Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

Submitted by:
Dr. P. Kim Sturgess, C.M., P.Eng., FCAE
CEO
WaterSMART Solutions Ltd.
#200, 3512 – 33 Street NW
Calgary, Alberta T2L 2A6
kim.sturgess@albertaWaterSMART.com

Submitted to:
Meghan Payne
Executive Director
Lesser Slave Watershed Council
Box 2607 - High Prairie, AB, T0G 1E0
info@lswc.ca

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1.0 Introduction

This project used hydrological modelling to quantify the effects of climate change, land use, and water allocations on the hydrology of the Lesser Slave Watershed and Lesser Slave Lake. This work used the Athabasca Integrated Regional Model (AIRM) (Alberta WaterSMART, 2017). AIRM was designed as a high-level model of the entire Athabasca River Basin (ARB), which required that the “Lesser Slave” sub-model first be refined to ensure it best represented the hydrology of the Lesser Slave Watershed, including wetland processes and Lesser Slave Lake storage and flow attenuation.

Once the model was verified to perform well within the watershed, results were obtained under observed historical conditions (1986 – 2015); these results included daily streamflow, lake levels, and average annual runoff by sub-basin. A tracer routine was used to track average daily contributions to streamflow from wetlands for each sub-basin. Second, the effects of water allocations were explored by simulating streamflow and lake levels under historical, doubled, and no water allocation scenarios. Third, the effects of forest disturbance and wetland degradation were quantified by simulating streamflow under land use scenarios where varying percentages of each sub-basin were modified, and under a final scenario where both forest disturbance and wetland degradation were simultaneously simulated. Finally, the effects of climate change were explored by running the model under various historical climate normals and future climate scenarios. These simulations allowed the range of natural variability in streamflow and lake levels to be estimated in the watershed, as well as how climate change could alter the hydrology of the Lesser Slave Watershed.

2.0 Study Area and Scope

The Lesser Slave Watershed simulated in this study follows the boundaries of the “Lesser Slave” sub-model in the ARB Initiative’s AIRM. The study area consists of the Lesser Slave River from Slave Lake, Alberta to its confluence with the Athabasca River; Lesser Slave Lake and all major tributaries upstream of the lake. In addition, major sub-basins Freeman River, Sakwatamau River, and a portion of the Athabasca River between Windfall, Alberta and Athabasca, Alberta were included since they share similar hydrologic character and geographic setting. Long streamflow records were also available for these sub-basins, which aided model calibration and validation. Because the model is designed to perform simulations at a regional scale, hydrologic outputs are only available at the outflows of large tributaries in the watershed and at several points along the Lesser Slave River.

This region is typical of a subarctic Köppen climate type, as evidenced by climate normals (1981 – 2010) from nearby climate stations at Whitecourt (ID 3067372) and Athabasca, Alberta (ID 3060321) (Environment Canada, 2017). Air temperatures are warm during the summer months, with daily averages in July of 16.0°C to 16.6°C, while January is cold (-11.2°C – -14.3°C). Average annual precipitation is 479 mm at Athabasca and 544 mm at Whitecourt. Snowfall accounts for approximately 23% of annual precipitation at Athabasca and 30% at Whitecourt.
3.0 Methods

3.1 Hydrological Model

Daily streamflow and Slave Lake water level were simulated using a semi-distributed hydrological model. The model and much of the input data were adapted from the AIRM, which contained a collection of five regional hydrological models used to model hydrology for the entire ARB.

The hydrological model used in this study is the “Lesser Slave” regional sub-model of AIRM, which consists of a modified version of the HBV-EC hydrological model (Bergström, 1992, Canadian Hydraulics Centre, 2010) emulated within the Raven Hydrological Framework (Craig et al., 2015). The model simulates watershed hydrology (including streamflow and lake level as well as meteorological variables such as precipitation, snow water equivalent, evaporation, and others) at a daily time step. To reduce computation time and complexity within the model, the study area was spatially aggregated into a collection of Hydrological Response Units (HRUs), where nearby areas within a sub-basin were grouped based on similar land cover and topographic characteristics. A full discussion of HRU delineation, specific algorithms used to simulate individual hydrological processes, and model calibration and verification is available in the ARB Initiative Interim Report (Alberta WaterSMART, 2017) and the general hydrological modelling workflow is outlined in full detail in Chernos et al. (2017).

