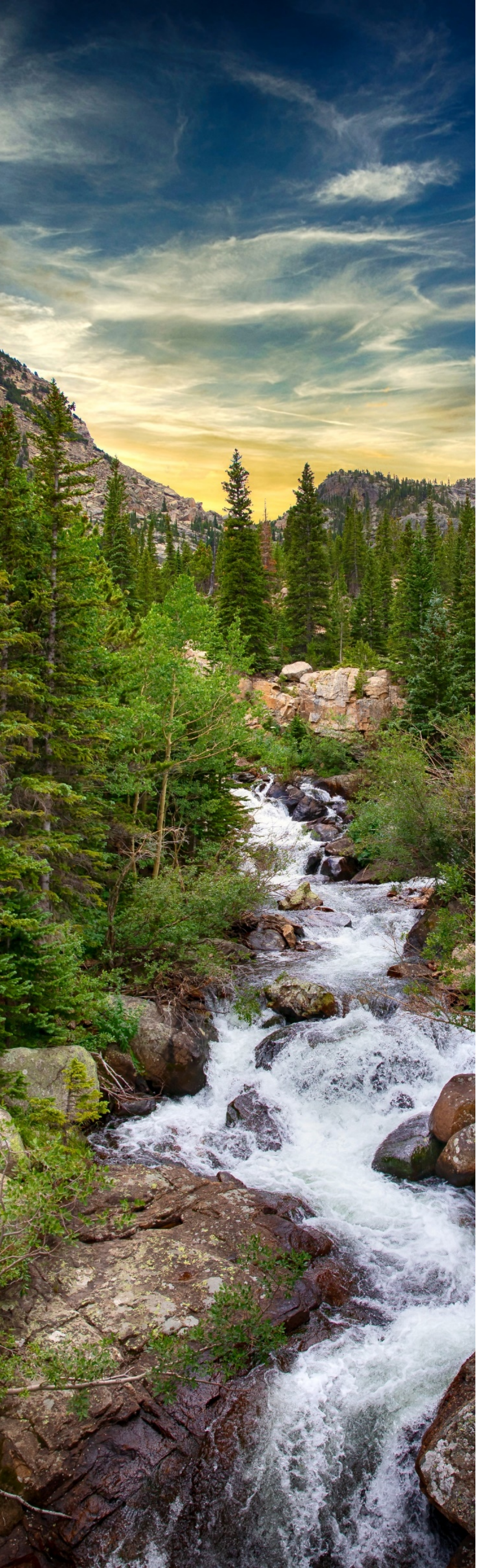

MacHydro

North Saskatchewan Basin Hydrological and Water Management Model

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MacHydro

North Saskatchewan Basin Hydrological and Water Management Model

August 6, 2025

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Contents

List of Figures

List of Tables

1 Document Version

Version	Date	Comment
1.0	2025-06-06	Initial finalized version
1.1	2025-06-17	Fixed typos in Table 10, supplemented Discussion with more discussion of model limitations
1.2	2025-06-25	Update values in Table 6.
1.3	2025-07-14	Update table captions to specify monthly averages or annual totals. Update to discussion section.
1.4	2025-07-23	Updates based on reviews from client and stakeholders
1.5	2025-07-29	Update to Closing language and added citation.
1.6	2025-08-06	Fixed typos.

2 Summary

A regional hydrological model was developed for the North Saskatchewan River Basin in Alberta, Canada. The North Saskatchewan River Model is a hydrological and water management model developed to evaluate the cumulative effects of land cover, climate change, and water management in the watershed. The model provides simulations at 39 points of interest along the mainstem and major tributaries in the watershed. The model was run under several climate change, land cover, and water management scenarios.

The hydrological model shows good process representation and strong performance statistics over a 30-year period at several watersheds of varying size, hypsometry, and vegetation/climate. The model incorporates differences in soil texture, landcover, and terrain. The model simulates naturalized streamflow, which is then used by the water management module to account for reservoir operations and water diversions/returns. Model validation demonstrates the model is a good tool to represent a range of conditions across the watershed. The model shows particularly strong performance in the mountainous headwaters and represents the seasonal pattern of most natural watersheds (i.e. un-regulated) in the North Saskatchewan River Basin.

Results are compiled as daily data, annual averages, and period averages for each point of interest as well as Performance Measures which were developed as basin-wide measures of system health. High-level results from this work found:

- Climate change scenarios run in the hydrological model project a future with less glacial contributions, earlier freshet, and more volatile summer flows due to more intense rainfall events.
- The model shows that forest disturbance has negligible hydrologic impacts at the watershed scale but can considerably alter the hydrology at local/tributary scales, leading to greater peak flows in areas with high forest disturbance.
- Water demand is concentrated along the mainstem North Saskatchewan River between Edmonton and Pakan. Upstream reservoirs regulate flow on the North Saskatchewan River, maintaining relatively high flows during the late summer through winter months (when natural flows would be low), and no water shortages are projected. Smaller water licenses on more arid, unregulated tributaries are likely to experience more water scarcity which could limit their ability to withdraw water.
- Shortages are likely to increase in the future and increased demand (particularly outside the mainstem) is likely to exacerbate the situation. In addition, this does not consider regulatory or operational changes including environmental flow needs (EFNs) and upstream dam operations.
- As surface water conditions become more challenging and demands on the system become greater, more proactive and adaptive water management will be required.
- Water withdrawals are limited only by the physical limits of river flow (i.e. until the river is dry). This modelling highlights that future work should identify flow thresholds and minimum flow requirements to sustain a proper functioning aquatic ecosystem.
- The North Saskatchewan River flow is regulated by Bighorn Dam and Brazeau Dam operations. Results from this modelling highlight that these dams potentially have the capacity to support low flow and/or peak flow management goals, but it remains unclear how these goals could be integrated with current operations and internal goals.

- Off-stream storage options were tested as a means of maintaining higher flows during low-flow periods and showed some success. A refinement of these options could be tested following a more concrete identification of flow requirements.
- The model is a tool that remains available for future work as the regulatory and water management environment evolves, new questions, scenarios, and/or performance measures are developed.

3 Study Area

The regional hydrological model developed for the North Saskatchewan River Basin, extending east from the Eastern Slopes of Alberta's Rocky Mountains to just east of the Saskatchewan border at Deer Creek (above the confluence of the Battle River). The study area consists of several biogeoclimatic zones, including the headwaters originating mountain ranges east of the Continental Divide including the North Saskatchewan River, Brazeau River, Cline River, and Siffleur River; foothills rivers including the Ram River, Nordegg River, Clearwater River, and Baptiste River; parkland rivers, including Modeste Creek, Sturgeon River, and Strawberry Creek; and prairie rivers including the Vermilion River and Beaverhill Creek (Figure 1). The model considered watersheds with long-term hydrometric records to calibrate and validate model performance (Table 1) and provides simulations at 39 points of interest along the mainstem and major tributaries in the watershed.

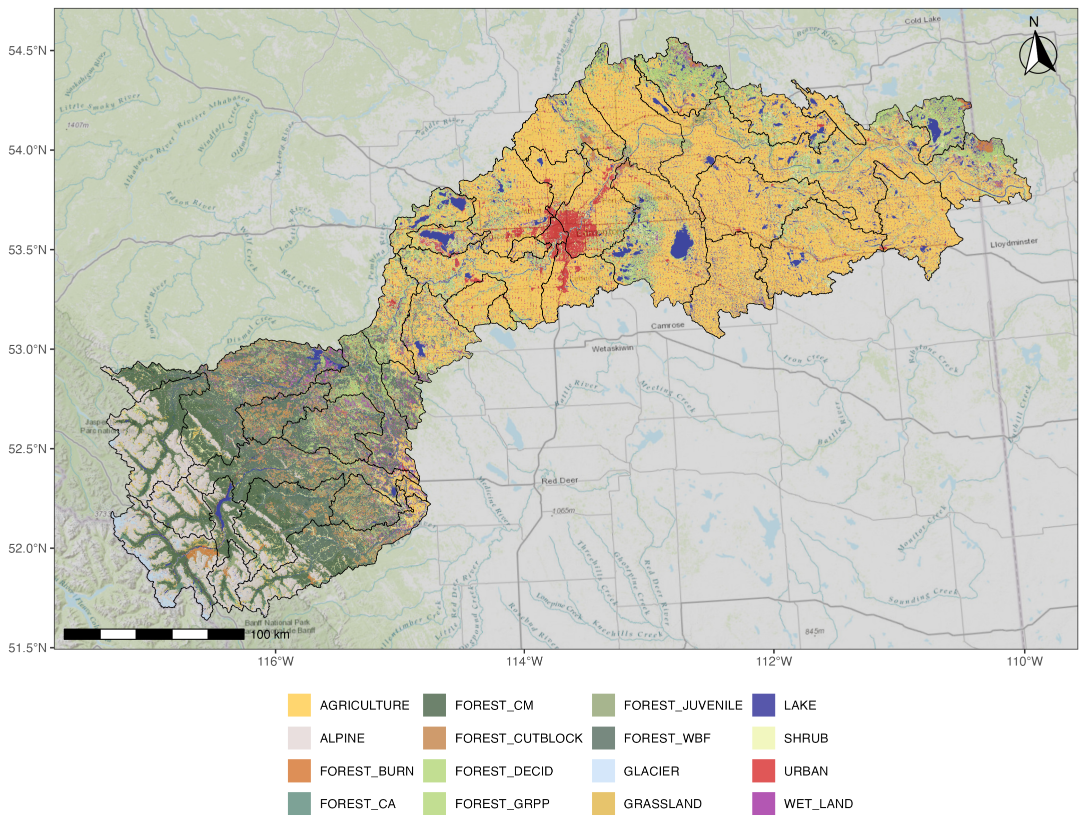


Figure 1. Map of the study area showing land cover current of the year 2022 and 39 sub-basins considered in regional model calibration.

The Albertan portion of the watershed can be thought of as several reaches, each with its own unique biogeoclimatic characteristics (NSWA, 2025). The Alpine reach is characterized by high relief, extending from 1000 m at Nordegg, AB to up to over 3500m at the highest peaks along the Continental Divide (Figure 2). The highest elevations of this reach consist of alpine (bare rock and alpine tundra) and glaciers. Land cover consists primarily of forests, with stands of subalpine fir and spruce at highest (below treeline) elevations and lodgepole pine at lower elevations, with aspen stands along the furthest east and lowest elevation portions of the watershed. The Foothills reach contains moderate relief, with peaks along the westernmost extent reaching above 2000 m and transitioning to lower relief further east. Landcover in this region consists of conifer forest (spruce and pine) as well as wetlands and some deciduous forest stands. Further east, the Parkland reach consists of a mix of deciduous forest stands, native grasslands, and agriculture distributed across low relief areas. This region also contains larger urban centers, including the City of Edmonton, St. Albert, and Leduc, as well as the Industrial Heartland. Prairie reaches cover the easternmost extent of the study area and are characterized by low-relief agricultural and grassland areas, with stands of deciduous forest. This region also contains prairie potholes: areas of low-lying ephemeral lakes that drain to waterways intermittently.

Table 1. Water Survey of Canada hydrometric stations used in this study.

Station Name	Station Number	Validation Site	Date Range	Drainage Area (km^2)
Regulated				
North Saskatchewan River Near Deer Creek	05EF001	Yes	1917-2023	57,098
North Saskatchewan River Near Pakan	05EC919		NA-NA	39,279
North Saskatchewan River At Edmonton	05DF001	Yes	1911-2022	27,997
North Saskatchewan River At Highway No. 759	05DE010	Yes	2007-2022	22,063
North Saskatchewan River Near Lodgepole	05DE006	Yes	1969-1977	20,480
North Saskatchewan River Near Rocky Mountain House	05DC001	Yes	1913-2022	11,013
Vermilion River At Lea Park	05EE002		1964-1970	7,829
Vermilion Park Lake Near Vermilion	05EE008	Yes	NA-NA	6,095
Brazeau River Below Brazeau Plant	05DD005	Yes	1956-2019	5,641
North Saskatchewan River Below Bighorn Plant	05DC010		1972-2017	3,886
Wabamun Creek Near Duffield	05DE003		1927-1995	533
Natural				
Vermilion River At Range Road No. 105	05EE010		2006-2022	3,875
Sturgeon River Near Fort Saskatchewan	05EA001		1914-2022	3,249
Clearwater River Near Rocky Mountain House	05DB001		1914-1975	3,213
Beaverhill Creek	05EB015		1975-1986	2,907
Brazeau River Below Cardinal River	05DD007	Yes	1961-2023	2,589
Sturgeon River At St. Albert	05EA002	Yes	1913-2022	2,587
Clearwater River Near Dovercourt	05DB006	Yes	1975-2023	2,248
North Saskatchewan River At Whirlpool Point	05DA009	Yes	1970-2022	1,913
Ram River Near The Mouth	05DC006	Yes	1967-2022	1,844
Vermilion River At Vegreville	05EE009	Yes	1987-2022	1,594
Redwater River Near The Mouth	05EC005		1978-2022	1,591
Baptiste River Near The Mouth	05DC012	Yes	1984-2022	1,337
Modeste Creek	05DE911	Yes	1996-2022	1,254
Saddlelake Creek	None		NA-NA	1,230
White Earth Creek Near Smoky Lake	05EC006		1985-1995	1,153
Whitemud Creek At Edmonton	05DF009		2013-2023	1,030
Nordegg River At Sunchild Road	05DD009	Yes	1971-2022	865
Prairie Creek Near Rocky Mountain House	05DB002	Yes	1922-2022	848
Cline River Near The Mouth	05DA004		1915-1918	818
Frog Creek	None		NA-NA	773
Sturgeon River Near Onoway	05EA004		1914-1931	719
Strawberry Creek Near The Mouth	05DF004		1966-2022	593
Rose Creek Near Alder Flats	05DE007		1972-2022	545
Siffleur River Near The Mouth	05DA002	Yes	1915-1996	500
Cardinal River Near The Mouth	05DD008		1962-1990	483
Atimoswe Creek Near Elk Point	05ED002		1975-2022	411
Wedgewood Creek	None		NA-NA	195
Weed Creek At Thorsby	05DF008		2005-2022	192

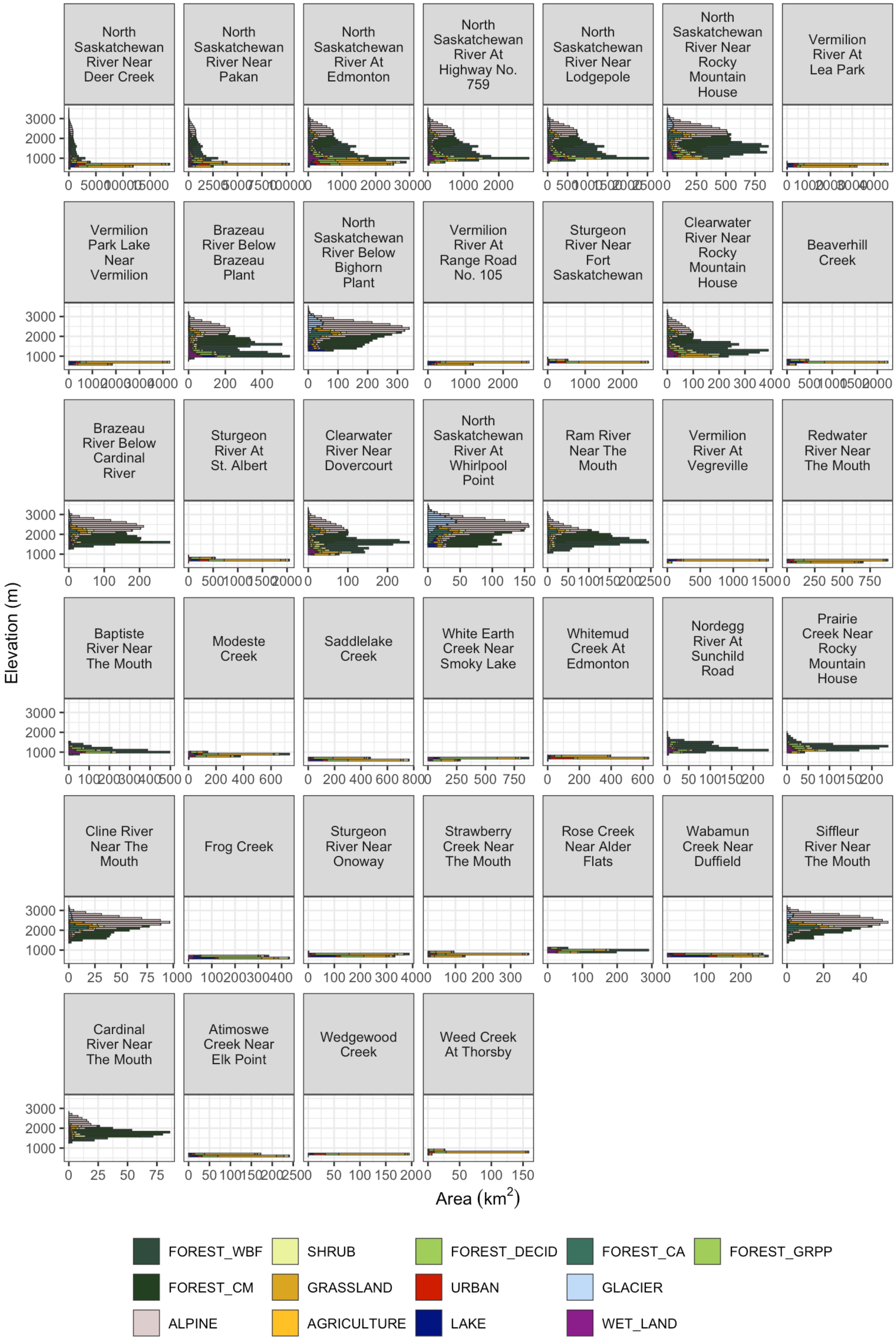


Figure 2. Hypsometry of watersheds considered in this study, sorted by upstream area.

4 Methods

4.1 Model Formulation

The semi-distributed hydrological model used in this study is an adapted version of the HBV-EC model, emulated within the Raven Hydrological Modelling Framework version 4.0beta (Craig et al., 2023). The model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep. The model spatially distributes daily minimum and maximum air temperature, precipitation, and relative humidity from all weather stations across the study region. The model simulates major hydrological processes including canopy interception, snow accumulation and melt, evaporation, soil infiltration, percolation, and baseflow, as well as surface runoff. Major processes are described below, while a comprehensive discussion of model algorithms can be found in Bergström (1992), Jost et al. (2012), and Chernos et al. (2020).

In the hydrological model, water inputs occur as precipitation, which is partitioned into rain or snow following the HBV linear transition based on air temperature. Precipitation interception by the forest canopy is estimated as a function of Leaf-Area Index (LAI; Craig et al., 2020; Hedstrom and Pomeroy, 1998). Snowmelt is calculated using a terrain corrected temperature index model, which accounts for vegetation shading, aspect, slope, and day length (Jost et al., 2012, Craig et al, 2020). Potential evapotranspiration is calculated using the Priestley–Taylor equation (Craig et al., 2023) and varies between vegetation types. Once water infiltrates the three-layer soil, it moves downwards through percolation and upwards through capillary rise. Soil water becomes surface runoff (i.e. streamflow) through (faster) interflow and (slower) baseflow pathways. In prairie pothole regions, non-contributing areas accumulate water in depression storage where it can evaporate and only overflows and contributes to streamflow when storage is exceeded.

