Natural and Externally Forced Hydroclimatic Variability in the North Saskatchewan River Basin: Support for EPCOR's Climate Change Strategy

EPCOR / NSERC CRD Project

Summary
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1 Executive Summary

The project "Natural and Externally Forced Hydroclimatic Variability in the North Saskatchewan River Basin: Support for EPCOR's Climate Change Strategy" was a two-year (Sep 2018 – Sep 2020) research project with the following objectives:

1. Develop projections of future climate and runoff for the North Saskatchewan River Basin (NSRB), that account for modes of natural variability and anthropogenic forcing;
2. Develop new tree-ring reconstructions of the seasonal flow of the NSR at Edmonton;
3. Evaluate the uncertainty in the tree-ring reconstructions and model projections of climate and streamflow;
4. Examine the climate sensitivity and historical trends in groundwater levels in the NSRB;
5. Determine changes in the timing and magnitude of extreme and sustained low flows in a warming climate; and
6. Assess the performance of EPCOR's water supply and waste water treatment systems, given projected climate and runoff.

These objectives were achieved by

1) Processing outputs from the latest generation of Regional Climate Models (RCMs) that simulate climate at high-resolution (25-50 km) and incorporate Land Surface Schemes (LSS) for the modeling of surface hydrology;
2) Using updated tree-ring chronologies from the NSRB, reconstructing the annual flow and seasonal flows, and stochastically downscaling these proxy flows to weekly estimates;
3) Calibrating and validating the MESH hydrological model for the NSRB above Edmonton, and running it with projections of temperature and precipitation from a 15-member ensemble of CanRCM4;
4) Comparing time series, and statistical and spectral characteristics, among
    a. Climate and runoff projections from different RCMs and multiple runs of the same RCM, and
    b. Output from model simulations of the historical climate and the tree-ring record of the natural variability of the hydroclimate of the NSRB;
5) Relating time series from groundwater observation wells to weather station data; and
6) In collaboration with EPCOR staff, identifying the most significant climate change risks in terms of their probability and their consequences for water supply and wastewater treatment.

The most innovative aspects of this research project relate to our novel methods for the reconstruction and projection of regional hydroclimate, involving the downscaling and processing of proxy (tree-ring) data and climate model outputs, and measuring sources and amounts of uncertainty. These methods clearly separate our work from conventional climate change studies, which use data from weather stations and global climate models. We developed climate change scenarios that include natural variability, and shifts in water resources among seasons and years, which is the most significant impact of a changing climate.

This report provides EPCOR with the most reliable and relevant projections of hydroclimatic variability and change for the planning and implementation of adaptive strategies for water resource management under climate change. In addition to the benefits that will accrue to our industrial partner, the research is advantageous for Canadian industry in general, and for scientific and engineering disciplines engaged in climate and water research. The project methods and results are transferable to other river basins and to other industries that depend on a reliable supply of surface water.

1.1 Key Findings

1. Central Alberta is getting much less cold. Daily minimum winter temperatures at Edmonton rose by more than 6° C over the past 135 years. This rise in lowest temperatures accounts for most of the increase in mean annual temperature of more than 2° C. Variability from year-to-year and decade-to-decade tends to obscure this statistically significant upward trend. There is strong decadal variability in total annual precipitation but no clear historical trend. This

significant decadal cycle in precipitation extends across the historical weather record. For temperature, it is concentrated in recent decades suggesting an interaction of natural variability and anthropogenic warming. Pacific Ocean-atmosphere oscillations are correlated with precipitation and temperature. The strongest teleconnections between these macroclimate patterns and historical climate are found during the cold-season months of November to March.

2. The gauge record of mean annual flows of the North Saskatchewan River (NSR) at Edmonton clearly displays inter-annual and decadal variability, which is 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. A linear trend in the annual flow of the NSR indicates a statistically significant decrease since 1912. Linear trends are not statistically significant in spring and fall; however, they are 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 and thus a lesser spring and summer snowpack in some years. Summers are warmer, and as a result, less snow and ice remain at high headwater elevations to sustain summer flow.