Rain and snow are intercepted at varying rates that are tied to the vegetation cover of each HRU. Snowmelt was modelled as a temperature index melt rate in which more vegetated cover types had lower rates of snowmelt to account for higher shading. Once water infiltrated the soil, it was routed through three soil layers and transported to the stream network as baseflow. Most land cover types had moderate soil depths, representing an average soil-water residence time. The exceptions to this were the Disturbed/Urban land cover type, where very shallow, impermeable soils made for rapid overland flow, and Wetlands, where a very deep soil layer led to long residence times, reflecting wetland roles in flow attenuation and water storage. Tracing the percent of streamflow contributions from wetlands was accomplished using Raven’s built-in tracer algorithm (Craig et al., 2015). Due to uncertainty in lake dynamics, in particular mixing and residence times, results from the tracer algorithm are unreliable downstream of Lesser Slave Lake.

3.2 Data

The hydrological model required daily maximum and minimum air temperature and precipitation data to simulate streamflow. These meteorological data were obtained from nearby Environment Canada (EC) climate stations at Slave Lake and Whitecourt and were available from 1986 – 2015 (Environment Canada, 2016). Several synthetic climate stations were generated to account for smaller-scale regional climate patterns by scaling observational records from EC stations using PRISM climate normals from 1961 – 1990 (Daly, 2002b, 2002a). A complete list of climate stations can be found in the ARB Initiative Interim Report (WaterSMART 2017).
Observed daily average streamflow and lake level data were obtained from Water Survey of Canada (WSC, 2016) hydrometric gauges within the study area and were used to calibrate and verify the hydrological model (Table 1). To account for lake storage and release dynamics, a stage-discharge-area-volume curve was designed using bathymetric data from the Alberta Geologic Survey (2008) and a stage-discharge relationship derived from WSC data at Lesser Slave Lake (Figure 1, Appendix A). Given that lake area was only used for calculating evaporation, and that a reliable stage-area relationship was not available, lake surface area was assumed constant at 1,170 km². All data used to derive the curves were collected since the installation of the weir at the lake outlet and therefore reflect the influence of the weir on the stage-discharge curve.

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

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station Code</th>
<th>Period</th>
<th>Drainage Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swan River Near Swan Hills</td>
<td>07BJ003</td>
<td>1970 – 2014</td>
<td>155</td>
</tr>
<tr>
<td>Driftpile River Near Driftpile</td>
<td>07BH003</td>
<td>1972 – 1986</td>
<td>835</td>
</tr>
<tr>
<td>Sakwatamau River Near Whitecourt*</td>
<td>07AH003</td>
<td>1972 – 2013</td>
<td>1,145</td>
</tr>
<tr>
<td>West Prairie River Near High Prairie</td>
<td>07BF002</td>
<td>1921 – 2012</td>
<td>1,152</td>
</tr>
<tr>
<td>East Prairie River Near Enilda</td>
<td>07BF001</td>
<td>1921 – 2013</td>
<td>1,467</td>
</tr>
<tr>
<td>Freeman River Near Fort Assiniboine*</td>
<td>07AH001</td>
<td>1965 – 2014</td>
<td>1,662</td>
</tr>
<tr>
<td>Swan River Near Kinuso*</td>
<td>07BJ001</td>
<td>1915 – 2012</td>
<td>1,900</td>
</tr>
<tr>
<td>Driftwood River Near the Mouth</td>
<td>07BK007</td>
<td>1968 – 2013</td>
<td>2,100</td>
</tr>
<tr>
<td>South Heart River Near Big Prairie Settlement</td>
<td>07BF905</td>
<td>2005 – 2012</td>
<td>6,001</td>
</tr>
<tr>
<td>Lesser Slave River at Slave Lake</td>
<td>07BK001</td>
<td>1915 – 2012</td>
<td>13,567</td>
</tr>
<tr>
<td>Lesser Slave Lake at Slave Lake</td>
<td>07BJ006</td>
<td>1979 – 2013</td>
<td>13,567</td>
</tr>
</tbody>
</table>