Small lakes were treated as lake storage with a linear rate of water release. Major lakes were treated as natural reservoirs where mass balance was calculated using storage curves derived from lake characteristics and flow attenuation coefficients. Treating a waterbody as a reservoir allows the model to simulate the mass balance of the lake and explicitly account for flow attenuation along the main channel. Both reservoirs and lakes freeze during below 0°C air temperatures, accumulate snow when frozen, and thaw once the overlying winter snowpack has melted away. Several reservoirs are simulated explicitly in the watershed (Table 2), these were chosen based on whether they had available monitoring, had water management of their outlets (i.e. dams), or were lakes explicitly identified as points of interest by the Working Group.

Table 2. Large lakes treated as reservoirs in the hydrological model

Name	Basin Outlet	Regulation	Crest Width (m)	Absolute Crest Height (m)	Weir Coefficient	Max Depth (m)	Lake Area (km2)
Wabamun Lake	Wabamun Creek Near Duffield	*Natural	5	724	0.6	11	82.0
Frog Lake	Frog Creek	Natural	5	576	0.6	28	58.4
Lac Ste. Anne	Sturgeon River Near Onoway	Fixed-Weir/ Natural	5	722.2	0.6	5	54.5
Abraham Lake	North Saskatchewan River Below Bighorn Plant	Regulated	50	1290	0.6	25	53.7
Brazeau Reservoir	Brazeau River Below Brazeau Plant	Regulated	20	948	0.6	20	34.8
Big Lake	Sturgeon River At St. Albert	Natural	5	0	0.9	4	21.4
Saddle Lake	Saddlelake Creek	Natural	5	608	0.6	10	6.3
Vermilion Lakes	Vermilion River At Range Road No. 105	Regulated	5	598.6	0.6	5	5.3
Vermilion Park Lake	Vermilion Park Lake Near Vermilion	Fixed-Weir/ Natural	5	575.5	0.6	10	2.2

4.2 Spatial Discretization

The modelled study area was divided into sub-basins to provide model outputs at major points of interest, calibrate and verify model performance at hydrometric gauges, and to characterize hydroclimatic heterogeneity in the study area. Sub-basin delineation was based on the outflow of major lakes and to align with hydrometric monitoring locations in the region.

The study area was further discretized into hydrological response units (HRUs) based on the unique overlay of elevation bands, hillshade, land cover, soil texture, and sub-basin. We derived 100 m elevation bands using the Canadian Digital Elevation Data digital elevation model (DEM; Natural Resources Canada, 2016). Hillshade is calculated using the hillshade function in the R terra package (Hijmans, 2023), which incorporates the slope and aspect of each grid cell. Land cover was obtained from Natural Resources Canada’s 2020 Land Cover of Canada (Latifovic, 2023) and forests were further delineated based on their Biogeoclimatic zone (Baldwin et al., 2019). Forests were dynamically adjusted within the model runs for forest fires, which were obtained from the Canadian National Fire Database (Natural Resources Canada, 2023) and forest harvest, which were obtained from Alberta Biodiversity Monitoring Institute’s Human Footprint dataset (ABMI, 2023). Finally, forests were dynamically adjusted within the model runs for forest fires and harvest; Forest HRUs were classified as to be “Burn” (or “Cutblock”) for the 25 years following the fire (harvest), and “Juvenile” for the following 25 years. Non-contributing areas were identified using AAFCs layer (AAFC, 2023). Soil texture was obtained from Soil Landscapes of Canada (SLC) version 3.2 (SLCWG, 2010).

4.3 Model Forcing Data

To run the hydrological model configurations used in this study, daily air temperature (maximum and minimum, °C) and precipitation (mm/day) are required. These data were obtained from Alberta Environment and Park’s (AEP’s) Hybrid Climate Dataset (Eum and Gupta, 2019). Individual points from the gridded hybrid dataset were obtained from 1950-2019 at a 1/4th degree resolution over the study area. Reference elevations are obtained for each data point and are used to correct observations to HRU elevations using specified lapse rates within the hydrological model. Since HRUs are at much higher resolution than the gridded climate dataset, spatial interpolation between weather stations uses Inverse Distance Weighting.

4.3.1 Future Climate Change Scenarios

Future climate change scenarios were also obtained from AEP's Hybrid Climate Dataset. In total, 12 climate change scenarios were provided by AEP, which had been selected using a methodology to account for the range of future climate variability under the full set of CMIP6 climate change projections and were bias-corrected against the historical observations using a multivariate bias correction and distribution-free shuffle (MBCDS) approach (Eum et al., 2020). These scenarios were available from seven General Circulation Models under a collection of Shared Socioeconomic Pathways (SSP), where SSP 1-2.6 represents a pathway with a high level of emissions reduction and SSP 5-8.5 represents an increase in emissions and a high degree of radiative warming (Table 3). Further details on the scenarios themselves can be found in Eum et al. (2020).

Table 3. Climate change scenarios provided by AEP under CMIP6, downscaled to the Alberta Hybrid Climate Dataset.

GCM	SSP 1-2.6	SSP 2-4.5	SSP 3-7.0	SSP 5-8.5
BCC-CSM2-MR	x	-	x	-
CNRM-CM6-1	x	-	-	x
EC-Earth3-Veg	x	-	x	-
GFDL-CM4	-	x	-	-
GFDL-ESM4	-	-	-	x
IPSL-CM6A-LR	x	-	x	-
Median	-	x	-	x
MRI-ESM2-0	-	-	x	x

Several headwater sub-basins have considerable glacier coverage and these glaciers can be an important component of streamflow, especially later in the summer. In addition, assuming current glacier extent persists into the future will overestimate available water. Therefore, glacier retreat was simulated in the hydrological model based on cumulative mass loss under each climate change scenario. In this configuration, Glacier HRUs were converted to Alpine once their net mass balance had reached a maximum mass loss. This maximum loss of mass value is analogous to an averaged ice depth across the glacier. Given this value is likely spatially variable, an estimate was made following Clarke et al. (2015) glaciological projections (Figure 3).

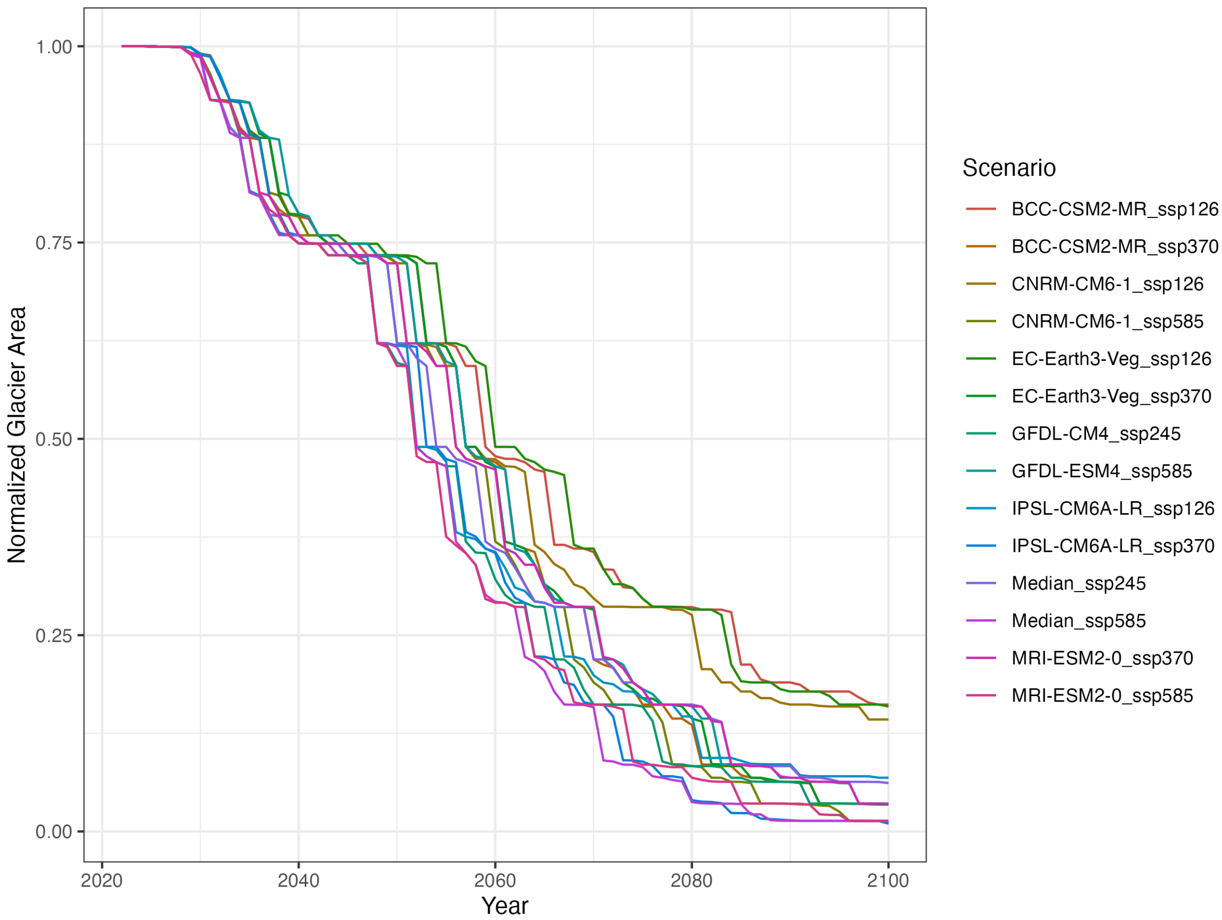


Figure 3. Normalized glacier area by year for each future climate change scenario run, relative to the current-day extent.

4.4 Water Management

4.4.1 Reservoir Operations

Natural Reservoirs

No operations were simulated on reservoirs that had static control structures (i.e. a weir or canal with a set/fixed height) or did not have a control structure at its outlet. This included the lakes simulated explicitly on the Sturgeon River (Lac Ste. Anne, Big Lake), as well as Frog Lake, Saddle Lake, Vermilion Park Lake on the Vermilion River, and Wabamum Lake. Although industrial activity in Wabamun Lake has historically led to considerable alteration of its lake levels (due to mining operations and power production, including pumping/diversions to/from the North Saskatchewan River), at the current time of writing, there are no active operations that are expected to alter natural outflow from the lake. In natural reservoirs, outflow is dictated by a stage-discharge curve (driven by the Weir Coefficient and Crest Width parameters) and the storage characteristics of the lake.

Bighorn Dam

Bighorn Dam is located at the outlet of Abraham Lake in the upper North Saskatchewan River (below Bighorn Plant) and is operated by TransAlta Corporation for the primary purpose of power generation. Operations for Bighorn Dam are modelled with the following goals in order of decreasing priority:

- Maintain water levels below the Dam spill elevation (ranging from 1321.3 m during the winter months down to 1316.1 m in July).
- Maintain water levels above the Low Service Level (4210 ft, 1283.2 m).
- Minimum flows on the North Saskatchewan River below the Dam exceed 1500 cfs (approx 42.5 m^3/s) from December through February, 1800 cfs (approx 50.9 m^3/s) in March, and 800 cfs (approx 22.6 m^3/s) otherwise.
- Maximum flows on the North Saskatchewan River below the Dam remain below 3000 cfs (approx 84.9 m^3/s) in January and February, 5000 cfs (approx 141.5 m^3/s) in December and March, and 5800 cfs (approx 164.1 m^3/s) otherwise.

These goals were developed to represent general conditions and may deviate due to different icing conditions that occur in real-time.

These goals provide a relatively wide range of possible water levels and outflows. To further constrain the model, a target stage for the lake is set to remain between the historical 25th and 75th quantiles of Abraham Lake water level over the last 30 years. This target stage is given a low priority, such that it is only met once all other watershed constraints are met (Figure 4). This pattern may not reflect day to day operations as they are informed by other management goals (most notably power demand and prices) but provides a general trend in operations.

Brazeau Dam

Brazeau Dam is located at the outlet of the Brazeau Reservoir in the lower Brazeau River (below Brazeau Plant) and is operated by TransAlta Corporation for the primary purpose of power generation. Operations for Brazeau Dam are modelled with the following goals in order of decreasing priority:

- Maintain water levels below the Dam spill elevation (ranging from 966.2 m during the winter months down to 964.2 m in June and July).
- Maintain water levels above the Low Service Level (3110 ft, 947.9 m).
- Minimum flows on the Brazeau River below the Dam exceed 650 cfs (approx 18.4 m^3/s).
- Maximum flows on the North Saskatchewan River below the Dam remain below 5300 cfs (approx 150.0 m^3/s) from December through March (ice period) and 12000 cfs (approx 339.6 m^3/s) otherwise.

These goals were developed to represent general conditions and may deviate due to different icing conditions that occur in real-time.

These goals provide a relatively wide range of possible water levels and outflows. To further constrain the model, a target stage for the lake is set to remain between the historical 25th and 75th quantiles of Brazeau Reservoir water level over the last 30 years. This target stage is given a low priority, such that it is only met once all other watershed constraints are met (Figure 4). This pattern may not reflect day to day operations as they are informed by other management goals (most notably power demand and prices), but provides a general trend in operations.

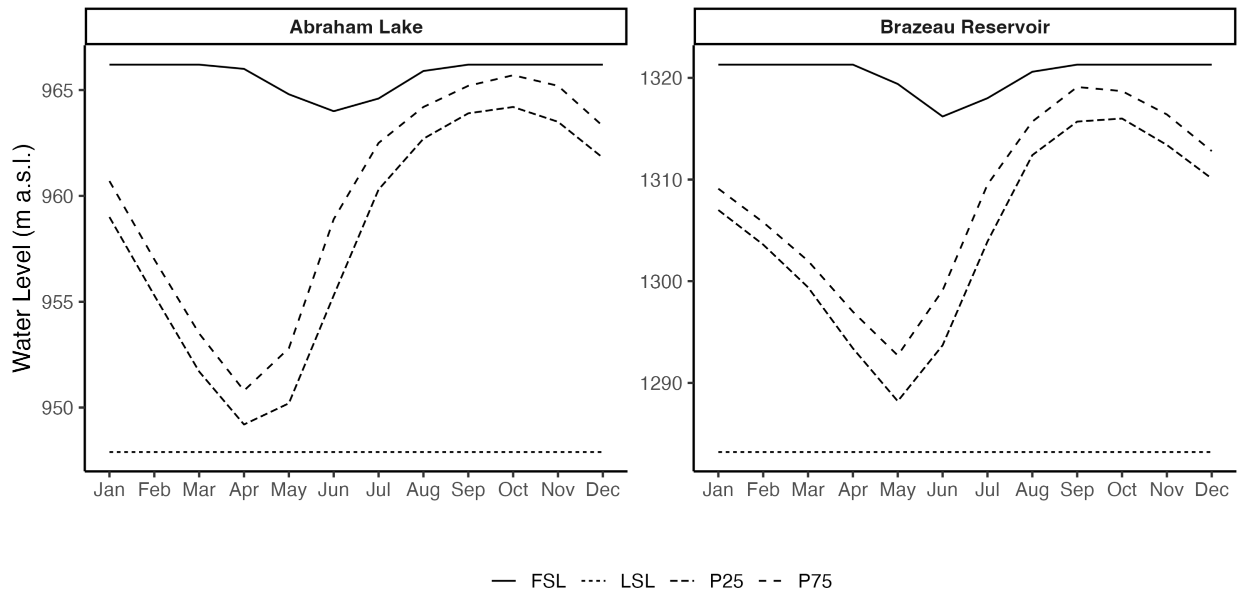


Figure 4. Stage (water level) targets for both TAU reservoirs, including the Low Supply Level (LSL), Full Supply Level (FSL), and 25th/75th quantiles (P25/P75).

Finally, there is a goal to maintain a combined minimum flow out of the Brazeau and North Saskatchewan River below the two dams to above 2500 cfs (approx 70.8 m^3/s). This goal is given the highest priority of any goals at either Brazeau or Bighorn dams.

Vermilion Lakes

Vermilion Lakes are a chain of 6 lakes located in the upper Vermilion River watershed between Two Hills and Morecambe, AB. A flow structure was built in 1976 south of Morecambe, AB, commonly referred to as the Morecambe Structure to address concerns with high runoff leading to flooding of the Vermilion Lakes and Two Hills Floodplain. The flow structure is a weir designed to maximize lake drainage and decrease the duration and magnitude of flooding. The structure is operated to draw down Vermilion Lakes prior to anticipated flooding, increase drainage on the Two Hills Floodplain, and decrease the duration of inundation, particularly in the summer when damage to crops would be more consequential. Historical operations have changed over the years, including a substantial period (1991-2005) when the structure was not in operation. The Morecambe Structure is modelled to reflect current operations and has the following goals, in order of decreasing priority:

- Maintain an outflow below 11.3 m^3/s between April 15 and October 15
- Maintain water levels in Vermilion Lakes above 598.78 m (minimum drawdown elevation).
- Reduce water levels to the minimum drawdown elevation (598.78 m) when inflows to the Vermilion Lakes is above 1.0 m^3/s between April 15 and October 15.
- Maintain water levels at the FSL (599.08 m).

4.4.2 Water Licenses

Water licenses are represented in the hydrological model as a diversion and return flow (if applicable) in a specified sub-basin. Water use occurs from the reach of the watershed (tributary or mainstream North Saskatchewan River) determined from the point of diversion as stipulated in the license and return flows are assumed to occur at the same location unless additional information is available to confirm return flows occur in a different sub-basin. Return flows are represented as a fractional portion of the diversion, as stipulated in the license. The model considers all water licenses within Alberta portion of the North Saskatchewan River Basin that had not expired as of January 2020.

Water Diversion and Return

Water allocations were obtained from the Alberta License Viewer for all licenses in the NSRB. Water use data was obtained from Alberta's Water Use Reporting System (WURS); additional water use and return data for the City of Edmonton was provided by EPCOR as well as several other licensees. Since the goal of this exercise is to replicate a base case of water use, representative of current conditions, the dataset was filtered to consider all reported usage since 2010. This selection considered 442 unique water licenses, of which 57 were classified as "Municipal", 4 as "Management", 191 as "Industrial", 134 as "Commercial", and 56 as "Agriculture". Licenses were grouped based on their reported Classification (i.e "Agriculture"; see Table 4) and for each classification, an average monthly diversion was calculated as the fraction of reported water diversion relative to the annual licensed Maximum Annual Diversion.

