The impact of climate change on water security in the Edmonton Metropolitan Region: A meta-analysis of existing knowledge and information

Final Report

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1. Key Findings

This report presents the results of an assessment of current knowledge and data related to the topic of climate change and water security in the Edmonton Metropolitan Region (EMR). Following is a list of our key findings from this comprehensive meta-analysis.

1. In the EMR, average annual temperature has risen by more than 2 degrees over the past 120 years. Most of the climate change has been an increase in the lowest temperatures; minimum daily winter temperatures have increased by 6 degrees. Thus, the EMR is getting much less cold.

2. There is no significant trend in the instrumental record of precipitation. Fluctuations in precipitation over the past 120 years are dominated by large differences between years and decades.

3. There has been a decrease in the average flow of the North Saskatchewan River (NSR) at Edmonton since the water level gauge was installed in 1911. This trend is consistent with a warmer climate and the resulting loss of glacier ice and summer snowpack at high elevations in the headwaters of the river basin. However, the decline is relatively small compared to large natural inter-annual and decadal variability in flow.

4. These natural cycles in water levels are very apparent in the paleohydrology of the NSR, a 900-year reconstruction of river flow from tree rings collected in the upper part of the river basin. The natural variability captured by the tree rings exceeds the range of flows recorded since 1911. The decadal cycle is particularly evident in the paleohydrology, and has been associated with long periods of consistently low river levels and hydrological drought. Droughts similar to the 1930s are not uncommon and have been longer and more severe in the past. The tree-ring record also shows periods of sustained high water levels, including the early 20th century when there was a large influx of settlers to Alberta during an unusually wet period.

5. Future projections from climate models suggest warmer and wetter conditions in winter and spring and, on average, drier conditions in mid to late summer. Regional Climate Models (RCMs) indicate much less extreme cold and a rise in the frequency of extreme heat. One of the most robust climate change projections is an increase in rainfall intensity. This will have important consequences for managing urban stormwater runoff. A warming climate will amplify both the wet and dry phases of the natural cycle in the regional hydroclimate. Years with heavy precipitation will tend to cluster in wet decades and with dry decades in between. The worst-case future scenario for the Prairie Provinces is the reoccurrence of consecutive years of severe drought, such as occurred in the 1930s and in preceding centuries. Natural variability of the regional hydroclimate is the source of the largest amount of uncertainty in the projection of future temperature and especially precipitation. It dominates the uncertainty caused by the use of different climate models and greenhouse gas emission scenarios.

6. In response to the projected climate changes, the seasonal pattern of river flow will shift, with future river levels peaking about one month earlier in May. Cold season (winter and early spring) flows will be significantly higher. River flows in June to August will be, on average, lower than in the past. As a warming climate amplifies the hydrological cycle, the range of river levels will expand, with larger departures from a shifting baseline of higher winter flows and lower summer flows.

7. Because water quality in the NSR is directly related to both runoff from the landscape and instream flows, it will be affected by climate change impacts on river flows and on runoff generated by precipitation and snowmelt. Higher concentrations of turbidity, colour, nutrients and algae are anticipated as a result of increased precipitation, a larger range of flows in the NSR, floods, droughts, forest fires, and higher water temperatures.

8. Absolute water use and demand has increased in recent decades in the EMR but at a much lesser rate than the increasing population. As a result, there has been a decoupling of per capita water use from growth in the economy and population of the EMR. This can be attributed to the effectiveness of water use efficiency and conservation strategies.

9. While there is little existing analysis of future water demand, one current study suggests 1) conventional water demand forecasting models tend to overestimate long-term demands by failing to account for water conservation, 2) future demand could depend on the link between outdoor watering in the summer and daytime maximum temperatures, which are projected to rise, and 3) water use depends on the timing of demand in a typical day and week.

10. The operation, and possibly structural integrity, of infrastructure for drainage, water supply, and treatment is vulnerable to climate change. Much of the risk is due to the expectation of more intense precipitation, prolonged low water levels, and more extreme weather events. Water allocation, and the design of storage and conveyance structures, is based primarily on average seasonal water levels, but otherwise water resources are managed to prevent the adverse impacts of water excess and shortages.

2. Introduction

This report is a summary of existing information and data relating to the impact of climate change on water security (the balance between future supply and demand) in the EMR. This meta-analysis of existing knowledge will support decision making to enhance the resilience of municipalities in the EMR to the impacts of climate change. The Climate Resilience Exchange project, led by the AOS Foundation, is supporting eight partner municipalities in the EMR (Figure 1) to define, select and implement coordinated actions to reduce regional vulnerability to climate-related impacts. Until fairly recently, climate was regarded as unchanging for practical purposes. Now planners, policy analysts and engineers are expected to consider the reality of climate change and add it to a long list of decision-making criteria.

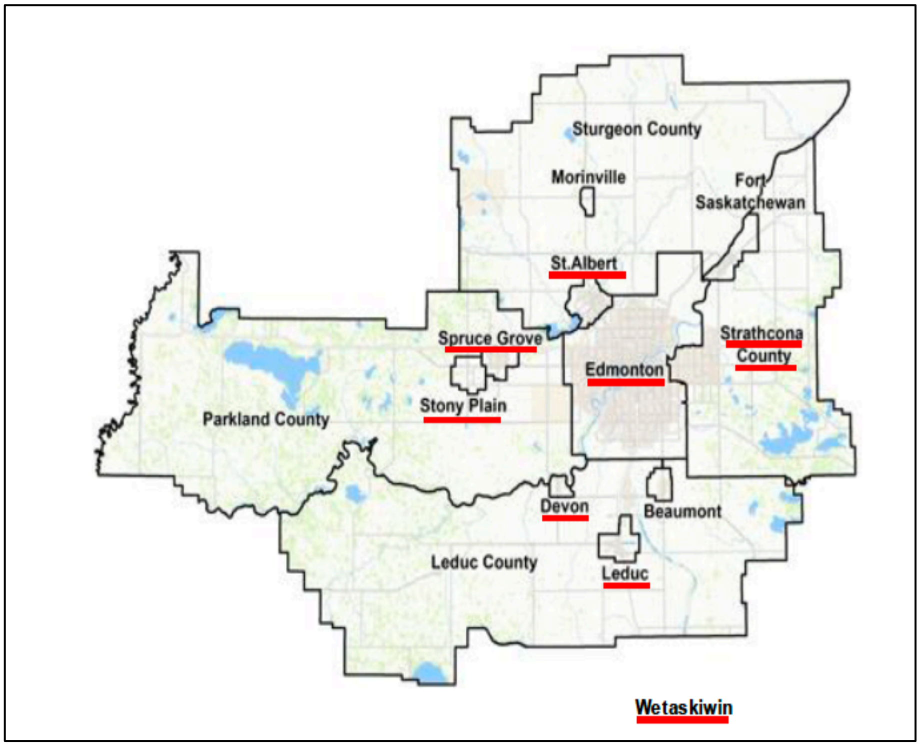


Figure 1: Partner municipalities in the EMR (AOS Foundation, 2017).

Our meta-analysis of existing knowledge and information concerning the impact of climate change on water security in the EMR includes a review and synthesis of:

- The historical flow of the NSR recorded at a series of gauges along the main stem of the river and its major tributaries;
- The paleoclimate record and paleohydrology of the North Saskatchewan River Basin (NSRB): the climate of past centuries and the reconstruction of NSR flows from tree-rings;
- The future climate of the NSRB and the potential impacts of projected climate changes on the NSR, including the volume and timing of flows, water temperature, and water quality as it pertains to water supplies for consumption and ecosystem maintenance;
- Historical water use (consumption and losses) in the EMR, by sector: municipal and residential, agriculture, commercial and industrial;
- Projected water use (consumption and losses) by sector, accounting for the impacts of future climate change, and future growth in the EMR; and
- Other relevant information:

    - The degree of natural climatic variability versus anthropogenic climate change;
    - The sources and degree of uncertainties in the projection of future climate and impacts on water; and
    - Projections of future climate for the EMR that are more detailed than those used previously by the Climate Resilience Exchange project (AOS Foundation, 2017).

2.1. Approach

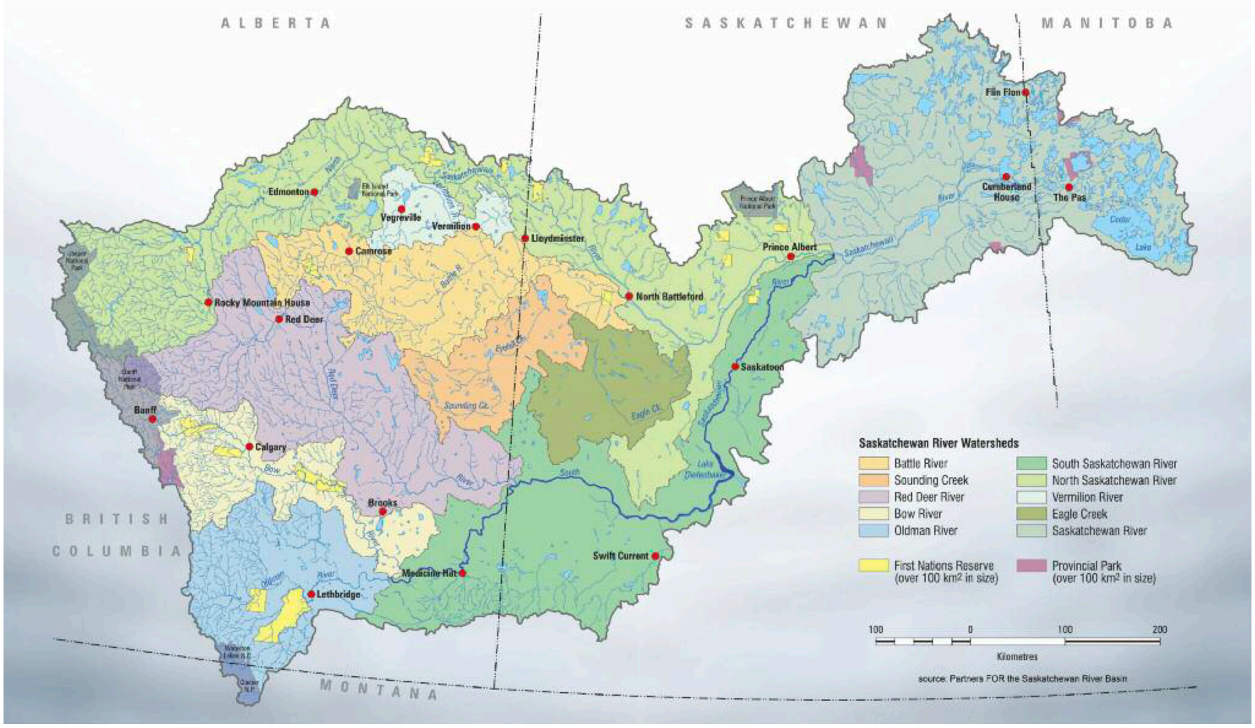
This synthesis report summarizes the state of existing knowledge and information across the full scope of the topic of climate change and water security, including historical and projected surface water supply, quality, and demand. It also highlights knowledge gaps and uncertainties, and provides with some key messages and recommendations regarding use of the findings and further data collection and research.

Our approach to this meta-analysis followed the principles and practices of scientific assessment, the deliberate process by which subject experts review and critically analyze diverse sources of knowledge, to reach value-added conclusions and identify knowledge gaps and uncertainties. We reviewed the existing knowledge base, supplementing PARC's existing large archive of scientific literature and data on climate change and water. We used Internet and university library bibliographic tools, and contacted our research collaborators, to obtain the full range of publications, reports, and databases related to climate change and water supply/demand in the NSRB.

3. Climate and Hydrology of the North Saskatchewan River Basin

3.1. Hydrology

The climate of the mountainous region of the NSRB (Figure 2) is characterized by high precipitation and low evapotranspiration, resulting in high water yield. In the eastern portion of the NSRB, average annual precipitation tends to be less than evapotranspiration, resulting in a moisture deficit in average years. In Alberta, the NSR extends approximately 1,000 km to the provincial boundary, draining an area of about 57,000 km^2 (NSWA, 2014). The NSRB is divided into 12 sub-watersheds, which are naturally different in climate, geology, soil, landscape, vegetation, all of which influence the river system (NSWA, 2014). The Cline, Brazeau, Ram, and Clearwater rivers, headwater tributaries above the EMR, generate 88% of the total annual runoff from snowmelt and precipitation (Golder, 2008b). Figure 3 shows the percentage of the annual streamflow yield contributed by each sub basin (NSWA, 2012).



source: Partners FOR the Saskatchewan River Basin

Figure 2: North Saskatchewan River Basin (NSRB) (NSWA, 2012).

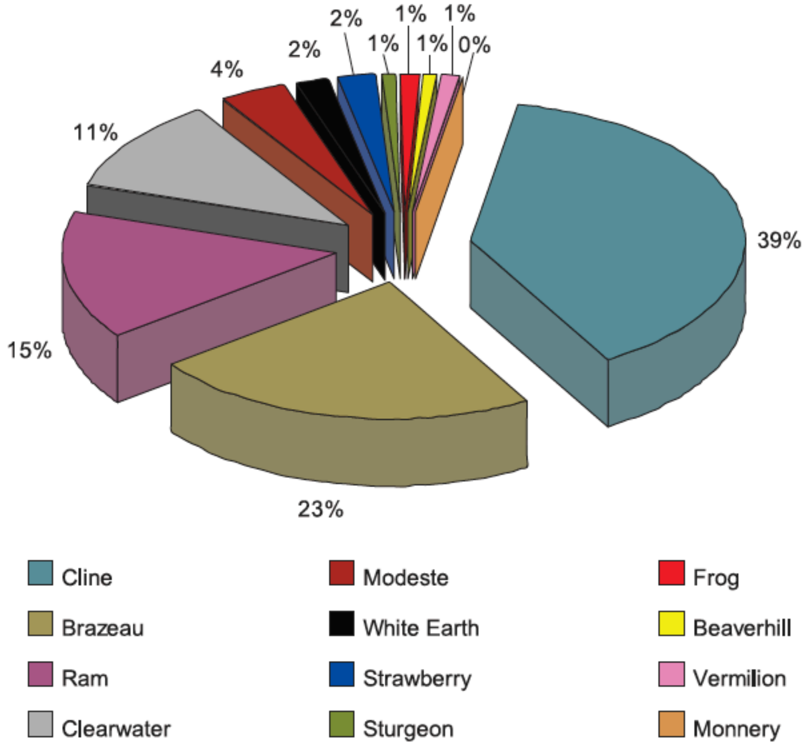


Figure 3: Annual yield of the North Saskatchewan River (NSR): Percentage by sub-watershed (NSWA, 2012).

3.1.1. Historical Streamflow Records

Monitoring of the NSR at Edmonton began in May 1911, and therefore flow data for every month of the year are available since 1912 and currently available up to the end of the 2015. Two dams (Bighorn and the Brazeau) regulate river flow upstream of Edmonton. Water is released from the reservoirs throughout the year for power generation and there is little capacity to control or mitigate flooding of the NSR (EPCOR, 2017). While operation of the dams has little overall effect on mean annual flows, it increases flows in the cold season (Oct – Apr) and decrease them in the warm season (May – Sep). This is illustrated in Figure 4, which is plot of mean monthly flow of the NSR at Edmonton from 1912-1971 prior to the Bighorn Dam, and from 1972-2015, after the construction of the Dam. The natural flow (the blue bars) is characteristic of mid-latitude mountain watersheds with a snow-dominated hydrologic regime, where approximately 40% of the annual discharge occurs in June and July from rainfall and melt of the mountain snowpack.

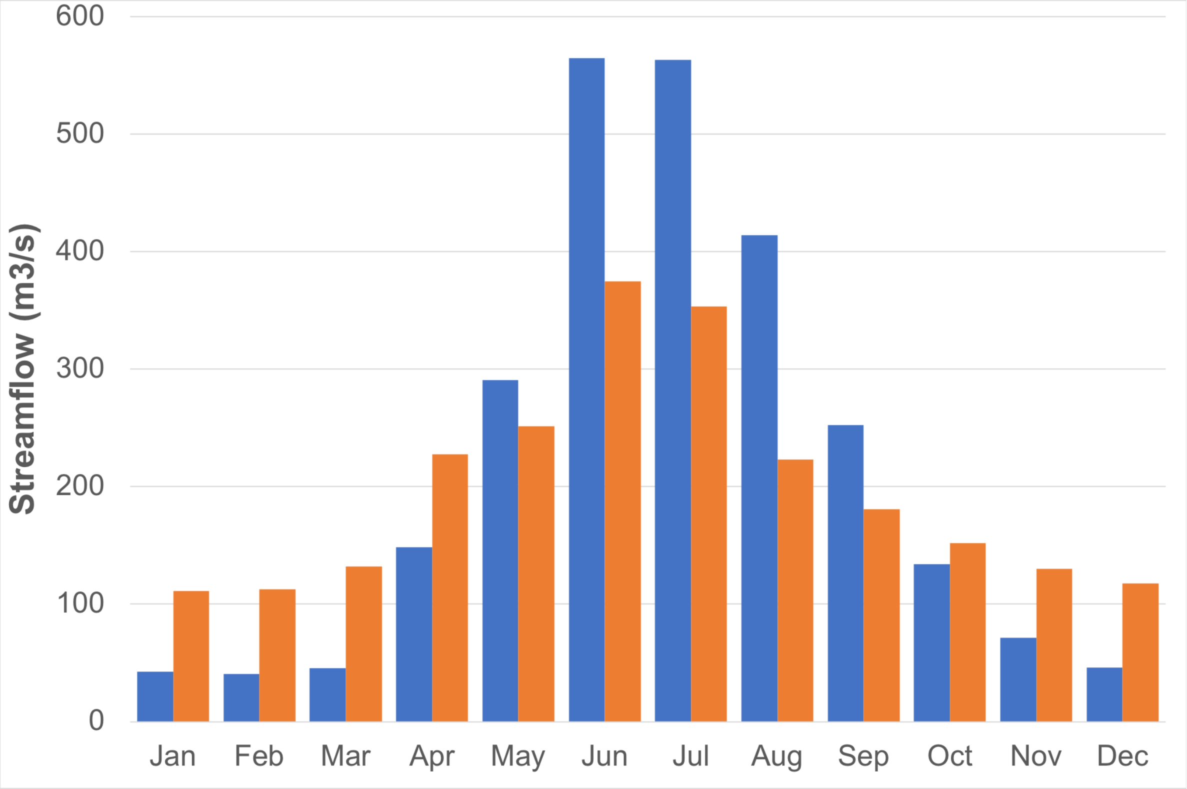


Figure 4: Mean monthly flow (m^3/s) of the North Saskatchewan River (NSR) at Edmonton from 1912-1971 (Blue) prior to the Bighorn Dam, and from 1972-2015, after the construction of the Dam.