* Used in model calibration

Figure 1. Lesser Slave Lake stage-discharge and stage-volume curves (Alberta WaterSMART, 2017).
3.3 Water Use Scenarios

Water licence data were obtained from the Alberta Environment and Parks water licence database. Data were filtered for licences within the Lesser Slave River Basin portion of the ARB and for active or renewable surface water licences. For each licence, the last five years of available reported usage and returns data were used. In cases where no usage or returns were reported, it was assumed that the entire allocation stipulated in the licence was used. Water use was calculated as usage minus returns for each licence, and then aggregated over each sub-basin within the Lesser Slave Watershed.

Water use was concentrated in the Lesser Slave River at Lesser Slave Lake sub-basin and in the South Heart River; modest water use occurred in the East Prairie and Swan River sub-basins (Figure 2). In addition to this baseline scenario with historical water use, two more model scenarios were run: one scenario where all water demands were set to zero, and a second scenario in which all water demands were doubled.

![Figure 2: Water use for each tributary in the Lesser Slave watershed. Omitted basins had no water use. Raw data can be found in Appendix B.](image)

3.4 Land Use Scenarios

Seven separate land cover change scenarios were used to isolate the effects of land use change on the hydrology of the Lesser Slave Watershed. These scenarios were designed to simulate the effects of
forest disturbance and wetland degradation. Under all scenarios, the percentage change in land cover was equally distributed (by relative proportion) in each sub-basin within the study area.

In the forest disturbance scenarios, areas of “Coniferous Forest” were converted to a “Disturbed” land use class, characterized by small shrubs and the lack of a forest canopy. This change reduces the effective forest cover over the area of interest, increasing sunlight and reducing precipitation interception, while not altering the soil properties. Under the three forest disturbance scenarios, 5%, 15%, and 30% of coniferous forests were converted. Within the model, the current-day land cover contains 732 km² of disturbed forest, which accounts for approximately 4.8% of the total forested area, and approximately 12.0% of the total coniferous-forested area.

In the wetland degradation scenarios, wetlands were converted to a “Disturbed/Urban” land use class, characterized by no surface vegetation and a shallow, impervious soil. This change removes any vegetation cover from the wetlands, and drains and compacts the soil over the area of interest. This creates an area that does not intercept any precipitation and does not store substantive water on the landscape, instead flushing surface water into nearby streams. Under the three wetland degradation scenarios, 5%, 15%, and 30% of wetland area was converted. In the baseline land cover within the model, “Disturbed/Urban” areas cover 1,082 km², while wetlands cover 8,275 km².

Finally, a cumulative effects scenario was simulated in order to evaluate the combined effects of forest disturbance and wetland degradation. Under this scenario, 15% of mature “Coniferous Forest” was converted to “Disturbed” and 15% of wetlands were converted to “Disturbed/Urban”.

3.5 Climate Scenarios

Several climate scenarios were used in the model to evaluate the hydrological response of the Lesser Slave Watershed to a changing climate. Six future scenarios were derived from the CanESM2 general circulation model for three 30-year periods (2010 – 2040, 2040 – 2070, and 2070 – 2100). Each climate scenario was run under two “Representative Concentration Pathways” (RCP): under RCP 4.5, a moderate scenario where greenhouse gas emissions stabilize and radiative forcing is stabilized by the year 2100, and under RCP 8.5, a severe scenario where greenhouse gas emissions continue to increase indefinitely. Eight historical climate scenarios were derived from 30-year climate normals from 1901 – 2000 (1901 – 1930, 1911 – 1940, 1921 – 1950, 1931 – 1960, 1941 – 1970, 1951 – 1980, 1961 – 1990, 1971 – 2000). Climate scenarios were generated using monthly climate normals obtained from ClimateWNA (Wang et al., 2012) for each climate station in the study region. Daily air temperatures were generated by scaling observed values by the absolute difference relative to historical values, while precipitation was generated by scaling all precipitation events by the relative (fractional) change from the historical period.
4.0 Results

