pipeline spur off the St. Mary Main Canal, 4.5 km upstream of the Raymond Hydro inlet. This reservoir had no negative impacts and was too small to have substantial positive impact, although there could be some local benefits, though reservoir balancing with other AESRD storage would need to be applied.

The following strategies were noted but were not modelled or pursued; they are shown in alphabetical order.

Dam upstream of Cardston/Lee Creek

This option was not of interest to participants.

Double municipal licence demands and double return flows, and check for the impact on waste assimilation

This strategy was not modelled because ESRD does not have a water quality model for the Oldman River.

Headwaters tourism opportunities

It was suggested that changes in flow could benefit fishing, rafting, guiding, lodging, and other recreation and tourism opportunities in the headwaters. The question was asked whether any studies are underway that might look at the significance of the tourism economy in or near the headwaters. This was not a modelling question and was noted but not explored during the project.

Hydro development opportunities

This strategy was not of interest to most stakeholders.

Increase flow at Lethbridge

Currently just downstream of the City of Lethbridge (e.g., Hwy 3 overpass) the river can be quite low in the summer, making recreational activities on the river difficult (e.g., tubing and boating) because of the need to walk to deeper water. This strategy was not modelled as flow values were never provided to which releases could be targeted. This could be done at some future time if data become available.

Increase on-farm efficiencies in irrigation districts

An example of this strategy might be to use irrigation district efficiencies to create wetlands. This option was not of interest to most stakeholders.

Possible flooding of non-urban land

It was suggested as a flood mitigation measure, that agricultural or forested land could be subject to overland flooding to protect more developed areas. This option was ruled out and not modelled. The physical geography of the region does not provide any opportunity to divert water because the valley is so incised downstream of the Oldman Dam.

Regional impacts of oil and gas

Several municipalities including the Counties of Cardston and Warner, and the Towns of Cardston, Raymond, Taber and Warner would like to know the impacts oil and gas activities are having on the water in the area. These impacts were not modelled because data were not available.

Reservoir at Taylorville site (SMRID)

This option was a proposed 52,000 cdm (42,000 AF) reservoir south and just east of St. Mary Reservoir, and east of St. Mary River. It was decided not to model this option.

Restore and improve river flows on Southern Tributaries

This option would involve changes to minimum flows on the southern tributaries over and above current flows; e.g., increase instream objective to see how much it could be increased before causing problems, such as from 10%-15%-20%. This concept led to more detailed work on the low-flow alternative for the St. Mary River, and this option was not refined further.

Risk management for expansion

Examine implications of economic growth to current users in the region. (specific example: Taber wonders if Rogers Sugar has concerns about water and they would like to know the impact of additional food processing on the water supply.) This strategy was briefly examined, but numbers were so small that they were essentially “invisible” to the model.

Several small reservoirs

Consider building reservoirs with capacity of 1,233 or 2,466 cdm (1000 or 2000 AF) along main canals in many locations. These would be less costly than larger structures to build and would enhance water availability within an irrigation district. This was floated as an idea, but not modelled.

Spillway on St. Mary main canal

This option would reduce flood risk in high runoff years, permit the main canal to collect water through drain inlets, etc. without putting SMRID structures at risk, add live storage (increase FSL at Chin and Ridge) from reduced flood risk, and allow increased power generation through all three plants. This strategy was not modelled as no overland flow data were available.

Surcharge the canals for short periods of time under high demand conditions

This was also an idea that was not modelled.

Transfer from BRID canal

Water transfer from the Bow River to the Oldman basin could be contemplated, and the BRID should be involved. This strategy could be examined when the models for the basins are integrated.

Use all reservoirs for original purposes (i.e., storing water for use)

Some reservoirs, such as Payne, are not always fully utilized because of development around them and recreational uses. The water in these reservoirs should be used before more storage is considered. This is how the reservoirs are operated in the model. Payne and other very small residential "lakes" are not modelled as reservoirs.

Water reuse opportunities

Return flows or diversions could be reduced and subsequent water reuse opportunities explored. Some strategies did look at the impacts of reducing irrigation district return flows.

5 Combining Strategies for Adaptation

Recognizing that the OSSK basins are complex and dynamic systems, it was expected that potential adaptation strategies would be implemented in combination, reflecting the needs of the basins and the appropriate degree of risk management. The project modelled three strategy combinations to demonstrate how adaptation strategies might be layered to produce cumulative and offsetting impacts. These combinations were constructed to show how:

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

All of the strategies used in the combinations were also modelled individually. Strategy descriptions and model results for each individual strategy appear in Section 4.1 of this report.

Full strategy title	Short title for PM charts
Category 4: Combined strategies	
C1. Chin Reservoir expanded + fully balanced + St. Mary augmentation	Chin + Low Flow Aug
C2. Chin Reservoir expanded + fully balanced + Kimball Reservoir + St. Mary augmentation	Chin + Kim + Low Flow Aug
C3. Chin Reservoir expanded + fully balanced + Kimball Reservoir + St. Mary augmentation + forecast-based rationing	Chin + Kim + Aug + Frcst Rtn

C1. Chin Reservoir expanded + fully balanced + St. Mary augmentation

This strategy includes a 74,000 cdm (60,000 AF) expansion of Chin Reservoir on the existing infrastructure footprint then focuses on optimizing this storage through management changes, making it the least expensive combination. Specific operating improvements in this strategy are fully balancing the expanded Chin Reservoir and augmenting low flows below St. Mary Reservoir.

Model results and impacts

Figure 53 shows the impact of each component in this combination, as well as the cumulative effect, on irrigation shortage days. As seen previously in Section 4, the key contribution from Chin Reservoir comes from adding the full storage (existing plus new) to the balancing system. Expanding and balancing Chin Reservoir reduces the number of shortage days across the 82-year record by 879 compared with current operations. Low-flow augmentation creates 226 additional shortage days during the period of record, but that component also provides environmental benefits, as noted below. By combining these two strategies, as shown in the far right bar in Figure 53, the number of shortage days is reduced by 529 days (14%) relative to current operations.

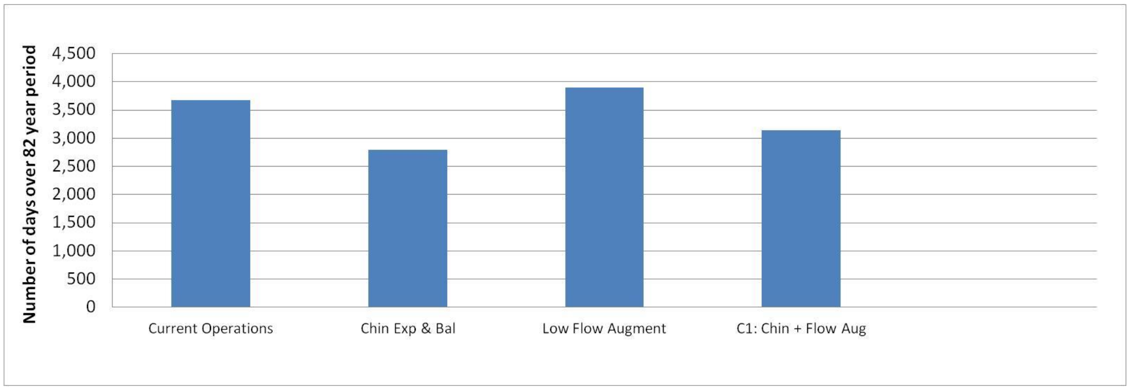


Figure 53: Total number of days in 82-year period with shortages across all irrigation districts

Figure 54 shows the distribution of shortage days across the irrigation districts. This combination (C1, the purple bar) reduces the number of shortage days during the 82-year period for all districts, but the reductions for TID and LNID are less than the others.

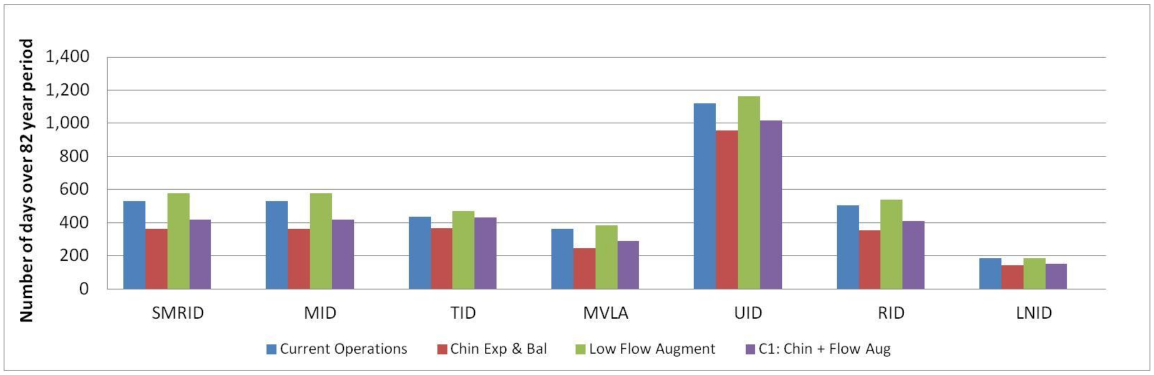


Figure 54: Total number of days in 82-year period with shortages by irrigation district

C1 has a positive environmental benefit on rainbow trout habitat in the St. Mary River, as shown in Figure 55, most of which is contributed by the low-flow augmentation component; the strategy had a very mild positive impact on cottonwood recruitment for the Oldman River near Lethbridge.

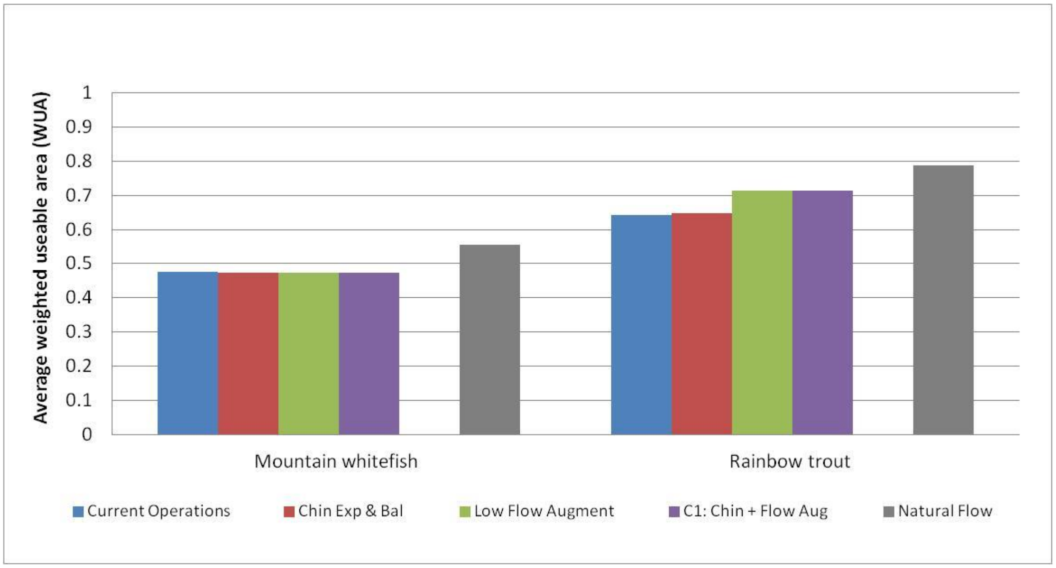


Figure 55: Average WUA of adult habitat for the 82-year period

Relevant OSSK Model run name

CB6.9_Chin&StMary

C2. Chin Reservoir expanded + fully balanced + Kimball Reservoir + St. Mary augmentation

The second combination strategy (C2) was based on both management changes and new infrastructure. In addition to expanding and balancing Chin Reservoir, C2 adds new storage with Kimball Reservoir (125,800 cdm or 102,000 AF), and then augments low flow below St. Mary Reservoir. This combination differs from C1 with the addition of Kimball.

Model results and impacts

The results show that adding Kimball Reservoir reduces shortage days less than expanding and balancing Chin Reservoir for the 82-year period (Figure 56). However, when the two were combined (the fourth bar), they reduced total shortages over the 82-year record by 1305 days. Augmenting the low flow below St. Mary Reservoir to complete the C2 combination raised the number slightly from 2368 to 2698 days, but this is still a substantial improvement over current operations with 3673 shortage days in 82 years. These results demonstrate that if a reservoir were built, the additional stored water could be used for purposes other than reducing shortages, such as augmenting low flows downstream of St. Mary Reservoir, while still maintaining substantial shortage reduction benefits.