3. An analysis of groundwater observation wells in the NSRB reveals that the hydrogeological system is sensitive to changes in precipitation and mean temperature and is modulated by inter-decadal climate oscillations. In unconfined aquifers higher (lower) temperatures are related to higher (lower) groundwater levels. In confined aquifers monitored by deeper observation wells, groundwater levels tend to be inversely related to temperature. The effect of temperature very likely reflects its relation to precipitation. The correlation of groundwater elevation to precipitation is more direct with significant positive correlations for many wells. Correlation analysis of the sensitivity of groundwater levels to teleconnection indices highlights the relevance of the lower frequency ocean-atmosphere oscillations. Water table elevation, especially in deeper aquifers, has a subdued and lagged response to climate variability. This acts as a natural smoothing of the annual variability, making the decadal variability more prominent.

4. Tree-rings collected from long-lived Douglas fir and limber pine in the upper reaches of the NSRB, where most of the runoff is generated, are an effective proxy of seasonal and annual water levels. There is a similar integrating and lagged response of tree growth and streamflow to inputs of precipitation, and thus ring-width and hydrologic data are significantly correlated. While the oldest wood sample dated to 527 AD, there was sufficient sample size after 1100 for the reconstruction of annual flows, and after1200 for the reconstruction of seasonal river flow. The paleohydrology of the NSRB includes periods of low flow that exceed the historical worst-case scenario in terms of severity and duration and decadal scale variability with successive years of high and low flows that last one to three decades. The multi-decadal and inter-annual modes of variability can be

linked to the influence of Pacific Ocean-atmosphere oscillations on the hydroclimate of western North America.

5. Our analysis of the high-resolution paleohydrology gave the long-term probability of hydrological drought of specific severities and highlighted the contrast between the range of river flows in the gauge versus proxy record. Minor droughts (flows in the 40th percentile - P40) occur at a rate of 1.7 to 7 years, but with periods having more or less drought, such as the 1920-1940 versus 1960-1975, respectively. Moderate drought (P30) reoccurs at a rate of between 2.5 and 5 years over the length of the proxy record (1110-2011), with highest frequencies during 1730-1750 and 1920-1935. The return period of severe drought (P20) ranges from 3.3 to 15 years with the highest frequency during 1620-1645 and 1860-1870. Extreme drought (P10) occurs at a rate of 6.7 to 20 years with highest frequency during the period 1629-1769, and a decrease in the occurrence rate from 1879 to 2011. The flow duration curve derived from the long paleo-flow record has a much longer tail representing a higher probability of low flows, exceeding the minimum weekly flow in the gauge record. This higher probability of low flows in the paleo versus gauge record is reflected in the drought severity-duration-frequency (SDF) curves, which suggest that use of the historical gauge record for drought planning underestimates the potential for severe drought.

6. Using output from 10 high-resolution Regional Climate Models (RCMs), we computed potential changes in average temperature and total precipitation for the near (2021-2050) and far (2051-2080) future, as compared to a baseline climate for the period 1981-2010. Winter temperature increases from 1 to 7 ° C with much more precipitation, ranging from about 10 to 35% higher with an outlier at 44%. The warming in summer is from 1.3 to 5.6 ° C, while the change in precipitation ranges from 10% less to 20% more. Time series plots of the climate variables show the rising minimum temperatures and total precipitation, especially in winter, and decreased precipitation in summer. Variability from year to year increases, especially for precipitation. Probability plots depict a shift in the distribution of seasonal temperature extremes from a baseline of 1951 – 2010 to the future period of 2041-2100. There is a large shift in the left tail of the frequency distribution towards higher values; thus minimum winter temperature become more concentrated around a few degrees below zero, suggesting a greater frequency of freeze and thaw in the future climate. On the other hand, there is a lower frequency of mean summer maximum temperature as it extends over a larger range and towards much higher extremes.