4.1 Hydrological Model

Model performance was generally good in the Lesser Slave Watershed, though in some sub-basins performance was more modest (Table 2). Performance was highest in the sub-basins with larger elevation gradients, such as the Swan, Sakwatamau, and Freeman Rivers, where monthly Nash-Sutcliffe Efficiency (NSE) values ranged from 0.71 to 0.82. Conversely, performance was worse in flatter sub-basins with larger human and/or groundwater influences, such as the Driftwood and West Prairie Rivers (NSE = 0.61 - 0.69). Model performance was also modest below Lesser Slave Lake (NSE = 0.47 - 0.52), likely due to additional uncertainties, specifically in the stage-discharge-volume-area curve of the lake, compounded by potential modelling uncertainty.

As part of the modelling effort for verifying AIRM (Alberta WaterSMART, 2017), meteorological variables were compared at several points within the watershed. Daily air temperature observations showed strong agreement with simulated results ($r^2$ ranging from 0.92 - 0.97 at several locations within the Lesser Slave Basin). Monthly total precipitation also showed good agreement ($r^2$ ranging from 0.64 - 0.67), while daily snow water equivalent was well simulated ($r^2$ ranging from 0.68 to 0.83).

Table 2: Performance statistics monthly Nash-Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS) for hydrological model calibration (2003 – 2015) and verification (1986 – 2003) periods

<table>
<thead>
<tr>
<th>Site</th>
<th>Calibration</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSE</td>
<td>PBIAS</td>
</tr>
<tr>
<td>Driftwood River Near the Mouth</td>
<td>0.69</td>
<td>30%</td>
</tr>
<tr>
<td>East Prairie River Near Enilda</td>
<td>0.69</td>
<td>-7%</td>
</tr>
<tr>
<td>Freeman River Near Fort Assiniboine</td>
<td>0.82</td>
<td>18%</td>
</tr>
<tr>
<td>Lesser Slave River at Slave Lake</td>
<td>0.52</td>
<td>-14%</td>
</tr>
<tr>
<td>Lesser Slave Lake at Slave Lake</td>
<td>0.52</td>
<td>0%</td>
</tr>
<tr>
<td>Sakwatamau River Near Whitecourt</td>
<td>0.76</td>
<td>18%</td>
</tr>
<tr>
<td>Swan River Near Kinuso</td>
<td>0.71</td>
<td>-13%</td>
</tr>
<tr>
<td>Swan River Near Swan Hills</td>
<td>0.60</td>
<td>-24%</td>
</tr>
<tr>
<td>West Prairie River Near High Prairie</td>
<td>0.62</td>
<td>35%</td>
</tr>
</tbody>
</table>

Model performance was on average worse during the verification period (1986 – 2003), likely due to less reliable input data. Likely there were larger errors in the climate forcing variables used in the model due to more missing data earlier in the climate record, thus requiring imputation, and to less reliable measurements. In addition, land cover data used in the hydrological model were based on current (2015) conditions and are likely less representative of land cover further from present-day.

Model performance meets or exceeds published performance statistics from other studies in the region. In particular, a similar study modelling hydrology in the Lesser Slave Watershed in 2009 using MIKE SHE modelling platform (WorleyParsons, 2009) produced monthly NSE values of 0.56 for the Lesser Slave River streamflow from 1988 – 2005, and 0.23 for Lesser Slave Lake water levels from 1985 – 2005.
Streamflow results are relatively similar to those reported in this study, while lake levels show a substantial improvement. Likewise, monthly NSE values for tributaries in the WorleyParsons (2009) study ranged from 0.56 at Swan River, to 0.23 at Driftwood River from 1985 – 2005, roughly comparable to or worse than results from this modelling study (Swan River = 0.71 - 0.65, Driftwood River = 0.69 - 0.35).