Table 4. Specific descriptions for each license Classification Type for all active licenses in the North Saskatchewan River Basin

Classification	Description
AGRICULTURE	REGISTRATIONS/FARMSTEADS/OTHER FARM USE, STOCKWATERING, IRRIGATION (PRIVATE), CONFINED FEEDING OPERATIONS/FEEDLOTS, FISH/FISH FARMS/HATCHERIES, GARDENS/MARKET GARDENS/U-PICK FARMS/GREENHOUSES (CROP), DISTRICT IRRIGATION, NA
COMMERCIAL	PUBLIC ROADS, CIVIL INFRASTRUCTURE & TELECOM, GRAVEL & AGGREGATE MINING & WASHING, PARKS & RECREATION/CAMPGROUNDS, GOLF COURSES, FOOD PROCESSING/SLAUGHTERHOUSES, WATER BOTTLING, AGRICULTURAL/INDUSTRIAL/OILFIELD SERVICES, SOD FARMS/TREE FARMS/GREENHOUSES (TREE & PLANT), CARWASHING/HOTELS/MOTELS/RESTAURANTS/CLEANERS, NA, EQUIPMENT/INDUSTRIAL EQUIPMENT, CEMENT & CONCRETE PLANTS, SNOW/ICE MAKING, DUST CONTROL/BRIDGE WASHING, SEISMIC/GEOTECHNICAL/WATER WELL DRILLING/PUMP TEST (PROVIDING GENERAL SERVICES)
EDMONTON & REGIONAL CUSTOMERS	LARGE CITIES (EDMONTON AND CALGARY), HAMLETS & RURAL MUNICIPALITIES (COUNTIES/MUNICIPAL DISTRICTS)
INDUSTRIAL	MULTI-STAGE HORIZONTAL HYDRAULIC FRACTURING (DRILLING & COMPLETIONS), OIL & GAS PLANT PROCESSING/OIL SANDS UPGRADER/PLANT UTILITY WATER, DRILLING (CONVENTIONAL & VERTICAL FRACTURING), INJECTION (WATER FLOOD/CONVENTIONAL OIL/ENHANCE OIL RECOVERY), HYDROPOWER, WASTE DISPOSAL/REMEDIATION, REFINERIES & UPGRADERS, PETROCHEMICAL, CHEMICAL & FERTILIZER PLANTS, OTHER MINING (MINERALS & METALS), THERMAL/COAL/GAS (THERMAL DISCHARGE RETURN FLOW), THERMAL/COAL/GAS (COOLING PONDS), QUARRYING/MILLING, NA, SAWMILLS & LUMBER MILLING, OIL SANDS (COLD BITUMEN), OIL SANDS (SAGD/CSS/THERMAL), UPSTREAM HYDROSTATIC TESTING & PIPELINE CONSTRUCTION & OPERATION
MANAGEMENT	LAKE LEVEL STABILIZATION, WETLANDS, FLOOD CONTROL OR DRAINAGE, STORAGE RESERVOIR FOR WILDLIFE OR FISH HABITAT ENHANCEMENT, NA
MUNICIPAL	HAMLETS & RURAL MUNICIPALITIES (COUNTIES/MUNICIPAL DISTRICTS), SUBDIVISIONS/CONDOMINIUM-TOWNHOUSES/MOBILE HOMES-COMPLEXES/COOPERATIVES/COLONIES, INSTITUTIONS/SENIOR-NURSING-CHILDREN'S HOMES/CORRECTIONAL CENTRES/SCHOOLS/TRAINING CENTRES/HOSPITALS/FIRE PROTECTION, POPULATION UNDER 2,500, POPULATION 2,500 TO 10,000, LARGE CITIES (EDMONTON AND CALGARY), POPULATION GREATER THAN 10,000, REGIONAL WATER LINES/REGIONAL MUNICIPAL SUPPLY SYSTEMS

Results display a seasonal pattern that varies between license Classification types (Figure 5). Municipal licenses display a seasonal pattern, with higher values during the summer months and lower values during the winter. Industrial licenses have a modest seasonal pattern, with some uptick in use during the summer, but a relatively consistent baseline use during the winter period. Agriculture, Commercial, and Management licenses display a very strong seasonal pattern, peaking in the summer with little use during the winter months.

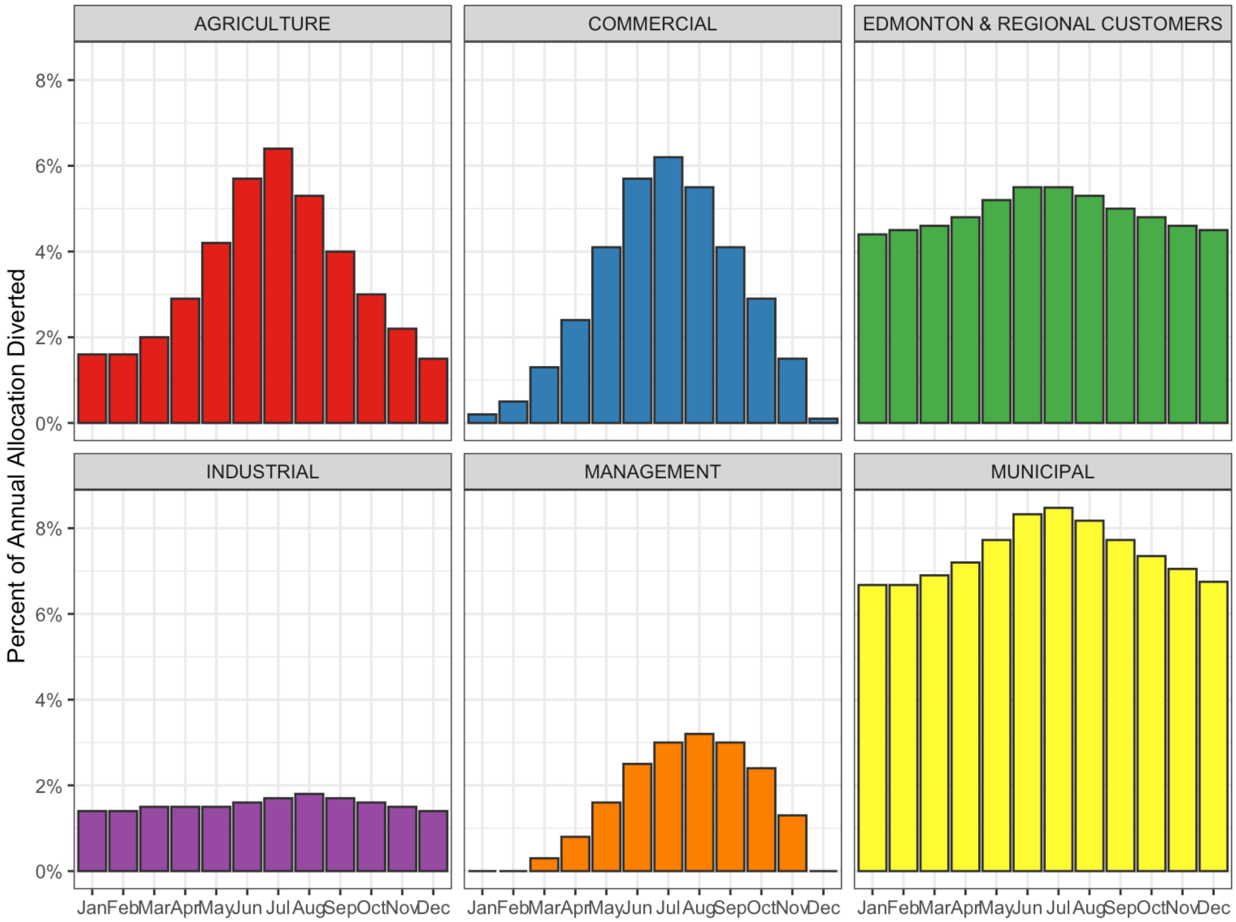


Figure 5. Monthly average estimated water diversion for each license Classification type, presented as the percent of licensed maximum annual allocation.

Water License Modelling

All active surface water licenses (non-expired as of January 2020) in the NSRB are represented in the model and are treated as water diversion from the sub-basin based on their specified point of diversion and, if applicable, a return flow, represented as a fraction of the water diverted. Licenses of less than 316,000 m^3/year (average of 0.01 m^3/s) maximum annual allocation were aggregated by Classification type for each sub-basin (all larger licenses are modelled independently). In total, this led to 228 water license nodes. Based on the Classification type for each license, a monthly pattern was applied to each license node by scaling the licensed diversion by the monthly projected percent of maximum annual allocation (Table 5) and this pattern was repeated for all years. Overall, this base case reflects the fact that, based on reported usage data, on average, licensed diversion is between 15% and 82% and varies considerably between Classification type. Return flows are treated as a fraction of diverted water, where the fraction is estimated based on the return flow divided by the maximum annual diversion as specified in the license and is constant throughout the year. In cases where no specified return flow is provided in the license database, it is assumed that no return flow is made (i.e return flow fraction of 0).

Each water license has a penalty associated for not meeting water demand, which is based on the ranked license priority (i.e. seniority), where higher priority licences have higher penalties for not being met such that in the case of water shortages, lower priority/penalty licenses are shorted first. For scenario analysis, the model allows for diversions to be scaled (for instance, to use 100% of the allocated consumptive use while maintaining the seasonal pattern of use) for all licenses, for subsets, or individually.

Table 5. Percent of maximum annual allocation that is assumed to be diverted by a water license for each Classification type.

Month	AGRICULTURE	COMMERCIAL	EDMONTON & REGIONAL CUSTOMERS	INDUSTRIAL	MANAGEMENT	MUNICIPAL
January	1.6%	0.2%	4.4%	1.4%	0.0%	6.7%
February	1.6%	0.5%	4.5%	1.4%	0.0%	6.7%
March	2.0%	1.3%	4.6%	1.5%	0.3%	6.9%
April	2.9%	2.4%	4.8%	1.5%	0.8%	7.2%
May	4.2%	4.1%	5.2%	1.5%	1.6%	7.7%
June	5.7%	5.7%	5.5%	1.6%	2.5%	8.3%
July	6.4%	6.2%	5.5%	1.7%	3.0%	8.5%
August	5.3%	5.5%	5.3%	1.8%	3.2%	8.2%
September	4.0%	4.1%	5.0%	1.7%	3.0%	7.7%
October	3.0%	2.9%	4.8%	1.6%	2.4%	7.4%
November	2.2%	1.5%	4.6%	1.5%	1.3%	7.1%
December	1.5%	0.1%	4.5%	1.4%	0.0%	6.8%
Total	*40.4%*	*34.5%*	*58.7%*	*18.6%*	*18.1%*	*89.0%*

Spatially, water allocation and use is concentrated to the North Saskatchewan River at and downstream of Edmonton. The bulk of this allocated diversion volume is classified as Industrial, with a smaller proportion classified as Municipal. When considering Consumptive Use (i.e. accounting for return flows), the proportion of licensed volume classified as Municipal and Industrial decreases since these licenses tend to have considerable return flows, unlike Agriculture and Commercial licenses, where the diversion is largely consumptive. Some tributaries, such as the Vermilion River, have a concentration of Agriculture licenses, while the Sturgeon River and Redwater River have a considerable proportion of Commercial licensed volume.

Table 6. Summary statistics for water licenses considered in this study under the Base Case. Returns flows are based on either license data or participant feedback where available. In the absence of this information, return flows were estimated based on other similar licenses.

Class	Count	Maximum Annual Diversion (m^3/year)	Return Flow (m^3/year)	Consumptive Use (m^3/year)
INDUSTRIAL	200	813,848,723	577,374,646	236,474,077
EDMONTON & REGIONAL CUSTOMERS	3	263,523,000	179,113,000	84,410,000
AGRICULTURE	5,675	18,724,905	225,880	18,499,025
MANAGEMENT	146	18,900,624	2,373,238	16,527,386
COMMERCIAL	228	22,011,470	6,814,658	15,196,812
MUNICIPAL	51	15,219,221	8,560,377	6,658,844

4.5 Model Calibration/Verification Data

Meteorologic and hydrometric observations were gathered from publicly available data sources to calibrate and verify the hydrological model (Table 7). This process is essential to ensure that the model is providing accurate results, to constrain uncertainty, and to ensure proper process-representation. Hydroclimatic data were available from several public data sources in or nearby the study area. Weather stations were available from Environment Canada (EC) with air temperature and precipitation observations. In addition, snow pillows and periodic (roughly monthly) snow surveys were available across the study area and are collected and maintained in the Canadian historical Snow Water Equivalent dataset (CanSWE v5; Vionnet et al., 2021). Streamflow (m^3/s) data were obtained from Water Survey of Canada (WSC) hydrometric stations in the study area with long-term records (Table 1).

Table 7. Meteorologic stations used to calibrate and validate hydrologic processes including lapse rates and snowmelt across the study area. AE corresponds to Alberta Environment, BCE corresponds to British Columbia Environment, EC to Environment Canada and MoSC to Meteorological Service of Canada.

Site	ID	Latitude	Longitude	Elevation (m)	Type	Source
KATHERINE LAKE	ALE-05BA814	51.68	-116.38	2380	Snow Survey	AE
MCCONNELL CREEK	ALE-05CA806	51.68	-115.98	2130	Snow Survey	AE
WILDCAT CREEK	BCE-2A32P	51.7	-116.63	2122	Snow Pillow	BCE
BALDY LO	2363	52.55	-116.12	2083	Weather Station	EC
GRAVE FLATS LO	2392	52.85	-117	2074	Weather Station	EC
CLINE LO	2379	52.18	-116.4	2050	Weather Station	EC
SOUTHESK PILLOW	ALE-05DD804P	52.67	-117.23	2045	Snow Pillow	AE
BOW SUMMIT (NEW)	ALE-05BA813	51.71	-116.48	2031	Snow Survey	AE
LIMESTONE	ALE-05DB802	51.9	-115.43	1970	Snow Survey	AE
LIMESTONE RIDGE PILLOW	ALE-05DB802P	51.89	-115.38	1970	Snow Pillow	AE
NIGEL CREEK	ALE-05DA804	52.2	-117.08	1920	Snow Survey	AE
BASELINE LO	1815	52.13	-115.42	1897	Weather Station	EC
BLACKSTONE LO	1822	52.78	-116.35	1570	Weather Station	EC
AURORA LO	1814	52.65	-115.72	1341	Weather Station	EC
BIGHORN DAM	2365	52.32	-116.33	1341	Weather Station	EC
NORDEGG RS	2423	52.5	-116.05	1320	Weather Station	EC
CLEARWATER	1848	51.98	-115.25	1280	Weather Station	EC
BRAZEAU LO	1823	53.02	-115.42	1088	Weather Station	EC
NORDEGG	ALE-05DC801	52.45	-116.1	1060	Snow Survey	AE
ROCKY MOUNTAIN HOUSE A	SCD-AL167	52.43	-114.92	1015	Snow Survey	MSoC
BRAZEAU RES.	ALE-05DD801	52.95	-115.68	970	Snow Survey	AE
CRIMSON LAKE	ALE-05DC802	52.42	-115.03	970	Snow Survey	AE
WINFIELD	2017	52.95	-114.58	910	Weather Station	EC
BRETON	1825	53.17	-114.48	843	Weather Station	EC
ENTWISTLE	2513	53.6	-114.98	780	Weather Station	EC
EDMONTON STONY PLAIN	1870	53.55	-114.11	766	Weather Station	EC
EDMONTON STONY PLAIN	SCD-AL040	53.55	-114.1	766	Snow Survey	MSoC
LEDUC	ALE-05DF801	53.27	-113.55	730	Snow Survey	AE
EDMONTON INT'L A	1865	53.32	-113.58	723	Weather Station	EC
CALMAR	1835	53.29	-113.86	720	Weather Station	EC
ELK ISLAND NAT PARK	1873	53.68	-112.87	716	Weather Station	EC
HOLDEN SOUTH	1898	53.08	-112.27	709	Weather Station	EC
SION	1976	53.88	-114.12	701	Weather Station	EC
TOFIELD NORTH	1990	53.55	-112.75	701	Weather Station	EC
ELK ISLAND PARK	ALE-05EB802	53.58	-112.83	700	Snow Survey	AE
MORINVILLE	ALE-05EA802	53.85	-113.48	700	Snow Survey	AE
ONOWAY	ALE-05EA803	53.72	-114.17	700	Snow Survey	AE
WESTLOCK	ALE-07BC801	54	-113.97	700	Snow Survey	AE
EDMONTON NAMAO A	SCD-AL039	53.67	-113.47	688	Snow Survey	MSoC
EDMONTON NAMAO A	1868	53.67	-113.47	688	Weather Station	EC
RANFURLY 2NW	1958	53.42	-111.73	673	Weather Station	EC
EDMONTON CITY CENTRE A	1867	53.57	-113.52	671	Weather Station	EC

EDMONTON WOODBEND	1872	53.42	-113.75	671	Weather Station	EC
BELLIS	ALE-05EC801	54.12	-112.08	670	Snow Survey	AE
BRUCE SNOW PL	ALE-05EE802	53.28	-112.07	670	Snow Survey	AE
MANNVILLE	ALE-05FE801	53.17	-111.2	670	Snow Survey	AE
PERRYVALE	ALE-07CA802	54.47	-113.17	670	Snow Survey	AE
LAVOY	1915	53.53	-111.87	670	Weather Station	EC
LLOYDMINSTER A	1920	53.31	-110.07	668	Weather Station	EC
UofA METABOLIC CENTRE	1801	53.52	-113.53	668	Weather Station	EC
OLIVER TREE NURSERY	1944	53.65	-113.37	648	Weather Station	EC
CLANDONALD	ALE-05ED801	53.57	-110.87	640	Snow Survey	AE
ST PAUL	ALE-05ED802	53.98	-111.02	640	Snow Survey	AE
TWO HILLS	ALE-05EE801	53.72	-111.72	640	Snow Survey	AE
WASKATENAU	ALE-05EC802	54.18	-112.83	640	Snow Survey	AE
VEGREVILLE	1977	53.51	-112.1	639	Weather Station	EC
ST LINA	1967	54.3	-111.45	632	Weather Station	EC
FORT SASKATCHEWAN	1886	53.72	-113.18	620	Weather Station	EC
ANDREW	1812	54.02	-112.23	610	Weather Station	EC
HILLMOND	3226	53.44	-109.72	584	Weather Station	EC

4.6 Model Outputs and Statistics

4.6.1 Daily Model Outputs

The model provides outputs for each sub-basin at a daily timestep. These include hydrologic variables as well as water management variables which are summarized in Table 8.

Table 8. Outputs from the model available at a daily timestep at each sub-basin.

Variable	Description	Units
Streamflow	The flow of water in the river or stream, presented as a rate (volume per second).	m^3/s
Stage	The water level of a lake or reservoir (often the absolute elevation above sea level, but sometimes as a relative level).	m
Volume	The volume of water in a lake or reservoir.	dam^3
Demand	The daily rate of maximum water withdrawal.	m^3/s
Potential Shortage	The daily rate of un-met demand.	m^3/s
Consumptive Use	The daily rate of met demand that is not returned to the system.	m^3/s

4.6.2 Long-Term Historical Period

Some indicators and performance measures are calculated relative to weekly quantile values for each site (i.e. Q20 Non-Exceedance). These statistics are derived from the reference case model run (i.e. simulated flow), which in this case is the historical (1991-2020) period under Current Condition water management (dam operations and water use). In some cases, this period is split into two regimes: Open-Water, which consists of April to October (inclusive), and Winter (November to March). Finally, single-year (or single regime) statistics are also calculated from this statistic, which reflect the quantile from the flow-duration curve (i.e. considering all daily flows).

4.6.3 Hydrologic Indicators

These daily model outputs are aggregated into annual statistics that were developed to capture the range of important hydrologic and water management conditions under each scenario for each site and are referred to here as hydrologic indicators. A description of each hydrologic indicator is provided in Table 9.

Table 9. Hydrologic indicators considered in this study, which are available at an annual timestep at each sub-basin.