Figure 4 shows that relatively high flows are maintained throughout the summer from the melt of snow and glaciers at high elevations. MacDonald et al. (2012) modeled the future snowpack of the NSRB, quantifying potential changes in snow water equivalent. They found that there may be little change in the annual maximum snow accumulation; however, spring snow melt likely will occur earlier as the climate warms and with an increase in the proportion of rain versus snow.

The accelerated retreat of mountain glaciers in recent decades is an indication of repeated years of negative mass balance, where melt of glacier ice in summer exceeds the contribution of new ice converted from the winter snowpack. Among the five major rivers that flow from the eastern slopes of the Rocky Mountains, the North Saskatchewan is fed by the largest ice volume and area of glaciers (about 1% of the watershed above Edmonton; Marshall et al., 2011). Recent trends and modeling of glacier mass balance suggest that glaciers on the eastern slopes of the Rockies will lose 80-90% of their volume by 2100, with a corresponding decline in glacier contributions to streamflow (Marshall et al., 2011). The contribution of glacier meltwater to the NSR is less than 3% the regulated flow at Edmonton during July through September (Comeau et al., 2009). While the loss of glacier ice has generated extra runoff from the larger glaciers, the number of glaciers is declining as the smaller ice masses disappear.

The Alberta government has generated naturalized streamflow data by adjusting the recorded flows to account for artificial storage and diversions, mostly the effects dams (Bighorn and the Brazeau). The time series of naturalized mean annual flows at Edmonton clearly show interannual and decadal variability, which has been linked to the strong influence of ocean-atmosphere oscillations (i.e., El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on the hydroclimate of western North America (St. Jacques et al., 2010, 2014; Gurrapu et al., 2016; Sauchyn et al., 2011, 2015b). Linear trend analysis of the naturalized flow of the NSR (Figure 5) indicates that there has been a statistically significant ($p < 0.05$) decrease of 38.6 m^3/s since 1912. It should be noted that this gauge station is located downstream of two water treatment plant intakes, and does not account for the portion of withdrawals that are returned to the NSR (EPCOR, 2017).

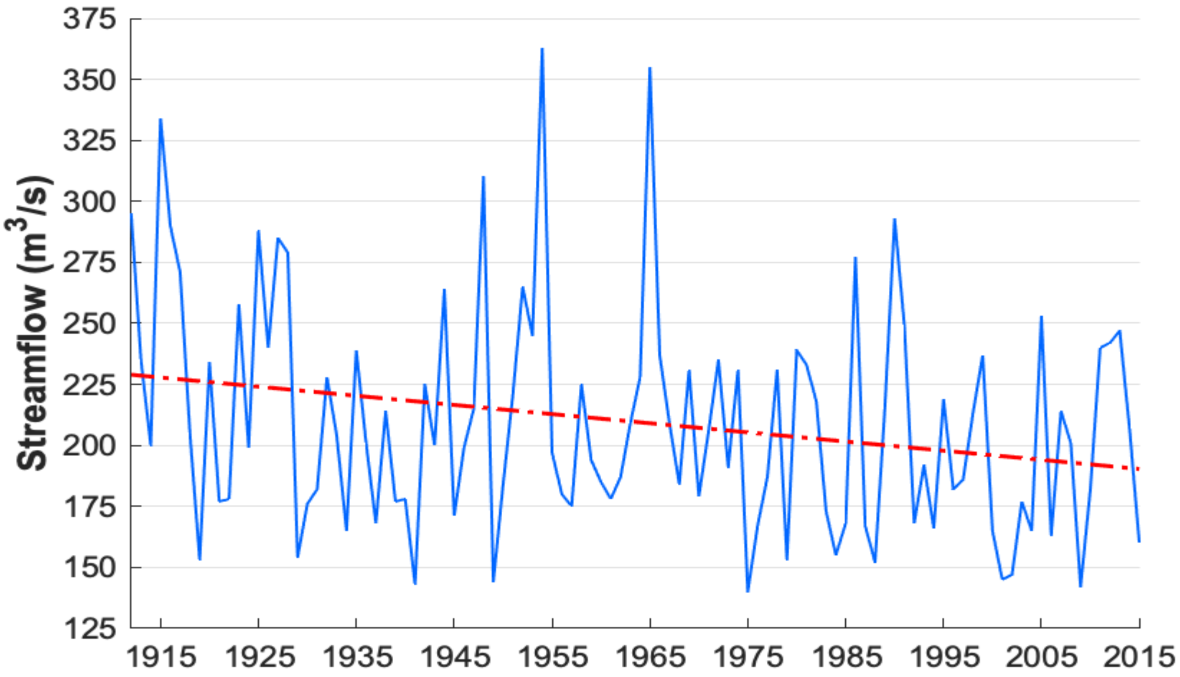
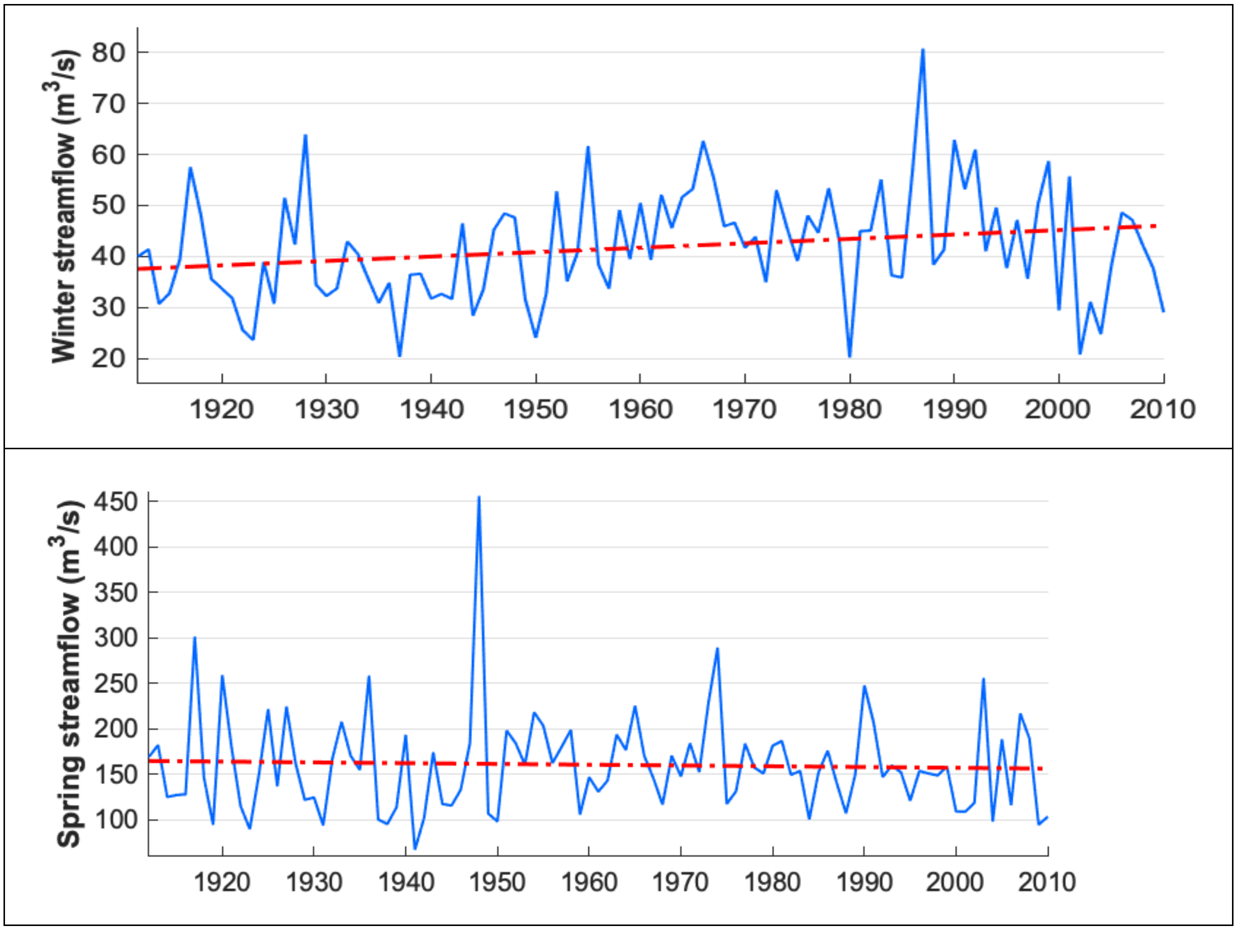


Figure 5: Mean annual flow (m^3/s) of the North Saskatchewan River (NSR) at Edmonton, 1912-2016. The red line represents a downward linear trend.

In Figure 6, naturalized streamflow from 1912-2010 is plotted for each season: winter (DJF: December through February), spring (MAM: March through May), summer (JJA: June through August), and fall (SON: September through November). The linear trends (red lines) are not statistically significant in spring and fall; however, they are significant ($p < 0.05$) in winter and summer, with an increase of 8.5 m^3/s and a decrease of 113.7 m^3/s, respectively. These streamflow trends are consistent with climate changes over the past century. Warmer winters have led to winter snowmelt events. Summers are warmer, and as a result, less snow and ice remain at high headwater elevations to sustain summer flow. These flow series are also marked by large differences between years and decades, such that short term trends can reflect natural variability rather than climate change.



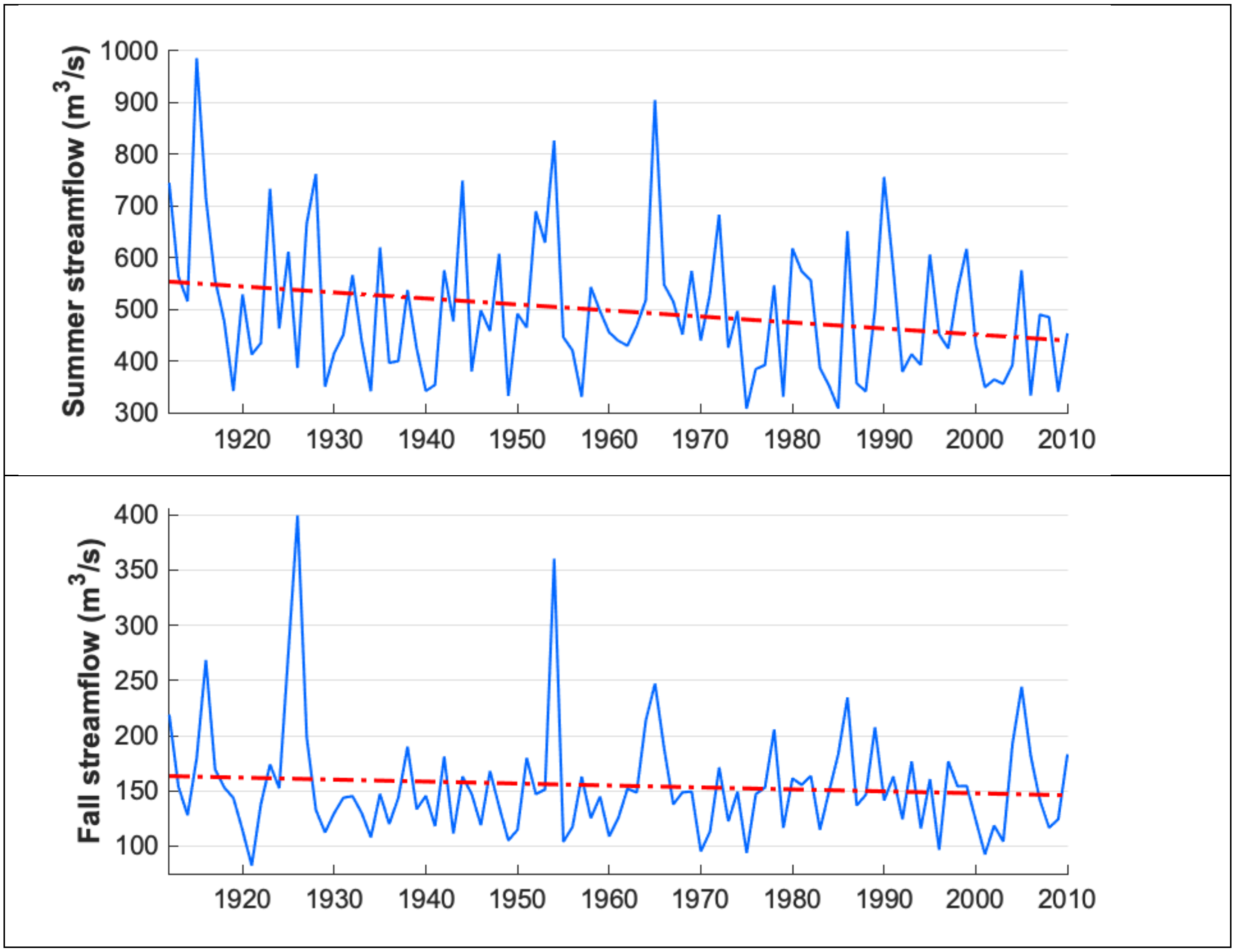


Figure 6: Naturalized flow (m^3/s) of the North Saskatchewan River (NSR) from 1912 to 2010 at Edmonton by season.

3.1.2. Groundwater

Further growth in Alberta's population and economy could place increasing demands on groundwater systems (Grasby et al., 2008; Worley Parsons, 2009; Hughes et al., 2017). The Paskapoo Formation in west-central Alberta is an important aquifer and source of groundwater for industrial use, primarily in the oil and gas sector (Hughes et al., 2017) Data on groundwater levels is available from the Alberta Groundwater Observation Well Network <http://aep.alberta.ca/water/programs-and-services/groundwater/groundwater-observation-well-network/>. Data from these observation wells demonstrates the influence of climatic variability on groundwater table elevation, but as yet there's no evidence of the impact of a warming climate on groundwater recharge (Perez-Valdivia et al., 2012). Research has shown that when ENSO and PDO are in their respective positive phases, groundwater levels reflect the associated warmer and drier winters and reduced groundwater recharge (Hayashi and Farrow, 2014; Perez-Valdivia et al., 2012).

3.1.3. Water Quality

The following summary of historical water quality conditions in the NSR is from a literature review of climate change impacts to the North Saskatchewan River provided by EPCOR Water Canada (2017b). Additional information on the water quality of Alberta Rivers is available from the Government of Alberta, River Water Quality Index <https://open.alberta.ca/opendata/river-water-quality-index-alberta>.

Colour

Dissolved organic material in water can give water a yellow-brown colour when present in high concentrations. Colour is often used to indicate the relative amount of dissolved organic carbon (DOC) or dissolved organic matter (DOM) found in surface waters due to organic material entering from the surrounding watershed. Colour can have a secondary effect on raw water quality, as it limits the amount of UV exposure in radiation in lakes and rivers and increases the survival of waterborne pathogens such as *Cryptosporidium*. Increased colour and subsequent survival of pathogens has been linked to waterborne disease outbreaks in large cities in industrialized nations (Williamson et al., 2017). Colour is removed during the production of drinking water for aesthetic considerations, but also because it includes precursors to potentially carcinogenic disinfection by-products and interferes with other treatment processes. Colour also interferes with UV disinfection because it reduces the transmissivity of UV light. Treatment processes for removing colour, tend to be costly and operationally complex. Thus, colour is a key parameter of concern for water treatment plants (WTPs).

Colour in the NSR is typically low during the winter months, but can quickly increase during spring runoff and other precipitation events (Figure 7). Large increases during the spring are due, in part, to increased inputs of particulate and organic matter from spring runoff that has accumulated over the winter months. Large precipitation events, such as the one which occurred upstream of Edmonton in August 2016 resulted in the highest recorded colour value at the WTPs. The large colour values affected the ability of the WTPs to produce drinking water of sufficient quality, production could not keep up with the demand, and voluntary water restrictions were put in to place. Colour in the NSR quickly dropped and the WTPs were able to resume drinking water production. However, colour continued to remain elevated into the fall and winter of 2016 at levels not previously recorded. This elevated colour significantly delayed the WTPs from switching production to direct filtration, which typically occurs in late fall or early winter when colour and turbidity values in the NSR are typically low. Further, uncharacteristically warm temperatures in February 2017 resulted in early spring runoff conditions requiring the plants to convert out of direct filtration. Colour in the NSR has shown notable interannual variability, presumably related to precipitation and spring runoff, however, there has been no consistent increasing or decreasing trend over time (Figure 8).