4.2 Current Hydrological Conditions

Streamflow in Lesser Slave Watershed tributaries generally followed a weak nival (snowmelt-dominated) regime (Figure 3, Figure 4). Streamflow was low during the winter and peaked in the spring (April - May) during snowmelt. From June to October, streamflow generally decreased, though streamflow periodically increased due to large summer storms. Spring flows were typically higher in sub-basins with higher elevations, such as the Swan, Sakwatamau, and Freeman Rivers, where more snow accumulated during the winter months. Conversely, basins with lower gradient and lower elevation, such as the South Heart and Driftpile River basins, had relatively low spring freshets. Streamflow in the Lesser Slave River did not exhibit a spring freshet, and instead slowly increased until it peaked in July. In general, flow downstream of the lake was less variable, mainly due to water storage and flow attenuation in Lesser Slave Lake.

Figure 3. Observed streamflow for the entirety of the Swan River Near Kinuso and Lesser Slave Lake at Slave Lake Water Survey of Canada records
Figure 4: Average daily simulated and observed streamflow for Lesser Slave Watershed tributaries from 1986 – 2015. Shaded areas correspond to 10 and 90% quantiles.

Runoff in the Lesser Slave Watershed was largest in the highest elevation sub-basins (Table 4 and Figure 3). Swan River near Swan Hills, where the elevation in parts of the basin was over 1300 m, the average
annual runoff was 366 mm; almost double that of the Driftwood (203 mm) and Driftpile rivers (210 mm), where sub-basin elevations ranged from 500 - 700 m. An exception to this is the Lesser Slave River at Slave Lake sub-basin. Although this sub-basin has low relief and a low elevation, a large portion of the sub-basin is covered by the lake, which has no vegetation to intercept precipitation.

Table 3: Simulated Average Annual Runoff (mm) and hypsometry for all sub-basins in the study area for the model simulation period (1986 – 2015).

<table>
<thead>
<tr>
<th>Sub-Basin</th>
<th>Average Elevation (m a.s.l.)</th>
<th>Stream Gradient (m/km)</th>
<th>Average Annual Runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swan River Near Swan Hills</td>
<td>1193</td>
<td>7.5</td>
<td>366</td>
</tr>
<tr>
<td>Freeman River Near Fort Assiniboine</td>
<td>1002</td>
<td>2.2</td>
<td>325</td>
</tr>
<tr>
<td>Lesser Slave River at Slave Lake</td>
<td>646</td>
<td>0.2</td>
<td>306</td>
</tr>
<tr>
<td>Sakwatamau River Near Whitecourt</td>
<td>967</td>
<td>2.6</td>
<td>297</td>
</tr>
<tr>
<td>Swan River Near Kinuso</td>
<td>890</td>
<td>3.8</td>
<td>271</td>
</tr>
<tr>
<td>Lesser Slave River at Highway No 2A</td>
<td>726</td>
<td>0.3</td>
<td>251</td>
</tr>
<tr>
<td>South Heart River Near Big Prairie Settlement</td>
<td>665</td>
<td>0.3</td>
<td>248</td>
</tr>
<tr>
<td>East Prairie River Near Enilda</td>
<td>830</td>
<td>3.5</td>
<td>245</td>
</tr>
<tr>
<td>Lesser Slave River at the Mouth</td>
<td>753</td>
<td>0.4</td>
<td>245</td>
</tr>
<tr>
<td>West Prairie River Near High Prairie</td>
<td>799</td>
<td>1.5</td>
<td>224</td>
</tr>
<tr>
<td>Driftpile River Near Driftpile</td>
<td>835</td>
<td>6.0</td>
<td>210</td>
</tr>
<tr>
<td>Driftwood River Near the Mouth</td>
<td>742</td>
<td>3.0</td>
<td>203</td>
</tr>
</tbody>
</table>
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Figure 5: Average Annual Runoff for all sub-basins in the Lesser Slave Watershed study area.