Indicator	Description	Units
Mean Annual Flow	The average annual streamflow, representative of the amount of water passing through this point in a calendar year.	m^3/s
Minimum 7-Day Flow	The minimum 7-day average flow. This flow is representative of the lowest flow levels over the year and has historically coincided with degraded water quality (and effluent dilution), and stress on aquatic environments.	m^3/s
Minimum Summer 7-Day Flow	The minimum 7-day average flow over the summer (June-September) period. This flow is representative of the lowest flow levels over the open-water period and has historically coincided with a heightened risk of droughts, degraded water quality, and is a critical period for aquatic ecosystems.	m^3/s
Q20 Non-Exceedances (Open-Water)	The number of days during the year when streamflow is below the 20th quantile of historical simulated streamflow during the April-October period.	Days
Q20 Non-Exceedances (Winter)	The number of days during the year when streamflow is below the 20th quantile of historical simulated streamflow during the November-March period.	Days
Peak Annual Flow	The average annual peak flow. This peak flow is typically a bank-full streamflow and associated with maintaining sediment transport processes and channel morphology.	m^3/s
Peak Flow Timing	The average Julian day of peak daily streamflow in a calendar year, representative of the timing of spring snowmelt-driven runoff which are important to aquatic ecosystems.	Days
Mean Annual Consumptive Use	The average annual water delivery minus returns.	m^3/s
Mean Annual Demand	The average annual water demand.	m^3/s
Total Annual Potential Shortage	The total annual (potential) unrealized water demand.	dam^3

In addition to calculating annual values, each hydrologic indicator is also averaged over each 30-year period (1961-1990, 1991-2020, 2021-2050, 2051-2080).

4.6.4 Performance Measures

In contrast to hydrologic indicators, which are calculated for each sub-basin of interest, performance measures are targeted statistics which are tied to a specific location and reflect a ‘global’ or basin-wide measure of system health. These measures focus on a range of issues, including water supply, water quality, aquatic habitat, environmental conditions, and socioeconomic implications. Each performance measure is calculated at an annual scale and averaged over each 30-year period. A summary of developed performance measures is provided in Table 10.

Table 10. Performance measures developed in this study, which are available at an annual timestep and as 30-year averages at key points across the watershed. Note all values here are based on model simulated outputs (i.e. not observations).

Performance Measure	Site	Description	Units
Edmonton Peak Flows	North Saskatchewan River At Edmonton	The number of days where the flow on the North Saskatchewan River at Edmonton exceeds 1300 m3/s. This flow is approximately equal to the lower bound of the 2-year peak flow. This is treated as a proxy for conditions where flood risk is higher, inundation of properties possible, and water treatment operations are threatened.	Days
Vermilion Low Flows	Vermilion River At Lea Park	The percentage of days from July to September that the streamflow is below the average natural Minimum Summer 7-Day Flow (0.25 m3/s) on the Vermilion River at Lea Park. This metric describes the variability and occurrence of low flows which often coincide with droughts.	%
Headwater Fish Habitat	Clearwater River Near Dovercourt	The number of days where flow on the Clearwater River is below the Instream Objective (IO). This is representative of conditions where headwater fish species are stressed and fishing is prohibited.	Days
Apportionment	North Saskatchewan River Near Deer Creek	The percentage of water that crosses interprovincial boundaries from Alberta to Saskatchewan. This metric is used to assess if the Master Agreement of Apportionment is satisfied whereby water is equitably shared.	%
Potential System Shortage	North Saskatchewan River Near Deer Creek	The cumulative volume of potential unmet water demand in a calendar year across the North Saskatchewan River Basin.	dam^3
Assimilative Capacity	North Saskatchewan River Near Pakan	The number of days where the flow on the North Saskatchewan River Near Pakan is below the long-term average 10th quantile of simulated historical (regulated) streamflow for the Open-Water (Apr-Oct; ~128 m^3/s) and Winter (Nov-Mar; ~106 m^3/s) periods. This flow is an approximation of low flow conditions in this reach where some water quality parameters (i.e. sulfate, chloride) may become elevated and waste assimilation may become more difficult.	Days
Loading Potential	North Saskatchewan River At Edmonton	The number of days where the flow on the North Saskatchewan River At Edmonton is above the long-term average 90th quantile of simulated historical (regulated) streamflow during the Open Water (Apr-Oct; ~450 m3/s) period. This flow is an approximation of high flow conditions in this reach where some water quality parameters (i.e. TSS, metals, e.coli.) may become elevated.	Days
St Albert Peak Flows	Sturgeon River At St. Albert	The number of days where the flow on the Sturgeon River at St Albert exceeds the 5-year peak flow (~27 m3/s). This is treated as a proxy for conditions where flood risk is higher and inundation is possible.	Days
Tributary Low Flows	North Saskatchewan River Near Deer Creek	The percent of gauge-days where flow at a location is below the long-term Minimum 7-Day Flow for the historical (regulated) period. This statistic is calculated at all tributaries (i.e. non-mainstem) locations, excluding the lower Brazeau River.	%
High Summer Water Temperature	North Saskatchewan River At Edmonton	The percentage of days from July to August that daily average water temperature exceeds 18C on the North Saskatchewan River at Edmonton. Water Temperature is estimated using an empirical relationship derived for the reach using air temperature and streamflow by Makowecki (2025).	%

4.7 Model Scenarios

Since the model takes inputs of climate (weather), land cover, and water management, any of these components can be altered, in isolation or cumulatively, to assess water resources under a specific scenario. Scenarios were developed in consultation and based on feedback from Working Group members and sessions; some scenarios were run in a live setting, and many were refined following them. In all cases, scenario names follow the following structure:

`[LandCover]_[Climate]_[WaterManagement]`

such that `CurrentConditions_Historical_EstUse` represents the Current Conditions land cover, with Historical (1950-2020) climate, and Estimated Use (i.e. base case) water management. The scenarios that are currently in the model application and available for analysis in this interface are detailed below.

4.7.1 Land Cover

- **CurrentConditions**: Land cover is representative of the estimated land cover for the year 2025, including current forest disturbance (fire and harvest), urban and agricultural expansion, and glacier coverage. Note that for future scenarios (2021-2100) glacier coverage dynamically changes following the depletion/melt of glacial ice.
- **ForestDisturbance**: Forest disturbance rolled back to 1961 (highest year of forest fire coverage on record), kept forestry disturbance at current level. Note that effects are highly localized in this scenario: (i.e. some areas have large footprint of fire effects, while others have no change in land cover relative to CurrentConditions).

The two scenarios are mapped in Figure 6 and a compilation of the percent of upstream area affected under each scenario is provided in Figure 7.

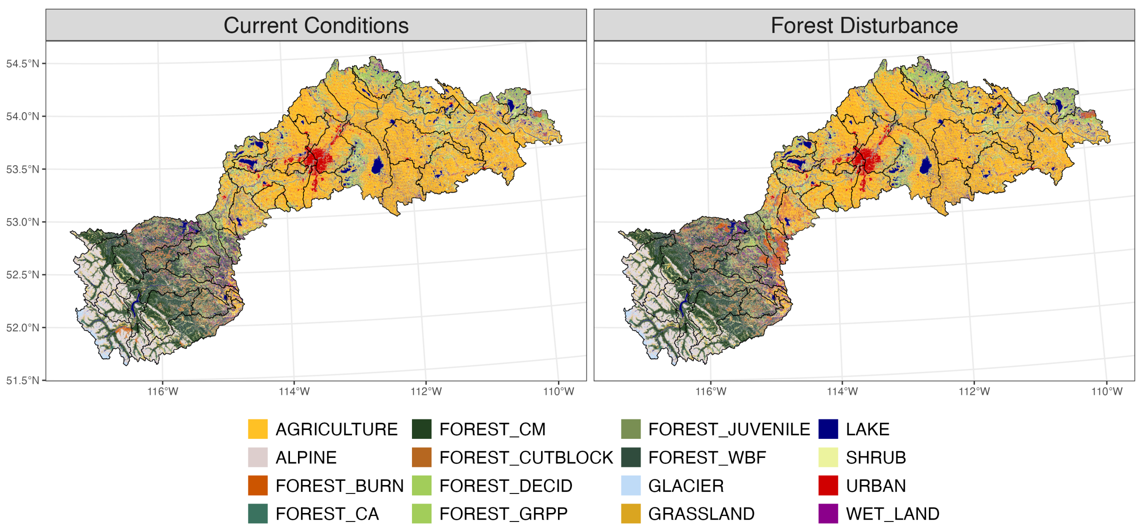


Figure 6. Land cover map of the study area under the two scenarios considered in this study.

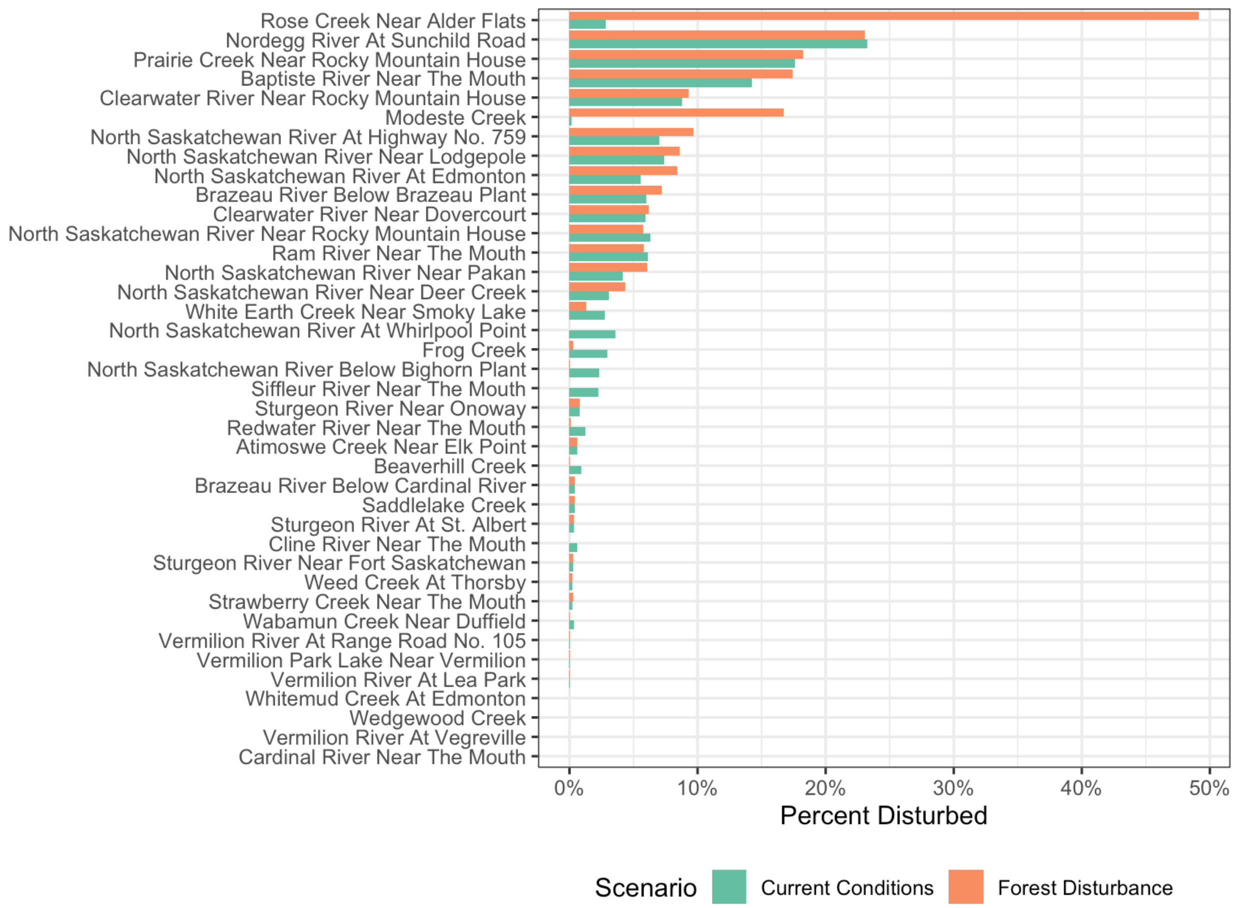


Figure 7. Percent of the upstream area disturbed (burn or cutblock) for each point of interest in the model.

4.7.2 Climate

All provided future climate change scenarios were run through the hydrological model and water management model. Results were then evaluated, and two future scenarios were selected for model runs during Working Group live settings. These two future scenarios were selected by identifying "worst-case" or stress-case scenarios (i.e. those with the most challenging hydrologic conditions) and are not meant to provide a probabilistic view on the most likely future conditions. In total, three climate scenarios were applied for scenario analysis in this study:

- **Historical**: Historical observations for 1951-2020.
- **CNRM-CM6-1_ssp126**: A future climate change scenario (2021-2100) for the CNRM-CM6 model, under the Shared Socioeconomic Pathway (SSP) 1-2.6, which represents a relatively low-emissions future. This scenario was used because it is one of the driest of the selected GCM runs, with a relatively lower degree of atmospheric warming, and less precipitation.
- **BCC-CSM2-MR_ssp126**: A future climate change scenario (2021-2100) for the BCC-CSM2-MR model, under the Shared Socioeconomic Pathway (SSP) 1-2.6, which represents a relatively low-emissions future. This scenario was provided because, although it is a relatively dry scenario, it also has the largest simulated flood of the scenarios.

4.7.3 Water Management

Several water management configurations were presented during Working Group meetings and refinements of those are summarised below.

Water Diversion

Three scenarios below make assumptions regarding water demand in the watershed, based on the current state of licensing, potential new licenses, and alterations to the amount of water withdrawn.

- **EstUse**: Estimated Water Use. This scenario is treated as the base case, where water management operates using our best estimate of current practices, including water use, diversions, and returns, as well as dam operations.
- **Growth**: A growth scenario where water diversions are increased by 1.7 for EDMONTON_&_REGIONAL_CUSTOMERS, 1.12 for MUNICIPAL, and 2.0 for INDUSTRIAL licenses, meant to represent increases in economic activity (including hydrogen and data center water use) and population growth (see WaterSMART 2023 for further discussion). All other water management operations continue as under EstUse.
- **FullAllocation**: A scenario where each water license diverts the totality of their water license (and returns the same fraction as they currently do). In this scenario, diversion multiplication factors are as follows: AGRICULTURE (2.48), COMMERCIAL (2.9), EDMONTON_&_REGIONAL_CUSTOMERS (1.7), INDUSTRIAL (5.38), MANAGEMENT (5.52), and MUNICIPAL (1.12). All other water management operations continue as under EstUse.

Off-stream Storage

Two off-stream storage scenarios were simulated with the broad objectives of refilling during high flow periods and providing additional outflow to the North Saskatchewan River during low flow periods. Assumptions in both cases are high level, conceptual approximations (i.e. proof-of-concept) of potential operations based on professional judgement, and do not reflect any actual operating plans or proposals.

- **Sundance**: An off-stream storage (42,000 dam^3) at Sundance location (adjacent to Wabamun Lake). Water from the North Saskatchewan River (above Edmonton) is pumped in at up to 7 m^3/s rate when flows at Edmonton are above 150 m^3/s and releases water to the main stem when flows are below seasonal Q10 (Open Water and Winter). No maximum release rate was specified.
- **DIZ**: An off-stream storage (50,000 dam^3) downstream of Edmonton. Water from the North Saskatchewan River above Pakan is pumped in at up to 1 m^3/s rate when flows above Pakan are above 200 m^3/s. The structure releases water to the North Saskatchewan River in June - Sept when flows are below the Open-Water Q10. No maximum release rate was specified. We note that the refill rate (1 m^3/s) is low but was kept at this value since the dam was not emptying during its operating period. Future work to refine these operations could explore higher refill rates.

On-stream Storage

- **EdmMax**: This scenario explores the ability to use existing upstream reservoirs to limit large peak flow events at Edmonton. A maximum flow target on the North Saskatchewan River at Edmonton is set to the 10-year peak daily return period of simulated streamflow (967 m^3/s). This management goal is given a lower penalty than TransAlta dam operations, with the exception of reservoir target water levels, which are junior to all other management goals. We note that this is not an operational threshold for flood mitigation but was rather chosen as a metric to explore options to mitigate high flow conditions.

- **EdmMin**: This scenario explores the ability to use existing upstream reservoirs to sustain minimum flow targets on the North Saskatchewan River at Edmonton. A minimum flow target on the North Saskatchewan River at Edmonton is set to the 10th quantile of simulated streamflow during the Open-Water (April-October) and Winter periods (135 m^3/s for April-October and 110 m^3/s otherwise). This management goal is given a higher priority than any water license, but a lower penalty than TransAlta dam operations, with the exception of reservoir target water levels, which are junior to all other management goals. We note that these minimum flows are not operational thresholds for water treatment or waste assimilation but were rather chosen as a metric to explore options to minimize low flow conditions.
- **EarlyRefill**: Target water levels for Brazeau and Bighorn Dams are shifted two weeks (14 days) earlier in the year. This is to reflect the fact that under climate change scenarios, spring freshet occurs earlier in the year, and failure to adapt seasonal operations means dams may be sub-optimally filling and emptying.
- **TAUStorage**: Water storage in Brazeau and Bighorn reservoirs are increased by 15% (and 1 m). Dam operations are corrected to reflect this increased capacity in both FSLs and target water levels. We note that this is a hypothetical scenario to increase the capacity of the dams and to our knowledge, not something that has been proposed publicly.

Note that several water management scenarios can be combined into a single model run. For instance, Growth could be combined with Sundance to provide a `GrowthSundance` water management scenario.

5 Results

5.1 Hydrological Model Performance

5.1.1 Hydroclimatic Validation

Hydroclimatic variables including air temperature, precipitation, and snow water equivalent were evaluated at independent regional weather and snow pillow/survey stations (Table 11). Results demonstrate that the model had strong performance at distributing air temperatures (r2 > 0.92) and minimal bias. Monthly precipitation showed good performance (r^2 = 0.74 – 0.99) with a modest negative bias at some lookout sites. We note that most of these sites only contained summer observations of precipitation and air temperature. Snow Water Equivalent showed good performance (r^2 = 0.88 - 0.92 at snow pillows, 0.23 - 0.73 at snow survey sites). A moderate negative bias at Southesk snow pillow is noted, as well a positive bias at Limestone Lookout (further east from Southesk) (Figure 8).

Table 11. Meteorological validation statistics for all sites used in this study. R2 corresponds to the pearson correlation coefficient, PBIAS to the percent bias, and N to the number of observations.