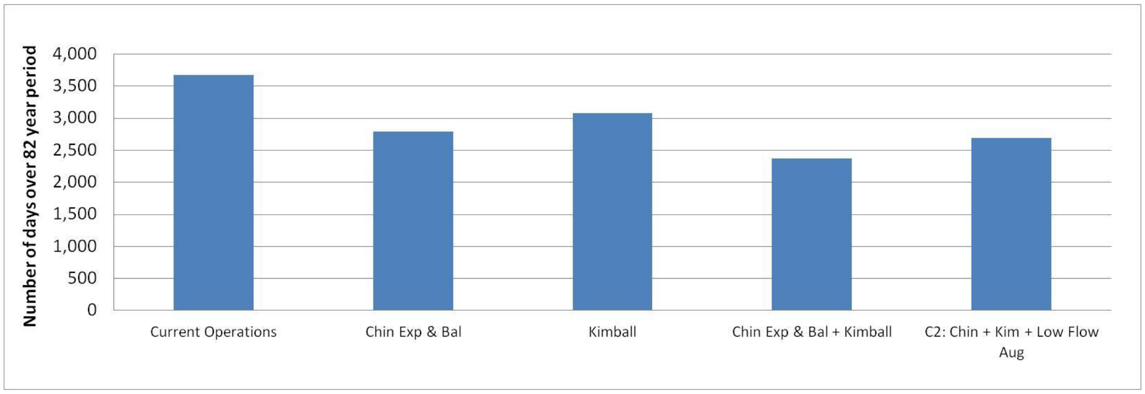


Figure 56: Total number of days in 82-year period with shortages across all irrigation districts

The reduction in shortage days compared to current operations was seen across all irrigation districts (Figure 57).

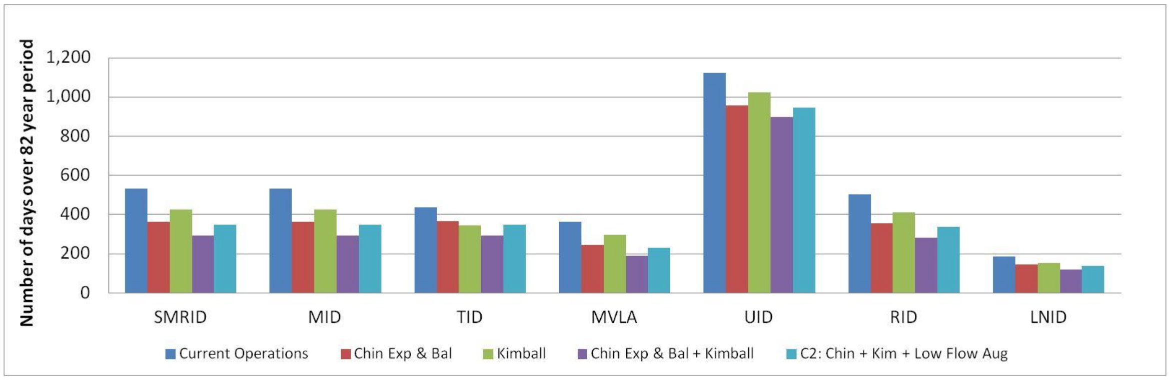


Figure 57: Total number of days in 82-year period with shortages by irrigation district

Figure 58 illustrates the improvement in rainbow trout habitat compared with current operations, resulting largely from the low-flow augmentation component of this strategy.

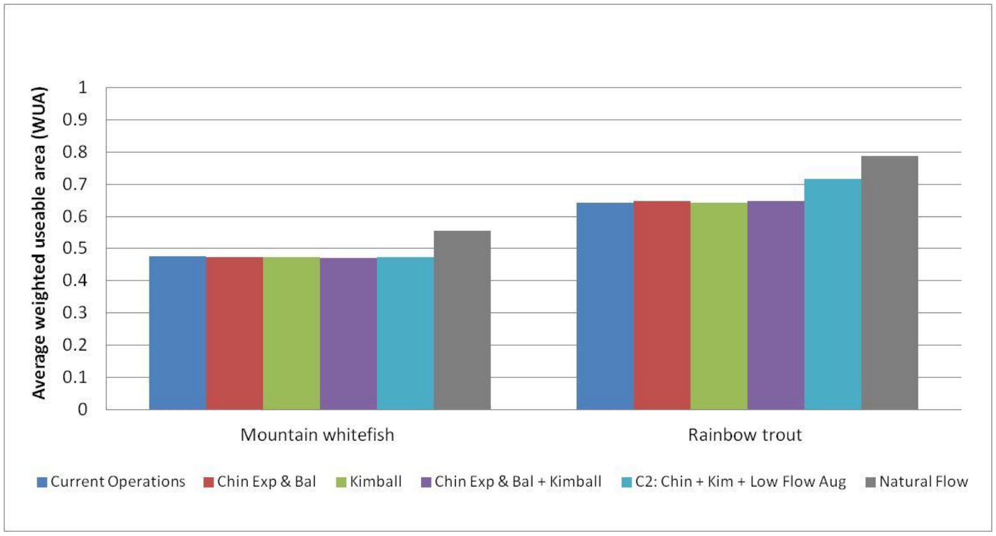


Figure 58: Average WUA of adult habitat for the 82-year period

However, this combination affected cottonwood recruitment on the Oldman River near Lethbridge, compared with current operations (Figure 59), eliminating one year of partial recruitment and one year of optimal recruitment. This was a function of slight flow reductions in the Oldman River on two occasions.

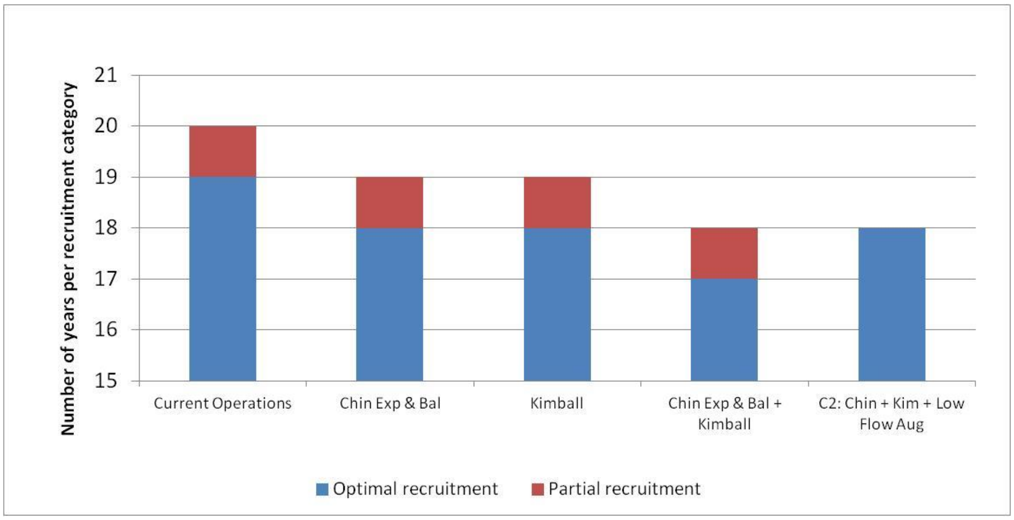


Figure 59: Years of cottonwood recruitment success for Oldman River near Lethbridge during the 82-year period

Relevant OSSK Model run name

CB6.9_Chin&Kimball&StMary

C3. Chin Reservoir expanded + fully balanced + Kimball Reservoir + St. Mary augmentation + forecast-based rationing

This strategy illustrates what could be done to respond to a severe multi-year drought. It adds all of the previously discussed storage and low-flow augmentation and then implements forecast-based rationing on the premise that storage alone is not enough to get through multi-year droughts. Although additional storage is very helpful in a single year drought, further and more aggressive reduction measures are needed to help make subsequent drought years more manageable.

Model results and impacts

The 2yr Min climate variability scenario was used to illustrate the effects of C3 as it is based on drier conditions. Figure 60 compares different storage and management options during the first year of a drought (2034). It shows that added storage by itself (the red line) is essentially the same as current operations (the green line). However, combining rationing with extra storage (the blue line) allowed for a nearly complete irrigation season, albeit with reduced volumes of water.

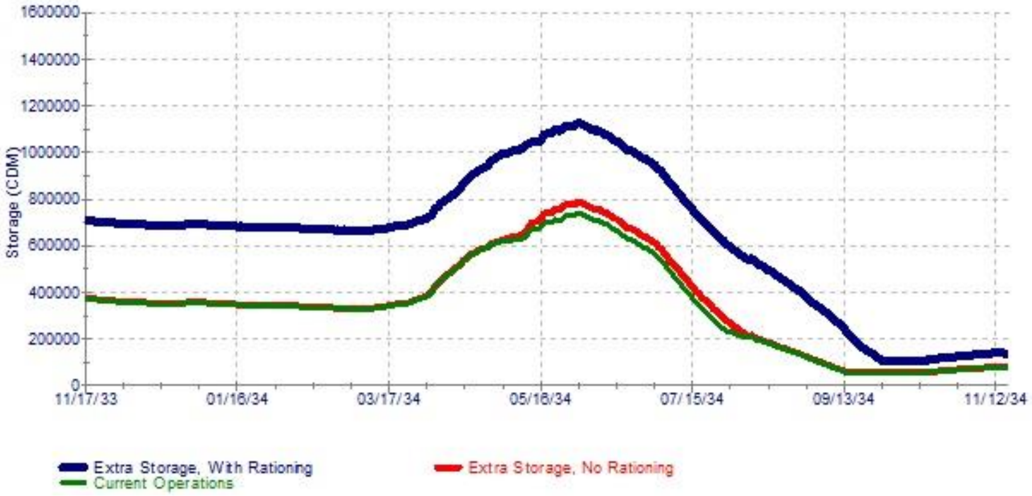


Figure 60: Storage in ESRD and Chin reservoirs (2033-2034)

Scenario: 2yr Min (CGCM3T6_3A1B), 30-year record

In the second year of a severe drought under the 2yr Min climate variability scenario, storage alone makes no difference to irrigation performance as supplies would have been exhausted in the previous year (2034). Figure 61 shows that extra storage combined with rationing enabled a longer irrigation period, again with substantially reduced volumes.

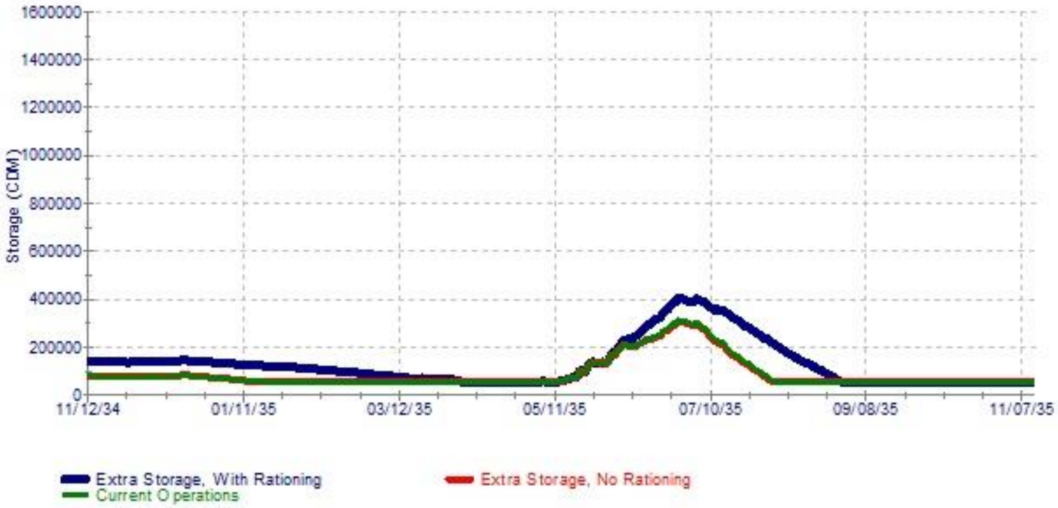


Figure 61: Storage in ESRD and Chin reservoirs in second year of severe drought (2034-2035)

Scenario: 2yr Min (CGCM3T6_3A1B), 30-year record

Returning to the historical record, Figure 62 and Figure 63 illustrate the impact that C3 would have had on the droughts in 1944-45 and 2001-02 respectively; the patterns were similar for the 1931-32 and 1936-37 droughts. The red line, which includes forecast-based rationing, shows how much the rationing component of this combination extends the irrigable season compared with current operations and the other components of C3.