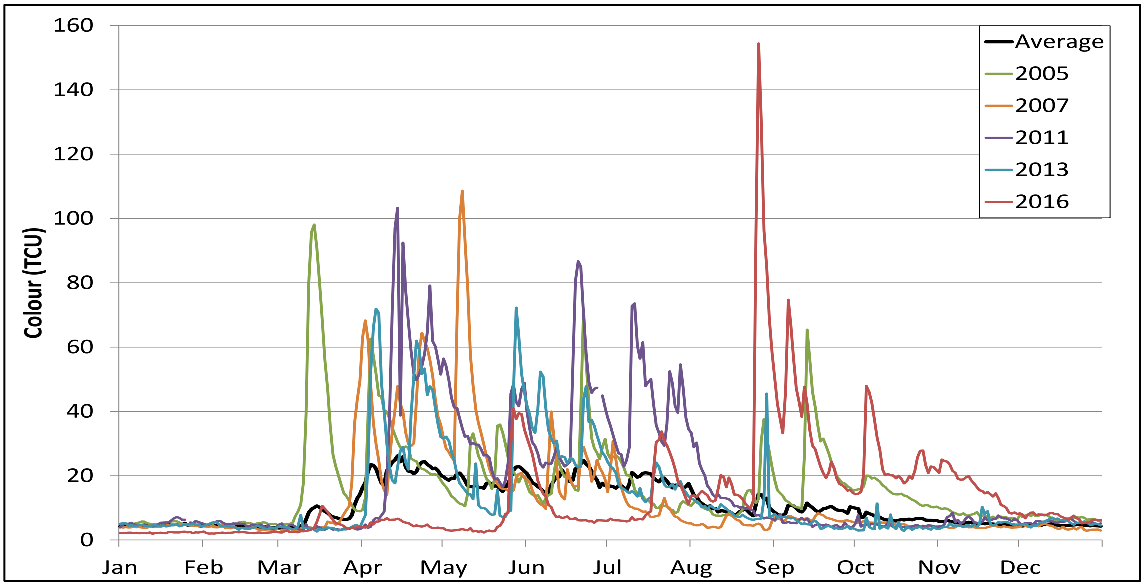


Figure 7: Daily mean colour at Rossdale WTP Intake average from 1997 to 2017 and select years (2005, 2007, 2011, 2013 and 2016) (EPCOR, 2017b)

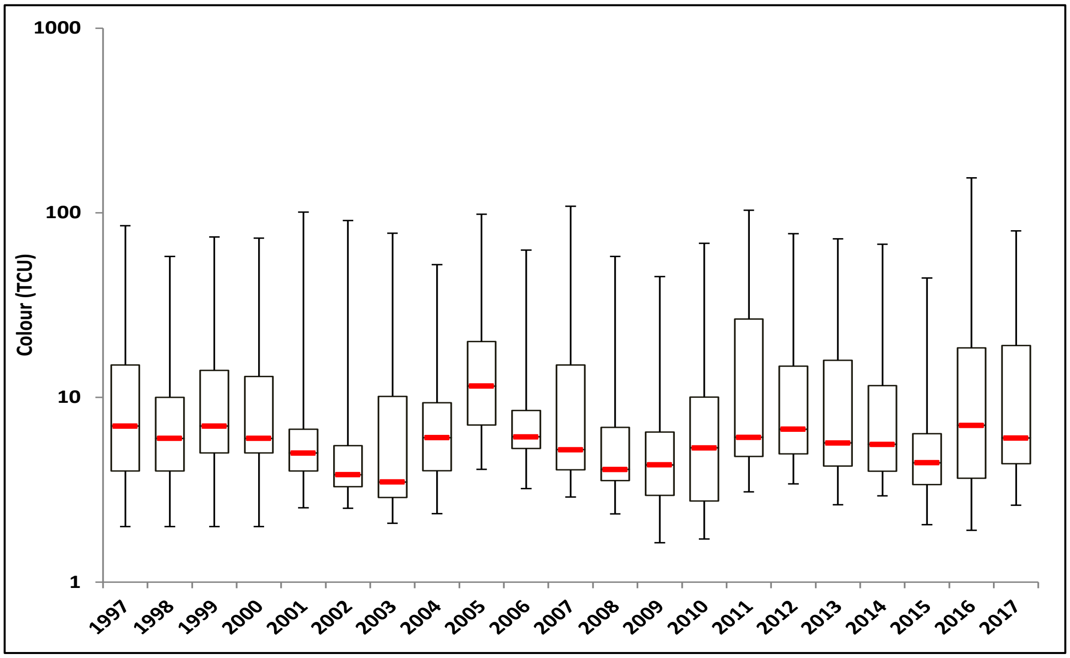


Figure 8: Colour at Rossdale WTP Intake 1997 to 2017 showing minimum, first quartile, median, third quartile, and maximum values (EPCOR, 2017b).

Turbidity / Total Suspended Solids

Turbidity is a measure of the clarity or cloudiness in water, and is also used as a proxy for total suspended solids. Increased turbidity can be caused by soil erosion, stormwater, runoff from disturbed landscapes, and algal growth. Water treatment plants remove turbidity for aesthetic reasons, but also because turbidity is an indicator of the effectiveness of water treatment, particularly the removal of pathogens. Increased turbidity and total suspended solids can affect aquatic life in a number of ways including altering habitat, smoothing fish eggs, algae and benthic invertebrate and clogging and abrasion of gills. Water quality guidelines for the protection of aquatic life exist for turbidity and suspended solids.

Turbidity in the NSR is directly linked to runoff and flow and it increases during runoff and the increased flows associated with spring melt (Figure 9). Additionally, turbidity typically increases during the summer months corresponding to increased flow in the river. During the fall and winter, when flows typically decrease, so do turbidity levels.

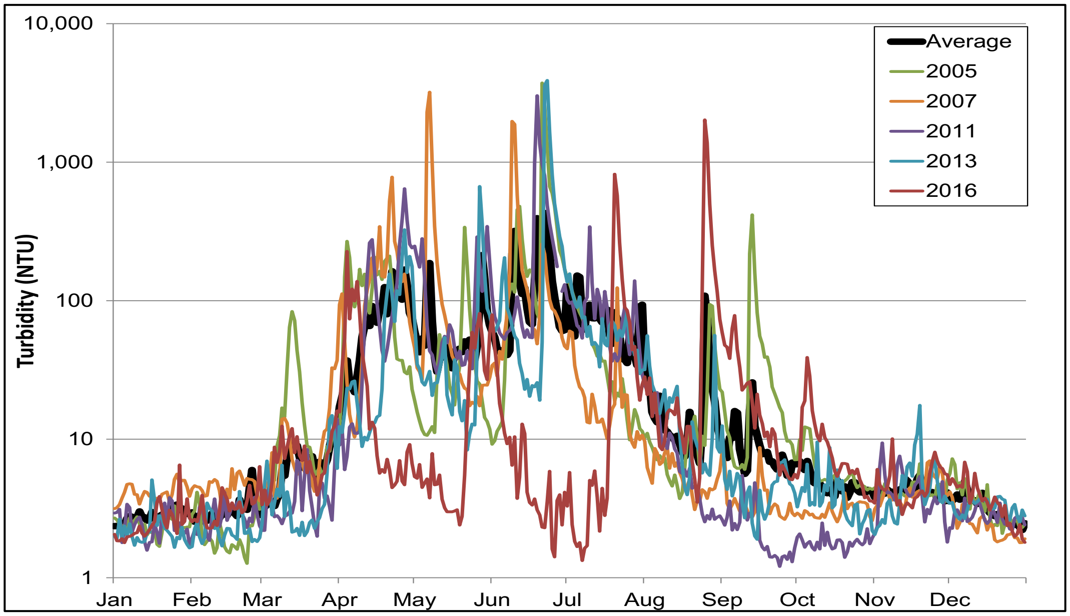


Figure 9: Daily mean turbidity at Rossdale WTP Intake average from 1997 to 2017 and select years (2005, 2007, 2011, 2013 and 2016) (EPCOR, 2017b)

Similar to colour, turbidity in the NSR has shown year-to-year variability, presumably related to variation in flow and runoff. There has been no consistent increasing or decreasing trend in turbidity in the NSR (Figure 10). Samples collected as part of the EPCOR Drainage's Environmental Monitoring Program have demonstrated that total suspended solids increase in the NSR as it flows through Edmonton, particularly during precipitation and runoff events, as a result of stormwater flows (Golder, 2018).

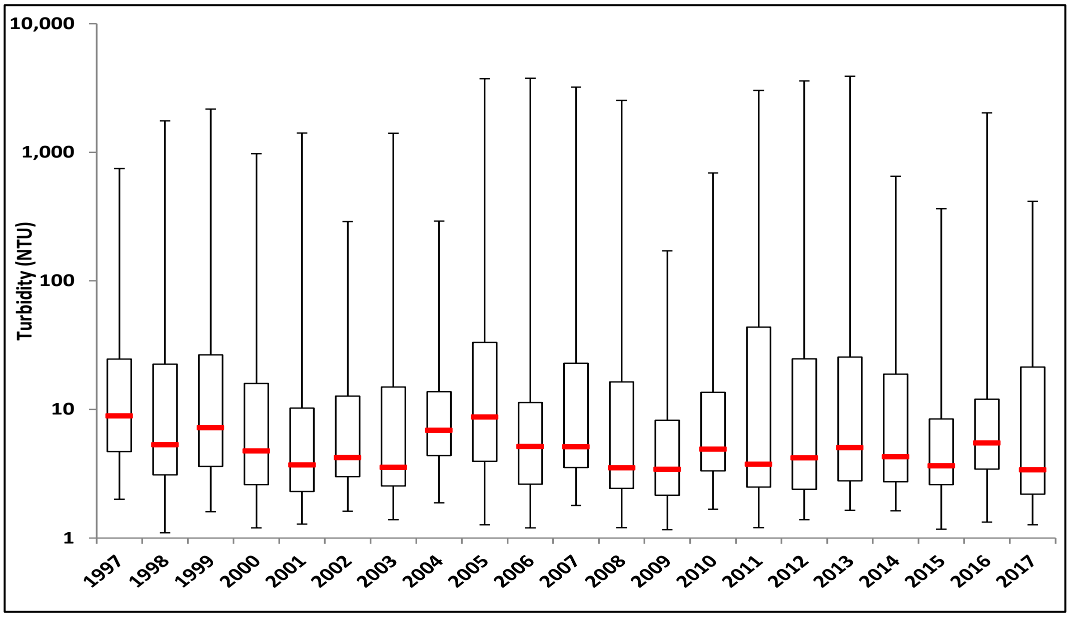


Figure 10: Turbidity at Rossdale WTP Intake 1997 to 2017 showing minimum, first quartile, median, third quartile, and maximum values. (EPCOR, 2017b)

Nutrients

While nutrients are required for healthy ecosystem function, excess nutrients can negatively affect aquatic ecosystems and can also affect the ability to produce and distribute clean drinking water. Elevated nutrients, most notably phosphorus, promote increased growth of algae, which are discussed in the next subsection. Elevated concentrations of nutrients such as nitrate, nitrite, and ammonia can have toxic effects on aquatic biota. In drinking water, elevated ammonia and nitrogenous compounds can be associated with unpleasant taste and odour issues, and extremely high concentrations of nitrite and nitrate can adversely affect human health. Nitrification, the process of microbes oxidizing ammonia and nitrite to nitrate, can result in decaying residual chlorine, which, in turn, can lead to microbial regrowth. When extra chlorine is added to compensate for the loss of disinfectant residual, there can also be a higher production of potentially harmful disinfection by-products.

In the NSR, concentrations of ammonia are typically low, with the exception of spring runoff period, due to the flushing of decaying organic material from the watershed. Nitrate and nitrite concentrations are not high enough to generally cause concerns for human or aquatic ecosystem health. Data collected by Alberta Environment and Parks (Figure 11) show that nutrient concentrations are low upstream of Edmonton, but are elevated downstream, and that concentrations were typically near established water quality objectives. Data collected as part of EPCOR Drainage's Environmental Monitoring Program (Golder, 2018) confirm the increasing trend of nutrients and have demonstrated that WWTP effluent as well as stormwater and CSO overflow contribute large nutrient loads. Increased concentration of nutrients has been observed as far as the Alberta/Saskatchewan border (and beyond); however, improvements made at WWTP have resulted in improved nutrient conditions compared to water quality prior to the upgrades (PPWB, 2016).

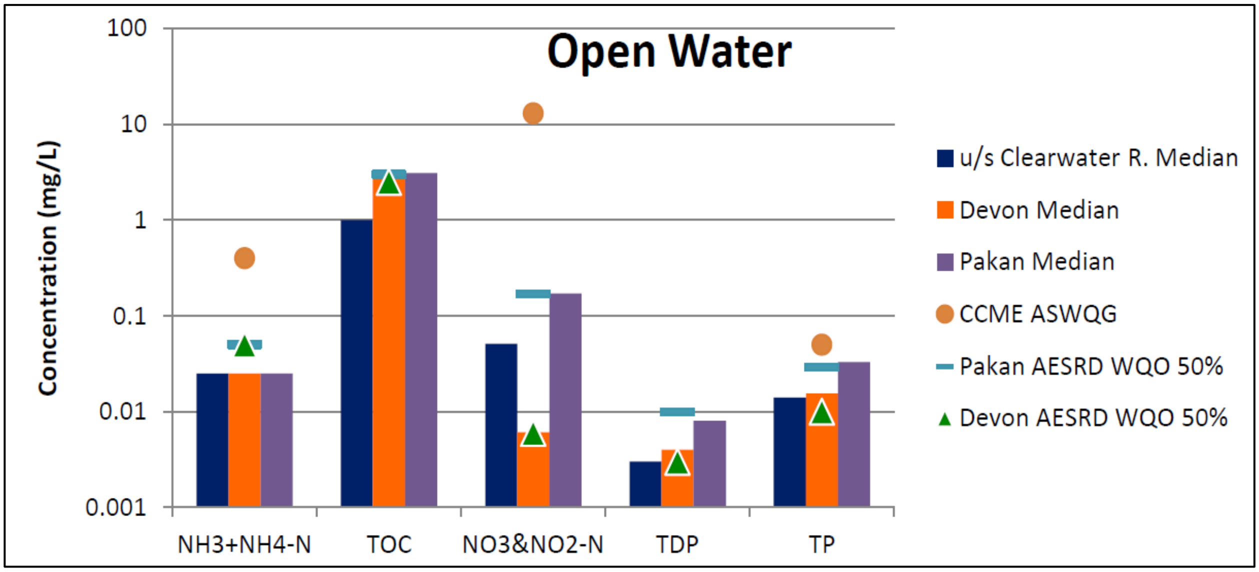


Figure 11: Nutrient concentrations along the NSR relative to water quality objectives (2007 – 2012) (Hutchinson, 2014).

Notes: The Clearwater sampling location is upstream of Edmonton near Rocky Mountain House, Devon is immediately downstream and Pakan is downstream of Edmonton. CCME ASWQG = Canadian Council of Ministers of the Environment Aquatic Surface Water Quality Guideline. AESRD WQO = Alberta Environment and Sustainable Resources Development Water Quality Objective. NH3+NH4-N = total ammonia. TOC = Total Organic Carbon. NO3&NO2-N = nitrate +nitrite. TDP = Total Dissolved Phosphorus. TP = Total Phosphorus.

Algae

Algae are photosynthetic organisms that are found in waterbodies either free-floating, or attached directly to substrates. Algae are a natural and essential part of aquatic ecosystems, but the overabundance of algae can have numerous and various effects on water treatment including clogging of intake screens and filters, increased chlorine demand, increased disinfection by-products, taste and odour issues, and algal toxins. Additionally, nuisance blooms of algae in rivers can alter natural habitat, decrease oxygen levels which can cause fish mortality and have a negative impact on human recreation.

The growth of algae is primarily governed by the availability of nutrients; most notably phosphorus, but in some cases, nitrogen. Additional factors such as temperature, flow, and turbidity (which affects light availability) determine the abundance of algae in the NSR.

Algae are typically in low abundance upstream of Edmonton; however, are much higher downstream of Edmonton due to nutrient loading from stormwater and WWTP effluent (Hutchinson, 2014). While algae are notably higher downstream of Edmonton, concentrations are typically below nuisance levels. Additionally, the algae community both upstream and downstream of Edmonton is dominated by diatoms, which are indicative of clean and healthy rivers. Some species of cyanobacteria (also known as blue-green algae) can produce algal toxins.

In the NSR, cyanobacteria typically have low abundances, including downstream of Edmonton. EPCOR monitors concentrations of total microcystins at the WTPs, which are a class of algal toxins that can affect human health. Concentrations of total microcystins are typically not detectible at the WTP intakes, and when detected, they are well below drinking water quality guidelines.

3.2. Climate

Environment and Climate Change Canada (ECCC), and its predecessors, have monitored water and weather across a national network of gauges since the 1880s. Historical weather and water data are readily available from the websites of the Water Survey of Canada <https://wateroffice.ec.gc.ca/> and the Meteorological Service of Canada <http://climate.weather.gc.ca/historical_data/search_historic_data_e.html>. These monitoring networks were first installed in western Canada to locate reliable sources of water for irrigation, transportation, and crop production. Thus, the location of the gauges on local streams, and of weather stations at agricultural research stations and airports, was initially the most important consideration when establishing these networks. Fortunately, the continuity of some of these hydrometric and meteorological stations has been maintained, because long records are vital for understanding the variability and change in our hydroclimate.

ECCC's database of Adjusted and Homogenized Canadian Climate Data (AHCCD) <http://ec.gc.ca/dccha-ahccd/default.asp?lang=En&n=B1F8423> was created for use in climate research including climate change studies (Vincent et al., 2012; AHCCD, 2017). It incorporates a number of adjustments applied to the original weather station data to address shifts due to changes in instruments and in observing procedures (Vincent et al., 2012; AHCCD, 2017). Two stations within the AHCCD network, Edmonton and Calmar, are located in the EMR and will be discussed further.

3.2.1. Temperature

Figure 12 is a time series of the mean annual temperature recorded at Edmonton starting in 1880. Annual average temperatures have ranged between -1° C in cold years to 5° C in the warmer years. Not only are there large differences in temperature between years, but there are consecutive years of warmer (e.g., mid 80s to early 90s) and cooler (e.g., mid 60s to mid 70s) weather. This variability from year-to-year and decade-to-decade tends to obscure a statistically significant upward trend. Nevertheless, the EMR is getting warmer; the mean annual temperature has risen by more than 2° C. Similar results were found by Jiang et al. (2017), where they analyzed the seasonal trends in precipitation and temperature across Alberta using the Canadian Gridded Temperature and Precipitation Anomalies (CANGRD) dataset, and found a consistent regional pattern of increasing temperature over all seasons.