Site	Daily Maximum Air Temperature			Monthly Precipitation			Snow Water Equivalent		
	R2	*PBIAS*	*N*	*R2*	*PBIAS*	*N*	*R2*	*PBIAS*	*N*
EDMONTON STONY PLAIN	1.00	−2%	10582	0.99	−3%	347	0.27	54%	233
LLOYDMINSTER A	0.99	4%	10447	0.86	−3%	346	—	—	—
VEGREVILLE	0.99	−1%	10431	0.74	−6%	323	—	—	—
ELK ISLAND NAT PARK	0.98	−11%	9466	0.84	−7%	315	—	—	—
ENTWISTLE	0.99	−2%	9251	0.93	−11%	344	—	—	—
UofA METABOLIC CENTRE	0.99	−4%	9161	0.88	−7%	326	—	—	—
EDMONTON WOODBEND	0.99	−1%	9044	0.92	−10%	297	—	—	—
FORT SASKATCHEWAN	0.98	−2%	8982	0.76	−13%	339	—	—	—
BRETON	0.98	−4%	8773	0.88	−2%	269	—	—	—
RANFURLY 2NW	0.99	−2%	8422	0.88	−12%	284	—	—	—
ANDREW	0.99	0%	8401	0.92	−5%	287	—	—	—
TOFIELD NORTH	0.99	−5%	8392	0.93	−6%	275	—	—	—
EDMONTON INT'L A	0.99	3%	7724	0.95	4%	256	—	—	—
BIGHORN DAM	0.94	−10%	6991	0.97	1%	233	—	—	—
ST LINA	0.99	9%	6286	0.91	−11%	207	—	—	—
HILLMOND	0.99	3%	6270	0.85	4%	206	—	—	—
CALMAR	0.98	−4%	6165	0.93	−7%	202	—	—	—
WINFIELD	0.99	−3%	5697	0.92	−10%	186	—	—	—
NORDEGG RS	0.95	−1%	5164	0.95	−5%	174	—	—	—
EDMONTON CITY CENTRE A	1.00	−1%	5032	0.98	−1%	169	—	—	—
SION	0.99	−1%	4686	0.92	−3%	161	—	—	—
CLEARWATER	0.99	−2%	3927	0.93	−3%	120	—	—	—
BRAZEAU LO	0.98	−1%	3044	0.94	−10%	113	—	—	—
BASELINE LO	0.95	7%	2980	0.93	−12%	113	—	—	—
AURORA LO	0.97	−6%	2632	0.91	−16%	103	—	—	—
EDMONTON NAMAO A	0.99	2%	2629	0.92	16%	91	0.72	−21%	15
BALDY LO	0.92	8%	2539	0.86	1%	101	—	—	—
CLINE LO	0.92	−2%	2103	0.90	26%	88	—	—	—
BLACKSTONE LO	0.96	−7%	1912	0.89	−7%	79	—	—	—
GRAVE FLATS LO	0.95	10%	1885	0.94	−2%	86	—	—	—
OLIVER TREE NURSERY	0.99	0%	1127	0.90	12%	72	—	—	—
BELLIS	—	—	—	—	—	—	0.52	1%	60
BOW SUMMIT NEW	—	—	—	—	—	—	0.54	−7%	142
BRAZEAU RES.	—	—	—	—	—	—	0.49	1%	71
BRUCE SNOW PL	—	—	—	—	—	—	0.63	1%	76
CLANDONALD	—	—	—	—	—	—	0.46	24%	60
CRIMSON LAKE	—	—	—	—	—	—	0.50	22%	58
ELK ISLAND PARK	—	—	—	—	—	—	0.61	9%	61
HOLDEN SOUTH	—	—	—	0.94	−5%	330	—	—	—
KATHERINE LAKE	—	—	—	—	—	—	0.49	−19%	111
LAVOY	—	—	—	0.99	−4%	207	—	—	—
LEDUC	—	—	—	—	—	—	0.28	20%	60
LIMESTONE	—	—	—	—	—	—	0.73	24%	144
LIMESTONE RIDGE PILLOW	—	—	—	—	—	—	0.82	33%	8647
MANNVILLE	—	—	—	—	—	—	0.31	57%	60
MCCONNELL CREEK	—	—	—	—	—	—	0.36	95%	114
MORINVILLE	—	—	—	—	—	—	0.52	40%	61
NIGEL CREEK	—	—	—	—	—	—	0.50	−29%	117
NORDEGG	—	—	—	—	—	—	0.61	−26%	58
ONOWAY	—	—	—	—	—	—	0.71	8%	59
PERRYVALE	—	—	—	—	—	—	0.46	−3%	61
ROCKY MOUNTAIN HOUSE A	—	—	—	—	—	—	0.99	62%	8
SOUTHESK PILLOW	—	—	—	—	—	—	0.88	−14%	3965
ST PAUL	—	—	—	—	—	—	0.23	46%	60
TWO HILLS	—	—	—	—	—	—	0.41	29%	61
WASKATENAU	—	—	—	—	—	—	0.56	20%	61
WESTLOCK	—	—	—	—	—	—	0.40	56%	61
WILDCAT CREEK	—	—	—	—	—	—	0.90	−47%	1564

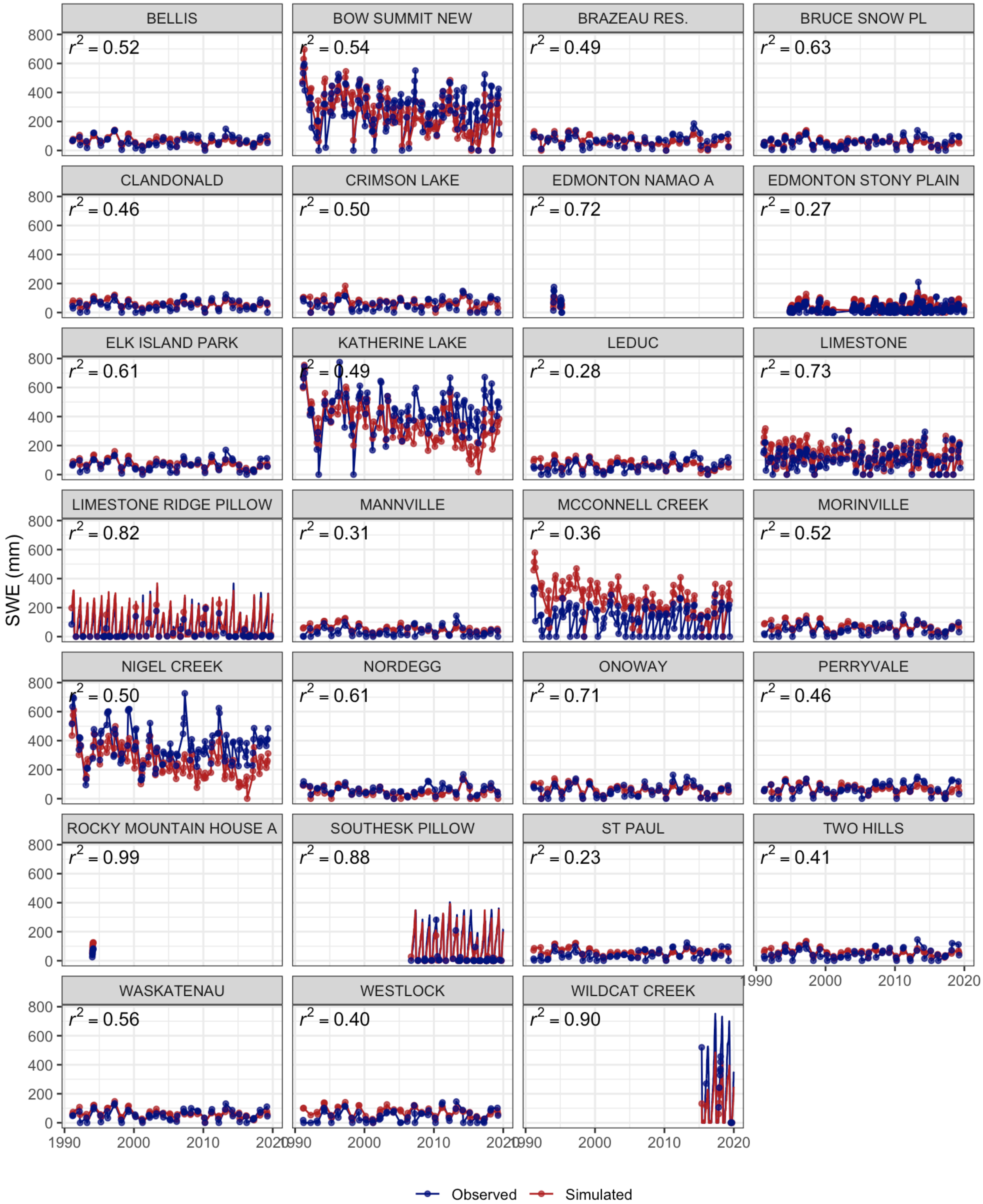


Figure 8. Observed and simulated snow water equivalent at all sites used in model calibration.

5.1.2 Streamflow Validation

The hydrological model was calibrated and validated using daily streamflow observations from the Water Survey of Canada hydrometric gauges in the region from 1991-2019. Older data were considered, but given changes in land use, climate, and water management, more recent data were selected for the final validation statistics. Average daily conditions were relatively well represented at most hydrometric gauges (Figure 9, Figure 10) with the timing of freshet and low flow well reproduced at all sites.

The model showed strong performance reproducing the timing and magnitude of streamflow at mountain headwater sites (North Saskatchewan, Siffleur, Brazeau, Ram, Clearwater). Performance was good on foothills rivers, although some sites showed a positive bias in early-season flows (Nordegg, Baptiste, Prairie).

In the parkland (Sturgeon, Modeste, Whitemud), model performance was relatively good at reproducing the timing and magnitude of flow. Performance statistics were lower than in the headwaters, reflecting the volatile/noisy nature of summer rainfall events and their representation spatially across the large model domain. Performance in this region was best for systems with significant waterbodies to attenuate flow (i.e. Sturgeon River).

In the prairie (Vermilion, Redwater) region, model performance was mixed. Performance statistics in the Vermilion River are relatively good, with minimal bias. However, in the Redwater River, and some other prairie watersheds, the model displays considerable positive bias. This is likely a function of the difficulty in modelling variable contributing areas/prairie pothole topography, flow attenuation and enhanced evaporation due to beaver dams, and sparse weather data in this region. At a basin scale, this prairie region has low runoff values and as such, these overestimates have a comparatively small impact on the North Saskatchewan River.

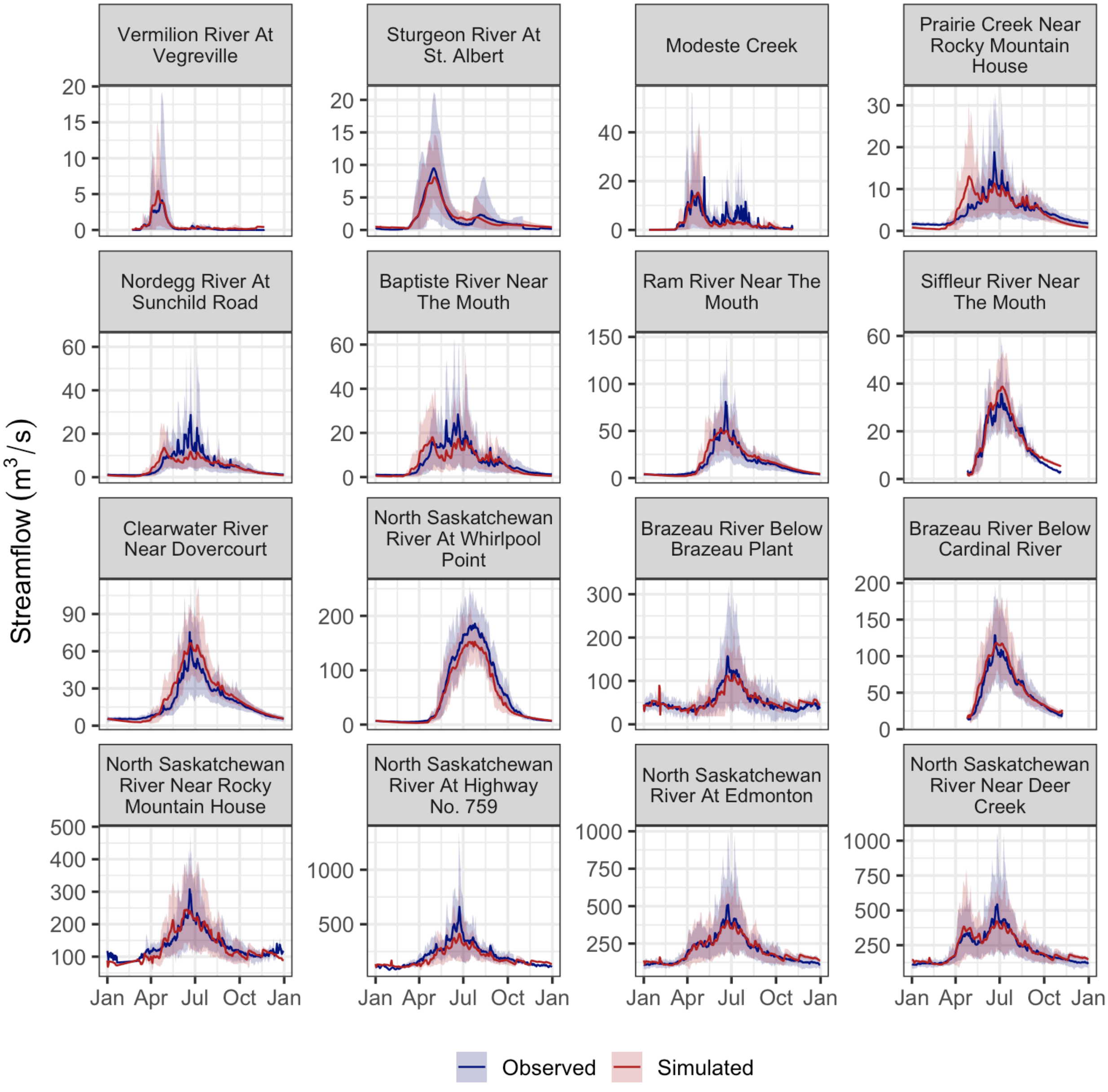


Figure 9. Observed and simulated streamflow at all sites used in model calibration from 1990-2019. Solid lines correspond to average flows while shaded areas correspond to 10-90% quantiles.

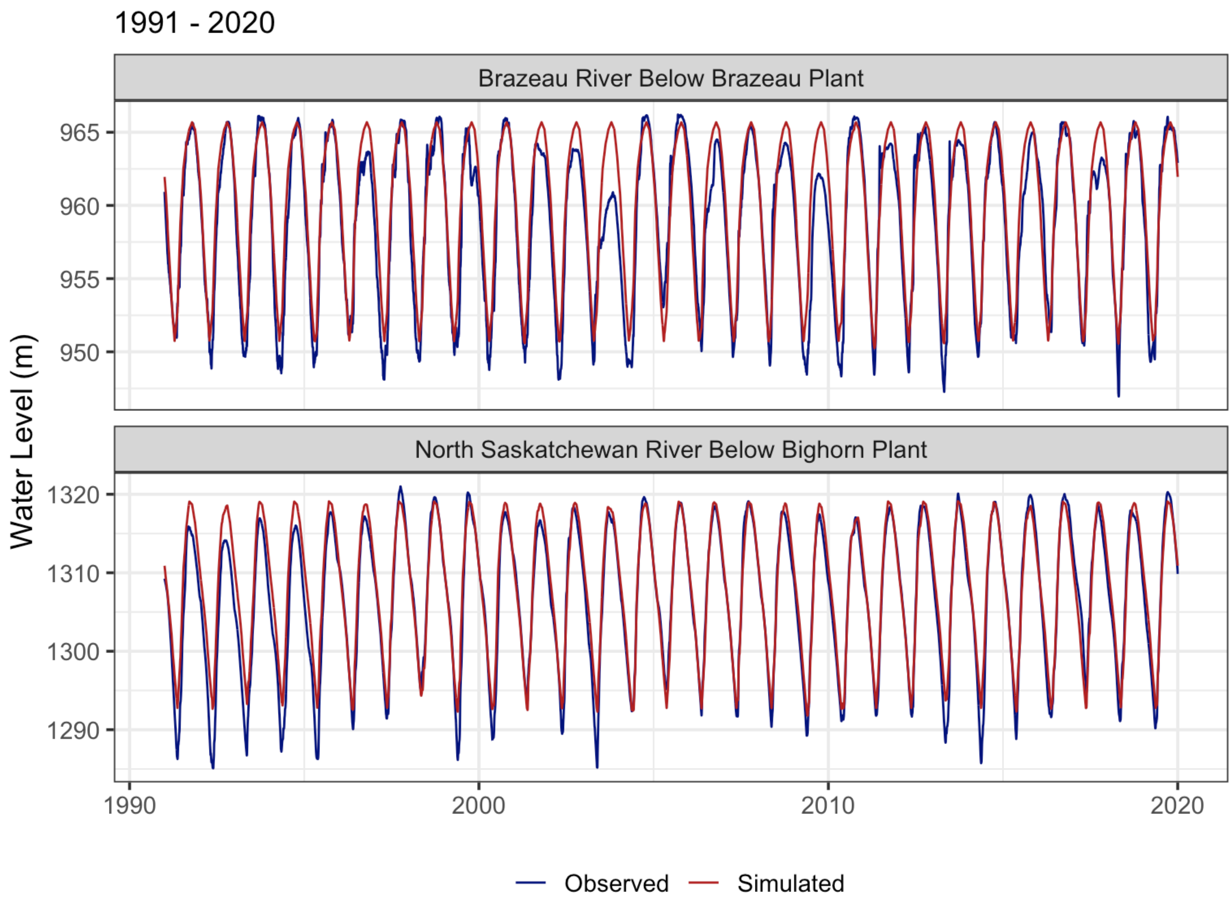


Figure 10. Observed and simulated water level at the two reservoirs from 1991-2019.

Overall, performance statistics demonstrate good model accuracy and low bias at most sites (<10%; Table 12). In the mountainous headwaters, performance is very strong, with Nash-Sutcliffe Efficiency (NSE) values over 0.80 on the North Saskatchewan and Siffleur rivers. Performance is relatively strong on other major tributaries with high relief, including the Clearwater, Ram, Brazeau, Nordegg, and Baptiste. Further east, performance is relatively strong in parkland tributaries, including Strawberry Creek, Modeste Creek, and Whitemud Creek. Performance is mixed on the easternmost prairie tributaries; performance is relatively good on the Vermilion River, but overestimates flow on the Redwater River. Overall, the model performs best in high-relief, snow driven watersheds, and has higher uncertainty in arid, prairie-pothole dominated low-relief watersheds.

Table 12. Hydrological model performance statistics for all hydrometric gauges in the regional model. Statistics include the Nash-Sutcliffe Efficiency (NSE), log-NSE, Kling Gupta Efficiency (KGE), Percent Bias (PBIAS), Mean Difference (MDiff) and number of daily observations (N) and are calculated over the 1991-2019 period.

Site	NSE	logNSE	KGE	R2	PBIAS	MDiff	N
North Saskatchewan River Below Bighorn Plant(Stage)	0.93	0.92	0.90	0.95	0%	1.23	10593
North Saskatchewan River At Whirlpool Point	0.90	0.93	0.83	0.94	−16%	-8.81	10593
Brazeau River Below Brazeau Plant(Stage)	0.88	0.88	0.90	0.91	0%	0.96	10593
Siffleur River Near The Mouth	0.79	0.86	0.81	0.84	11%	1.73	1315
North Saskatchewan River At Highway No. 759	0.66	0.63	0.65	0.72	−15%	-37.84	3147
Sturgeon River At St. Albert	0.66	0.65	0.58	0.68	−3%	-0.06	3640
North Saskatchewan River At Edmonton	0.65	0.64	0.59	0.65	1%	2.11	10958
Clearwater River Near Dovercourt	0.64	0.71	0.62	0.69	17%	3.14	10593
Baptiste River Near The Mouth	0.63	0.69	0.60	0.63	−8%	-0.58	10945
Brazeau River Below Cardinal River	0.62	0.79	0.65	0.67	9%	5.05	5176
North Saskatchewan River Near Deer Creek	0.61	0.67	0.58	0.62	3%	5.63	10942
Ram River Near The Mouth	0.53	0.76	0.42	0.54	9%	1.38	10958
Prairie Creek Near Rocky Mountain House	0.51	0.41	0.51	0.53	−2%	-0.1	10593
Nordegg River At Sunchild Road	0.44	0.75	0.31	0.50	−14%	-0.77	10227
North Saskatchewan River Near Rocky Mountain House	0.44	0.38	0.48	0.48	0%	0	6502
Brazeau River Below Brazeau Plant	0.42	0.10	0.34	0.43	1%	0.36	10958
Vermilion River At Vegreville	0.25	0.27	0.23	0.36	33%	0.18	7152
Modeste Creek	0.21	0.57	0.16	0.23	−18%	-0.76	5752

Finally, since the model is used to characterize seasonal patterns in streamflow and water level, statistics comparing observed and simulated average weekly values over the 1991-2020 period are provided (Table 13). Overall, seasonal patterns show strong model performance, with relatively low mean differences in flow relative to observations. The timing of streamflow is well reproduced at all natural sites.