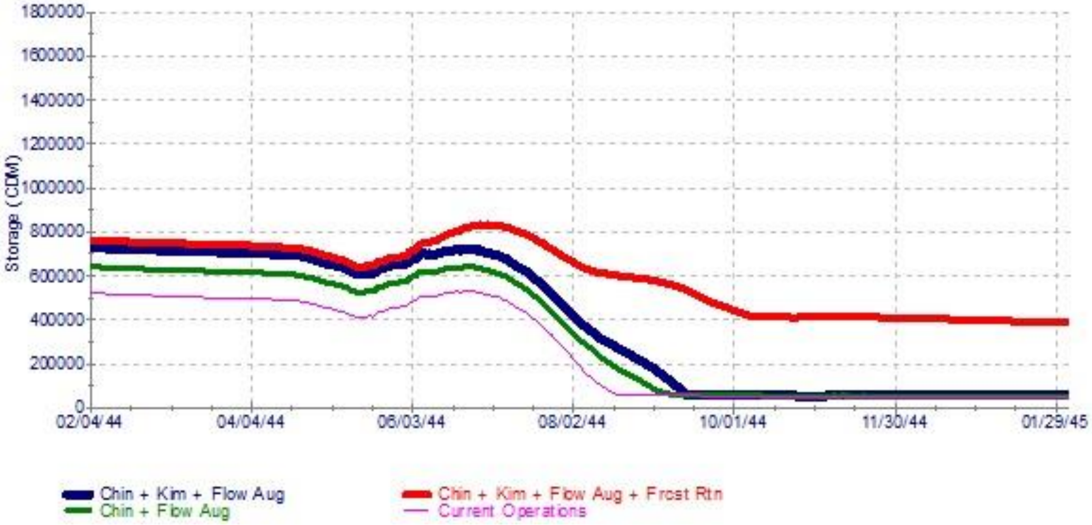


Figure 62: Storage in ESRD and Chin reservoirs (1944-1945)

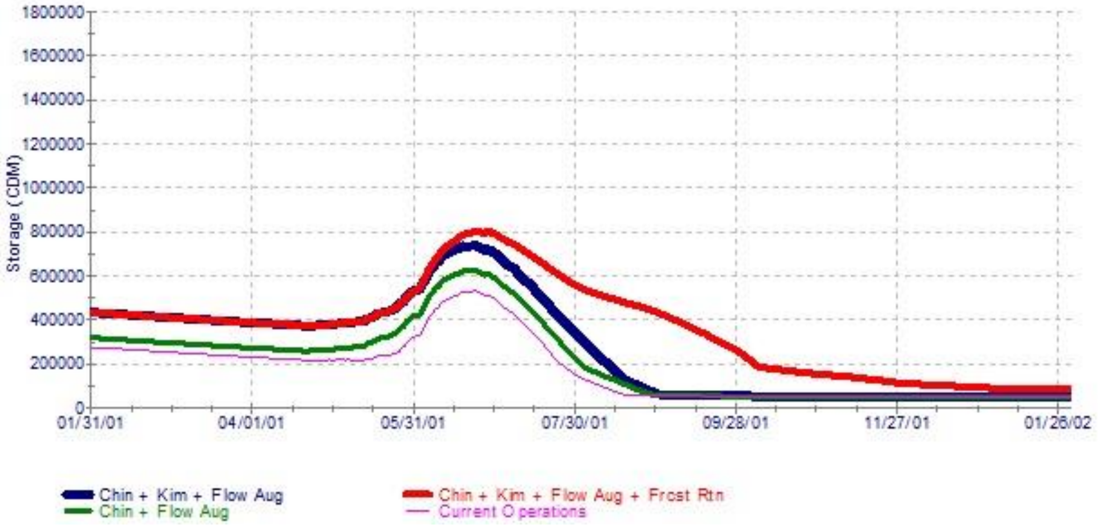
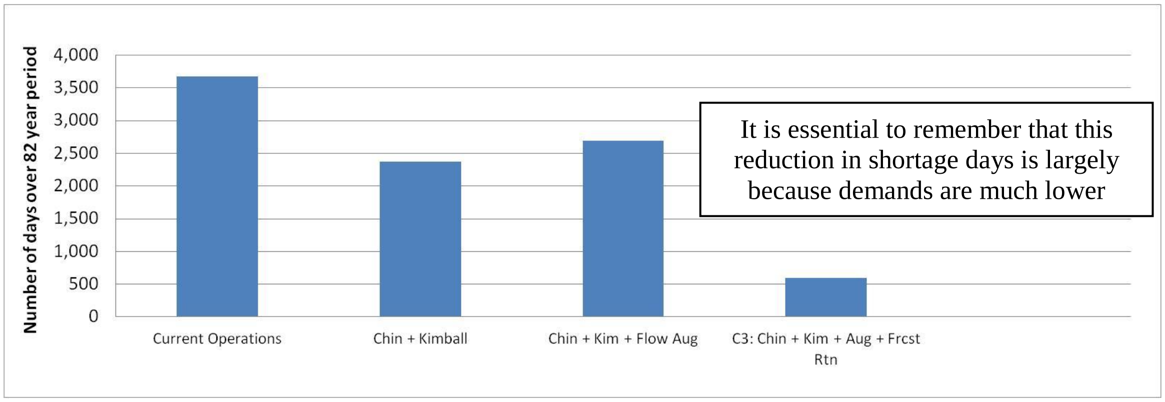


Figure 63: Storage in ESRD and Chin reservoirs (2001-2002)

Looking at PMs for this combination, Figure 64 shows the impact on shortage days for the 82-year period of record. As seen above, C2 (Chin + Kimball + low-flow augmentation) reduces shortage days by 26% compared to current operations (2698 vs. 3673 days). Adding forecast-based rationing to this combination dramatically reduces shortage days further, but it is essential to remember that this is largely because demands are much lower. As discussed in the forecast-based rationing strategy, this drought situation suspends FITFIR but shows that collaboration, as demonstrated in 2001, can add significant value to strategies that incorporate more storage to help meet the needs of junior water licence holders.



It is essential to remember that this reduction in shortage days is largely because demands are much lower

Figure 64: Total number of days in 82-year period with shortages across all irrigation districts

This strategy reduces shortages to zero during the 82-year period for nearly all irrigation districts (Figure 65), but in most cases this is due to demands being reduced intentionally rather than previously undelivered water arriving. In other words, less water is being supplied to the irrigation districts even though the figure shows a reduction in shortages. Although reduced, UID still retains some shortages as they are high in the basin and are completely unsupported by storage, and must allow a minimum flow to pass by before they are allowed to withdraw for irrigation.

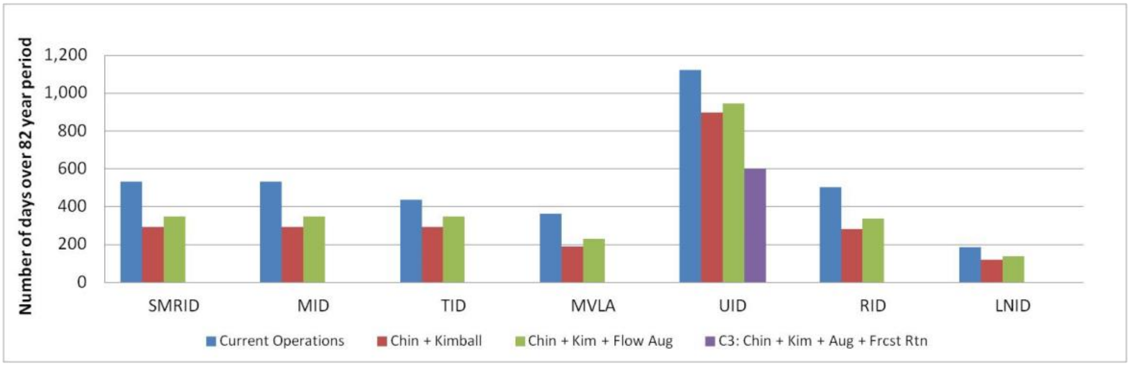


Figure 65: Total number of days in 82-year period with shortages by irrigation district

Lethbridge and Medicine Hat, as large municipalities modelled with appropriate licence priority, also saw substantial reductions in shortages as rationing reduced the burden on storage.

C3 positively affected the percentage of natural flow before the Oldman-Bow River confluence, the apportionment proxy (Figure 66). With current operations, 35% of the 82 years of record were below 50% of natural flow at the Oldman-Bow confluence, while for C3, the proportion was 29%. Combinations C1 and C2 had a negligible effect on this performance measure, each with a value of 34%.

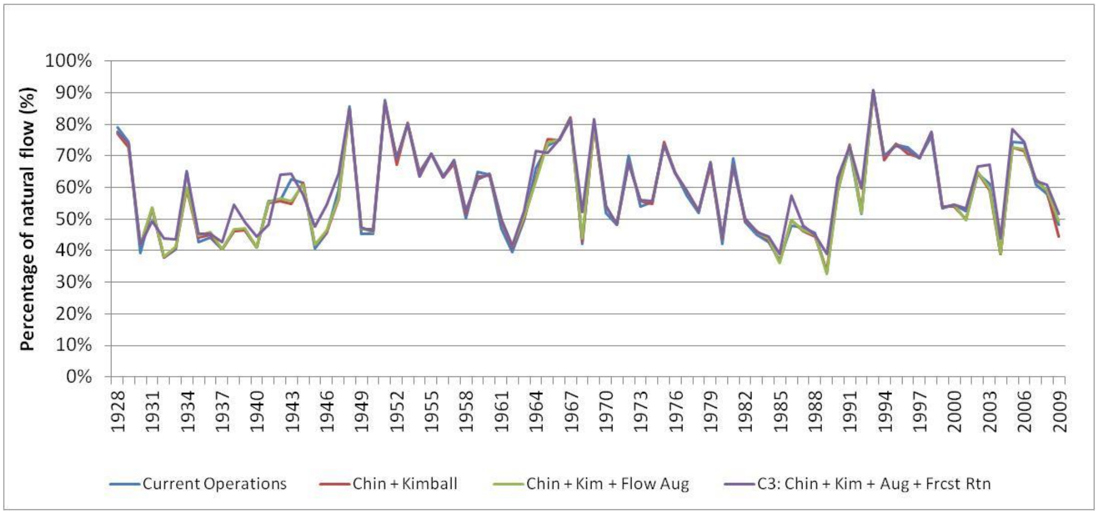


Figure 66: Percentage of natural flow before the Oldman-Bow River confluence

Relevant OSSK Model run names

CB6.9_Chin&Kimball&StMary&Ration
CB6.9_Chin&Kimball&StMary&Ration-2yrMin

5.1 Comparison of Combination Strategies

The three combination strategies can be compared for the seven plotted PMs. In most cases, the combinations improve performance compared to current operations, but it is important to remember that C3, which includes forecast-based rationing, is intended to address severe and extended droughts and that demands for water would be lower as a result of implementing this strategy.

PM 1: Annual Weekly Minimum Flows

Minimum weekly flows were generated for five locations in the OSSK basins: Oldman River at Lethbridge, Oldman River upstream of the Belly, Waterton River at mouth, Belly River at mouth, and South Saskatchewan River at Medicine Hat. As Figure 67 shows, C2 with low flow augmentation and without rationing was most affected by three specific drought years in the historical record (1936, 1944, and 2001). The charts for the four other flow locations similarly reflect flow reductions for C2 in those years.

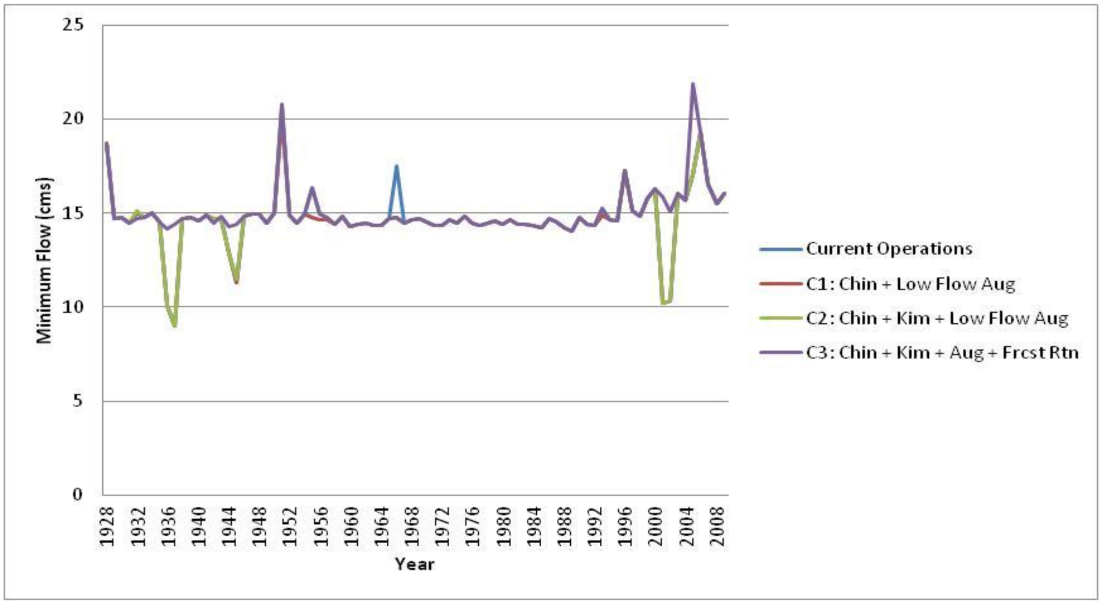


Figure 67: Minimum weekly flow - Oldman River at Lethbridge

PM 2: Minimum Flows for Fisheries

C3, and specifically the addition of forecast-based rationing, performed the best for meeting instream fish requirements in the Oldman River at Lethbridge (Figure 68).