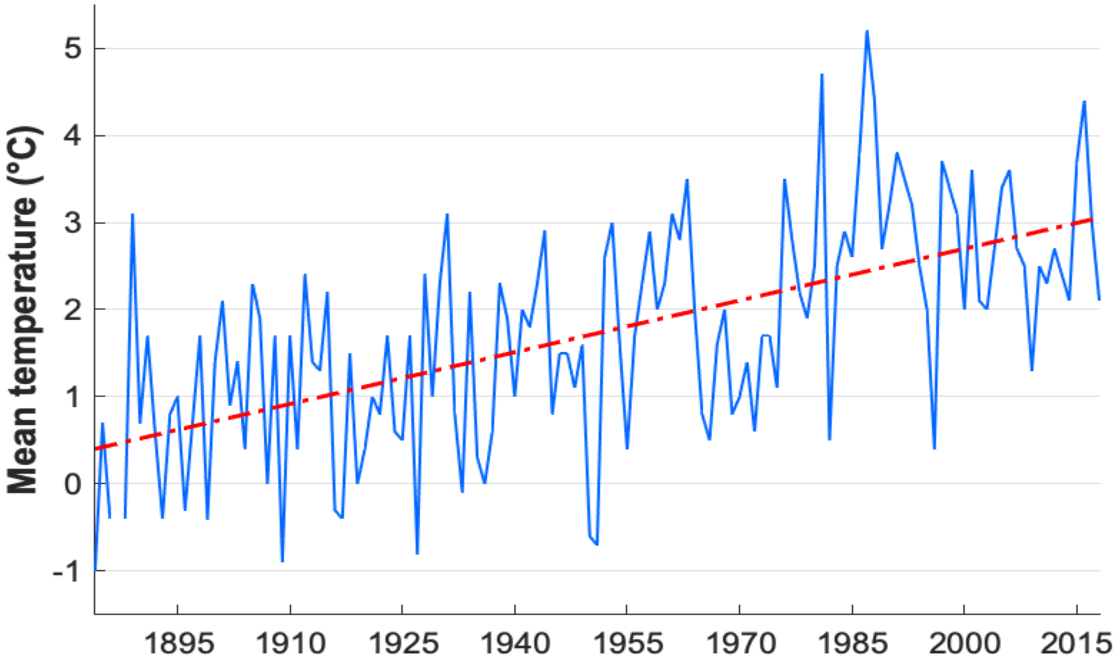


Figure 12: Mean annual temperature at Edmonton since 1884 and the linear upward trend in red.

While Figure 12 illustrates a statistically significant ($p < 0.001$) rise of 2.7° C in average annual temperature in the EMR, this temperature series averaged for the whole year hides an important fact; most of the warming is occurring in winter, and to the lowest temperatures. Thus, the EMR is not getting hotter, it is getting much less cold (e.g., similar to results of Vincent et al., (2012) for southern Canada). Figure 13 is a plot of the mean daily minimum winter (DJF) temperature at Edmonton from 1884 to 2018. The statistically significant ($p < 0.001$) increase is 6.5° C. There is large natural variability around this upward trend. The warmest winter was in 1931 during a very strong El Niño. Over the past three decades, the two coldest winters had a mean daily minimum temperature of approximately -20° C. These would have been average winters for most of the 20th century.

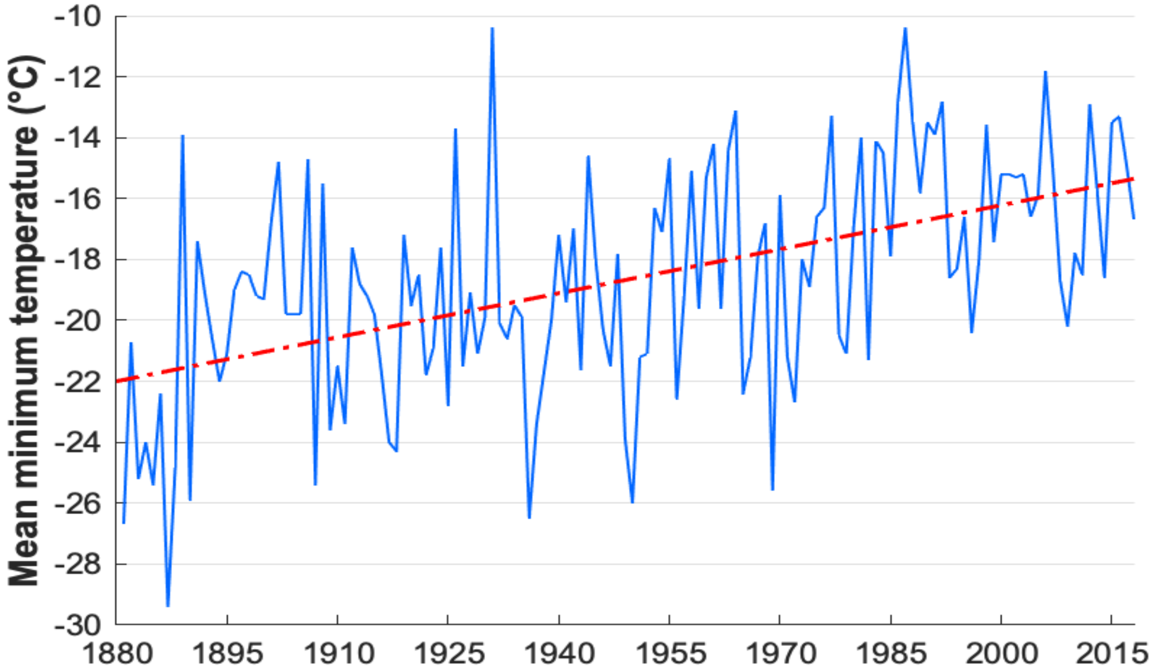


Figure 13: Mean daily minimum winter (DJF) temperature (ºC) at Edmonton, 1884-2018.

3.2.2. Precipitation

Contrary to the annual temperatures, there is no clear trend in total annual precipitation. Because there is strong decadal variability in the precipitation series, trend detection is sensitive to the timing and length of the period of record. Rainfall within the region tends to be the result of low-pressure air masses drawing air from the south towards the eastern slopes of the Rockies, where the mountainous terrain amplifies rainfall (DeBoer, 1990). The annual total precipitation for Edmonton is plotted in Figure 14. It ranges from 250 to 800 mm from dry to wet years.

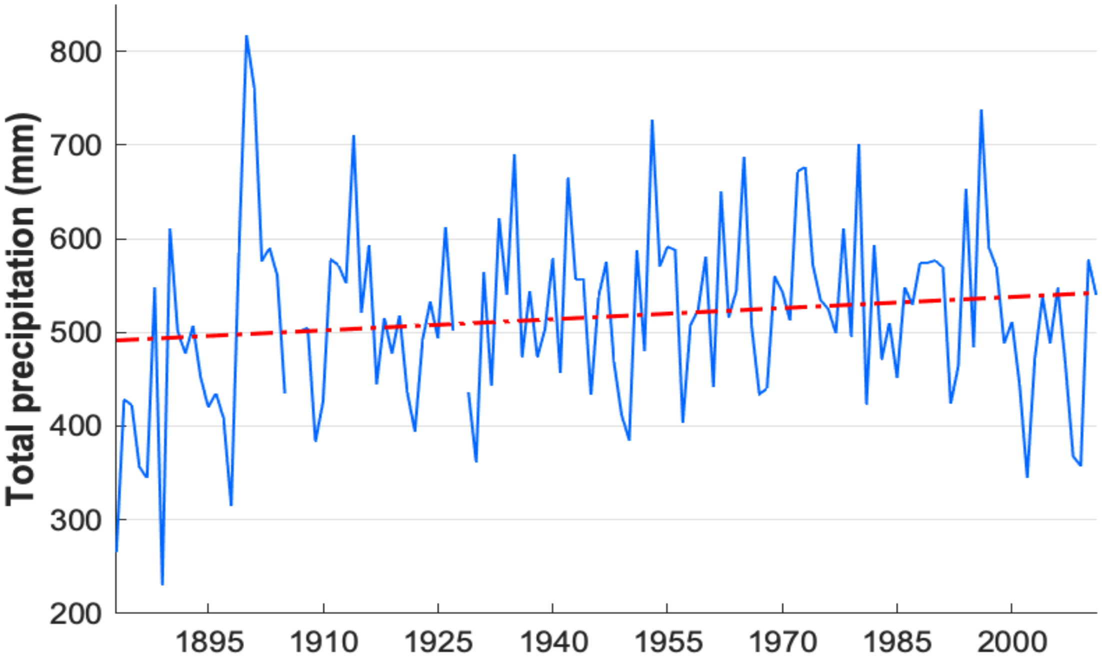


Figure 14: Total annual precipitation at Edmonton since 1884 and the linear trend in red.

The annual cycle of monthly precipitation at Edmonton is shown in Figure 15. The wettest months are June and July. The boxes show the interquartile range (25-50%) with the red line depicting the median value. The whiskers show the full range of the data with the exception of a few outliers marked with red crosses. The range of precipitation in the summer months (JJA) is wider indicating a higher variability of precipitation than in winter months (DJF). Thus, the year-to-year variability in precipitation mostly depends on how much rain falls in the summer months.

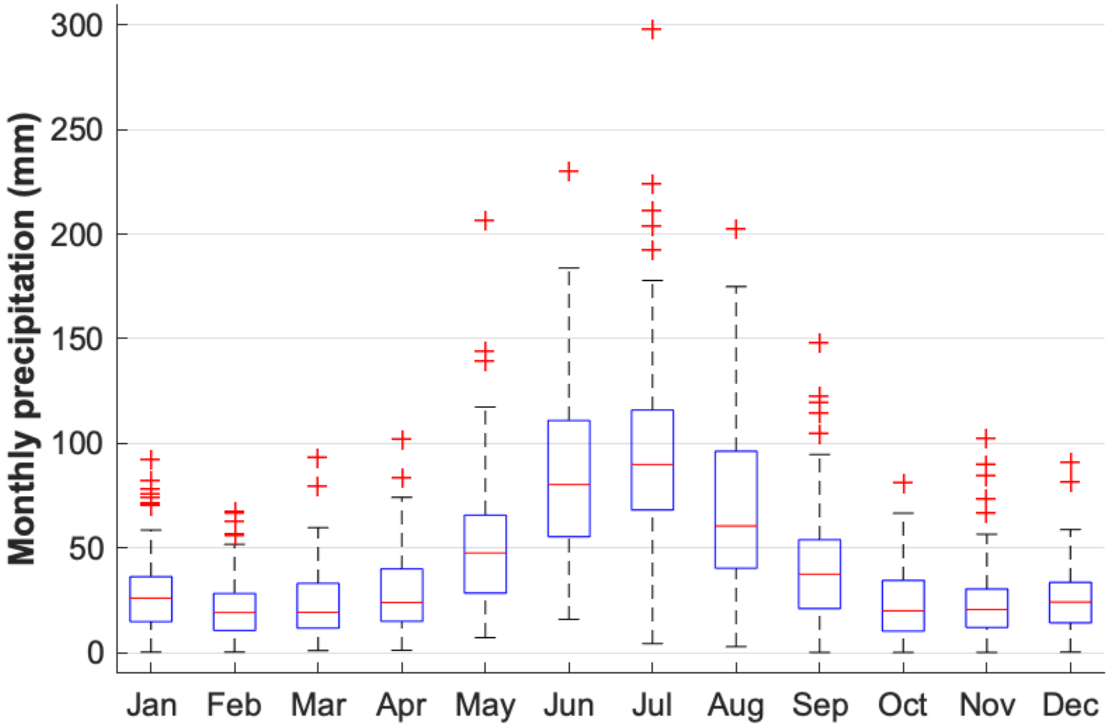


Figure 15: Annual precipitation cycle at Edmonton and the range of precipitation for each month.

Even though there is more precipitation in spring and summer, winter precipitation (mostly snow) is more effective in producing soil moisture and runoff, since much of the summer rainfall is lost by evapotranspiration. Researchers combine precipitation and temperature data, using indices such as the Standardized Precipitation Evapotranspiration Index (SPEI), to analyze episodes of water excess and deficit. Using historical weather data for the Saskatchewan River Basin (SRB), Masud et al. (2015) found a moderate risk of drought in the NSRB as compared to higher risk in the more southern part of the SRB. The higher in temperatures projected by climate models likely will increase the severity of the future drought (Jaing et al., 2014; Masud et al., 2015).

3.3. Natural Variability of the Regional Hydroclimatic

Various indices describe the atmosphere-ocean oscillations that drive much of the variability of the climate system at annual to decadal time scales. Indices that describe the dynamics of the Pacific Ocean include the PDO, the Pacific North American (PNA), and the ENSO. These natural climatic patterns, such as the PDO, can persist over multiple decades and obscure climate change effects (Fye et al., 2006; Moore et al., 2007). These cyclical hydroclimatic patterns need to be considered when planning for wet excess water and drought. The long-distance links (“teleconnections”) between these ocean-atmosphere oscillations and temperatures in Alberta are strongest in winter; for example, El Niño (La Niña) is related to an increase (decrease) in winter temperature.

The PDO is a long-term cyclical (25 to 30 years) climatic driver that shifts from cool to warm phases. Cool PDO phases are associated with cool winter and spring temperatures over western North America, and wet conditions in the Rockies and Prairies (Mantua et al., 1997; St. Jacques et al., 2010; Bonsal and Shabbar, 2011). There is a strong negative relationship between the PDO and streamflow in south and central Alberta, thus, water levels are higher when the PDO is in its negative phase and drier when the PDO is positive (St. Jacques et al., 2010). ENSO effects are better understood and follow a more predictable cycle than those of the PDO (Whitfield et al., 2010). The extreme phases of ENSO are inversely related to precipitation during the cold season: El Niño (La Niña) is associated with below (above) average precipitation in our region.

Gurrapu et al. (2016) demonstrated the strong influence of the PDO on peak river flows in western Canada, including in the NSRB. They analyzed of the annual peak flow time series from eight gauges in the NSRB, including the record at Edmonton. They found two distinct flood frequency curves for the years of negative (1912-1924, 1947-1976, 2009-2013) and positive (1925-1946, 1977-2008) PDO. The curves diverge at higher return periods, indicating that flood flows are much more likely during the negative (cool) phase of the PDO, which is associated with wetter conditions in southern and central Alberta.

4. The Paleohydrology of the NSRB

Dendrohydrology

Changes in the distribution of water resources on a seasonal and annual basis, as well as between watersheds, will be a potential risk from climate change in the Canadian Prairies (Sauchyn and Kulshreshtha, 2008; Sauchyn et al., 2012; Sauchyn et al., Forthcoming). The most challenging future scenario is a shift in the frequency and severity of climate extremes and departures from average conditions (e.g., excessive moisture and drought).

Understanding the long-term natural variability of the regional hydroclimate is an important precursor to research on the impacts of climate change. Natural proxy records of hydroclimatic behaviour, such as tree-ring chronologies, provide a depth of knowledge of past climate-driven non-stationarities in hydrologic variables at fine temporal and spatial resolutions. Tree-ring data from long-lived trees growing at dry sites are a proxy of seasonal and annual water levels. The growth of these trees is limited by the availability of soil moisture and thus the same weather variables (precipitation, temperature, evapotranspiration) that determine river flow also control tree growth, and there is a similar integrating and lagged response of tree growth and streamflow to inputs of precipitation (Sauchyn and Ilich, 2017).

Tree-rings have been used to estimate streamflow in most of the river basins in Canada's western interior, including the NSRB (Case and MacDonald, 2003; Sauchyn et al., 2011, 2015; Sauchyn and Ilich, 2017). While the hydrometric gauge data for the NSR at Edmonton spans over 100 years, paleoclimatic reconstructions extend the record natural hydroclimatic variability by more than 800 years. The main findings from this paleohydrology research include (Sauchyn et al. 2011; 2015a; Sauchyn and Ilich, 2017):

- The NSR was settled during one of the wettest periods on record;
- The full range of the natural variability of the flow of the NSR is not captured within the gauge record; and
- Droughts similar to the 1930s are not uncommon and have been longer and more intense (i.e., reduced moisture within consecutive years).

Figure 16 is the reconstructed naturalized water-year flow for the NSR (1110-2010), plotted as departures from the mean water-year flow. This format highlights (in red) historical low flows (e.g., 1930s, 1980s, 2000s), as well as periods of low flow that exceed the historical worst-case scenario in terms of severity and duration (e.g., 14th century). The paleohydrology is characterized by decadal-scale cycles and periodic shifts in variance (Sauchyn et al., 2011; Fleming and Sauchyn, 2012). Dominant high-frequency (2-7 year) and lower-frequency (~60 year) modes of variability are associated with periodic fluctuations in Pacific Ocean SSTs (e.g., ENSO and PDO) (Sauchyn et al., 2011, 2012, 2015a; Sauchyn and Ilich, 2017).

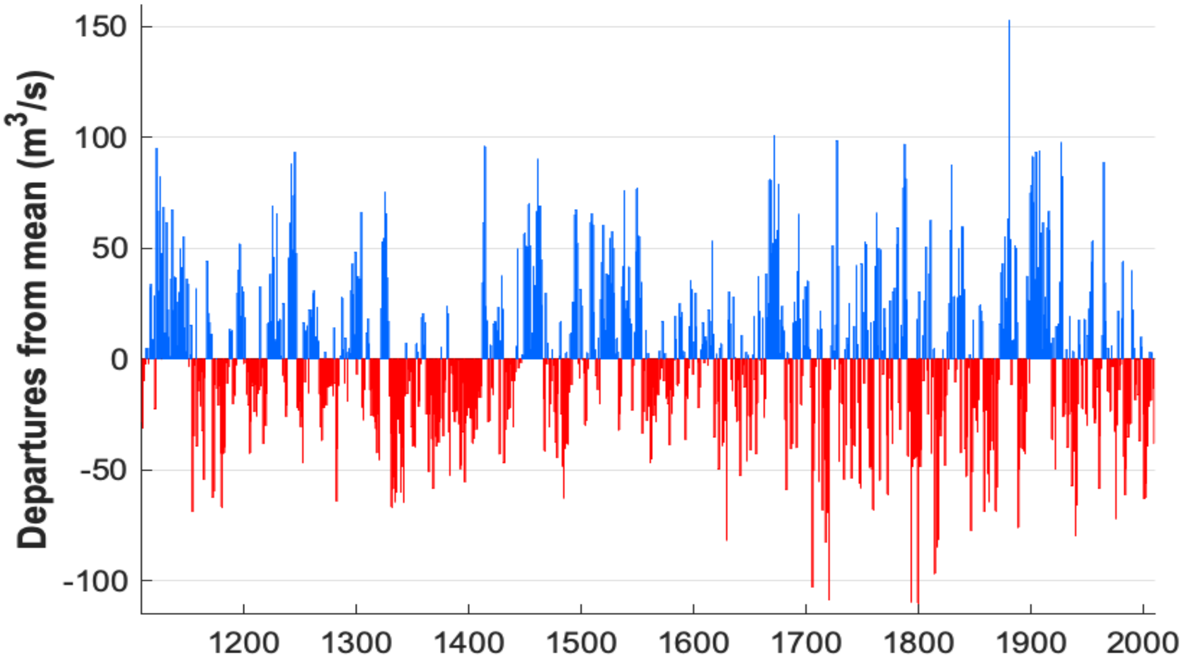


Figure 16: North Saskatchewan River (NSR) reconstructed water-year flow, 1110-2010, plotted as positive (blue) and negative (red) departures from the mean (Sauchyn and Ilich, 2017).