Table 13. Hydrological model performance statistics for hydrometric indicators at hydrometric gauges in the regional model with at least 20 years of data. Statistics include the Pearson Correlation Coefficient (R2), Percent Bias (PBIAS), and number of daily observations (N) and are calculated over the full 1991-2020 period.

Site	NSE	logNSE	KGE	R2	PBIAS	MDiff	N
North Saskatchewan River At Whirlpool Point	0.95	0.96	0.84	0.99	−16%	-8.67	53
Sturgeon River At St. Albert	0.95	0.88	0.85	0.96	2%	0.03	53
North Saskatchewan River At Edmonton	0.94	0.92	0.84	0.96	1%	2.51	53
Brazeau River Below Cardinal River	0.93	0.94	0.90	0.97	9%	4.96	29
North Saskatchewan River Near Deer Creek	0.93	0.92	0.85	0.94	3%	6.08	53
Ram River Near The Mouth	0.91	0.91	0.86	0.92	9%	1.37	53
Siffleur River Near The Mouth	0.91	0.91	0.88	0.96	11%	1.66	28
Brazeau River Below Brazeau Plant	0.87	0.83	0.74	0.90	1%	0.44	53
Clearwater River Near Dovercourt	0.85	0.87	0.81	0.97	17%	3.1	53
North Saskatchewan River Near Rocky Mountain House	0.83	0.74	0.80	0.88	−3%	-4.08	48
Vermilion River At Vegreville	0.83	0.87	0.59	0.94	39%	0.2	40
North Saskatchewan River At Highway No. 759	0.81	0.83	0.72	0.92	−10%	-20.07	53
Modeste Creek	0.76	0.79	0.66	0.81	−18%	-0.71	37
Baptiste River Near The Mouth	0.75	0.83	0.74	0.76	−9%	-0.59	53
Nordegg River At Sunchild Road	0.67	0.85	0.63	0.72	−14%	-0.76	53
Prairie Creek Near Rocky Mountain House	0.62	0.56	0.67	0.70	−2%	-0.11	53

5.2 Climate Change Ensembles

The hydrological model was run under 14 future climate change scenarios. Results, compared against the Historical (1991-2020) period, show considerable changes in the timing and magnitude of streamflow (Figure 11). In the prairie and parkland watersheds (Modeste Creek, Vermilion River), results show a pervasive shift towards an earlier freshet (earlier snowmelt) and suggest generally more water in these streams, particularly during the summer periods, owing to more intense rainfall events. In the foothills (Baptiste River) this trend continues, showing earlier freshet and higher summer flows; particularly in the 2051-2080 period. In the mountainous headwaters, this trend is complicated by the retreat of glaciers, particularly in the latter half of the century. In the North Saskatchewan River at Whirlpool Point, the 2021-2050 period sees considerable increases in flow, particularly during the spring and summer months, due to higher snowpack and greater glacial melt. By the 2051-2080 period, flow is typically receding before July 1, and flows remain lower throughout the remainder of the summer, highlighting the loss of glacier contributions during the summer.

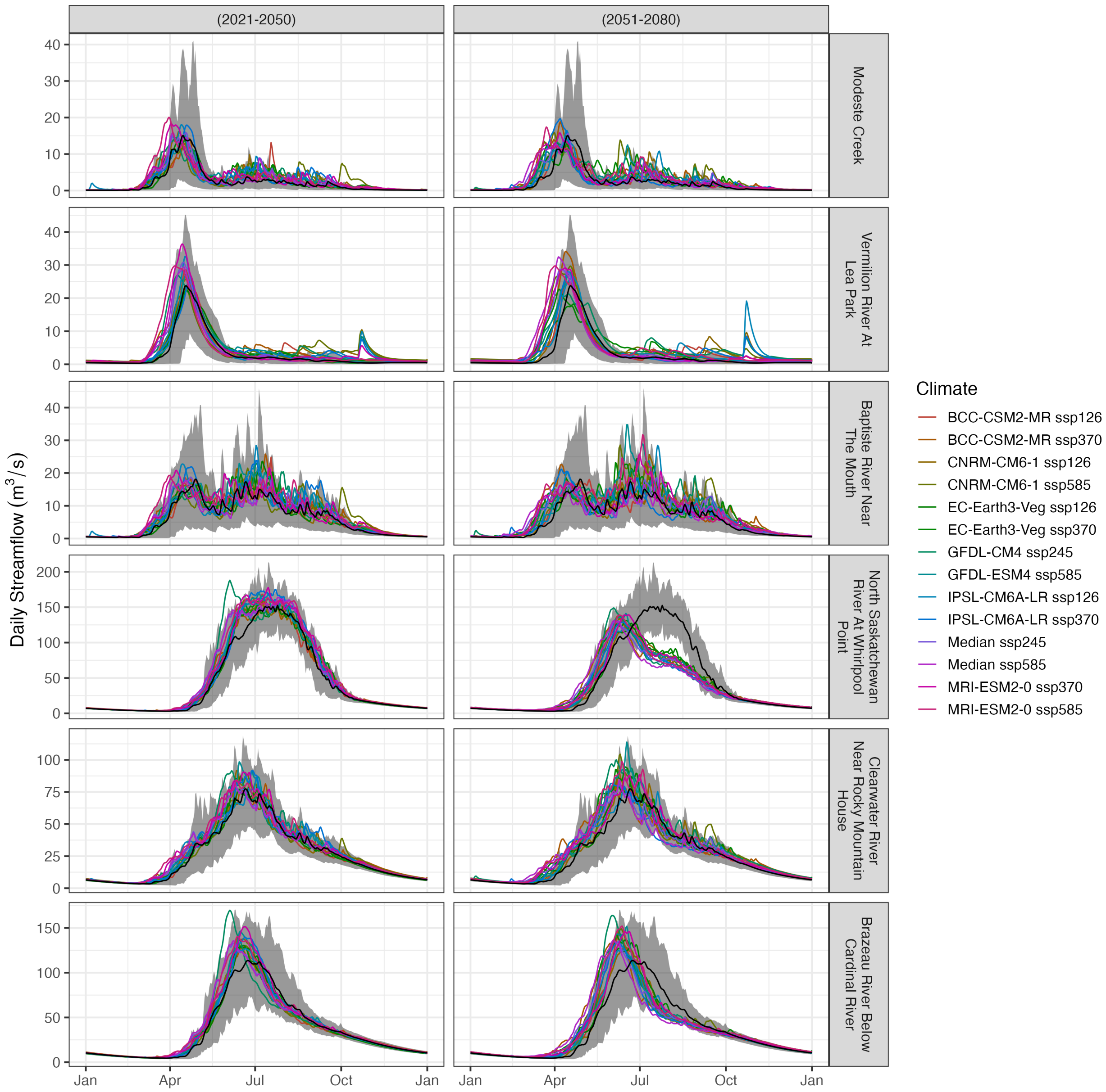


Figure 11. Average daily streamflow for selected sites in the North Saskatchewan River Basin under each climate change scenario run in this study against the Historical (1991-2020) period (in black). The grey shaded area corresponds to the 10-90% quantiles of the Historical period (i.e. 4 in 5 years flow falls within this range).

5.3 Forest Disturbance

The model was run under two land cover scenarios: one with Current Conditions and another with increased Forest Disturbance. Results show that there is negligible change in the Performance Measures under the two land cover scenarios under the Historical period (Figure 12). In general, flow is slightly higher across the basin under the forest disturbance scenario, leading to lower Assimilative Capacity Days and less Tributary Low Flows and Vermilion Low Flows. An increase in disturbed forest leads to less interception and more snow and rain reaching the soil surface, which is only partially offset by increased evaporation in open areas.

(1961-1990) (1991-2020)

Scenario	Apportionment (%)	Assimilative Capacity (Days)	Edmonton Peak Flows (Days)	Headwater Fish Habitat (Days)	High Summer Water Temperature (%)	Loading Potential (Days)	Potential System Shortage (dam³)	St Albert Peak Flows (Days)	Tributary Low Flows (%)	Vermilion Low Flows (%)
CurrentConditions_Historical_EstUse	98.38	37.54	0.00	92.93	89.06	21.79	54.31	1.71	8.43	20.57
ForestDisturbance_Historical_EstUse	98.39	36.07	0.00	92.86	88.65	22.79	57.34	1.71	8.94	25.64

Figure 12. Application screenshot of the Performance Measure table for selected scenarios over the Historical period.

It is worth noting that most of these Performance Measures are designed to evaluate conditions over large areas and/or watersheds and many of the effects of forest disturbance are felt most severely at local scales, where the degree of forest disturbance may be proportionally greater. In this scenario, there is no detectable change in flow at the North Saskatchewan River at Whirlpool Point; a larger watershed where flow is strongly driven by high alpine snowmelt and glacier melt (Figure 13). Conversely, low relief Rose Creek shows considerable impacts, since a large proportion of this watershed was disturbed (over 50%) and there are no alpine high runoff areas to dilute the effect of forest disturbance. Finally, at the North Saskatchewan River Near Pakan, small to negligible changes are noted since the watershed area by that point is so large, disturbances in some areas are offset by regrowth in others, and runoff occurs from a variety of diverse landscapes such that the effects of localized disturbance are dampened. Overall, the effects of forest disturbance are dependent on the proportion of the watershed that is altered, the degree to which the watershed relies on runoff from those forested reaches, and the precipitation in the disturbed areas. All of these factors tend to mean that in most cases, the effects of forest disturbance are mostly localized, where they can have considerable impacts on the timing and magnitude of streamflow, but are less likely to impact the large watersheds to a notable degree.

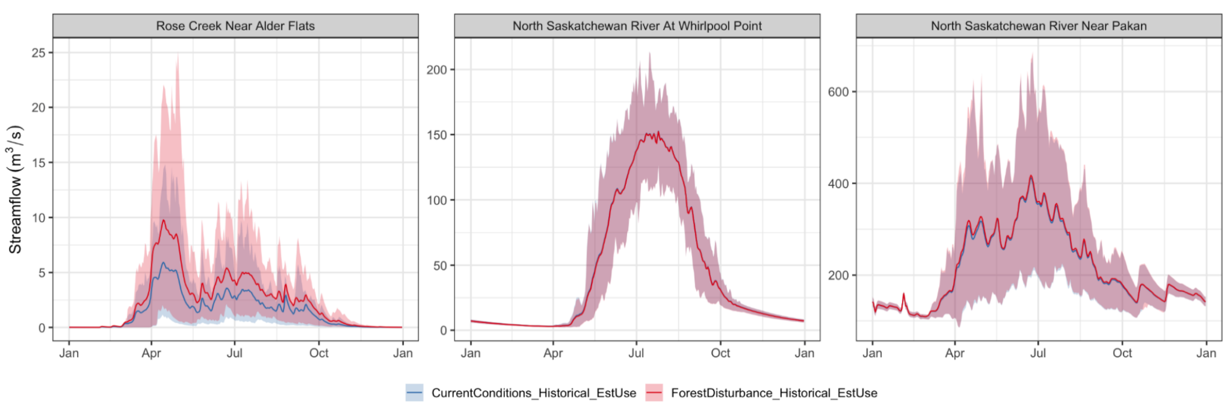


Figure 13. Average daily streamflow for selected sites in the North Saskatchewan River Basin under the Historical (1991-2020) period under two land cover scenarios. Shaded areas correspond to 10-90% quantiles.

5.4 Water Management Scenarios

5.4.1 Growth and Full Allocation

Scenarios under the Historical period show that the effect of increased water usage is felt more severely in tributaries where flows may already be low and/or volatile. At the basin-scale, the Mean Annual Demand under EstUse is 11.0 m^3/s, of which 3.6 m^3/s is consumptive use. For comparison, Mean Annual Flow for the North Saskatchewan River near Deer Creek is approximately 223.5 m^3/s and the Minimum 7-Day Flow is 106.6 m^3/s. Mean Annual Demand (Mean Annual Consumptive Use) increases to 19.5 m^3/s (6.2 m^3/s) under the Growth scenario, and 38.0 m^3/s (12.8 m^3/s) under FullAllocation. One key difference is that under the Growth scenario, this increased water demand is concentrated to the Edmonton-Pakan corridor, on the mainstem, while Full Allocation also increases water demand in more arid tributaries. This effect is clear in the Potential System Shortage PM, which has a negligible increase between EstUse and Growth (~23 dam^3), but a considerable increase under FullAllocation (1,497 dam^3). Likewise, Vermilion Low Flows, Assimilative Capacity, and Apportionment are both considerably worse under the FullAllocation Scenario, though Apportionment is still well above its 50% threshold (Figure 14).

(1961-1990) (1991-2020)

Scenario	Apportionment (%)	Assimilative Capacity (Days)	Edmonton Peak Flows (Days)	Headwater Fish Habitat (Days)	High Summer Water Temperature (%)	Loading Potential (Days)	Potential System Shortage (dam^3)	St Albert Peak Flows (Days)	Tributary Low Flows (%)	Vermilion Low Flows (%)
CurrentConditions_Historical_EstUse	98.38	37.54	0.00	92.93	89.06	21.79	54.31	1.71	8.43	20.57
CurrentConditions_Historical_FullAllocation	94.24	65.18	0.00	92.93	89.75	20.71	1497.43	1.71	9.71	32.13
CurrentConditions_Historical_Growth	97.22	47.07	0.00	92.93	89.52	21.11	77.71	1.71	9.05	25.64

Figure 14. Application screenshot of the Performance Measure table for selected scenarios over the Historical period.

An annual timeseries of the Potential System Shortage performance measure shows that not only is the average annual volume of shortage likely to increase in the future, but the frequency of greater shortages is also likely to increase, even under EstUse (Figure 15). Including increased demand, shown here with the Full Allocation scenario, this pattern is likely to exacerbate the situation. This increasing pattern of shortages occurs entirely in tributaries, since the mainstem North Saskatchewan River never goes dry. We highlight here that under both scenarios, the limit on water withdrawal is set to 0, such that water can be withdrawn until the river or tributary at the license point-of-interest is dry and does not contemplate environmental flow needs or minimum flows. As such, this pattern of increasing water shortages does not consider regulatory changes, such as minimum flow requirements and changes in upstream dam operations, and therefore likely underestimates potential future water shortages.

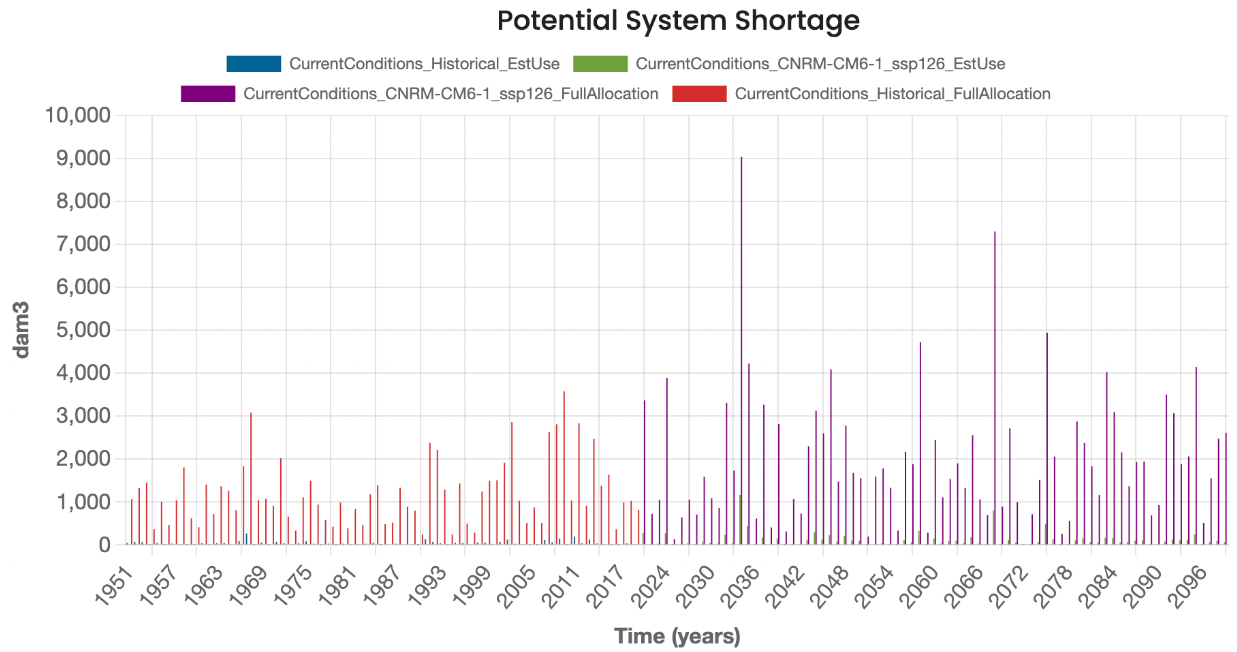


Figure 15. Potential System Shortage across the basin under Estimated Use and Full Allocation for the historical and future climate change periods.

5.4.2 Sundance and DIZ

Both off-stream storage scenarios show small hydrologic effects, more noticeable under the Sundance scenario. The Sundance storage scenario can reduce the Assimilative Capacity PM by over 20%. Notably, neither off-stream option affects Potential System Shortage because they service the mainstem, where flows are not limited (i.e. no constraint on diversions, provided the river is not dry). Of note, Sundance can approximately mitigate the Assimilative Capacity degradation of the Growth scenario (Figure 16).

(1961-1990) (1991-2020)

Scenario	Apportionment (%)	Assimilative Capacity (Days)	Edmonton Peak Flows (Days)	Headwater Fish Habitat (Days)	High Summer Water Temperature (%)	Loading Potential (Days)	Potential System Shortage (dam^3)	St Albert Peak Flows (Days)	Tributary Low Flows (%)	Vermilion Low Flows (%)
CurrentConditions_Historical_EstUse	98.38	37.54	0.00	92.93	89.06	21.79	54.31	1.71	8.43	20.57
CurrentConditions_Historical_SundanceGrowth	97.23	37.04	0.00	92.93	89.63	20.32	77.81	1.71	8.43	20.57
CurrentConditions_Historical_Sundance	98.38	29.71	0.00	92.93	89.17	21.11	54.31	1.71	8.43	20.57
CurrentConditions_Historical_DIZ	98.38	37.46	0.00	92.93	89.06	21.79	54.31	1.71	8.43	20.57

Figure 16. Application screenshot of the Performance Measure table for selected scenarios over the Historical period.

The effect of the off-stream storage operations is most clearly shown during a dry year, where late-season flows are supplemented to maintain flows above the 10th Quantiles (Figure 17). In this case, EstUse flows drop below 110 m^3/s in early September; both Sundance (red) and DIZ (green) supplement flows by releasing stored water, with DIZ turning off in October (the end of its operating season) and Sundance continuing until mid-October, when its storage was depleted.