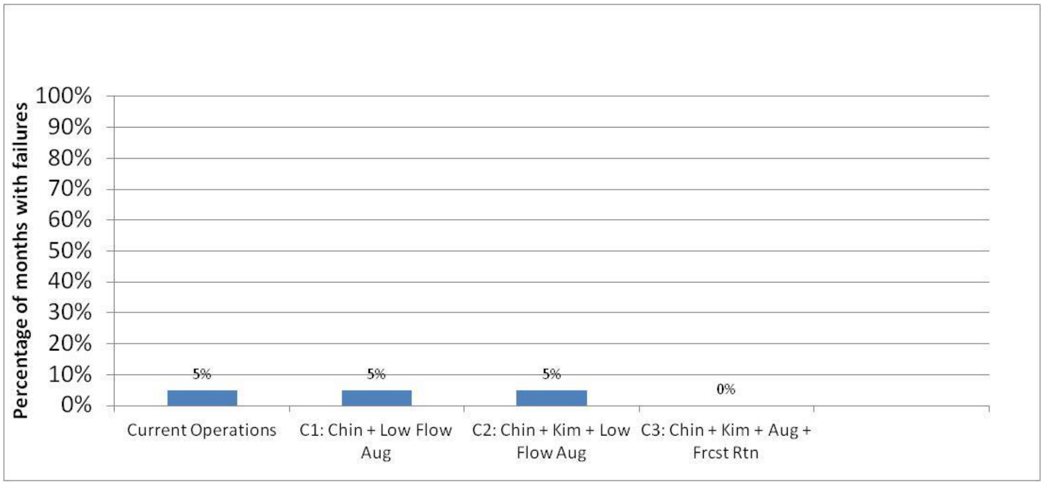


Figure 68: Percentage of months in 82-year period when instream fish requirements were not met in the Oldman River at Lethbridge

PM 3: Cottonwood Recruitment

Figure 69 compares how well the combination strategies did with respect to cottonwood recruitment for the Oldman River near Lethbridge during the 82-year record, and Figure 70 does the same for the mouth of the Waterton River. In both cases, the strategies have a relatively small impact on recruitment.

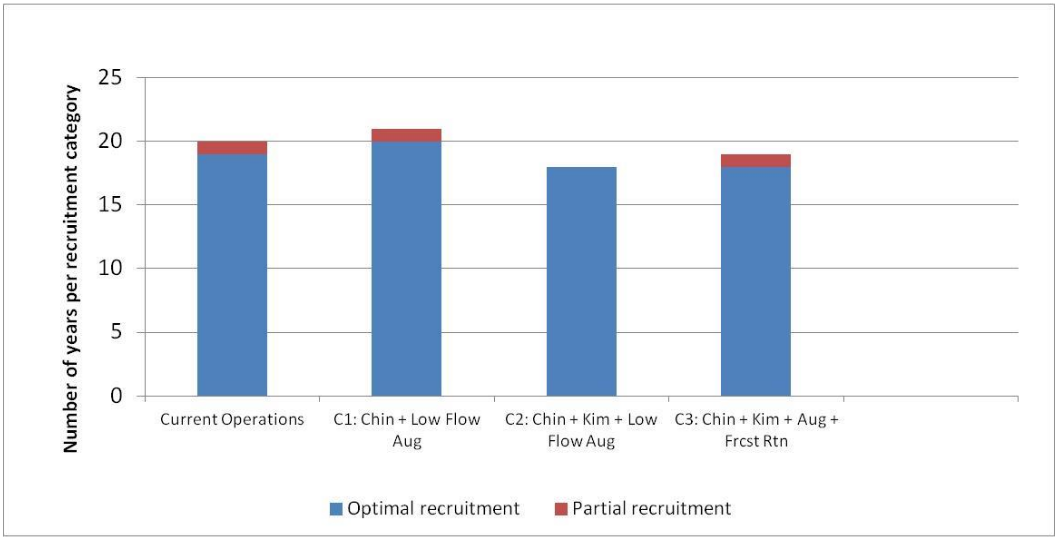


Figure 69: Years of cottonwood recruitment success for Oldman near Lethbridge in the 82-year period

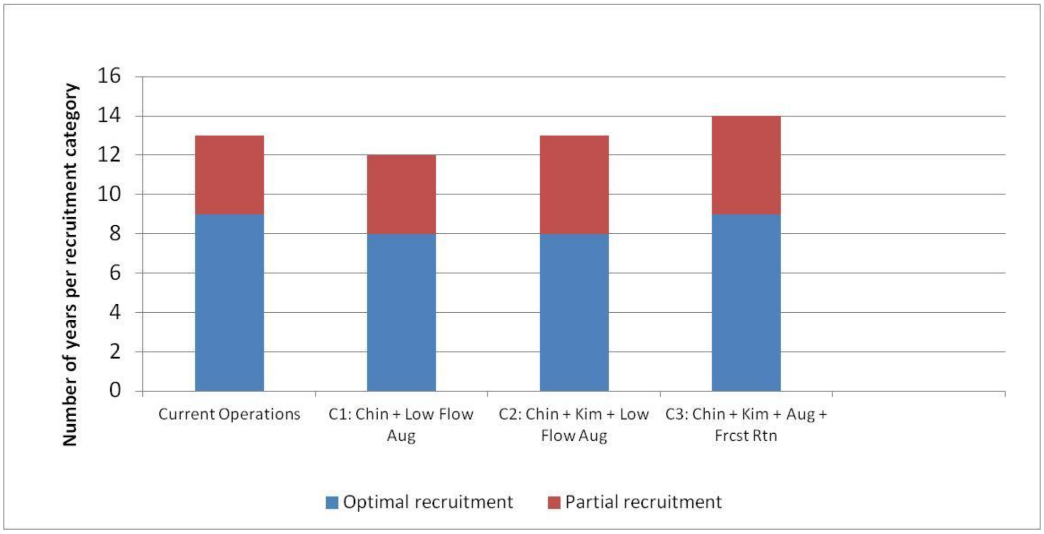


Figure 70: Years of cottonwood recruitment success for Waterton mouth in the 82-year period

PM 4: Fish Weighted Usable Area (WUA)

As Figure 71 shows, the combination strategies had no impact on downstream habitat for mountain whitefish, but the low-flow augmentation component in all three combinations improved downstream rainbow trout habitat availability.

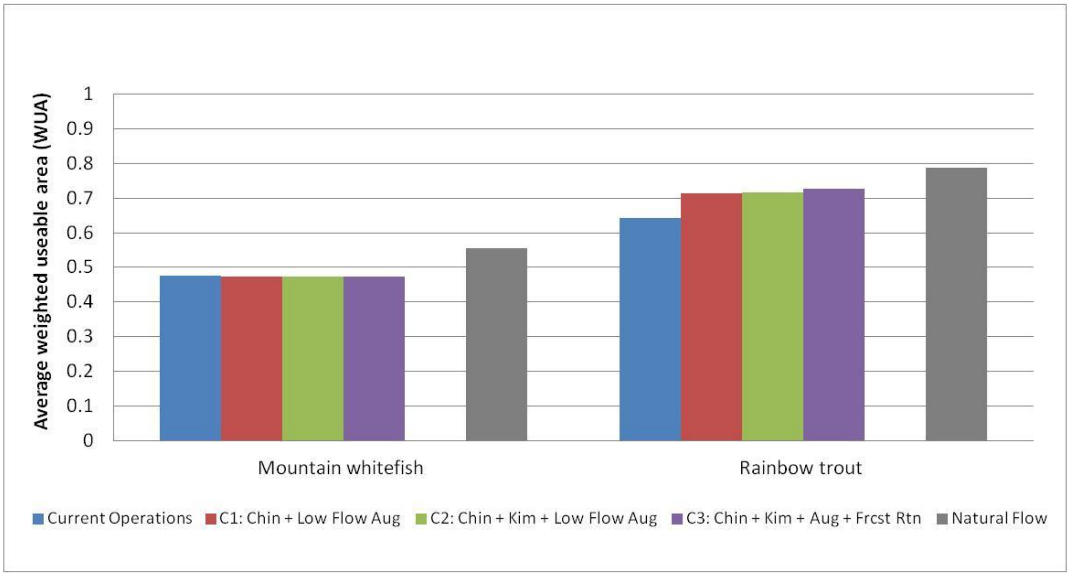
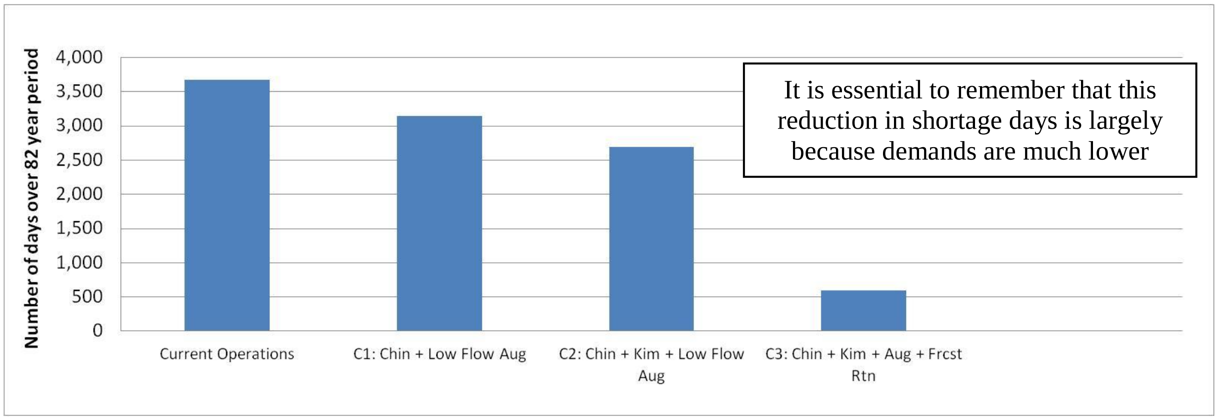


Figure 71: Average WUA for adult habitat for the 82-year period

PM 5: Cumulative Irrigation Shortage Days

Figure 72 and Figure 73 summarize the performance of the combinations in reducing irrigation shortage days, but C3 must be interpreted cautiously, as previously stated. Shortage days are dramatically reduced, but this is because demands are also reduced by instituting forecast-based rationing.



It is essential to remember that this reduction in shortage days is largely because demands are much lower

Figure 72: Total number of days in 82-year period with shortages across all irrigation districts

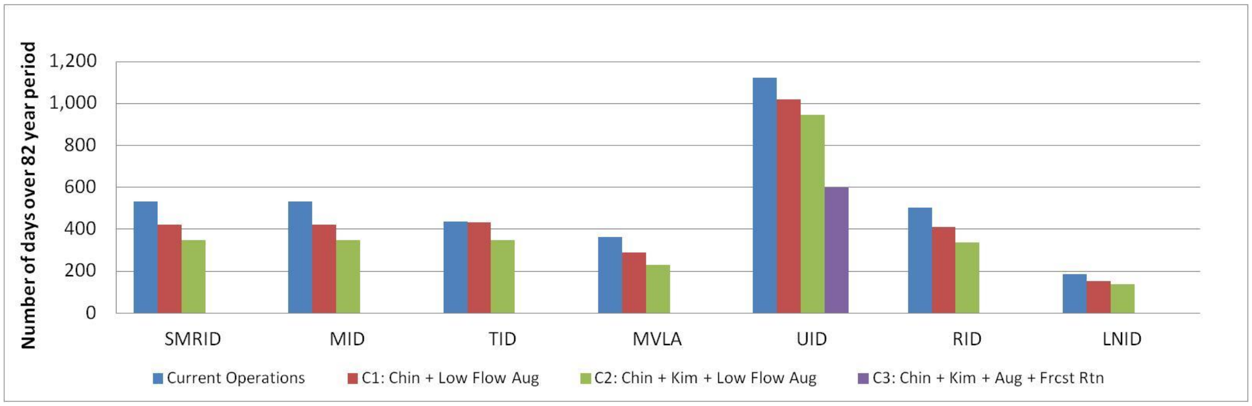


Figure 73: Total number of days in 82-year period with shortages by irrigation district

PM 6: Total Annual Outflow from Oldman River as Percent of Natural Flow (Apportionment Proxy)

There was very little difference in performance of the combination strategies for this indicator, as Figure 74 shows, although C3 did send additional flow downstream. With current operations, 35% of the 82 years of record were below 50% of natural flow at the Oldman-Bow confluence; the proportion was 34% for C1 and C2, and 29% for C3.