Previous reconstructions of the annual flow of the NSR (Sauchyn et al. 2011; Sauchyn et al., 2015a) provided critical information about past hydroclimatic variability, however, most users of water on the NSR are largely dependent upon the instantaneous flows (EPCOR, 2017b). Recently, Sauchyn and Ilich (2017) and Kerr and Sauchyn (2018), respectively, developed time series of weekly flow estimates for the NSR for the past 900 years at Edmonton and the past 600 years at the Alberta – Saskatchewan boundary. The downscaling the tree-ring reconstructions to weekly flow data was achieved by combining the methods and advantages of stochastic hydrology and paleohydrology (Sauchyn and Ilich, 2017). These long high-resolution records provide water management agencies with reconstructions of river flow for the assessment of water conveyance, storage, and treatment infrastructure and protocols under extreme hydroclimatic conditions.

4.1.1. Paleolimnology

Lakes within the NSRB hold significant value as habitat for aquatic life, as well as water sources for municipalities, industry, and agriculture. The physical and chemical properties, and fossil remains of biota in lake sediments can be used to infer the past hydrologic conditions of lakes and the relative importance of natural versus anthropogenic-driven changes. Paleolimnology provides important context for the interpretation of recent hydrological changes, although at coarser resolution than that enabled by tree-rings. Hutchinson Environmental (2014) examined the paleolimnology of Pigeon and Wabamun Lakes preserved in the sediments stored in these two lakes. The sediment cores spanned 120 and 270 years, respectively, producing a time series that captured the period of major land disturbances from agriculture in the 1900s, residential development in the 1950s, and the time before the arrival of non-native settlers (Hutchinson Environmental, 2014). Comparing the paleolimnology data to land use histories, water quality records and weather data records suggested that recent physical and chemical changes in the lake resulted from declining lake levels and climate change. Although climatic warming during the 20th century is thought to enhance algal production (Paerl and Huisman 2008), most paleolimnological research to date suggests that agriculture and urbanization have had much more of an effect on prairie water quality than has the impact of climate change (Hall et al. 1999, Leavitt et al. 2009, Bunting et al. 2011).

5. The Future Climate of the NSRB

The strongest indication of recent global climate change is an increase in the average air temperature of the entire world. At a global scale, a relatively cool year in one region is offset by above average temperature in another place, and thus the signal of global warming emerges from the background of natural variability. Figure 17 is a graph of monthly global air temperature anomalies (differences from average) since 1880. Since the late 1970s, every year has been warmer than the 20th century average, although some years are cooler or warmer than a linear trend because of natural variability and the many factors besides humans that influence the climate.

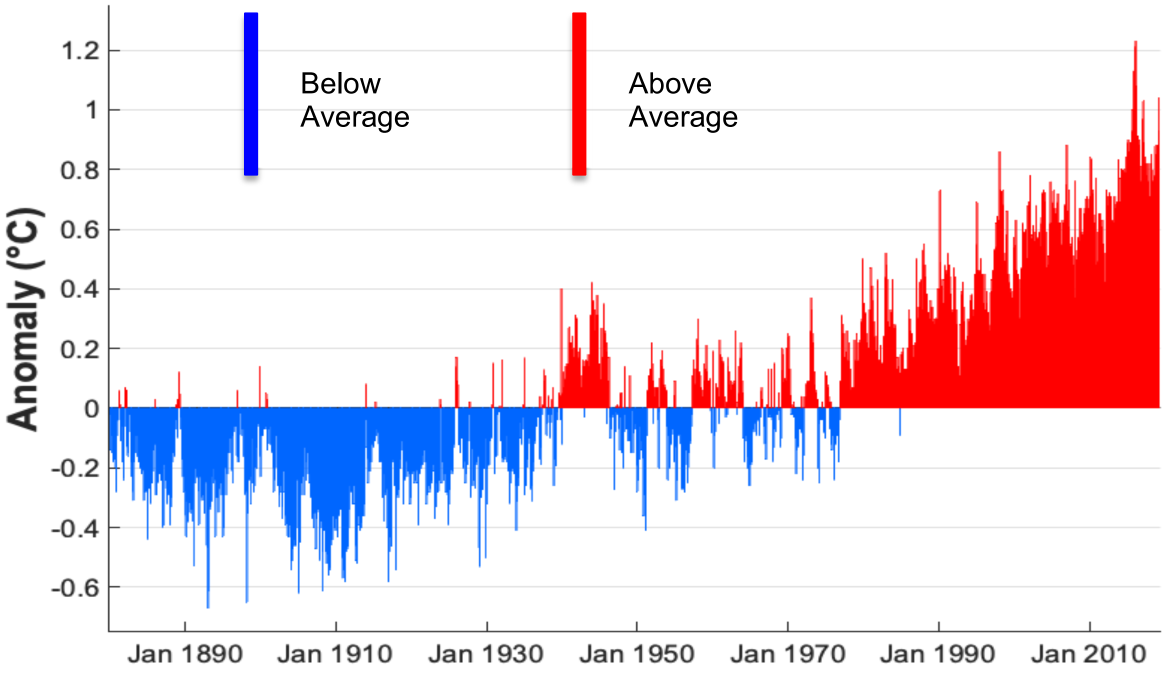


Figure 17: Global monthly air temperature anomalies (differences from average), 1880-2018 (NOAA, 2018).

Various studies within the Canadian Prairies have validated climate changes projected by global and regional climate models (GCMs and RCMs) by comparing model output to recorded temperature, precipitation, streamflow regimes, evapotranspiration, and drought (Lapp et al., 2012; MacDonald et al., 2012; PaiMazumder et al., 2012; Barrow and Sauchyn, 2017; Bonsal et al., 2017; Jiang et al., 2017; St. Jacques et al., 2018; Vaghefi et al., 2019). Uncertainties are assessed by examining the consistency among different climate models and ensemble of runs of single models (Mailhot et al., 2012). In the Prairie Provinces, the natural variability of the regional hydroclimate is the source of the largest amount of uncertainty in the projection of future temperature and especially precipitation (Barrow and Sauchyn, 2019). The two other sources of uncertainty, the climate models and emission scenarios, become more important into the future, but at the end of the 20th century, natural variability still accounts for most of the difference among projections of future precipitation.

Analysis of the differences in precipitation and temperature between current and future periods indicate warming in all seasons, but especially winter, and a decrease in summer precipitation, but increases in other seasons (PaiMazumder et al., 2012). The severity, frequency and maximum duration of both short- and long- term droughts are also projected to increase compared to those within the 20th century (PaiMazumder et al., 2012; Kuo et al., 2015; Bonsal et al., 2017). These increases in drought frequency will affect surface and groundwater resources, suggesting an uncertain future in terms of drought and excess moisture risk, involving an increase in the frequency and severity of drought with a higher degree of inter-annual variability (Bonsal et al., 2017).

5.1. Regional Climate Model Simulations

Previous research on the future climate of the NSRB has been based on output from GCMs of relatively course scale (100s of kms). In some cases, such as the State of Knowledge Summary report for the All One Sky Foundation (AOS, 2018), the GCMs were statistically downscaled, based on the statistical relationship between model and observed weather data. For the purpose of this report we have generated future projections of the climate of the EMR using output from high-resolution (10 to 25 km resolution) Regional Climate Models (RCMs).

Possible climatic changes in average temperature and precipitation for the EMR for near (2021-2050) and far (2051-2080) future compared to the baseline (1981-2010) were computed using an ensemble of 10 RCMs from the North American domain of the Coordinated Regional Climate Downscaling Experiment (NA-CORDEX). All RCMs were forced with RCP 8.5, a high emissions pathway. For each model, monthly data for 1981-2080 were extracted for the North America and converted into °C and mm/month for temperature and precipitation respectively. Seasonal and annual mean temperature and total precipitation for the EMR were obtained by averaging values for grid points within the boundary of the region. Changes in 30-year average temperature and precipitation for near and far future compared to baseline were calculated for each RCM and multi-model mean changes are presented in Table 1. The mean temperature and total precipitation are expected to increase on seasonal and annual scales, with the greatest changes during the cool period (fall, winter). The summer season is expected to increase by 3.5 °C with almost no change in the amount of total precipitation. Annual and seasonal variability (i.e., variations in the mean state of the climate) are also projected to increase for both climatic parameters.

Table 1: Multi-model mean changes in temperature and precipitation for near (2021-2050) and far (2051-2080) future compared to baseline (1981-2010).

Period	Climatic Variable	2021-2050	2051-2080
Annual	Mean temperature (°C)	1.9	3.7
	Maximum temperature (°C)	1.7	3.4
	Minimum temperature (°C)	2.1	4.0
	Total precipitation (mm)	32.5	54.2
	Total precipitation (%)	6.9	11.5
Spring (MAM)	Mean temperature (°C)	1.8	3.0
	Maximum temperature (°C)	1.6	2.7
	Minimum temperature (°C)	2.1	3.3
	Total precipitation (mm)	9.5	26.9
	Total precipitation (%)	10.5	29.4
Summer (JJA)	Mean temperature (°C)	2.3	3.5
	Maximum temperature (°C)	2.4	3.6

	Minimum temperature (°C)	2.1	3.6
	Total precipitation (mm)	9.0	7.4
	Total precipitation (%)	3.9	3.3
Fall (SON)	Mean temperature (°C)	1.3	3.7
	Maximum temperature (°C)	1.1	3.5
	Minimum temperature (°C)	1.7	3.8
	Total precipitation (mm)	17.2	25.0
	Total precipitation (%)	21.2	30.9
Winter (DJF)	Mean temperature (°C)	2.2	4.9
	Maximum temperature (°C)	1.9	4.1
	Minimum temperature (°C)	2.5	5.5
	Total precipitation (mm)	8.8	15.3
	Total precipitation (%)	13.9	24.0

Raw climate model simulations of extreme cold and hot days, and maximum daily precipitation for Edmonton are presented below. Since these are model simulations, the sequence of annual weather events is arbitrary. Another run of a RCM would produce events in a different order, although statistically (the variability and trend) would be very similar.

Figure 18 represents the number of extreme cold days (-35 to -25 ˚C) at Edmonton from 1950-2100, as simulated by the Canadian RCM version 4. This figure illustrates how the EMR is becoming much less cold in winter. As a result, snow will melt in winter leaving less snowpack at the time of spring melt. Also, in warming winter precipitation will occur as rain.

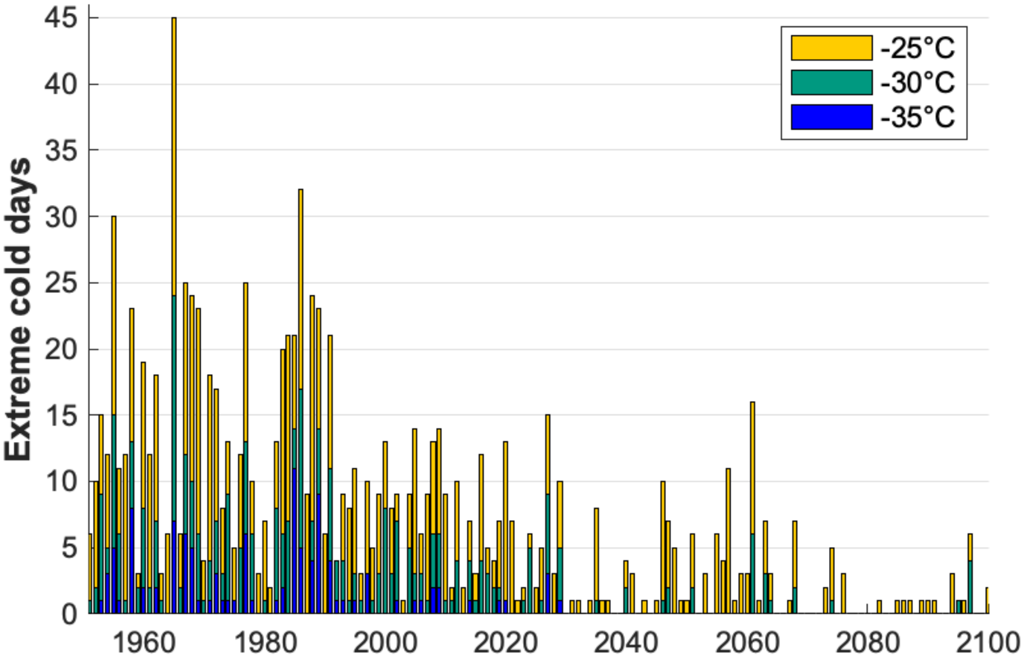


Figure 18: Number of extreme cold days at Edmonton, 1950 to 2100, as simulated by the CRCM4_cesm2 and the RCP 8.5.

Figure 19 shows the number of extreme hot days (30 to 40 ˚C) at Edmonton from 1950-2100 as simulated by the model RCA4 and the RCP 8.5. As the number of days with temperatures above 30 ˚C increases, more water will be returned to the atmosphere by evapotranspiration, leaving less water in the soil, rivers and lakes. Higher temperatures also raise demand for water used for cooling and irrigation purposes.

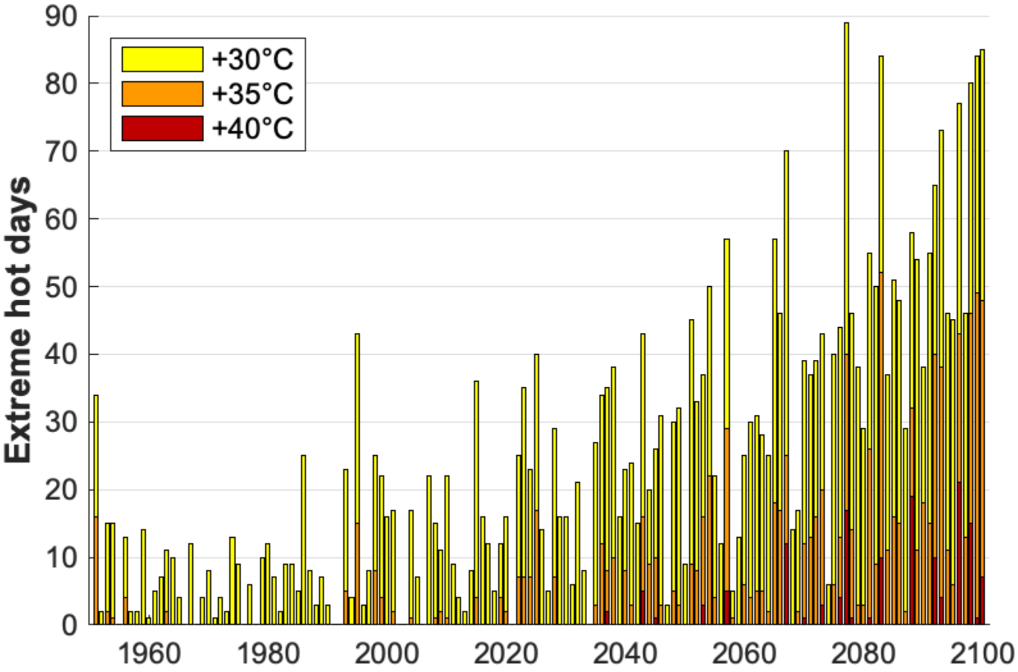


Figure 19: Number of extreme hot days at Edmonton, 1950 to 2100, as simulated by the RCA4_cesm2 and the RCP 8.5.

Figure 20 is a plot of the projected maximum daily precipitation changes at Edmonton from 1950 to 2100 as simulated by the CRCM5_cesm2 and the RCP 8.5. Figure 20 shows the potential for heavy precipitation in a warming climate. Although there is no trend present, one future day of rain far exceeds prior extreme events. There is inter-annual and decadal variability; years with heavy precipitation events tend to cluster in wet decades and with dry decades in between.

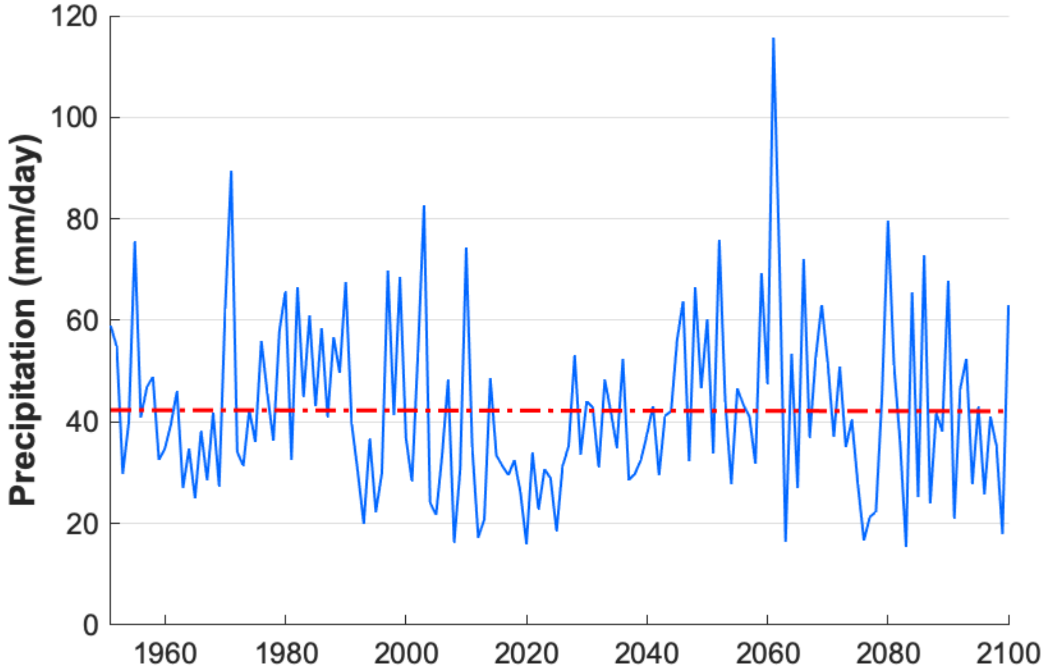


Figure 20: Maximum daily precipitation at Edmonton, 1950 to 2100, as simulated by the CRCM5_cesm2 and the RCP 8.5.