7. A direct approach to projecting future watershed hydrology involved 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. The advantage of this approach is the coupled simulation of climate and hydrology. Whereas runoff is the depth of water passing through the watershed, it is directly related to streamflow. We computed the difference in runoff projected by 7 RCMS for the near (2021-2050) and far (2051-2080) future compared to a baseline of 1981-2010. Multi-model mean changes in total runoff for the NSRB at

Edmonton indicate 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%. An expanding range of annual runoff suggests the potential for much higher water levels than in the past, but also flows that are just as low as the historical minimums.

8. We used the physically based hydrological model MESH, and climatology from the Canadian Regional Climate model version 4 (CanRCM4), to project future flows of the NSR at Edmonton. MESH was run using future precipitation and temperature from a 15-member ensemble of bias-corrected CanRCM4 data and the high emission scenario RCP 8.5. By using an ensemble of climate projections from a single model and one RCP, we were able to capture the variability and uncertainty in future climate and hydrology that results from the internal natural variability of the regional hydroclimate. Ensembles of annual hydrographs for the baseline (1951 - 2010) and future periods (2041-2100) show a clear shift in peak flows to earlier in the year. Winter flows are consistently higher and summer flows are lower relative to the recent past. The modeled river flows shows large variability around a trend of increasing annual flow. The range of flows exceeds those observed in the recent past. This very likely represents the amplification of the hydrological cycle in a warmer climate. Low flows reach those in the gauge record, even though a warming climate will be characterised by more precipitation and, on average, higher water levels. The timing of high flow shifts around mid 21st century with fewer maximum flows in late summer and fall, and an increased frequency in spring. They also very much exceed historical recorded maximum flows.

9. By both reconstructing (1100-2010) and projecting (2021-2080) the flow the NSR at high-resolution (seasonal to weekly), we are able to examine the extent to which the climate models simulate the natural variability of the regional hydroclimate captured by the tree-ring records. A wavelet transform of winter and spring river flow reveals that both the paleo record and projections have significant high-frequency variability corresponding to the influence of ENSO, although whereas this mode of variability spans 2-8 years for the proxy streamflows, it is confined to a more narrow range (2-4 years) for the modeled river hydrology. Decadal scale variability is more prominent in the tree-ring record, suggesting that the climate models may not be fully simulating this significant mode of variability. We reached the same conclusion by comparing the tree-ring reconstruction of the regional hydroclimatic to warm season (Mar-Aug) precipitation (mm) from historical (1850-2005) runs of 9 Earth System Models based only on natural forcings. Whereas low-frequency (decadal) variability accounts for 6-14% of the total variance in modeled warm season precipitation, it represents 25% of the variance in the tree-ring inferred hydroclimate. This underestimation of decadal variability by the models has important implications for the projection of future climate and in particular the extended periods of wet and dry conditions.

2 Introduction

Much of the impact of anthropogenic climate change on social and natural systems results from changes to regional hydrological regimes including shifts in the seasonal distribution of surface water supplies, and increases in the frequency and severity of hydroclimatic extremes (Abbott et al. 2019; Jiménez Cisneros et al. 2014; Marvel et al. 2019). These impacts are among the most problematic regional impacts of global climate change especially in water-limited landscapes and where watershed hydrology is dominated by the melt of a cold season snowpack. Both of these geographic characteristics apply to the mid- and high-latitude snow-dominated river basins of western Canada where periodic droughts are economically and ecological limiting.. This region also has been subject to considerable climate change.