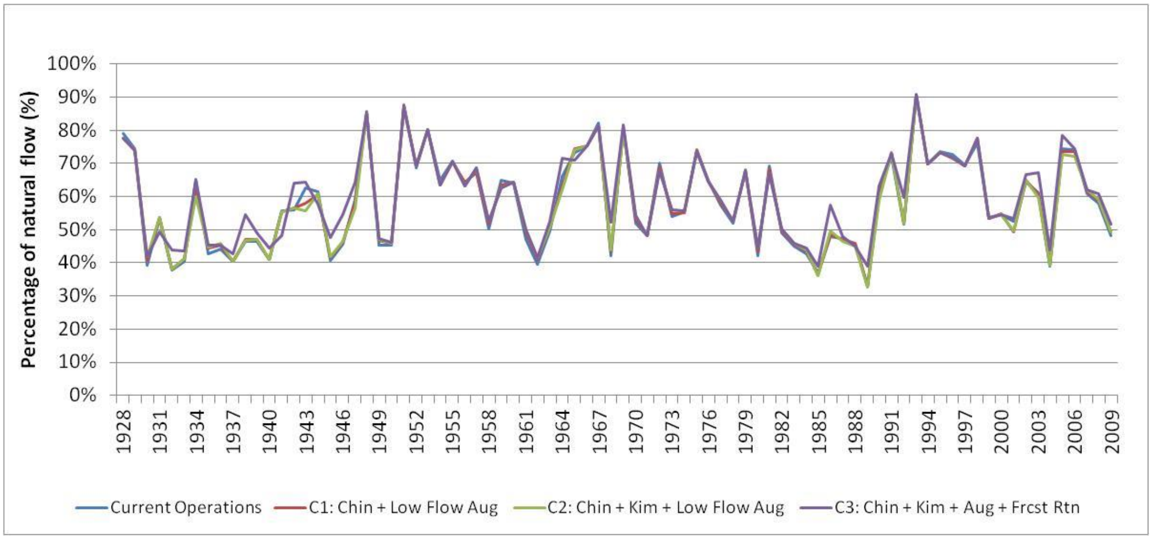


Figure 74: Percentage of natural flow before the Oldman-Bow River confluence

PM 7: Energy Generation

As Figure 75 indicates, the three combination strategies generally had similar effects on hydro power generation, causing a slight decrease during the 82 years of record. The exception was at Raymond, where C1 and C2 resulted in nearly negligible increases, while C3 caused a small decrease from current operations. Under the strategies presented, and according to conversations with stakeholders, hydro power production appears not to be a limiting factor in decision making.

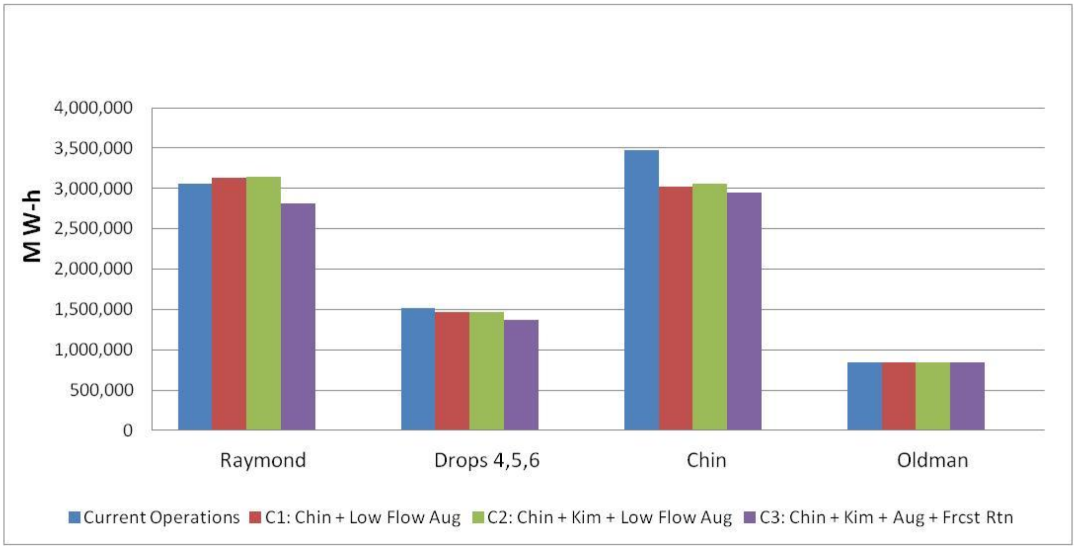


Figure 75: Total energy generation during the 82-year period

6 Next Steps

The findings from this project reflect important new ways of thinking about and planning for responses to climate variability and change in the OSSK basins. They are offered as starting points that can serve to stimulate enhancements and new approaches to water and watershed management. As data become available, additional risk management strategies can be assessed using the publicly available OSSK model.

This work recognizes and supports water management strategies that are already underway in the region, such as water conservation, efficiency and productivity plans developed under the *Water for Life* strategy and being implemented by Alberta's major water using sectors. Use of stored water for enhancing environmental health is becoming fairly common in some parts of the region thanks to the research and practice of providing functional flows for riparian health and for supporting fish populations. In the OSSK basins, irrigation and municipalities are the primary sectors involved with this work. The draft Irrigation Strategy and the draft South Saskatchewan Regional Plan are moving forward and will affect how water is used and managed in the region. The Oldman Watershed Council has also done a great deal of work in the basin and is especially engaged in headwaters protection.

Project results from climate variability scenarios and the history of drought in the region suggest it would be prudent to put in place and test procedures, agreements, and other tools that would be needed in the event of a prolonged drought. These include legal agreements, operational details, forecast-based triggers for action, and other processes for monitoring and managing a drought. The successful collaborative arrangements that emerged in the 2001 drought were generally agreed to be a good starting point but many participants suggested that had the 2000-2001 drought continued for one or more additional years the agreement would not have been practical as an effective response for the water users.

Results from this study were based on an integrated system model that enabled the use of stored water to provide benefits throughout the Oldman, Southern Tributaries and eastern St. Mary irrigated areas. It was the opportunity to balance reservoir use in an integrated manner that provided the environmental benefits as well as the municipal and irrigation supply from current and potentially increased storage reservoirs. The model results suggest that expanding offstream storage at Chin Reservoir and adding the entire storage of the expanded reservoir to the ESRD balancing system would offer a number of benefits to the basins. A business case for expanding Chin should be developed and the parameters defined and negotiated under which it could be added to the integrated reservoir balancing system.

The modelling also reinforced that management changes can create opportunities to meet environmental needs through means such as functional flows and low-flow augmentation. While dams would never be built exclusively for environmental needs, additional storage could enhance environmental health opportunities, and directing new storage in this way would help offset potential environmental damage if new structures are built for multiple objectives. These other objectives would include a modest increase in security of supply under adverse conditions of drought, potential benefits for junior licence holders by reducing the impact on irrigation districts from participating in water sharing agreements through rationing within their senior licences and, depending on the location, some possible flood mitigation for downstream infrastructure.

The OSSK region remains a desirable location for population and economic growth, both of which will place new demands on water supplies. The added value of expanded storage capacity in a few select locations should be further evaluated, in consideration of the substantial climate variability patterns seen in the historical and pre-historical past. In this study, those locations would be an expanded Chin Reservoir and an appropriately sized Kimball Reservoir in the event of a permanent reduction in supply should the US be in a position to take the full amount of water to which it is entitled in the St. Mary system.

It will be important to assess the risk tolerance for a prolonged drought and the willingness to pay to pre-empt such risks. Alberta will also need to continue to monitor the US interest in its entitlement flow under the IJC agreement and be ready to respond and protect the environmental and economic systems that depend on the current flow regime.

Given the experience in southern Alberta, most of the climate variability focus of this project was on drought. However, several major floods have occurred within living memory and the region must also be prepared for those events. Reservoirs in the OSSK basins can play only a limited role in flood mitigation, and strategies are needed to ensure that flood plain planning and development are done responsibly and that appropriate municipal flood protection measures are taken. Land and water management are closely connected and strong focused efforts are needed to better integrate them.

Project results will be shared with audiences that have an interest in the OSSK basins or in potentially designing a similar project for their region. Members of the project team are available to present this work to participant organizations and other forums as appropriate. All project participants and decision makers in the region are encouraged to seek further opportunities to examine, pursue, and test the ideas suggested in this report through their own jurisdictions, agencies, and networks.

Efforts will continue to raise awareness and share information with the public about water management and the trade-offs that sometimes need to be made in dynamic systems like the SSRB. Only by having a good basic understanding of the water management challenges and trade-offs can people be prepared to consider potentially more aggressive adaptation strategies when the need arises. The OSSK model will be freely available for use on the University of Lethbridge server for those with greater interest in exploring other objectives and alternatives for water management in the OSSK basins.

In the next several months the Red Deer, Bow, Oldman and South Saskatchewan river models will be integrated into a single model using the OASIS system. This tool will support discussions around integrated water management across the whole SSRB, not just by basin. It will be useful to consider apportionment implications under various historic and climate variability conditions as well as to integrate land use and land cover changes and how they may affect streamflow and water availability across southern Alberta.

The Bow River Operational Model is being applied to assess flood mitigation options throughout the Bow River System, including the Highwood River, Sheep River, Elbow River, and headwaters of the Bow River main stem. The purpose of that collaborative study is to evaluate the many options for future flood mitigation and to assess the combined effect on downstream infrastructure and people.

As part of the continued work in the SSRB, a land cover and land use model will be applied over the entire SSRB, including the Oldman and South Saskatchewan systems. This may provide additional insights into managing for drought and floods under the ever-changing conditions of weather and climate variability and for longer term extreme climate conditions.

Having identified some promising strategies for responding to climate variability and change in the OSSK basins, it would be prudent to undertake further study and analysis to look at these in more detail. More extensive assessment of the socio-economic and environmental costs and benefits of our findings was not part of the project mandate and is needed. This type of collaborative water management opportunity identification, assessment and analysis is fundamental to maintaining and building the resiliency of Alberta's river systems and the communities that rely on them in the face of growing demands and uncertain climate.

Appendix A: SSRB Adaptation Project Introduction Memo

South Saskatchewan River Basin Adaptation to Climate Variability Project
May 2012

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

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

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

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

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

Foundational Blocks: Initial Assessment

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

Bow River Basin: Adaptation and Live Test Year

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

Oldman River Basin and South Saskatchewan River Modelling

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

Foundational Blocks: Development

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

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

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

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

Appendix B: Project Participants

The table below lists individuals who participated in some or all of the OSSK Working Group meetings.