6. The Potential Impacts of Projected Climate Changes on the NSR

Water allocation, and the design of storage and conveyance structures, is based primarily on average seasonal water levels, but otherwise water resources are managed to prevent the adverse impacts of flooding and drought. While drought and flooding are difficult to predict, their probability is strongly linked to periodic fluctuations in sea surface temperatures, known as the PDO and ENSO (See Box 2.6 in Bonsal et al., 2019). Uncertainty in the projection of future precipitation amounts and extremes depends less on the use of different models and greenhouse gas emission scenarios and more on the ability of the models to simulate internal variability of the regional climate, such as changes in the teleconnections between the ocean-atmosphere oscillations (e.g., the ENSO and PDO) and the regional hydroclimate (Barrow and Sauchyn, 2019).

Recent extreme weather events in the Prairie Provinces have been some of the most costly natural disasters in Canadian history. This includes record dry months and historically high water levels. The impacts of excesses and deficits of water differ with respect to the timing, duration, intensity, and extent of flood and drought events. Meteorological drought (a lack of rain) can immediately affect dryland farming, while hydrological drought (low water levels) impacts irrigation, municipal and industrial water supplies. The impacts of a short intense drought, for example a month without rain, are much different than the cumulative effects of a long period of low water levels. Flooding of the rivers flowing from Rocky Mountains are damaging because population is concentrated along rivers. Inundation of agricultural land is common given the large area of depression storage (sloughs and wetlands).

Flooding and drought are excesses and deficits of water relative to a baseline of normal water levels. But the baseline is shifting. Flooding and drought events, and the natural cycles of wet and dry, are now occurring in a warming and more humid climate. A warmer global climate amplifies regional hydrologic extremes. This expanding range of hydroclimate around a shifting baseline of normal conditions is evident in climate model projections of total and extreme precipitation (e.g., see Figure 19).

Studies of the drought of the early 2000s (Fang and Pomeroy, 2008) and 2015 (Szeto et al., 2016), and floods in 2013 in southwestern Alberta (Teufel et al., 2017; Pomeroy et al., 2015), concluded that these naturally occurring events were intensified by human-caused climate change. The analysis of rainfall data generated by climate models indicates that a warming climate will cause a significant shift in the intensity, duration and frequency of rainfall events from historical values. Heavy rainfall events both generate flooding and terminate dry spells (Brimelow et al., 2014). Prairie storms can be difficult to forecast more than a few days in advance and thus the termination of drought is difficult to anticipate. Heavy rain in June 2002 occurred across the southernmost prairies (Szeto et al., 2011), while drought persisted farther north through 2002 including much of central and northern Alberta.

One of the most robust climate projections, globally (IPCC, 2014), nationally (Bonsal et al., 2019) and regionally (Gizaw and Gan, 2015) is an increase in rainfall intensity. This will have important consequences for managing urban stormwater runoff. In rural areas, land and infrastructure could be periodically inundated by excess precipitation, including in winter when in the future precipitation is increasingly likely to fall as rain. This excess water will occur as the warmer climate converges with the wet phase of the PDO and ENSO. Similarly, the dry phase also will be amplified, when there is an absence of rain but also higher temperatures than in the past (Tam et al., 2018). Climate model projections of temperature, precipitation and water balance indices suggest increasing exposure of the Prairies to drought, especially in summer and fall (Bonsal et al., 2019). The worst-case future scenario for the Prairie Provinces is the reoccurrence of consecutive years of severe drought, such as occurred in the 1930s and in preceding centuries (Sauchyn et al., 2015). The warmer climate will amplify the impacts of a future prolonged drought. The impact of forest fires within the NSRB could also affect flows in the NSR, as the loss of vegetation can result in less water being retained by the soil, and higher flows downstream, ultimately impacting the amount and timing of flows.

6.1. Anticipated Changes in Streamflow

While the 100-year gauge record, and the 900-year reconstructed flow record provide important information regarding the reliability and timing of flows in the NSR, they assume stationarity – that the historical record captures the range of variability that will be observed in the future (EPCOR, 2017a). Climate change however, will result in increased temperatures, variable precipitation patterns, and increased severity of the timing and frequency of extreme events, throughout the NSRB. Thus, the historical flow record may not predict future flows within the NSR (EPCOR, 2017a).

Golder (2008a) modelled flows within the NSR at Edmonton using a range of modelled temperature and precipitation increases. Their results found that five of the six models predicted a 5 to 15% increase in annual flows (but a decrease during the summer and fall months due to decreased precipitation and increased evaporation due to warmer temperatures), and one model predicting a decrease of 11%. Increases in flow in the NSR are predicted for the winter and spring months due to the predicted increase in precipitation falling as rain as opposed to snow, and earlier spring runoff due to warmer temperatures.

Kienzle et al., (2012) got similar results for modelled flows of the Cline River sub-basin in the headwaters of the NSR. They simulated the impacts of climate change in the Cline River watershed), under historical (1961–1990) and a range of future climate conditions (2010–2039, 2040–2069, and 2070–2099). Projected annual flows found to increase by approximately 1 % in the 2020s, 5 % in the 2050s, and 11.5 % in the 2080s (Kienzle et al., 2012). Projected increases in air temperature and precipitation resulted in mean annual increases in potential and actual evapotranspiration, groundwater recharge, soil moisture, and streamflow in the Cline River watershed. Increases in both high and low flow magnitudes and frequencies, and large increases to winter and spring streamflow are predicted for all climate scenarios. A clear shift in the future hydrological regime is predicted, with significantly higher streamflow between October and June, and lower streamflow in July–September. Results from this research also predicted that spring runoff would occur up to 4 weeks earlier in the 2080s (Kienzle et al., 2012). Similarly, St. Jacques et al., (2018) found that projected total runoff could shift to an earlier spring peak in runoff and drier late summer. They also noted that declining glacier melt contributions to streamflow will take place at approximately the same time as streamflow is predicted to decline due to climate warming.

These projected changes will also impact groundwater resources within the NSRB. Kienzle et al. (2012) modelled that annual soil moisture and groundwater recharge will increase in the Cline River watershed; however, both are expected to increase during the winter and spring, and decline during the summer and fall. However, more research regarding how future climate changes in precipitation and temperature variables will impact these resources and groundwater impacts on flows within the NSR is required (EPCOR, 2017b).

6.2. Projections of NSR flows from RCMs

Results from both Golder (2008a) and Kienzle et al., (2012) show trends for increased flow during winter and spring, earlier spring melts and decreased flows during the summer and fall. These shifts in the seasonal distribution of river flow are in response to projections climate changes: a warmer wetter winter and a warmer and possibility drier summer. Summer flows are also impacted by the reductions in the extent of glacier ice and summer snowpack at high elevations in the headwaters. These previous studies completed 8-10 years ago were based on the use of data from GCMs to as inputs to hydrological models. Whereas these studies were able to projects changes in average seasonal flows, the methodologies did not enable the predictions of changes in the variability over time. Therefore, for the purpose of this report we include preliminary results from research at PARC sponsored by EPCOR Water Canada.

Figure 21 is a time series of the recorded (1981-2010) and simulated (2010-2100) annual flow of the NSR at Edmonton. The simulated flows were generated using the MESH hydrological model and future weather data from the Canadian RCM4 for two greenhouse gas concentration scenarios (RCPs 4.5 and 8.5). Figure 21 indicates that the future flow of the NSR will include the annual and decadal variability that is evident in our 900-year tree-ring reconstruction of the river flow. However, the range of annual flows will exceed those observed in the recent past. This very likely represents the amplification of the hydrological cycle in a warmer climate. Low flows, in particular, frequently reach or exceed those in the gauge record, even though a warming climate will be characterised by more precipitation.

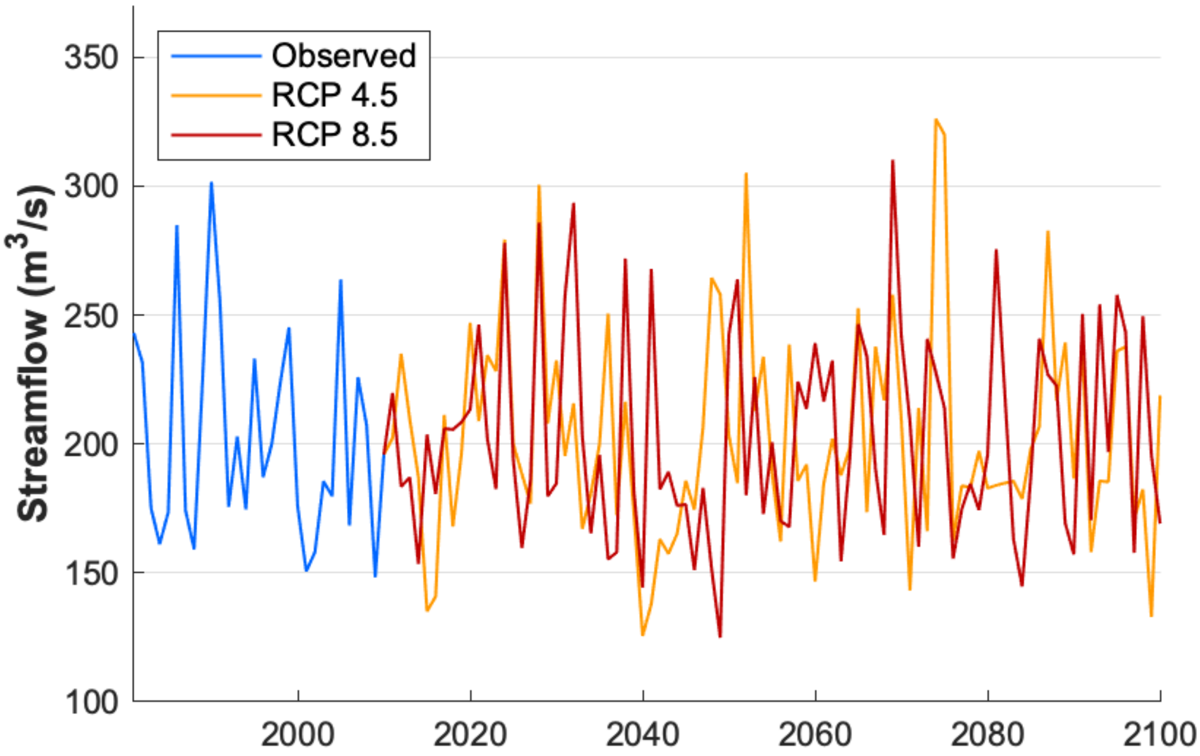


Figure 21: A time series of observed (1981-2010) and simulated (2010-2100) annual flow of the North Saskatchewan River (NSR) at Edmonton (Source: Muhammed Rehan Anis, PARC Post-Doc).

A complementary approach to projecting future streamflows in the NSRB involves extracting runoff data directly from the RCMs, because they include land surface schemes that simulate the hydrological response to the climate changes simulated by the RCM (St. Jacques et el., 2018). Whereas runoff is the depth of water passing through the watershed, it is directly related to streamflow since most of the runoff eventually passes into the stream channel. Table 2 gives the potential changes in total runoff for the NSR at Edmonton. These changes are the difference in the average runoff projected by 7 RCMS for near (2021-2050) and far (2051-2080) future compared to a baseline of 1981-2010. Multi-model mean changes are summarized in Table 2. The results suggest that total annual runoff could potentially increase on average by 8%. The highest increase is expected during winter months (39%) and summer runoff is projected to decrease by approximately 10%. Also, RCMs are projecting increased variability of annual and seasonal runoff. The shifts in variability are significant findings that can be derived only by using multiple model simulations of high resolution. These projected changes in runoff, both trends and variability, are illustrated in Figures 22 through 26 of the bias-corrected projected changes in total annual and seasonal runoff from one model. Because the plots show both the near (2021-2050) and far (2051-2080) future spanning 60 years, the historical period has been expanded beyond the 30-year baseline (1981-2010) to span 60 years (1951-2010) of observed and simulated historical runoff.

Table 2: Multi-model mean changes in total runoff for near (2021-2050) and far (2051-2080) future compared to baseline (1981-2010).

Period	Climatic Variable	2021-2050	2051-2080
Annual	Total runoff (mm)	1.7	19.0
	Total runoff (%)	0.7	8.1
Spring (MAM)	Total runoff (mm)	5.9	12.1
	Total runoff (%)	12.7	26.0
Summer (JJA)	Total runoff (mm)	-12.6	-13.3
	Total runoff (%)	-9.4	-9.9
Fall (SON)	Total runoff (mm)	2.3	5.8
	Total runoff (%)	5.3	13.5
Winter (DJF)	Total runoff (mm)	1.6	4.8
	Total runoff (%)	12.6	39.2

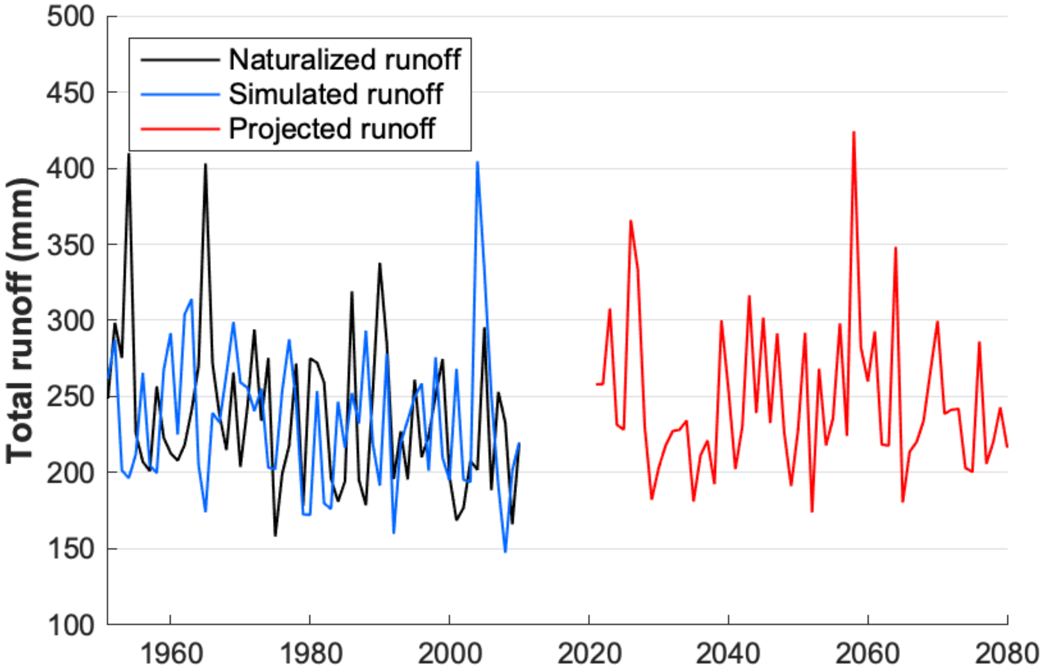


Figure 22: Total annual runoff in the NSRB above Edmonton for 1951-2010 and 2021-2080.

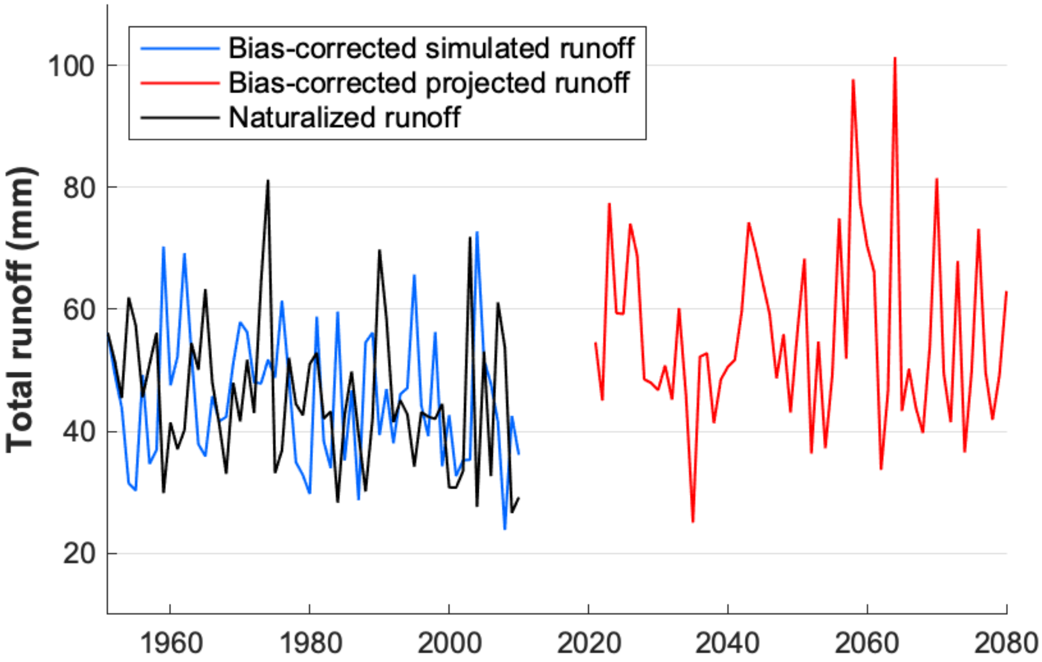


Figure 23: Total spring (MAM) runoff in the NSRB above Edmonton for 1951-2010 and 2021-2080.