Since 1948, Canada has warmed at twice the global rate; while in western Canada the increase in temperature has been about three times more rapid than global warming (Bonsal et al. 2019; Mudryk et al. 2018). A warming climate will result in decreases in the depth of the snowpack, length of the snow cover season, and the proportion of precipitation falling as snow (Mudryk et al. 2018), with a corresponding reduction in end-of-season snowpack and summer water levels and streamflow (Bonsal et al. 2019). Declining streamflow has been observed in rivers draining the eastern slopes of the central/southern Rocky Mountains(St. Jacques et al. 2010).

In recent decades, there has been growing demand for the water supplied from the Rocky Mountains of western Alberta. This province has a population of about 4.3 million. It also has most of Canada's oil and gas industry and irrigated agricultural land. Snow in the Rocky Mountains is the backbone of the industrial water supply. The bank of surplus water from wasting alpine glaciers has been mostly spent, and mass balance is shrinking quickly (Marshall et al. 2011). While the Rocky Mountains are the water towers of the western Interior, most of Alberta is sub-humid, with large seasonal and inter-annual variability and extreme weather typical of a mid-latitude continental climate. Of the 20 most damaging weather events in Canadian history, 16 occurred in Alberta (Sauchyn et al., 2020).

The research project "Natural and Externally Forced Hydroclimatic Variability in the North Saskatchewan River Basin: Support for EPCOR's Climate Change Strategy" was launched in September 2018 with support from EPCOR and NSERC. This project represents further collaboration between researchers from the University of Regina and EPCOR. Previous research produced 1) a tree-ring reconstruction of the flow of the North Saskatchewan River from 1110 to 2010, 2) stochastic scaling of annual proxy flows to weekly estimates, and 3) projections of future climate of the NSRB using output from Global Climate Models (GCMs). The current project represents an opportunity to provide EPCOR with the most reliable and relevant projections of hydroclimatic variability and change by combining an updated tree-ring reconstruction of river flow with new more robust and detailed projections of future climate and hydrology. The results of this project will inform EPCOR's adaptation planning for water resource management under climate change. The statistical processing and assimilation of paleo-hydrological and climate model data will enable us to develop scenarios of future hydroclimate and shifts in water resources among seasons and years, which is the most significant impact of a changing climate.

2.1 Objectives and Approach

The research objectives are to

1. Develop projections of future climate and runoff for the North Saskatchewan River Basin (NSRB), that account for modes of natural variability and anthropogenic forcing;
2. Develop new tree-ring reconstructions of the seasonal flow of the NSR at Edmonton;
3. Evaluate the uncertainty in the tree-ring reconstructions and model projections of climate and streamflow;
4. Examine the climate sensitivity and historical trends in groundwater levels in the NSRB;
5. Determine changes in the timing and magnitude of extreme and sustained low flows in a warming climate; and
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These objectives were achieved by

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3. Calibrating and validating the MESH hydrological model for the NSRB above Edmonton, and running it with projections of temperature and precipitation from a 15-member ensemble of CanRCM4;
4. Comparing time series, and statistical and spectral characteristics, among
    a. Climate and runoff projections from different RCMs and multiple runs of the same RCM, and
    b. Output from model simulations of the historical climate and the tree-ring record of the natural variability of the hydroclimate of the NSRB;
5. Relating time series from groundwater observation wells to weather station data; and
6. In collaboration with EPCOR staff, identifying the most significant climate change risks in terms of their probability and their consequences for water supply and wastewater treatment.

The geographic focus of our project is the NSRB above Edmonton (Figure 1), which is Canada's 5th most populous urban area with about 1.4 million residents. The average annual temperature at Edmonton 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 ° C (Anis et al., 2020). The water supply for this metropolitan region is the North Saskatchewan River (NSR). The headwater tributaries (Cline, Brazeau, Ram, and Clearwater rivers) generate 88% of the total annual runoff. Glaciers and a high elevation snowpack maintain river flow through the summer months. A decrease in the average annual flow of the NSR at Edmonton since 1911 is consistent with a warmer climate and the resulting loss of glacier ice and summer snowpack at high headwaters elevations. However, the decline is relatively small compared to large natural inter-annual and decadal variability in flow. Most of decreased flow is in summer; winter flows have been trending upward.