Organization	Representative(s)
Alberta Agriculture and Rural Development	Andrea Gonzalez Bob Riewe Jennifer Nitschelm Rod Bennett Roger Hohm Dale Miller (AMEC)
Alberta Environment and Sustainable Resource Development	Andrew Paul Brian Hills Craig Johnson Dave McGee Dennis Matis John Mahoney Terrence Lazarus Terry Clayton Werner Herrera
Alberta Innovates – Energy and Environment Solutions	Jon Sweetman
Alberta Irrigation Projects Association	Ron McMullin
City of Lethbridge	Doug Kaupp Maureen Gaehring
City of Medicine Hat	Grayson Mauch
Lethbridge Northern Irrigation District	Alan Harrold
Oldman Watershed Council	Bob Tarleck Cheryl Fujikawa Joan Tingley (ATCO Power) Kelly Scott (ATCO Power) Shannon Frank Shirley Pickering (Highwood Management Plan – Public Advisory Committee) Stefan Kienzle
Raymond Irrigation District	Gordon ZoBell
SEAWA – South East Alberta Watershed Alliance	Bob Phillips Maggie Romuld
SouthGrow	Pete Lovering
St. Mary River Irrigation District	Jan Tamminga
Taber Irrigation District	Chris Gallagher Kent Bullock
Town of Cardston	Jeff Shaw
Town Coaldale	Don Wentz
Town of Taber	Garth Bekkering
United Irrigation District	Fred Rice
University of Lethbridge	David Hill Stewart Rood
Village of Milo	Michael Monner

Organization	Representative(s)
Alberta WaterSMART	Lorne Taylor Megan Van Ham Mike Kelly Mike Nemeth Ryan MacDonald
HydroLogics Inc.	Daniel Sheer Dean Randall Megan Rivera A. Michael Sheer
Prairie Adaptation Research Collaborative	Dave Sauchyn Jeannine St. Jacques

Appendix C: Project Vision, Principles, Goals and Benefits

Vision Statement

In order to evaluate opportunities that exist to increase adaptive management capacity and integrated watershed response, the Oldman and South Saskatchewan River System (OSSK) will be modelled and managed as an integrated system, from headwaters and tributaries to the Alberta border, with due consideration given for the growth and change of the key users and purposes along its course as well as potential future impacts of climate variability. 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, water management objectives and climate variability forecasts.

Project Principles

- Causing no significant, measurable, incremental environmental harm
- Assuming the Oldman and South Saskatchewan sub-basins remains closed to new allocations
- Meeting Alberta’s annual apportionment commitments to Saskatchewan
- Maintaining minimum flow requirements for municipalities
- Supporting the long term population, economic, and irrigation growth forecasts
- Meeting known First Nations’ water needs
- Respecting Alberta’s legal water priority system (FITFIR)
- Achieving Alberta’s policy goals in Water for Life Strategy
- Aligning with South Saskatchewan Regional Plan development
- Not proposing that any one water user bear the costs of providing benefits to other users.
- Focusing on seeking solutions not historic causes
- All work and information related to the project will be made public

Project Goals

- Develop a common understanding of river flow and the respective timing and uses of water by license holders 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 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.
- Determine within reasonable ranges the costs and benefits to existing water users and/or to other users from different management scenarios.
- Evaluate regional implications for water supply and timing under historic conditions, given current and forecast future demand. Provide the capability to evaluate these conditions from forecast changes in climatological conditions.

- Based on the modeling 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.
- This robust and agreed upon model can then be applied to climate variability and change scenarios using the model. If time and budget permit, the application of various climate scenarios will be begun under this round of funding. If budget or time constraints prevent that, the climate scenarios would be applied using the next round of funding.
- 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 modeling that may be needed and recommend the agreed upon adaptive management model to government. Revisions and improvements will be run on completed model as needed.

Expected Benefits

- Working collaboratively to identify and vet potential innovative solutions to the challenges facing our river basin
    - Improved management and mitigation options related to risk to high value and volume users from drought
    - Improved knowledge of risks and mitigation options, if any, from moderate flood events
    - Options to improve aquatic ecosystem protection in prioritized reaches
    - Options to improve access to senior priority water for human use
    - Improved economic development opportunities under sustainable conditions
    - Improved recreational opportunities in certain reaches
- Improved and shared data, knowledge, and management information
- A comprehensive river system model to assess possible impacts of climate variability on the river system and develop adaptation strategies.
- Preliminary adaptation strategies for the system to flexibly adapt to various climate variability scenarios
- Puts useful, credible new tools into the hands of decision-makers and advisors for the long run
- Common ground, common goals and credibility through public and community involvement from the beginning

Note: In addition to river operations and infrastructure, there is 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 may not have the time or scope to address them all thoroughly.

Appendix D: Developing Climate Scenarios for the OSSK Basins

A foundational concept in water resource engineering is the assumption of stationarity – that climate and hydrology fluctuate within a constant range of variability represented by instrumental records (Milly *et al*., 2008). Basing the allocation, distribution and storage of water on the analysis of instrumental records also assumes that these observations adequately represent the long-term trends and variability in climate and water variables. Reconstructions of the climate and hydrology of the past millennium reveal fluctuations at time scales (multi-decadal) that exceed the length of most instrumental records (Sauchyn *et al*., 2008, 2011). This scale of variability is important for our understanding of the stationarity of the regional climate regime, and for water resource planning and management for infrequent events, specifically extreme and sustained low water levels. There is mounting evidence of increased variability and more extreme hydroclimate in the warming atmosphere (*e.g*., Kharin *et al*., 2007; Durack *et al*., 2012). Only physically based climate models can provide credible projections of future hydroclimate.

The methodology applied to the Oldman River Basin accounts for this interannual to decadal variability. We model naturalized streamflow at the Oldman River near Lethbridge as a function of the ocean-atmosphere oscillations, *e.g*., the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (SOI) (see St. Jacques *et al*., 2010, 2013) that drive the natural variability of the regional hydroclimatic regime. The generalized-least-squares (GLS) regression model is

$$\begin{aligned} Q = 550.74 - 0.22\,trend - 13.56\,PDO - 16.74\,SOI_{P1} \\ -14.61\,PDO_{P2} - 7.80\,SOI_{P2} + \varepsilon_t \end{aligned} \qquad (eqn\ 1)$$

where Q denotes mean daily flow over the water year, *trend* denotes a simple linear trend, the PDO and SOI indices are lagged: $P1$ and $P2$ denotes the climate index leading streamflow one year and two years respectively, and the error term ε_t follows an ARMA(2,1) residual model. The GLS model captures a large proportion of the variance in the naturalized streamflow of 1912-2009 ($R^2_{\mathrm{innov}} = 0.60$, $R^2_{\mathrm{reg}} = 0.50$). In this project, we drive the GLS models of annual streamflow using output from an ensemble of 50 runs generated by ten global climate models (GCMs) from the Phase 3 of the Coupled Model Intercomparison Project (CMIP3) which were chosen because they simulate the spectral and geographic characteristics of relevant teleconnection patterns (Furtado *et al*., 2011; Lapp *et al*., 2012) (Table 1). The projected PDO and SOI indices were variance scaled to correct for bias. Variance scaling was found to be among the better performing bias correction methods surveyed by Teutschbein and Seibert (2012)**.** Using data from these 50 runs from the ten GCMs and our GLS statistical model, we simulated annual flows for the Oldman River near Lethbridge over the period 1905 to 2096. Future climate is externally forced by rising greenhouse gases (GHG), according to three GHG emission scenarios: the A2 (high emissions), A1B (medium emissions), and B1 (low emissions) SRES scenarios. The simulations for all three of the SRES scenario are plotted in Figure 1, along with the gauge record and the all-model mean annual flow.

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

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

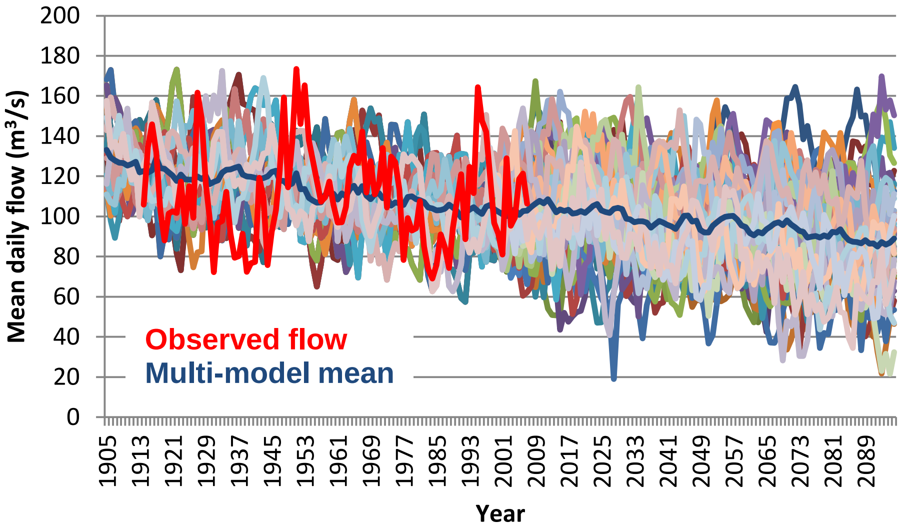


Figure 1: Simulated streamflow, for 1905-2096, for the naturalized Oldman River near Lethbridge. Each simulation corresponds to one of 50 runs of ten CMIP3 global climate models. The greenhouse gas forcing is according to the moderate A1B emission scenario. The observed gauge record (red) and all-model mean (dark blue) also are plotted. Daily mean flow smoothed by a 5-point binomial filter.

The projections are of slightly smoothed mean daily flow over the water year (October 1-September 30), using a 5-point binomial smoother. The high-frequency residual variance removed by the low-pass filter was characterized using the historical flows from 1912-2009. It followed a Gaussian distribution (μ = -0.02, σ = 16.74) which was randomly sampled in order to add back the missing high frequency variance. The outputs from the 50 simulations are re-sampled following Dettinger (2005, 2006) and St. Jacques *et al*. (2013), generating sufficient data for the construction of cumulative distribution functions (CDFs), from which the probability of exceeding critical values for hydrologic parameters can be determined. Re-sampling these complete simulated flows (*i.e.*, projected low frequency plus added randomly generated Gaussian noise) 20,000 times produced the probability distribution functions (PDFs) shown in Figure 2 and cumulative distribution functions CDFs shown in Figure 3 for the selected years 2006, 2050, and 2096. These plots clearly show a future shift to lower mean annual flows and a greater probability of extreme low flows. From here on, we concentrate our analysis on the period 2025-2054 because its relative immediacy is of concern for the stakeholders in the Oldman River watershed.

The GLS-based projection method of St. Jacques *et al.* (2013) produces projected annual mean daily flows whereas the South Saskatchewan River Basin - Adaptation to Climate Variability Project required projected daily flows. We followed the approach of Woodhouse and Lukas (2006a, 2006b) of mapping projected mean daily flows to the daily hydrographs from analogue years. Appropriate analogue years were chosen using the QPPQ transform (or quantile translation) approach (Hughes and Smakhtin, 1996). This processing of the projected and historical streamflow data to produce an ensemble of time series of projected (plausible) daily flows is illustrated in Figures 4 through 8. First, we derived the average CDF of projected flows for the 30-year period (2025-2054) (Figure 4) from the projected CDFs for the individual projected years as derived from the Dettinger resampling approach (*e.g.*, Figure 3). We also generated the empirical CDF in Figure 5 from the historical 1912-2009 mean daily flows of the naturalized Oldman River near Lethbridge.

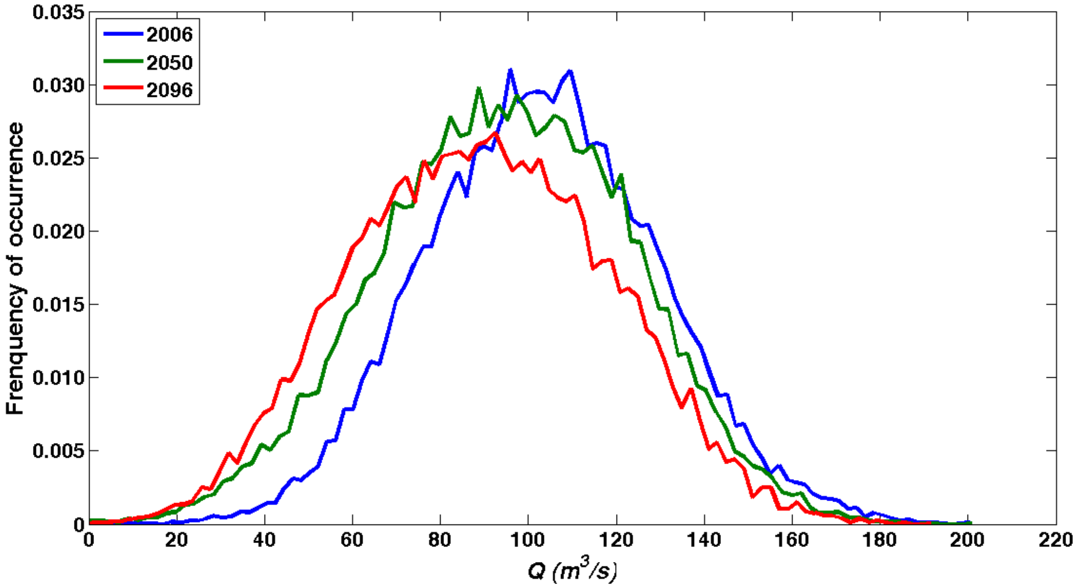


Figure 2: Probability distribution functions (PDFs) of mean daily flow for the naturalized Oldman River near Lethbridge for the selected years 2006, 2050 and 2096.