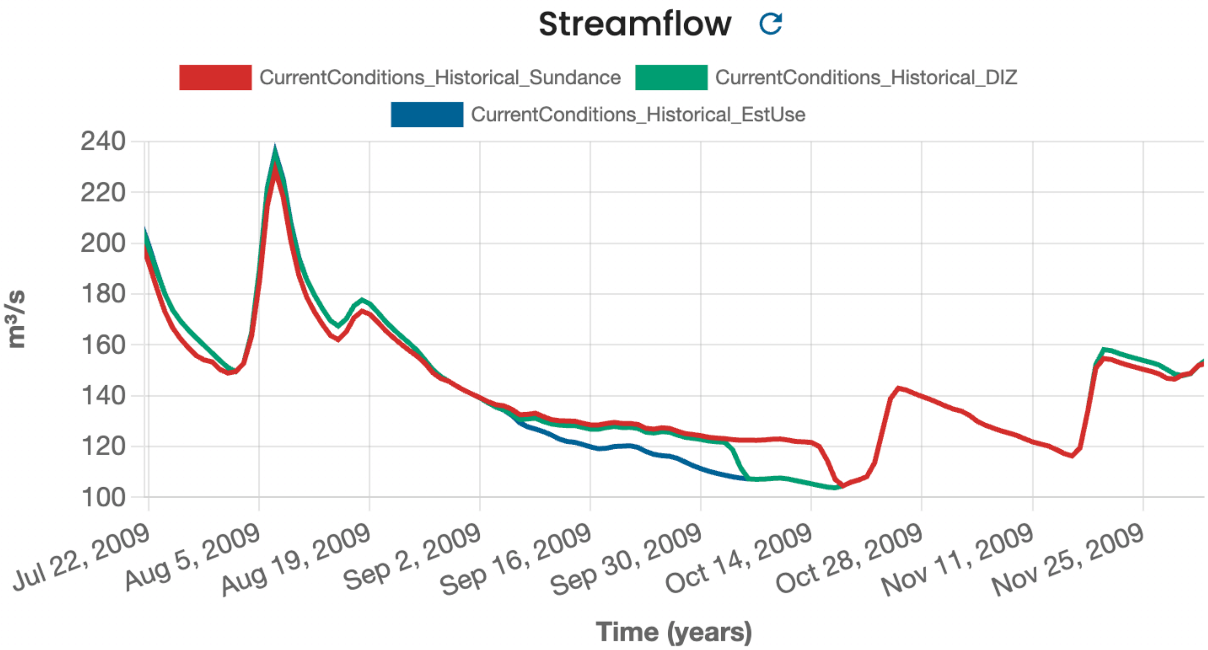


Figure 17. Application screenshot of the daily streamflow for selected scenarios over a dry year (2009).

Storage in both scenarios is shown in Figure 18. Results show that DIZ remains relatively full in most cases, while Sundance has a strong seasonal pattern where it refills in the spring and empties during the fall and winter months. Often, Sundance storage is depleted during the winter months (Feb-Apr). This reflects the dynamic that Sundance operates during the entire year and is primarily relied on to supplement flows during the lowest flows of the year, which typically occur during the late winter periods. By comparison, DIZ operates only during the summer period, which it can satisfy without depleting its storage. We highlight that the operations modelled here do not reflect actual or proposed plans and instead are presented as off-stream storage plans for conceptual objectives. Both sites have storage between 40,000 to 50,000 dam^3, which is approximately 5% of the storage in Bighorn Dam/Abraham Lake and means it could discharge 10 m^3/s continuously for approximately 58 days.

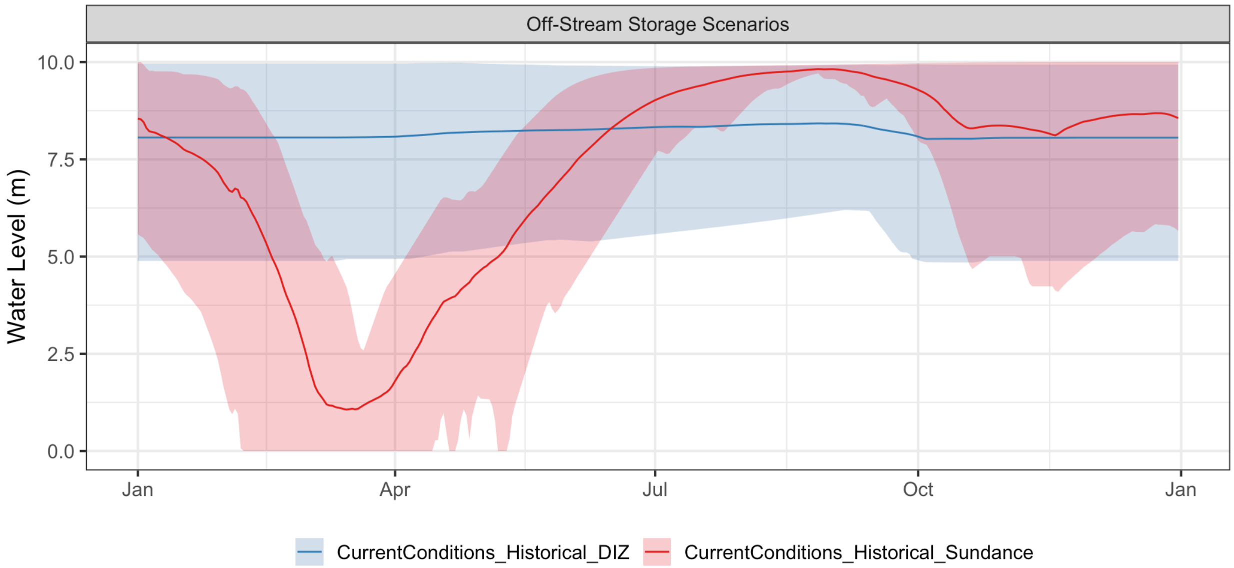
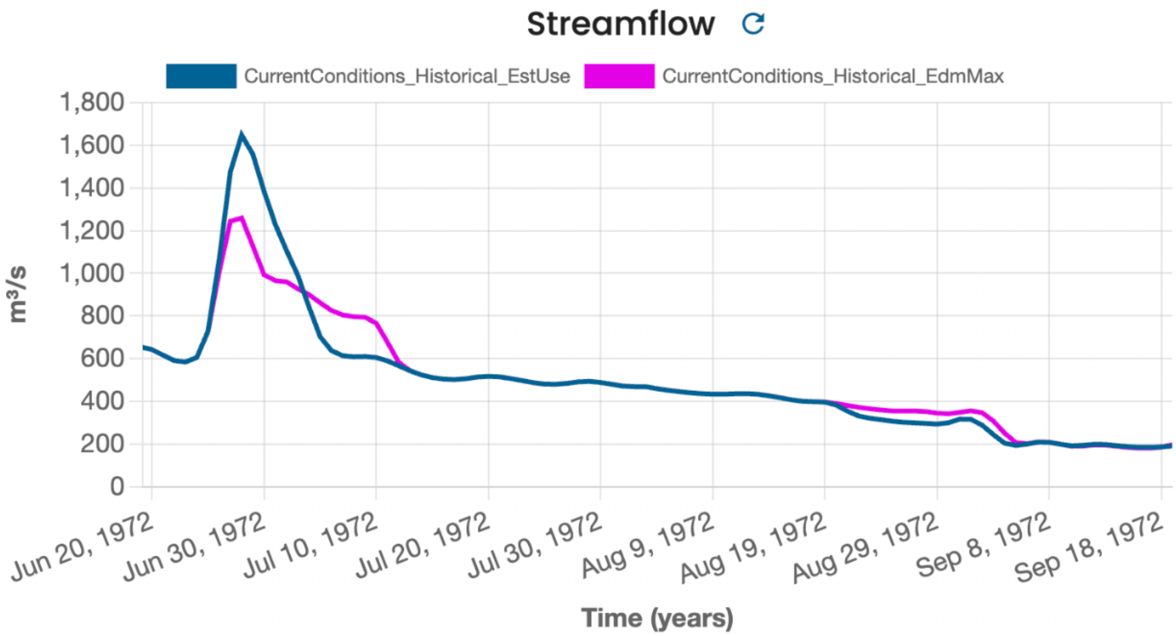


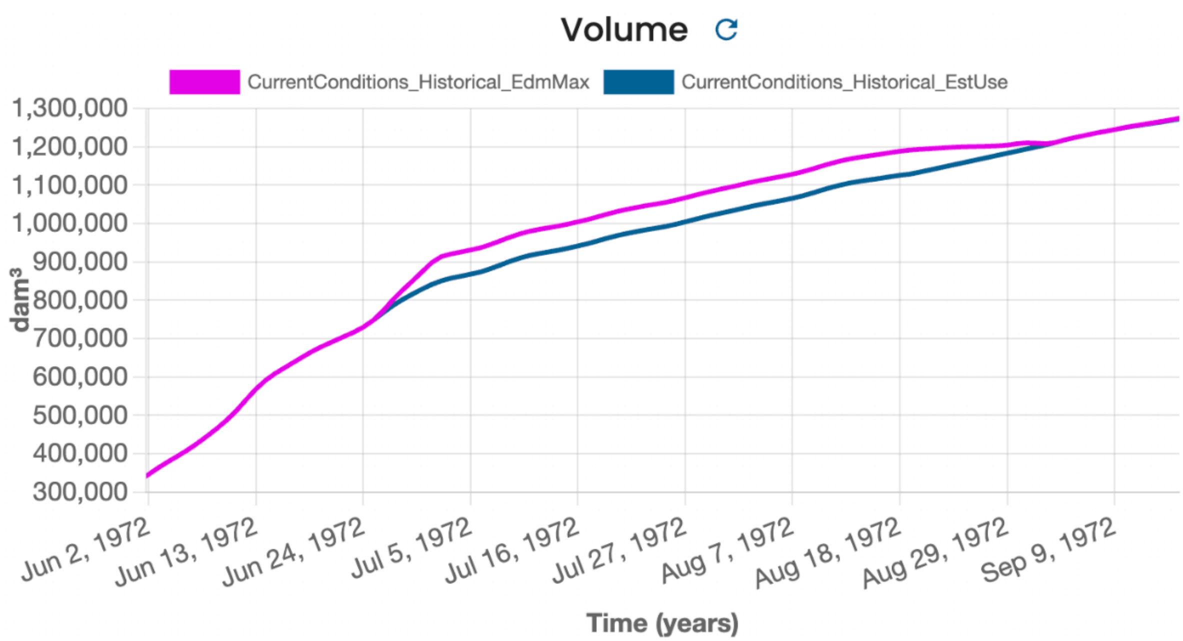
Figure 18. Water level in both off-stream storage scenarios over the 1990-2019 period. The solid line corresponds to the average water level and the shaded area to the 10-90% quantiles.

5.4.3 Edmonton Max Flow

The effect of setting a target maximum flow for the City of Edmonton relies on storing water in the upstream reservoirs (Brazeau and Bighorn). Results show that in some circumstances, peak flows can be mitigated, though not maintained below the target of 967 m^3/s. In 1972 (Figure 19), flows at Edmonton exceeded 1200 m^3/s briefly, but were reduced from the simulated peak of over 1600 m^3/s under EstUse. This reflects the impact of Bighorn (and Brazeau) Reservoir at storing additional inflows and subsequently releasing them following the event. However, this highlights that the dams are only effective for mitigating peak flows if the source of the flood event is upstream, and since these dams are located relatively high in the system, this is often not the case, which limits their flood mitigation ability to setting outflows to their combined minimum (73 m^3/s).



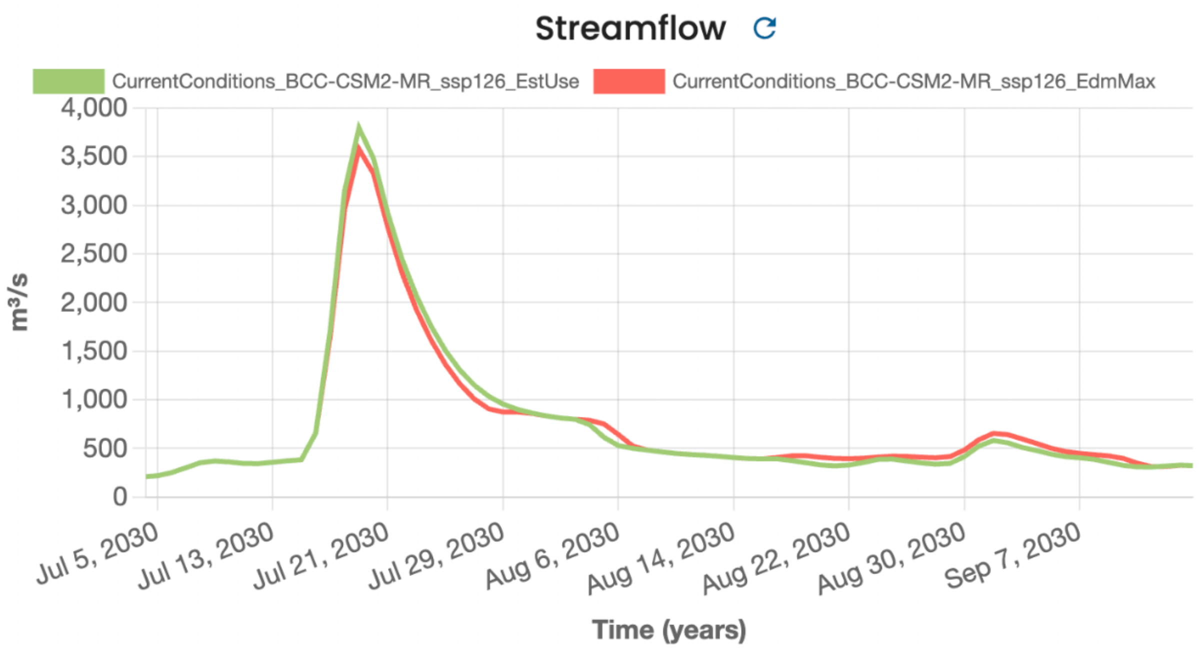
(a) Application screenshot of the daily streamflow for the North Saskatchewan River at Edmonton for selected scenarios over a high flow year (1972) where EstUse is in blue, and EdmMax is in pink.



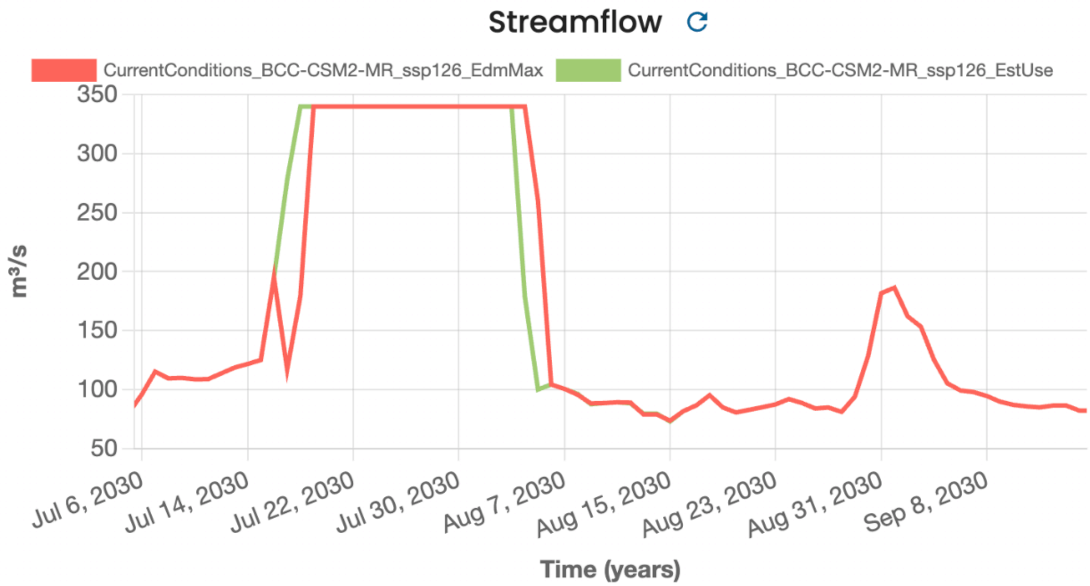
(b) Application screenshot of the daily reservoir volume the Bighorn Reservoir for selected scenarios over a high flow year (1972) where EstUse is in blue, and EdmMax is in pink.

Figure 19. Timeseries of daily streamflow for the North Saskatchewan River at Edmonton and storage volume for Bighorn Reservoir under the 1972 high flow event.

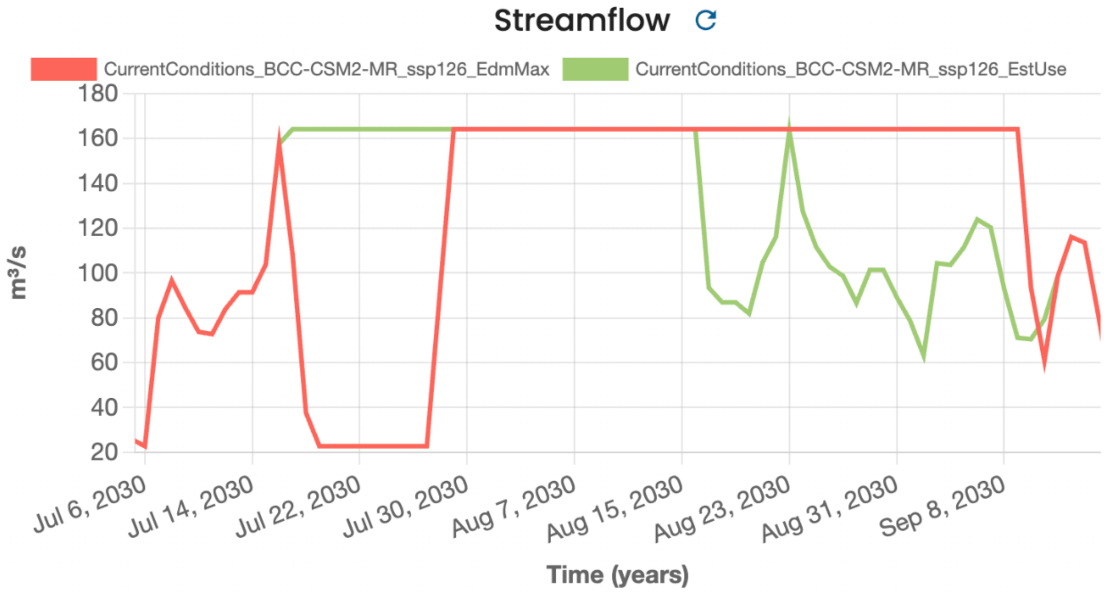
Under a future scenario (BCC-CSM2-MR_ssp126), the timing and magnitude of this event make the mitigative effect of the dams low. Operations were only able to reduce flows at Edmonton by a very small amount, and outflow at Brazeau and Bighorn are both temporarily reduced, but the dams quickly fill up and then have to return to maximizing outflow to maintain water levels below the FSL (Figure 20). This lack of effect occurs for several reasons. First, this event occurred in mid-July, when operators are trying to refill the dams to have full supply for the fall and where FSL is relatively low (minimum FSL of 1316 m at Bighorn on June 15). Second, the model did not consider proactive operations by dam operators, such as where a forecast suggesting a large storm would lead to operations to empty the reservoir to create available storage for the coming event. Third, the dams are located relatively high in the watershed, and therefore when large precipitation events occur downstream, their effect is limited to reducing flows from outflow maximums to minimums; this amounts to an approximately 140 m^3/s reduction at Bighorn and approximately 315 m^3/s at Brazeau (i.e. a maximum reduction of approximately 455 m^3/s at Edmonton). This particular event generated very large streamflow downstream of dams, for instance on the Clearwater River (Figure 21) flows exceeded 550 m^3/s, by far the highest in the simulated record.



(a) Application screenshot of the daily streamflow for the North Saskatchewan River at Edmonton for selected scenarios over a high flow year (2030) where EstUse is in green, and EdmMax is in orange.



(b) Application screenshot of the daily streamflow for the Brazeau River below Brazeau Plant for selected scenarios over a high flow year (2030) where EstUse is in green, and EdmMax is in orange.