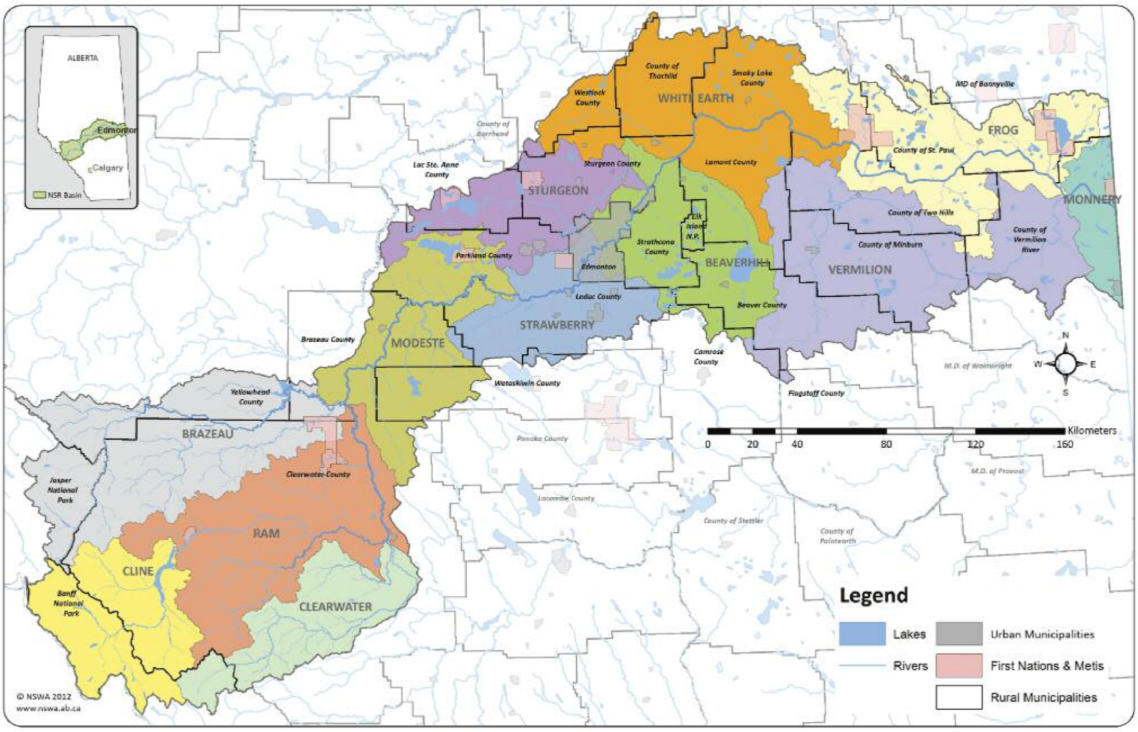

Figure 1. The North Saskatchewan River Basin in Alberta (Source: NSWA, 2012; www.nswa.ab.ca)

Previous studies of the impacts of climate change on runoff in the NSRB have applied coarse output from Global Climate Models (GCMs) to a hydrological model or taken runoff data directly from simple simulations of hydrology embedded in Regional Climate Models (RCMs). The objective of our research described is to inform water supply and adaptation planning to climate change in the Edmonton region with a much more advanced and higher-resolution modeling of the climate and hydrology of the NSRB. We present an analysis of past and future climate and hydrology. We compare pre-industrial paleohydrology to model simulations of future climate and river flow. Research on the extent to which anthropogenic climate change departs from natural variability informs an assessment of the resilience of water resource policy and infrastructure, which were designed to operate under historical climatic variability. Human-induced climate trends are superimposed on natural multi-decadal climate variability, which is more evident and impactful at regional scales.