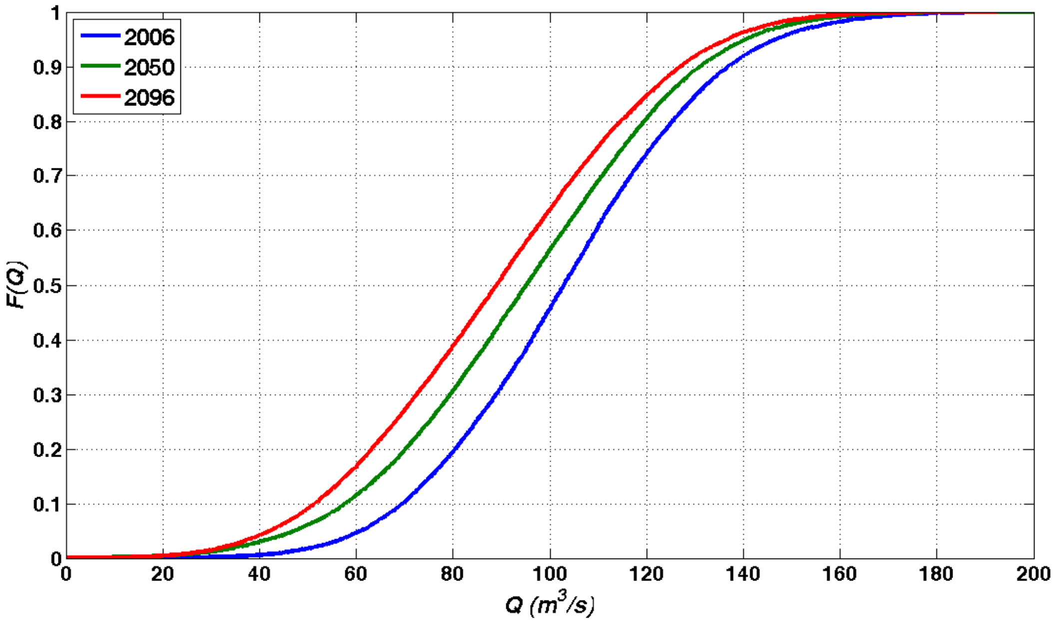


Figure 3: Empirical cumulative distribution functions (CDFs) of mean daily flow for the naturalized Oldman River near Lethbridge for the selected years 2006, 2050 and 2096.

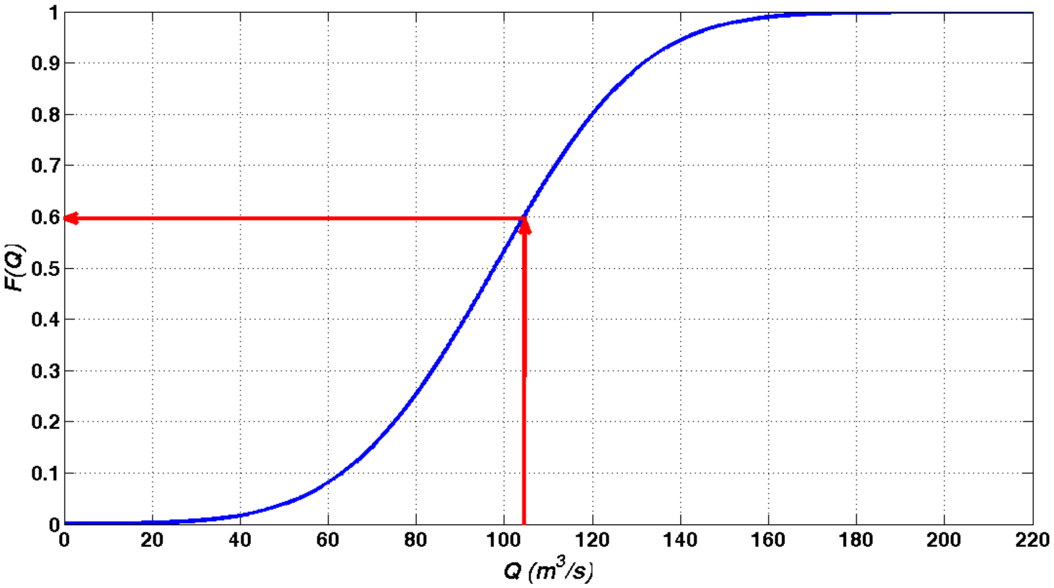


Figure 4: The CDF of projected mean daily flows of the naturalized Oldman River near Lethbridge for the period 2025-2054. The red arrows show that there is a probability of 0.60 that mean daily flow will not exceed 104.4 m^3/s.

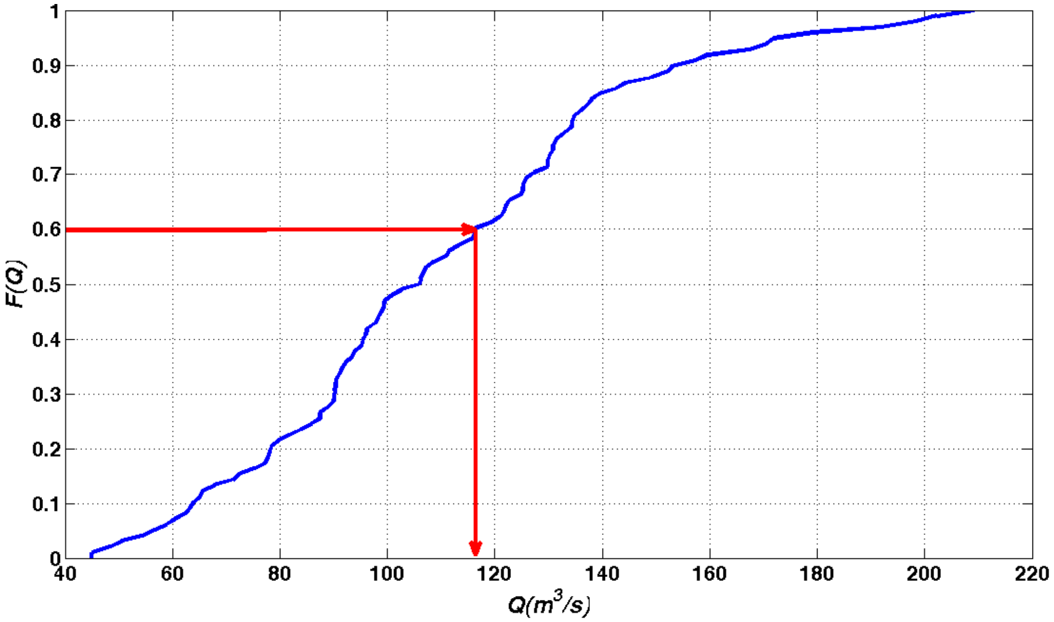


Figure 5: The empirical CDF of historical mean daily flows of the naturalized Oldman River near Lethbridge for the period 1912-2009. The red arrows show that there is a probability of 0.60 that mean daily flow does not exceed 116.4 m^3/s.

By matching flows of equal probably using a QPPQ transform, we identified a historical analogue for each run of a GCM and each future year, that is, 50 GCM runs x 30 years = 1500 model years. For example, from a run with climate data from GCM CGCM3.1(T47) run 3 (emission scenario A1B), our statistical model projected a mean annual flow of 104.4 m^3/s for the year 2026. According to the CDF for the period 2025-54, there is a probability = 0.60 that this flow will not be exceeded. The historical flow of equal probability was 116.4 m^3/s in 1913. Thus the hydrology of 1913 is the closest analogue to the hydrology projected for 2026 using climate data from GCM CGCM3.1(T47) run 3 forced by GHG emissions according to the A1B scenario (Figure 6). The daily flows for 1913 were then log-normal scaled by the projected mean and projected standard deviation to arrive at the projected daily flows for 2026 as illustrated in Figures 6-8. The strong quadratic relationship between mean and standard deviation of the historical daily flows (Figure 7) permits scaling of both parameters. The advantage of mapping to analogue years using the QPPQ transform lie in the way relatively high-flow projected years arising because of a projected negative PDO phase are mapped to corresponding high-flowing historical years arising from the negative PDO phase; and similarly mapping low-flow positive PDO phase projected years to low-flow positive PDO phase historical years. There is accumulating evidence that the annual hydrograph form varies between the two PDO phases (St. Jacques *et al.*, *in review*.).

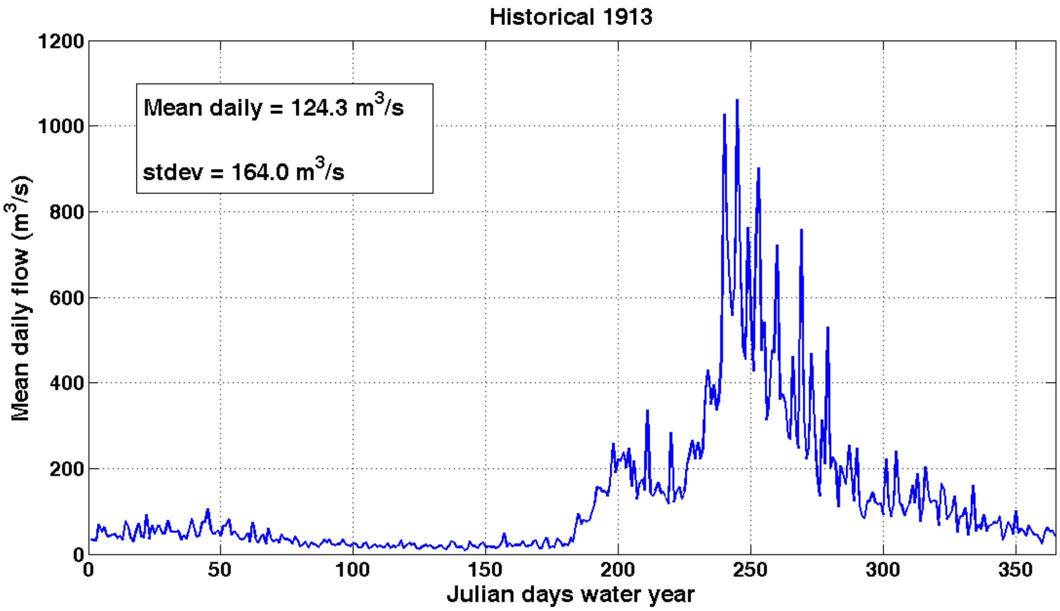


Figure 6: Historical mean daily flows for 1913 of the naturalized Oldman River near Lethbridge.

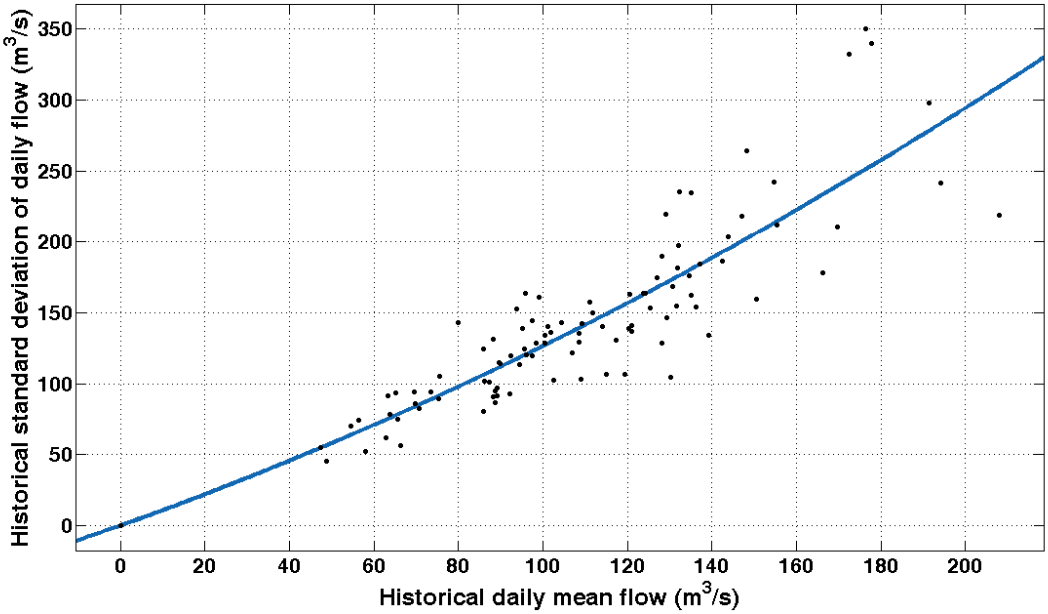


Figure 7: A scatterplot showing the strong quadratic relationship between the means and standard deviations of daily flow of the historical naturalized Oldman River near Lethbridge (1912-2009).