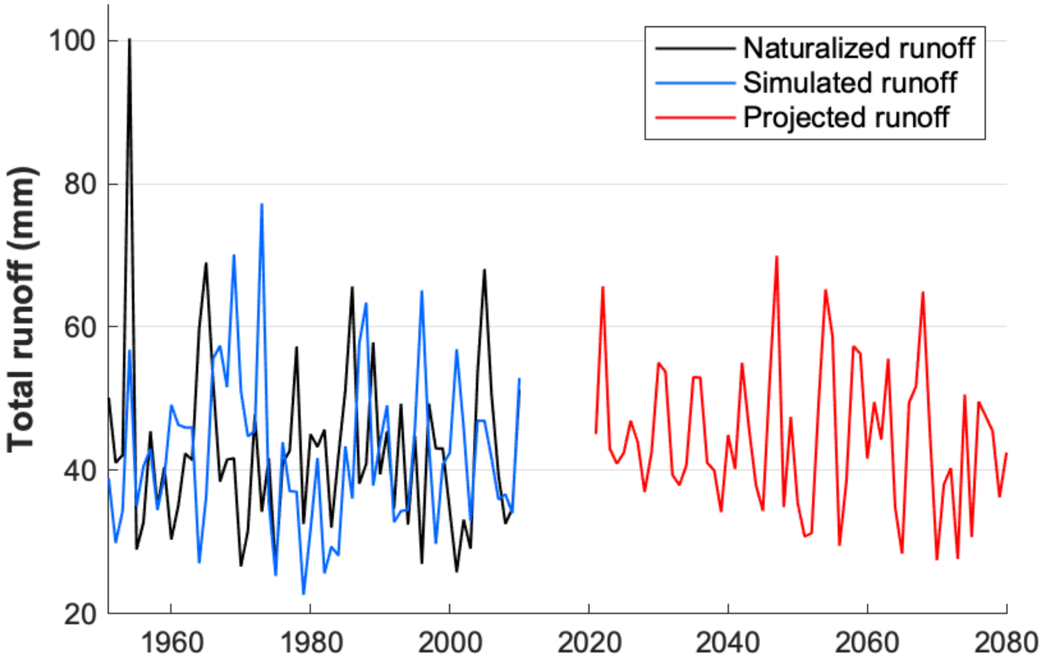


Figure 24: Total summer (JJA) runoff in the NSRB above Edmonton for 1951-2010 and 2021-2080.

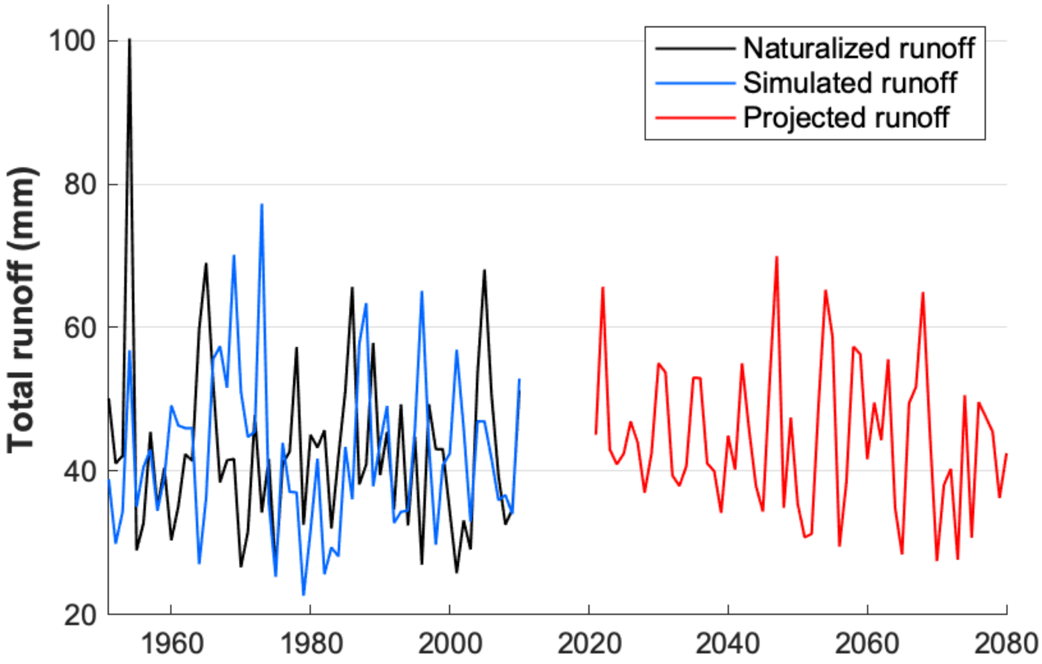


Figure 25: Total fall (SON) runoff in the NSRB above Edmonton for 1951-2010 and 2021-2080.

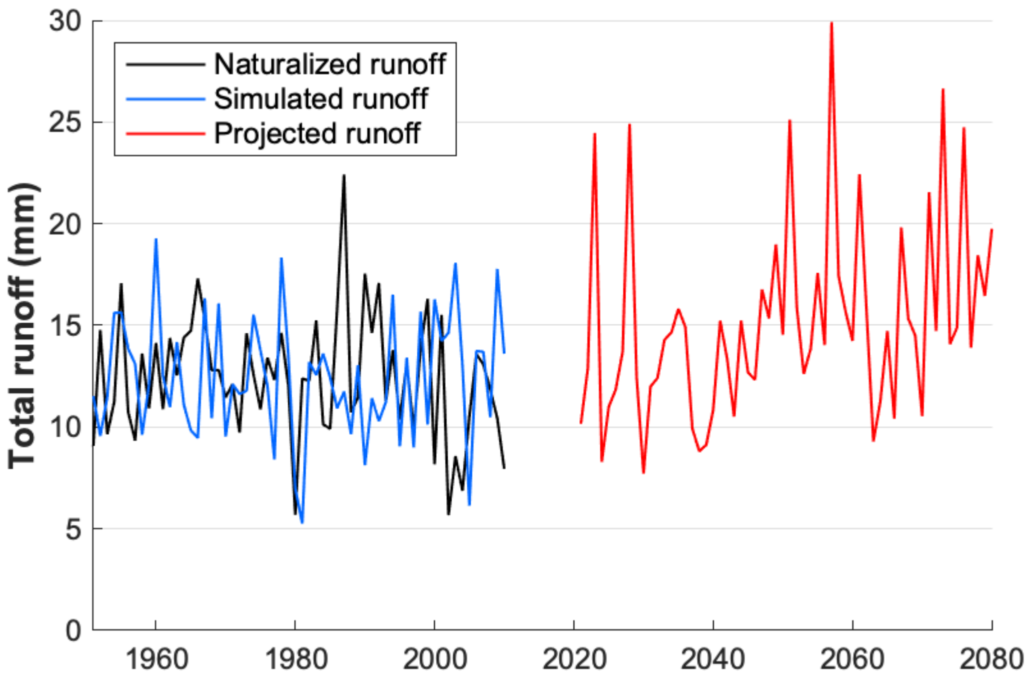


Figure 26. Total winter (DJF) runoff in the NSRB above Edmonton for 1951-2010 and 2021-2080.

6.3. Potential Impacts of Climate Change on Water Quality

The following summary of potential impacts of climate change on water quality in the North Saskatchewan River is mainly from a literature review provided by EPCOR Water Canada (2017b), however, some text has been modified, and additional recent references have been included. While it is not understood precisely how water quality in the NSR will respond to climate change, it is well understood that water quality is directly related to both runoff from the landscape and instream flows, both of which will be affected by climate change. Increased concentrations of turbidity, colour, nutrients and algae are anticipated through various mechanisms including: increased precipitation, more variable flows in the NSR, floods, droughts, forest fires and warmer water temperatures. These changes are summarized in Table 3, and discussed in greater detail below.

Table 3. Summary of climate change's projected impacts to water quality in the NSR

Climate event	Resulting Impact in Water Quality
Increased precipitation and higher intensity events	Increased erosion resulting in increased turbidity, colour and nutrients
Higher flows in the NSR	Increased resuspension of material, increased turbidity
Lower flows in the NSR	Initially reduced turbidity, but large reductions of flows could increase nutrients and other parameters

Droughts	Initially reduced turbidity and colour, but large increases when precipitation returns
Forest fires	Initial large pulse and extended increase of colour, turbidity and nutrients
Warmer water temperatures	Increased growth rates of algae, decreased dissolved oxygen, increased availability of nutrients

Increased total precipitation, as well as the increased frequency and intensity of heavy rainfall events, is expected to increase the concentration of many water quality parameters. Nearing et al. (2004) predicted that for every 1% increase in precipitation, erosion would increase by 1.7%. If this relationship holds for the NSRB, a predicted increase in precipitation of up to 19% (Golder 2008a) could result in a 32% increase in erosion. Increased erosion rates would increase turbidity, colour and nutrients in the NSR. Higher flushing rates and increased erosion from increased precipitation is expected to result in increased colour (Ritson et al. 2014). Similarly, climate change induced precipitation changes will result in substantial increases of total nitrogen loading (Sinha et al. 2017).

Higher flows in the NSR will increase the bank erosion and the resuspension of bed sediment. Turbidity in the NSR is directly related to the resuspension of material with rising flows. Higher turbidity is expected during the winter and spring seasons, when projected mean annual flows are higher than in the past. Large flood events will produce with very high turbidity levels.

Warmer and drier conditions, and decreased flows in the NSR, are predicted for the late summer and fall. Lower runoff and decreased flows in the NSR will generally result in lower turbidity in the water entering Edmonton. However, with less volume of water in the NSR, the capacity of the NSR to dilute stormwater and WWTP effluent will be reduced, potentially increasing the concentrations of parameters such as nutrients. Higher evaporation and reduced flows will also concentrate nutrients and other parameters in the NSR. Elevated concentrations of nutrients, lower turbidity, lower flows and increased water temperatures are optimal conditions for algal growth potentially favoring the formation of blooms and increased cyanobacteria. Conversely, higher turbidity and colour with higher flows will inhibit the growth of algae.

Droughts are expected to initially decrease colour, but will often generate a large “flush” once rainfall occurs, with colour remaining elevated for a considerable time (Ritson et al. 2014, Mosley 2015). For example, in the absence of a large spring runoff or large precipitation events early in 2016, turbidity and colour were atypically low. A large precipitation event in August 2016 resulted in the highest colour values recorded by the WTPs and colour remained elevated for a prolonged period, very similar to what is predicted by Ritson et al. (2014).

Warmer and drier conditions in Alberta are anticipated to increase the frequency and severity of forest fires (Stralberg et al. 2018), with corresponding declines in water quality (Robinne et al. 2017). A study conducted in the headwaters of watersheds in the Rocky Mountains in southern Alberta found that large forest fires resulted in a doubling of dissolved organic carbon *(*DOC) in the first two years post-fire, elevated DOC concentrations four years post-fire, and a predicted continuation of elevated DOC for several years (possibly decades) post-fire (Emelko et al. 2011). The same fire study also demonstrated that turbidity levels were three times higher than unburned watersheds, even four years post-fire (Emelko et al. 2011) and that phosphorus remained elevated for over seven years (Emelko et al. 2015). A recent study by Robinne et al. (2017) calculated the global risk of forest fires to cause significant declines in drinking water quality and found that the watersheds with headwaters in the Rocky Mountains had some of the highest risks globally.

Warmer temperatures themselves are also expected to result in changes in water quality. Longer growing seasons and increased decomposition of organic material in soils is anticipated to result in increased export of colour (Ritson et al. 2014) and increases have been observed in some locations in North America and Europe (Monteith et al. 2007). Climate models for the headwaters of the NSR indicated that spring melt could occur up to four weeks earlier by the year 2080 (Kienzle et al. 2012). Warmer temperatures will also result in longer ice-free seasons, earlier spring runoff events, and more precipitation falling as rain as opposed to snow resulting in a shorter period where turbidity and colour remain low.

Warmer air temperatures translate in higher water temperatures with implications for most water quality parameters (Delpha et al. 2009). A recent study of the Athabasca River (Xinzhong Du et al., 2019) predicted an increase in river water temperatures from climate change and suggested that “increasing stream temperatures would affect water quality dynamics in the ARB by decreasing dissolved oxygen concentrations and increasing biochemical reaction rates in the streams”. Rates of chemical reactions are proportional to water temperature, causing a change in the solubility and relative concentrations of reactants and products. Temperature affects the dissolved oxygen level in water, photosynthesis of aquatic plants, metabolic rates of aquatic organisms, and the sensitivity of these organisms to pollution, parasites, and disease. Microorganisms are more active in warm water, resulting in increased availability of nutrients. Warmer temperatures will also result in longer ice-free seasons and will result in increased growth rates of algae.

7. Historical Water Use

Information on the use and consumption of water in the EMR is available from the annual reports compiled by EPCOR Water Canada and from studies for the North Saskatchewan Watershed Alliance (NWSA) by AMEC (2007) and Thompson (2016). Additional data are available from the Alberta Water Use Reporting System <http://aep.alberta.ca/water/reports-data/water-use-reporting-system/default.aspx>. The following map (Figure 27) of the Edmonton regional water system and the communities served by EPCOR, which are most in the region, although some (i.e. Devon) have their own systems. Each municipality is responsible for calculating and monitoring their own water use metrics. Detailed water use data and accurate population figures (to calculate per capita metrics) are not readily available other than for the City of Edmonton. Residential per capita metrics for the larger municipalities (e.g., Sherwood Park) in the EMR are likely similar to those recorded for Edmonton, although it would depend on the type of commercial/industrial customers in their service areas.

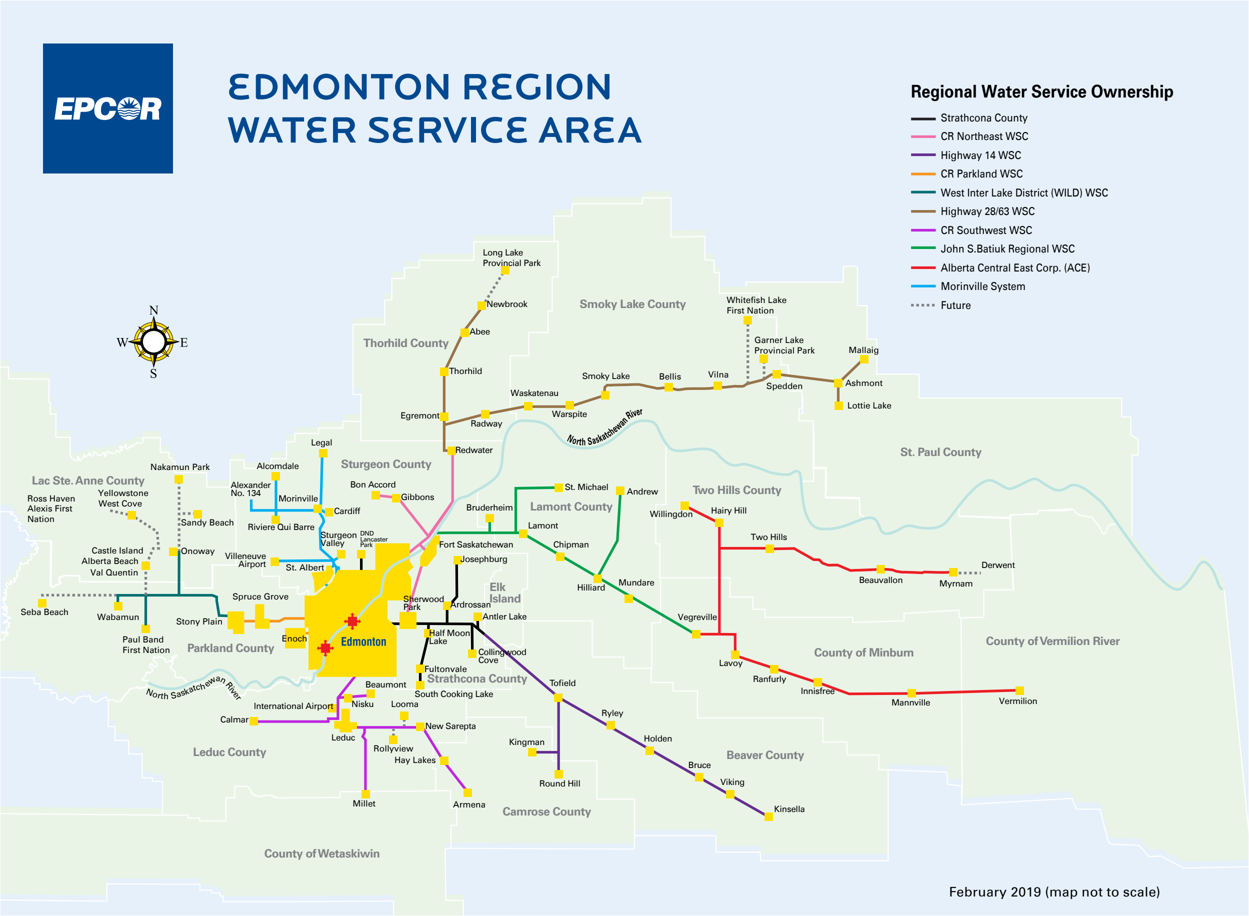


Figure 27: The Edmonton regional water system and the communities served by EPCOR.

Data from the Alberta Water Use Reporting System indicate that more than 2/3 of licensed surface water use (70%) in the NSRB occurs within the Capital Region (Strawberry, Sturgeon, Beaverhill sub-basins). This region had a slight increase in water allocations and use in 2016 compared to 2006, with a large increase in commercial water use (68.6M m^3), and decrease in industrial water use (46.0M m^3). About 20% of the licensed surface water use occurs within the Headwaters Region (Cline, Brazeau, Ram, Clearwater, Modeste sub-basins). In 2016, this region had major increases in commercial water use (1.9M m^3), and there was also a slight increase in municipal (1.1M m^3) water use, while there was a decrease in industrial water use (1.85M m^3). Water allocations and use within the basin had changed slightly by 2016 compared to 2006: 2% increase for licensed withdrawals and 7% increase for licensed use (Thompson, 2016).

Unlike the closed sub-basins (Bow, Oldman and SSR) in southern Alberta, in the NSRB water licences are still being granted by Alberta Environment and Parks. About 20 percent of the NSR is allocated, while much less water is extracted. That is, full allocations are not being used and much of the water that is extracted is returned to the NSR. The amount of water in the NSR is large relative to the volume of water withdrawn by the Water Treatment Plants (WTPs) for drinking water purposes, which is less than 3% of the total daily flow (EPCOR, 2017a). This information about licensed allocation of water from the NSR provides context our meta-analysis of water consumption using data provided by EPCOR. Figure 28 is a graph of the total annual demand, from 1971-2018, for the Edmonton regional water system. There are two notable inflections in this demand curve. Demand rose through the 1970s and then leveled off until 2000 when there was another rise in demand to a slightly higher level. The mean average day demand for 2001-2018 was 363 ML/d, and mean peak hour demand was 741 ML/d.