We processed outputs from a 15-member ensemble of runs of the Canadian Regional Climate Model (version CanRCM4). Then we ran a fully calibrated numerical hydrological model, using the future climatology from CanRCM4. This ensemble approach enables us to capture uncertainty resulting from the internal variability of the regional hydroclimate. An ensemble of hydrographs under future climate conditions, and information about the future timing and magnitude of extreme water levels, informs a climate risk assessment of the resilience of water resource policy and infrastructure, which were designed to operate under historical climatic variability. Human-induced climate trends are superimposed on natural multi-decadal climate variability, which is more evident and impactful at regional scales. Natural variability of the regional hydroclimatic regime is the dominant source of uncertainty in the projection of the future climate of Canada's western interior (Barrow and Sauchyn, 2019). Our interpretation of the future contribution of natural variability is very much informed by our prior reconstruction of the flow of the NSR from tree rings. This 900-year record of hydroclimatic variability includes evidence of prolonged periods of low flows exceeding in severity and duration the minimum flows in the gauge record (Sauchyn et al., 2015). Therefore, important context for our study of climate change and water security in the NSRB is the extent and drivers of hydroclimatic variability in this region.

3 Implications of our Findings

Our modeling and analysis of the future climate and hydrology of the North Saskatchewan River Basin (NSRB) gave results that have important implications for the availability, management and use of surface water in the Edmonton metropolitan region. Most of the recent climate change in this region has been an increase in the lowest temperatures; minimum daily winter temperatures have increased by about 6 °C. 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.

A decrease in the average flow of the North Saskatchewan River (NSR) at Edmonton since 1911 is consistent with a warming 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. Natural cycles in water levels are very apparent in the paleohydrology of the NSR, an 815-year reconstruction of seasonal river flow from tree rings collected in the upper part of the river basin. The decadal cycle is particularly evident in the paleohydrology, with long periods of consistently low river levels and hydrological drought.

Future projections from RCMs suggest warmer and wetter conditions in winter and spring and, on average, drier conditions in mid to late summer. More precipitation will occur as rain rather than snow, with advanced spring snow melt. A warming climate will amplify both the wet and dry phases of the natural cycle in the regional hydroclimate. One of the most robust climate change projections is an increase in rainfall intensity.

In response to the projected climate changes, the seasonal pattern of river flow will shift, with future river levels peaking about one month earlier during May. will result in earlier peak streamflows. Cold season (winter and early spring) flows will be significantly higher, and the timing of maximum annual flows will shift from summer to spring. There also will be a larger range of low flows. As winter becomes wetter, it is no longer the season of minimum flow. They will tend to occur in late summer and throughout the fall with the loss of snow and ice at high elevations which historically have maintained summer river levels. As a warming climate intensifies 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.

Lower river levels in June to August will have implications for surface water supplies during the season of highest demand. Data from recent decades indicates that absolute water use and demand has increased but at a lesser rate than the increasing population of the Edmonton region (Anis et al., 2020). As a result, there has been a decoupling of per capita water use from growth in the economy and population of the region. Whereas this more efficient use of water supplies represents an important adaptation to a changing climate, other adjustments to water policy, planning and management will be required given the changes in climate and water supplies projected by our study.

Changes in the severity of extreme hydrological events, and in the seasonal distribution of water resources, will have major impacts on terrestrial and aquatic ecosystems, and on the availability of municipal and industrial water supplies. 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.

Both incremental long-term changes in water levels, and extreme fluctuations around the changing baseline, will have impacts requiring adaptation of water resource planning and policy. Data from recent decades indicates that absolute water use and demand has increased but at a much lesser rate than the increasing population of the Edmonton region. As a result, there has been a decoupling of per capita water use from growth in the economy and population of the region. Water allocation and the design of storage and conveyance structures, such as reservoir and irrigation canals, are based mainly on average seasonal water levels, but otherwise water resources are managed to prevent the adverse impacts of flooding and drought. 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.

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