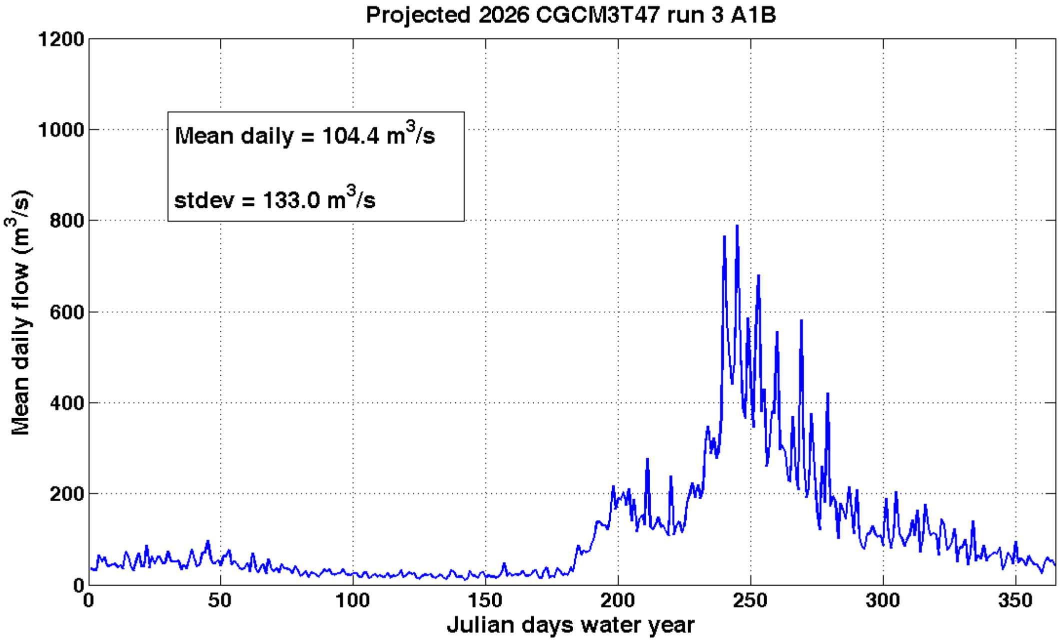


Figure 8: Projected mean daily flows for 2026 for the naturalized Oldman River near Lethbridge simulated using output from the GCM CGCM3T47 run 3, GHG emission scenario A1B. Scale same as in Figure 6.

It is projected that under global warming, spring will occur earlier in the year through-out western North America, including southern Alberta; in particular, snowmelt runoff timing will advance (Cayan *et al*., 2001; Stewart *et al*., 2005). This advance in peak flow has serious implications for reservoir and irrigation management during the growing season and particularly at the end of summer. Therefore, we included this in our model, following the approach of Stewart *et al*. (2004). A strongly significant linear relationship ($R^2 = 0.26$, $p = 5.0 \times 10^{-6}$) exists between the date of 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 at Lethbridge, and Carway, Alberta total winter precipitation (October-May) and Carway spring temperature (April-July).

$$CT = 305.58 - 7.56\, spring\ temperature - 0.0007\, winter\ precipitation \qquad (eqn\ 2)$$

The changes in CT for 2025-2054 were projected for each GCM run by driving the regression model in eqn. 2 with the projected spring temperature and winter precipitation from the GCM grid cell that contained Carway. Because the GCMs are biased, the projected changes in CT cannot be used directly to shift the hydrograph. Using the corresponding 20th simulation run for each GCM and emissions scenario, we calculated the mean CT for 1966-1995. Then, for a given run and projected year, we calculated the projected advance to be the projected CT minus the mean CT for 1966-1995. We adjusted the projected daily hydrographs by the projected advances in spring runoff timing. The mean number of days the CT advanced was 8.6 days. For example, spring runoff is projected to advance 29 days in 2027 for the CGCM3T47 run 31 B1 emissions scenario (Figure 9). Our projected advances are comparable in magnitude to those found by Stewart *et al.* (2004) who included a few southern Alberta headwater gauges in their study.

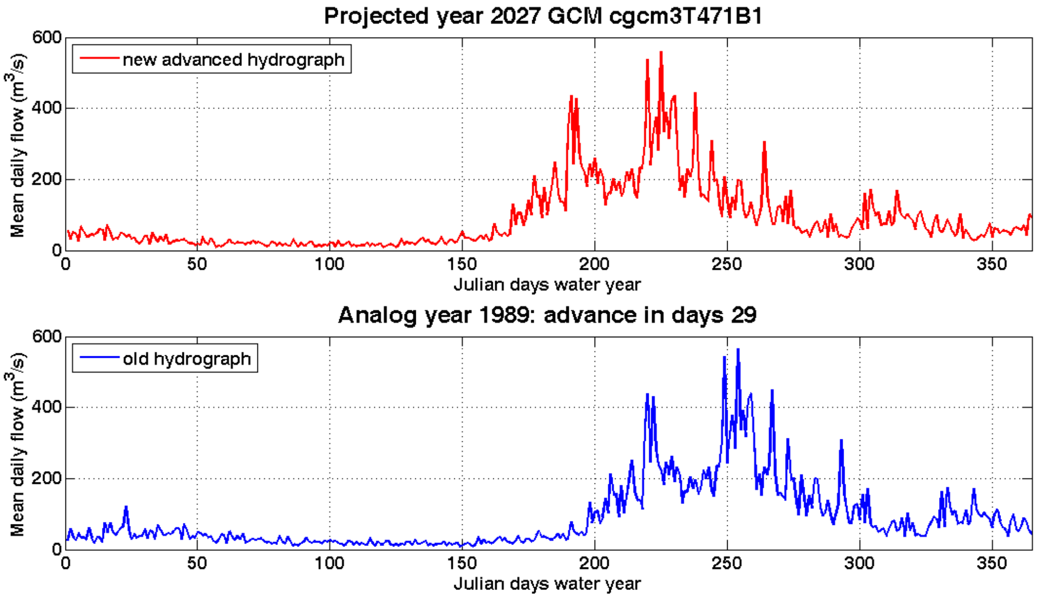


Figure 9: Projected 29 day advance in CT for 2027 for the CGCM3T47 run 1 under B1 emissions scenario.

Once projected data was in hand for each gauge, several methodologies were attempted to apply them to the Oldman and South SasKatchewan Basin Model (OSSK). The original intent was to apply each gauge's projections individually, but the misalignment of analogue years created a number of extremely high negative inflows on a daily basis. These negative inflows were well in excess of anything recorded in the historical naturalized record, so this approach had to be abandoned. Instead, to maintain consistent analogue years (and deal with time constraints) a single projected gauge was chosen to act as a "super-gauge."

We chose to use the natural flow at Lethbridge location for this purpose as it was maximally downstream whilst remaining unaffected by predictions in the Bow River. This gauge was then be disaggregated according to historical monthly patterns at each upstream location (e.g., Pincher Creek in January typically contributes 1.5% of the total natural flow at Lethbridge, so it's inflow in each January was calculated as 1.5% of the super-gauge projections for that day).

There is a major advantage to this empirical approach to deriving plausible future daily streamflows from climate model projections and a statistical model of the teleconnection between sea surface temperature anomalies (PDO and ENSO) and the hydrology of the Bow River Basin. Conventional approaches to developing scenarios of future water levels are based on the coupling of a dynamical hydrological model and "delta" scenarios of projected changes in mean climate (EBNFLO Environmental AquaResource Inc., 2010). This standard practice has the advantage of the dynamical simulation of the processes that generate runoff; but the disadvantage of requiring vast amounts of geophysical data to calibrate and validate the model, limiting the domain the model to a few decades (typically 1961-1990) in terms of range of variability and extremes. The variability that is projected, using this conventional approach, is inherited from the calibration period. Unfortunately, the highest observed variability in the Oldman River system occurred ~1930-1959 and not during the typical calibration period of

1961-1990. The scenarios that are produced generally are restricted to projections of changes in mean monthly or annual volumes or levels between past and future 30-year periods. However, watersheds and infrastructure are not managed for average conditions, but rather for extremes: flooding and especially drought. The method adopted here explicitly incorporates the climate forcing of the interannual to decadal variability of the hydrological regime over the entire instrumental record of 1912-2009. Our statistical models of streamflow at specific gauges are not calibrated to replicate a historical daily hydrograph but rather the dominant models of variability in the regional hydroclimate. By statistically linking this variability to the climate forcing, we are able to re-evaluate the teleconnection between climate and hydrology for future years using output form climate models that, in our assessment, have the capacity to simulate the internal variability of the climate system that emerges under greenhouse gas forcing. The limitation of this novel approach is that we do not attempt to model dynamically the watershed hydrology, and therefore we cannot simulate, for example, the mid-winter melting of snow over frozen ground in a warmer climate. This limitation is not problematic in these near-future projections where the objective is to determine the effect of changes in large-scale climate patterns on extreme water levels. Whereas the conventional (engineering) approach has advanced hydrology and simple climate, our novel (scientific) approach has advanced climatology and simple hydrology.

References

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

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

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

Durack, P.J., S. Wijffels, and R.J. Matear (2012) Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. Science 336: 455, doi: 10.1126/science.1212222

EBNFLO Environmental AquaResource Inc. (2010) Guide for Assessment of Hydrologic Effects of Climate Change in Ontario, Prepared For The Ontario Ministry of Natural Resources and Ministry of the Environment in partnership with Credit Valley Conservation, June 2010.

Furtado, J.C., E. Di Lorenzo, N. Schneider and N.A. Bond (2011) North Pacific Decadal variability and climate change in the IPCC AR4 models. Journal of Climate 24:3049-3067.

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

Kharin, V.V., F.W. Zwiers, X. Zhang, and G.C. Hegrel (2007) Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. Journal of Climate 20: 1419-1444.

Lapp, S.L., J.M. St. Jacques, E.M. Barrow, and D.J. Sauchyn (2012) GCM projections for the Pacific Decadal Oscillation under greenhouse forcing for the early 21st century. International Journal of Climatology 32: 1423-1442, doi:10.1002/joc.2364.

Milly P. C. D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer (2008) Stationarity is dead: whither water management? Science 319(5863): 573-574.

Sauchyn, D., A. Pietroniro and M. Demuth (2008) Upland watershed management and global change – Canada’s Rocky Mountains and western Plains. Chapter 3 In “Mountains, valleys and flood plains: managing water resources in a time of global change”, Routledge

Sauchyn, D., C. Perez-Valdivia, and J. Vanstone (2011) Modes and forcing of hydroclimatic variability in northern Rocky Mountain watershed since 1063. Canadian Water Resources Journal 36(3): 205-218.

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

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

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

Stewart I.T., D.R. Cayan and M.D. Dettinger (2004) Changes in snowmelt runoff timing in western North America under a ‘business as usual’ climate change scenario. Climatic Change 62: 217-232.

Stewart I.T., D.R. Cayan and M.D. Dettinger (2005) Changes toward earlier streamflow timing across western North America. Journal of Climate 18: 1136-1155.

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

Teutschbein, C. and J. Seibert (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. Journal of Hydrology 456-457: 12-29.

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

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

Appendix E: Full List of OSSK Performance Measures

- Annual weekly minimum flows
- Annual daily minimum flows
- Fish survival flows
- Low flow stability from September to April
- Cottonwood recruitment
- Fish WUA
- Irrigation shortage days
- Irrigation shortage volume
- Irrigation shortage days before September 30
- Irrigation shortage volume before September 30
- Percentage of natural flow annually before the Bow-Oldman confluence
- Energy generation
- Fish Rule Curve violations
- Tier shortage days
- Tier shortage volume
- ESRD reservoir volume on August 31
- Bankfull flood exceedances
- Percentage of years when ESRD reservoirs reach Full Supply Level – 1 m by June 21
- Probability of refill by date for the Oldman, St. Mary, and Waterton reservoirs
- Total number of flood events for the Oldman at Lethbridge and S. Sask. at Medicine Hat
- Total number of daily low flow events for the Oldman at Lethbridge and S. Sask. at Medicine Hat
- Total number of weekly low flow events for the Oldman at Lethbridge and S. Sask. at Medicine Hat
- Annual average number of ESRD reservoir recreation days
- Annual average number of instream recreation days