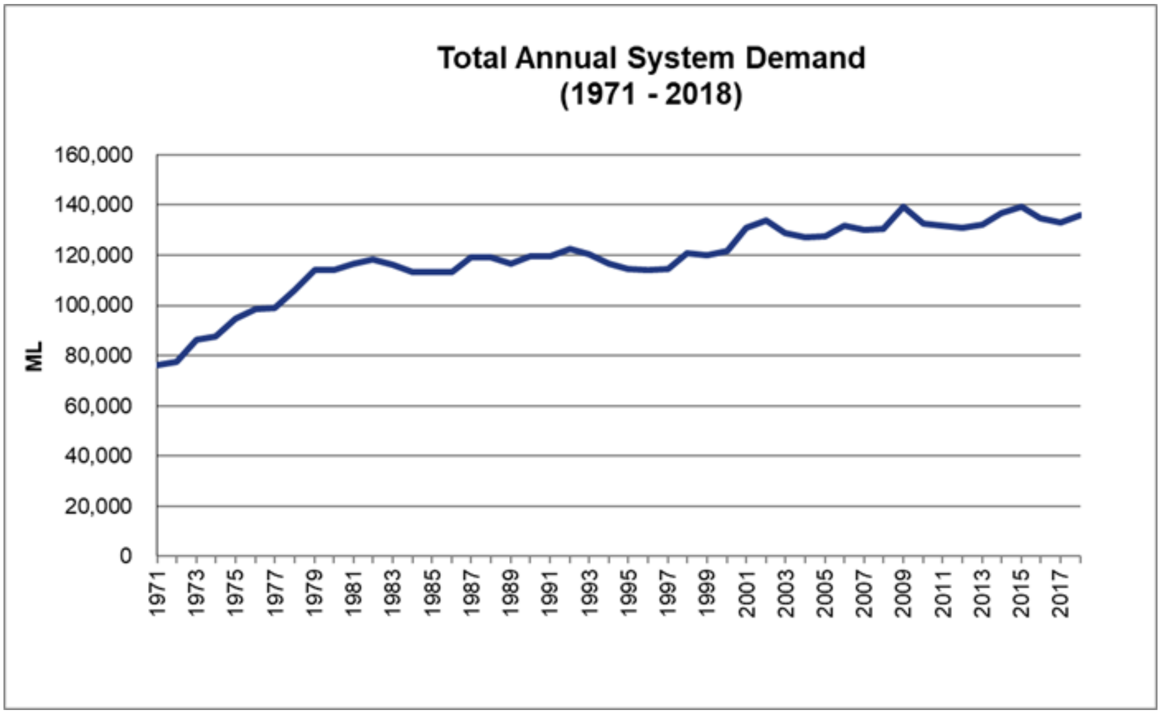


Figure 28: Total annual demand, from 1971 to 2018, for the Edmonton regional water system.

Figure 29 of average daily demand from 1971-2018 makes a distinction between the City of Edmonton, which accounts for most of the demand, and the larger metropolitan region. Regional water use has increased at a faster rate than in the city; it was almost 5 times higher in 2018 than in 1971, while in-city water use was only 1.5 times higher. By 2018, raw water intake increased by 24% compared to 1983. Data for in-city commercial total water consumption are available for 1991-2018 only and the consumption decreased by 31% over this period.

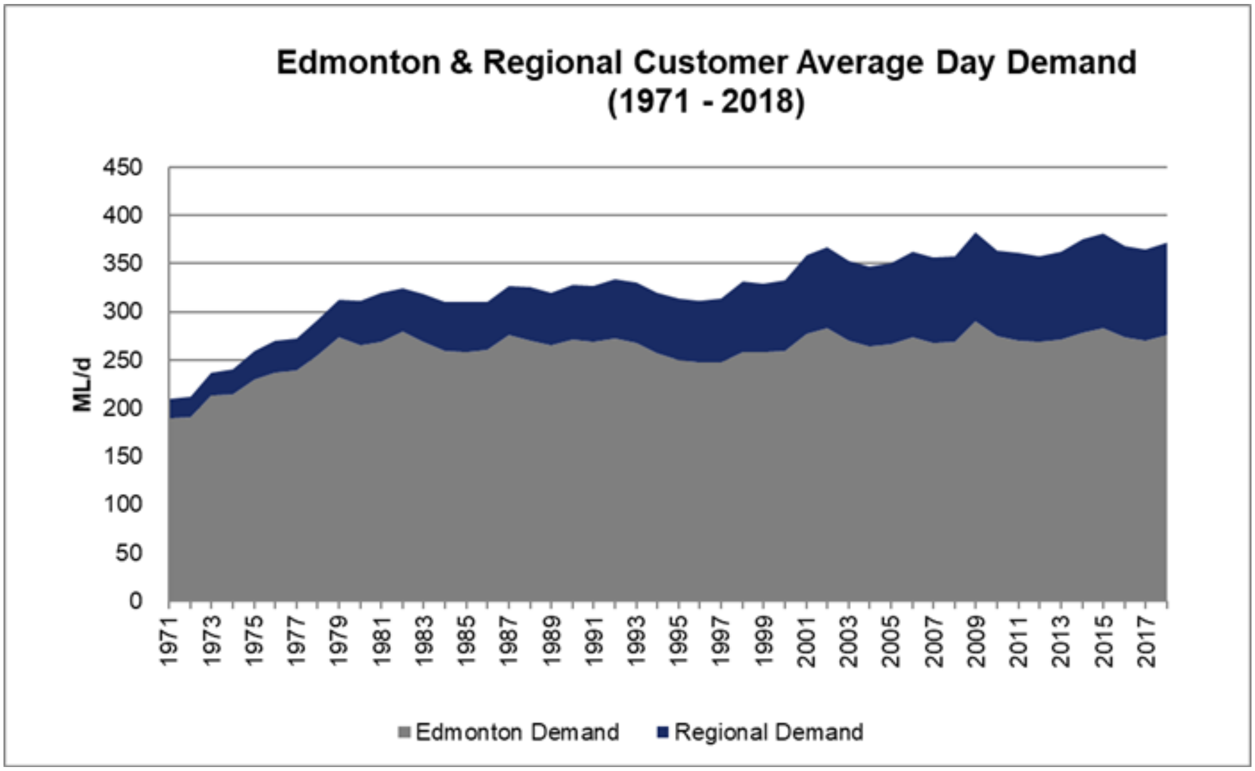


Figure 29: Average daily water demand from 1971 to 2018 for the City of Edmonton and the larger metropolitan region.

While total EPCOR consumption (residential, multi-residential, commercial and regional) in 2018 (126,045,062 m^3) was 78% higher than in 1971, per capita Edmonton water consumption decreased for both residential and total water use. In 2018, Edmonton residential per capita water use was 183 L/capita/d, which is 22% lower than 1991-2000 average and 27% lower than 2001 value. Total Edmonton per capita water use in 2018 was 42% lower than the 1971-1980 average (31% lower than 2001), at 289 L/capita/d, while the city's population increased by 2.1 times, from 462,572 (1971-1980 average) to 951,000 (2018). Figure 30 clearly illustrates the decoupling of water demand from population growth. Since about 1980 per capita demand has declined at a significant rate while the population approximately doubled. Programs and practices for the conservation and more efficient use of water have obviously been effective. Outdoor water use typically accounts for much of the water demand in North American cites. Although Edmonton has a relatively short summer compared to other cities, climate change projections of short winters, and longer warmer summers could increase the demand for outdoor water use. The next section of this report considers the forecasting of future water demand.

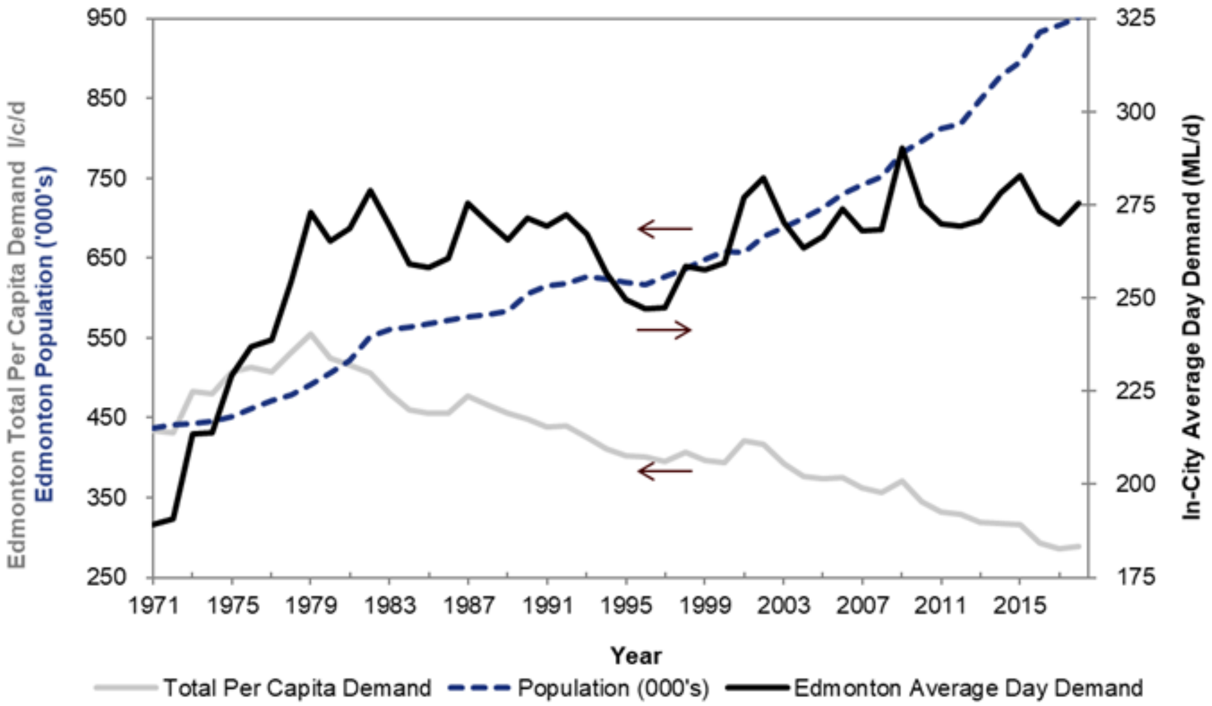


Figure 30: Average daily demand, population, and total per capita demand per year for the City of Edmonton from 1971 to 2018.

8. Projected Water Use

Demand for water will grow in coming decades because Alberta's population is expected to reach 6.4 million by 2046, an increase of about 2.1 million people from 2017. It also is becoming more concentrated in urban centres; by 2046 almost 8 in 10 Albertans are expected to reside in the Edmonton Calgary corridor (Treasury Board and Finance, 2018). Based on population growth alone, increase demand for water is anticipated; however, water use and demand depend on other factors, including policies, population, infrastructure, technology, human behaviour and climate. While future water demand has been forecasted for Alberta river basins and for the NSRB in Saskatchewan, these studies considered different combinations of the determinants of demand and some studies are outdated, for example, the forecasting of demand by 2015 (City of Calgary, 2007). Only one study (Liu and Davies, 2019), which is currently underway at the University of Alberta, applies directly to the EMR. We describe this project after first briefly summarizing the research in adjacent river basins.

AMEC Earth & Environmental (2007) completed an overview of current and future water use in Alberta for the Ministry of Environment. They examined licensed and actual water use to October 2006 for six sectors: municipal and residential, agricultural, commercial, petroleum, industrial and other. Forecasting was based on expected changes in population and economic activity. Thus, they were "business-as-usual" predictions since they did not account for improvements in water use efficiency. A 21% increase from current water use (2005) was the net result for the entire province; however, most of this increase was attributed to rising water demand in the irrigation and industrial (petroleum) sectors, and thus concentrated in the southern and more northerly river basins, respectively. For the NSRB, projections of the increase in water demand over 20 years (2005-2025) ranged from 15% for a low growth scenario to 118% for a high growth scenario. The increase in demand for a medium growth scenario was about 34% percent.

Kulshreshtha et al. (2012) examined future water demand in the NSRB in Saskatchewan. They made a distinction between direct anthropogenic (socio-economic) water demand, and demand subject to natural and policy-related factors, including evaporation, apportionment of water, instream water flow needs, and meeting environmental protection/preservation targets. Future water demand was estimated for three scenarios: baseline, climate change, and water conservation. Future increases in water demand were as high as 47% above the 2010 baseline scenario. Applying projected changes in temperature increased the demand by another 17%, while the adoption of water conservation practices reduced the future baseline demand by 12%. The authors noted a lack of research on climate change impacts on water demand, and another limitation they identified was a lack of information on the extent to which water conservation results in reduced water demand.

Chen et al. (2006) estimated 60 years of future daily water demand at Calgary based on statistical relationships between climate variation, population growth and water use. They found that water demand is sensitive to the number of days with a maximum temperature above 10º C. Therefore, future water demand may exceed the licensed water withdrawal when natural climatic variability coincides with an upward trend in temperatures to produce unusually hot summer days. This may necessitate water conservation programming plus temporary water restrictions (limiting of outdoor use) and water reuse strategies.

For their Water Efficiency Plan, the City of Calgary developed a medium-term (1-10 years) forecasting model to examine the effects of policy and water conservation, as well as alternative assumptions about growth, on water demand. By modeling system demand, and dividing it by population projections to 2015, they constructed three water demand forecasts: 453 liters per capita day (lpcd) if only metering is implemented, 440 lpcd with current water conservation programming, and 424 lpcd assuming widespread marketplace adoption of low-water use toilets and washing machines.

Accurate prediction of water usage is important for both short-term (operational) and long-term (planning) aspects of urban water management. Water demand forecasting models tend to overestimate long-term demands because they generally do not account for water conservation practices and reductions in per capita usage, such as the declining water consumption per customer recorded by EPCOR over the past three decades at Edmonton. There is evidence of a decoupling of population growth and urban water demand. As populations and economies grow, water demand does not necessarily increase at a proportional rate, given effective conservation and efficiency practices. A major “Residential End Uses of Water Study” (DeOreo, et al., 2016) of North American water utilities found a 22% decrease in average annual indoor household water use from 1999-2016. Edmonton was one of three Canadian cities included in the study.

To improve the accuracy of demand forecasts for municipal water management, Liu and Davies (2019) are developing a model for Edmonton, and applying it, along with climate change scenarios, to long-term water demand forecasting. Climate change projections (2019-2100) from the Pacific Climate Impacts Consortium (PCIC, 2013) provide daily temperature and precipitation values from 1950-2100. The model provides a projection of total demand based on inputs of historical weather and water use data; in this case, data for 20 years of daily and weekly water-demand and meteorological variables. Their data-driven forecasting model is run in the framework of a system dynamics model that can be used to replicate physical structures and processes and explore the future demand for various water end uses under different scenarios related to policy, climate, and population changes (Wang and Davies, 2018). The daily and weekly water demand models for Edmonton constructed by Liu and Davies (2019) reveal that maximum and average temperatures produce more accurate results than minimum temperature, probably because outdoor watering in summer relates more strongly to daytime average and high temperatures than to the daytime low. Furthermore, models using indices of the timing of water demand (e.g., “day-in-week”, “day-in-month”) produced significantly better results than those without these indices that capture the periodicity of water demand. Based on climate variables and the previous week’s demands, the model will be used to predict the outdoor water demand, an important component of municipal water demand.

9. Research Gaps

Decision-makers in the Edmonton Metropolitan Region EMR recognize that to develop and implement climate resilience policy, they require information about

- The historical flow of the North Saskatchewan River (NSR) and its major tributaries;
- Longer records of the climate and hydrology of the North Saskatchewan River Basin (NSRB):
- Projections of the future climate of the NSRB and the potential impacts on volume and timing of flows of the NSR, and water quality as it pertains to water supplies;
- Historical and projected water use; and
- Other relevant topics including uncertainties in the projection of future climate and impacts on water;

This report summarizes a relatively large body of knowledge related to climate change and water security in the EMR. The amount and quality of information is, in general, sufficient to inform a high-level assessment of future water security risks for the EMR; however, the depth of information differs among the knowledge requirements listed above. Research and information gaps arise not only from differences in the extent of previous work, but they also reflect a lack of documentation and analysis on the application of the science of climate change to regional and municipal adaptation planning. Research gaps include:

1. Projection of the variability of future flows of the NSR, which is subject to considerable uncertainty. Climate change scenarios consistently suggest higher winter water levels and reduced flows in summer; however, this represents a change in seasonal flows in an average year. The most challenging consequence of a warming climate, on the other

hand, will be a shift in the distribution of extreme water levels resulting from the interaction of natural hydroclimatic variability and the impacts of anthropogenic climate change. How is a warming climate modifying the natural cycles and frequency/magnitude of water level extremes? Answering this question will require the combined use of climate data that predate anthropogenic climate change and climate model projections of higher resolution than applied to the EMR thus far.

2. Little is known about the role of groundwater in maintaining levels in the NSR, and the potential availability of groundwater as an alternative future water supply, especially in the event of consecutive years of lower river flows. This research gap should be addressed, to some extent, by the new study "Groundwater contributions to the North Saskatchewan River and Edmonton region water resources" led by the University of Alberta and co-sponsored by EPCOR and Alberta Innovates.

3. Water quality is a significant issue as it relates to climate change and fluctuations in future water levels. Water quality monitoring by provincial government agencies and by EPCOR provides a rich database for the analysis of trends and variability and how water quality data correlate with weather and hydrological variables.

4. Similar to water quality, data are available for a more thorough analysis of water use, consumption and demand. The study of historical water use is important for the modeling of future demand, since the assumptions that underlie these models are based on historical trends and the effectiveness of water conservation.

5. Projections of municipal water use have only recent included the potential impacts of climate change. Current research at the University of Alberta has begun to address this research gap although further work likely is required given that it is the first study of its kind. The scope of research on future water demands should be expanded to include in-stream flow needs. Much is written about environmental flows but not in the context of whether they will be harder to achieve in a future warmer climate.

6. While various studies have examined aspects of climate change and surface water in Alberta, the application of this science to adaption and resilience planning is at a very early stage. Therefore, a significant knowledge gap exists between climate change / water science and resilience planning processes and practices. A collaboration among scientists, planners and policy makers should address, 1) expressing, communicating and dealing with uncertainty, 2) critical thresholds in relevant climate and water variables, 3) the best scale and use of climate data, and 4) whether municipal infrastructure and services are most vulnerable to natural variability, extreme events or incremental climate change.

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