(c) Application screenshot of the daily streamflow for the North Saskatchewan River below Bighorn Plant for selected scenarios over a high flow year (2030) where EstUse is in green, and EdmMax is in orange.

Figure 20. Timeseries of daily streamflow for three locations under the 2030 high flow event and climate change scenario BCC-CSM2-MR_ssp126.

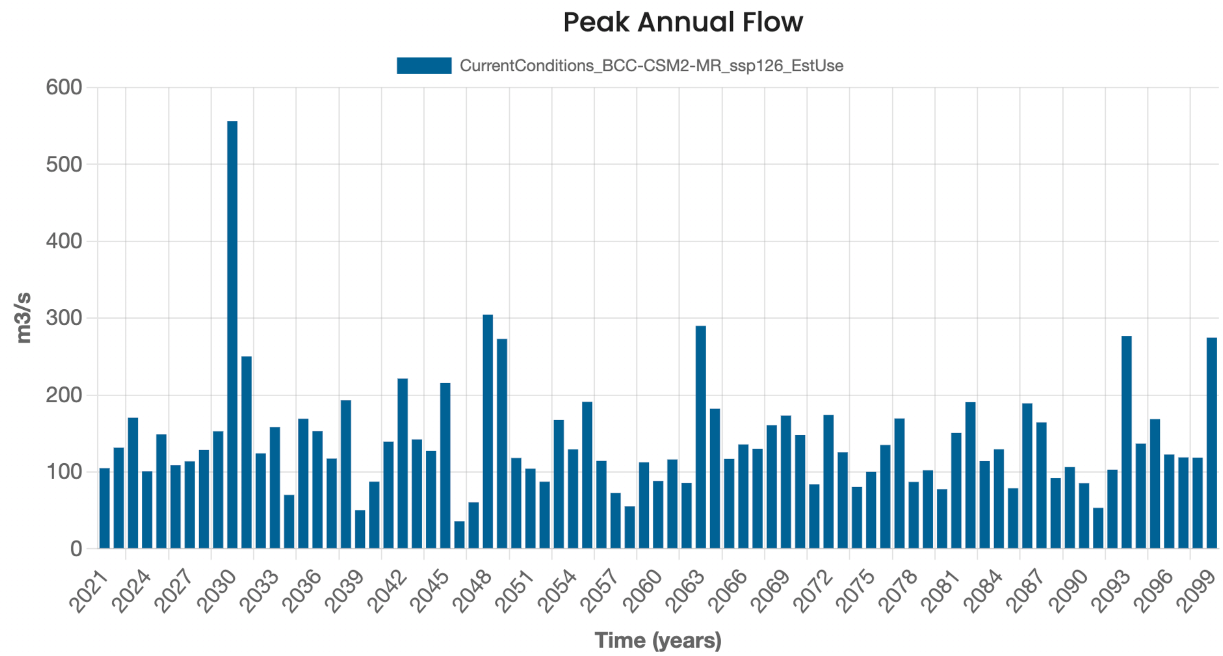


Figure 21. Annual statistics for the Clearwater River Near Rocky Mountain House under the climate change scenario BCC-CSM2-MR_ssp126, highlighting the 2030 high flow event.

5.4.4 Edmonton Min Flow

Under the Historical period, setting a management goal to increase flows during low-flow periods can almost fully eliminate the number of days that fall below the Assimilative Capacity thresholds (Figure 22). It achieves this without any additional effects on the Performance Measures, such as increased shortages.

(1961-1990) (1991-2020)

Scenario	Apportionment (%)	Assimilative Capacity (Days)	Edmonton Peak Flows (Days)	Headwater Fish Habitat (Days)	High Summer Water Temperature (%)	Loading Potential (Days)	Potential System Shortage (dam³)	St Albert Peak Flows (Days)	Tributary Low Flows (%)	Vermilion Low Flows (%)
CurrentConditions_Historical_EstUse	98.38	37.54	0.00	92.93	89.06	21.79	54.31	1.71	8.43	20.57
CurrentConditions_Historical_EdmMin	98.38	1.57	0.00	92.93	89.06	21.25	54.31	1.71	8.43	20.57

Figure 22. Application screenshot of the Performance Measure table for selected scenarios over the Historical period.

Under the CNRM-CM6-1_ssp126 future scenario, by the latter half of the century, conditions become much more challenging for low flows with an earlier freshet and longer late-summer dry period (Figure 23). These conditions make it more difficult to maintain flows above the low-flow targets. Of note, under EstUse, Assimilative Capacity PM is just over 37 days in the 1991-2020 period, but roughly doubles (70 days) by 2051-2080. With the EdmMin target, this number can be reduced to 10 days.

(1961-1990) (1991-2020) (2021-2050) (2051-2080)

Scenario	Apportionment (%)	Assimilative Capacity (Days)	Edmonton Peak Flows (Days)	Headwater Fish Habitat (Days)	High Summer Water Temperature (%)	Loading Potential (Days)	Potential System Shortage (dam³)	St Albert Peak Flows (Days)	Tributary Low Flows (%)	Vermilion Low Flows (%)
CurrentConditions_CNRM-CM6-1_ssp126_EstUse	98.35	69.80	0.87	90.77	93.87	22.43	105.79	1.10	8.97	32.93
CurrentConditions_CNRM-CM6-1_ssp126_EdmMinGrowth	97.25	10.27	0.83	90.77	94.09	21.57	10282.35	1.10	8.97	32.97

Figure 23. Application screenshot of the Performance Measure table for selected scenarios over the Historical period.

However, since this management goal is given a higher priority than water licenses, this efficiency partly reflects shortages of licenses. This shortage is only discernible with the Growth scenario addition in the future period (Figure 24). Particularly, further into the future (2070s onwards), the additional water demand of the Growth scenario cannot be supplied with these higher in-stream objectives, without additional operational considerations.

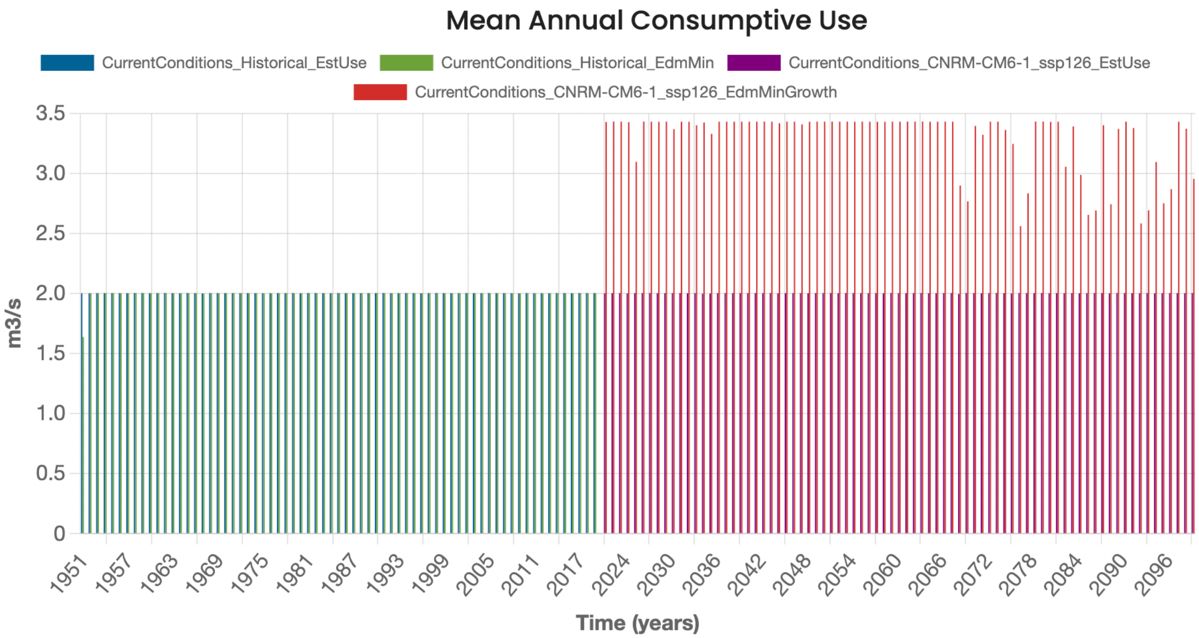


Figure 24. Mean Annual Consumptive Use at the North Saskatchewan River at Edmonton. This value reflects all upstream consumption for each scenario.

One of the reasons that the minimum flows cannot be met in the future period is the poor inflows in some years. In the spring/summer of 2069, storage in Bighorn Dam approaches empty under EstUse, and is emptied by December 2068 under the EdmMinGrowth scenario (Figure 26). This is due to the poor freshet received the previous spring (2068 water year mean annual flow was the lowest to-date), which led to the dam only filling to roughly 50% of its capacity. These conditions are projected to occur periodically under the future climate change scenario in the latter half of the century. We note that real-world operations under the EdmMinGrowth scenario would likely adaptively manage the low-inflow scenario and would likely scale back minimum flows to avoid emptying the dam.

5.4.5 Reservoir Operations and Storage

Changing climatic conditions are impacting the timing and availability of water, and projected growth will lead to increases in the demand and diversions of water. Given these changes, the current operating rules at Bighorn and Brazeau Dams are likely to become less efficient under future conditions and may need to be adjusted to better reflect the future state of the watershed. Here two conceptual scenarios are presented which provide an estimate of their relative impact on downstream conditions.

First, the rule curves setting target water levels for both dams are shifted two weeks earlier in the year (see Figure 4), to reflect the change in the timing of spring freshet; assuming current rule curves continue in the future would mean in dry and early freshet years, the dam would be emptying, anticipating more inflows that may not materialize. Modelling results show that some improvements to Performance Measures are noted in Figure 25 between EdmMinGrowth and EdmMinGrowthEarlyRefill. EarlyRefill leads to modest improvements in the Dam's ability to reduce Assimilative Capacity exceedance days, reduce Loading Potential days, and reduce Potential System Shortages relative to EdmMinGrowth.

(2021-2050) (2051-2080)

Scenario	Apportionment (%)	Assimilative Capacity (Days)	Edmonton Peak Flows (Days)	Headwater Fish Habitat (Days)	High Summer Water Temperature (%)	Loading Potential (Days)	Potential System Shortage (dam³)	St Albert Peak Flows (Days)	Tributary Low Flows (%)	Vermilion Low Flows (%)
CurrentConditions_CNRM-CM6-1_ssp126_EstUse	98.35	69.80	0.87	90.77	93.87	22.43	105.79	1.10	8.97	32.93
CurrentConditions_CNRM-CM6-1_ssp126_EdmMinGrowth	97.25	10.27	0.83	90.77	94.09	21.57	10282.35	1.10	8.97	32.97
CurrentConditions_CNRM-CM6-1_ssp126_EdmMinGrowthEarlyRefill	97.24	9.17	0.80	90.77	94.03	17.90	8924.94	1.10	8.97	32.97
CurrentConditions_CNRM-CM6-1_ssp126_EdmMinGrowthEarlyRefillTAUstorage	97.23	8.53	0.77	90.77	94.14	16.97	8574.92	1.10	8.97	32.97

Figure 25. Application screenshot of the Performance Measure table for selected scenarios over the 2051-2080 period.

Second, increased storage (considered here at a 15% increase) in Bighorn and Brazeau reservoirs is simulated. This is run as a test to see if increased storage can alleviate some of the water stress during extreme low water years, particular in conjunction with EdmMin, Growth, and EarlyRefill. Results suggest the increased storage can marginally improve Performance Measures tied to mainstem low flows (such as Potential System Shortage and Assimilative Capacity) but not completely mitigate them as in the Historical period (Figure 25). While both operational strategies (increased storage and earlier fill curves) both improve the dams' ability to store water, they are insufficient in low flow years if the EdmMin flow target is required (Figure 26). While storage at Bighorn dam was depleted under EdmMinGrowth by late November, storage was not depleted until late December 21 with the inclusion of EarlyRefill, and not until December 29 with the inclusion of TAUstorage. However, in all cases these mitigative measures were not sufficient to prevent the dam storage from depleting. Put another way, the EdmMin flow target is not likely feasible in future low flow years, even with some (though likely not exhaustive) adjustments to current operations.

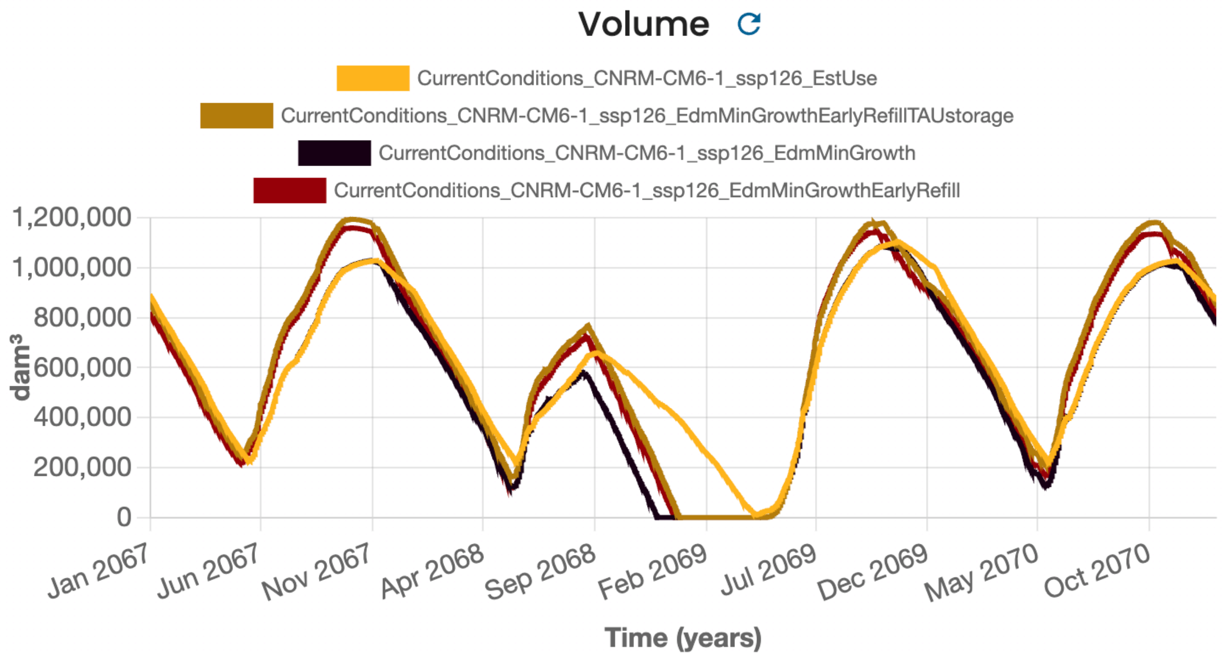


Figure 26. Application screenshot of the daily reservoir storage for the Bighorn Dam for selected scenarios over a low flow period under CNRM-CM6-1_ssp126 climate scenario. EstUse is in orange/yellow, EdmMinGrowth in black, EdnMinGrowthEarlyRefill in red, and EdmMinGrowthEarlyRefillTAUstorage is in brown.

6 Discussion and Limitations

The hydrological and water management model developed for the North Saskatchewan River Basin showed overall good performance. The model is process-based and was able to reproduce hydroclimatic conditions across the watershed with good fidelity and provides confidence that the model is “right for the right reasons”. As such, it is a useful tool to quantify and characterize the hydrologic conditions at points of interest, represent the current state of water management (licensing, operations, and regulatory environment governing surface water quantity), simulate scenarios with differing land cover, climate, and water management configuration, and support collaborative watershed decision making.

The model shows some persistent weaknesses in simulating streamflow that should be considered when evaluating model outputs. Model performance was weakest in the most arid and agriculturally dominated areas (i.e. the prairie region), mostly during the late summer and winter months (post-snowmelt). This is likely due to several factors, most notably the difficulty in simulating prairie pothole dynamics, the geographic heterogeneity of precipitation intensity in summer convective storms, winter conditions (when many of these creeks go dry and/or freeze), and the likely anthropogenic influence on the landscape (land conversion, dugouts/local pumping, agricultural practices, snow farming, etc.).

The model underestimates peak flow events: this bias in peak flows is likely compounded by several factors. Forcing data likely underestimates the intensity and/or magnitude of precipitation during large events (due to under-catch, spatial heterogeneity, etc.). Likewise, the model may underestimate the non-linear response of large storms due to soil processes (soil connectivity) and surface runoff (overland flow, overtopping beaver dams). Finally, peak flows may be underestimated in regulated portions of the watershed in part because the model follows simplistic operational management goals. Although the water management model provides a “best guess” at dam operations, it only considers the provided information and does not consider additional information which may inform how infrastructure is operated during a large event (i.e. such as precautionary actions to release higher outflows in anticipation of greater incoming/forecasted inflows). By the same token, the model may modestly over-estimate low flow periods on the mainstem of the North Saskatchewan River. This is also likely, at least in part, due to the model’s simplistic implementation of minimum flow releases from the dams, which in practice may have been superseded by other considerations, that are not codified in this water management model, such as ice effects, dam maintenance, or other management activities.

Storage options and flow regulation results show some flexibility in the current system. Off-stream storage facilities, as currently modelled, show some ability to supplement lower flow conditions. The large reservoirs in the headwaters have considerably greater ability to achieve the same management goals and additionally can mitigate some peak flow events. However, this comes with several caveats. First, flood mitigation operations would require more detailed modelling and integration of flood forecasting information to properly mitigate events, including proactive lowering of reservoir levels in anticipation of large inflows and possibly maintaining additional available storage during flood season. Additionally, flood mitigation work should recognize that both major reservoirs are located relatively high in the watershed, and as such, have limited ability to mitigate high flows when the rainfall event is concentrated downstream of these facilities. Furthermore, any alteration of Bighorn or Brazeau dam operations would be contingent on operators willing to consider additional management goals in their operations. While modelling shows that in the base case there is considerable flexibility in their operations, this flexibility may very well be valuable to their business (e.g. being able to react quickly to changing power prices). Without the input of dam operators, it is uncertain how feasible changes in operations are.

Water demand is concentrated along the mainstem of the North Saskatchewan River between Edmonton and Pakan. Potential shortages (i.e. unmet modelled water demand) are occasionally simulated for licenses on more arid tributaries during the late summer and winter months. In all cases, unmet demand is referred to as a “potential” shortage because we cannot ascertain how each individual licensee accesses water and whether they store water in dugouts or other temporary storage infrastructure and/or have adapted their operations to only access water when it is available in-stream. On the mainstem North Saskatchewan River, no potential shortages are simulated in the historical base case. This reflects the considerable flow of the North Saskatchewan River and that there are currently no limits on water withdrawals in the basin (on the mainstem or on its tributaries) that are implemented in the model above the physical constraint of a dry river. This modelling decision was made in consultation with regulators and Working Group members and reflects the lack of defined environmental flow needs studies and/or defined thresholds for the mainstem and its tributaries. This highlights a data gap that could be addressed by future studies to better identify flow thresholds and minimum flow requirements to sustain a proper functioning aquatic ecosystem.

Finally, the minimum flow management goals set in this work are set based on statistical thresholds and are completed here as a demonstration of the ability of the system and potential infrastructure to support these low flow thresholds. In the absence of available minimum flow requirement studies, these values were used. Overall, this highlights that further work should be completed to refine what flow requirements are necessary to maintain aquatic ecosystem health, followed by more detailed modelling with these values, to better understand the effectiveness and efficiency of these flow regulation options.

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8 Closure

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