4.3 Water Use Scenarios

Under all three water use scenarios, average lake levels were similar (Figure 4). Under the no water use scenario, lake levels increased approximately 0.016 m (1.6 cm), while under the doubled water use scenario water levels decreased approximately 0.016 m. Changes in variability were roughly comparable; 90% quantile peak water levels were 0.01 – 0.02 m higher under no water use than under
Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

the current water use scenario.

![Lesser Slave Lake Water Use Simulations](image)

**Figure 6**: Simulated average daily Lesser Slave Lake water levels under water use scenarios.

Streamflow in most Lesser Slave Watershed tributaries was largely unaffected by different water use scenarios. Changes in streamflow due to water use were only detectable in the Lesser Slave River below Lesser Slave Lake and in the South Heart River. In the Lesser Slave River, the no water use scenario led to an average increase in streamflow of 1.0 – 1.5 m³/s relative current water usage. In the South Heart River, the difference in streamflow for these two scenarios was 0.5 – 1.0 m³/s. Over the entire Lesser Slave River watershed, water usage accounts for less than 1% of the average annual streamflow.

### 4.4 Land Use Scenarios

Under forest disturbance scenarios, there was a moderate increase in Lesser Slave Lake water levels relative to the simulated baseline (Figure 7). Increases were greatest during the early summer (May - July) and less during the later summer and fall. This was likely due to the lack of vegetation in recently disturbed areas, allowing for a higher winter snowpack due to less interception. Increases in streamflow were observed primarily in the Swan, Sakwatamau, and Freeman Rivers (Appendix H), and were most apparent during freshet (May - June) and were not detectable for the remainder of the year. These changes were most apparent in the higher-elevation tributaries likely
because these areas contain more forest, while lower elevation sub-basins were primarily covered in wetlands, agriculture, and grasslands. Given that two of the higher-elevation sub-basins (Sakwatamau and Freeman) do not drain into Lesser Slave Lake, the effect on lake levels was damped relative to what was simulated in some tributaries.

![Lesser Slave Lake average daily lake level under forest disturbance scenarios.](image)

**Figure 7.** Lesser Slave Lake average daily lake level under forest disturbance scenarios.

Under the wetland degradation scenarios, Lesser Slave Lake water levels increased relative to the simulated baseline (Figure 8). Increases were relatively even across the year, and were approximately double the response seen in the corresponding forest disturbance scenario. The 90% quantile of lake levels increased substantially during the summer months, suggesting that lake levels were more variable and more prone to episodic high water events under these scenarios. This response was likely because over the wetland degradation scenarios assumed an impervious surface would be created, leading to rapid runoff and removal of the flow-attenuation properties of wetlands, which allows for rapid changes in lake level due to large summer rainfall events. Increases in streamflow in this scenario were primarily found in lower-elevation tributaries, while upper elevation reaches showed no discernible response. Affected tributaries, such as the Driftwood River and Lesser Slave River at the Mouth, displayed elevated streamflow peaks and more variable flows due to faster runoff in converted regions.
Figure 8. Lesser Slave Lake average daily lake level under wetland degradation scenarios.

Under the cumulative effects scenario, Lesser Slave Lake water levels increased relative to the baseline (Figure 9). Increases were relatively uniform throughout the year, totaling approximately 0.1 m. Increases in streamflow were most apparent along the Lesser Slave River, where increases were approximately 5 m³/s and relatively uniform across the year. Upstream of Lesser Slave Lake, increases in streamflow in major tributaries (Appendix H) were modest, and only discernable during spring freshet.
Figure 9. Lesser Slave Lake average lake level under baseline and cumulative effects scenario.

Overall, for both wetland degradation and forest disturbance scenarios, increasingly large levels of disturbance lead to linearly proportional increases in runoff over an annual timescale (Figure 10). For most tributaries in the study area, the effects of wetland degradation are substantially larger than for forest disturbance. For instance, in the South Heart River, a 5% wetland degradation scenario is approximately equal to a 25% increase in forest disturbance. Conversely, in higher relief and higher elevation sites, such as the Freeman, Sakwatamau, and Swan Rivers, wetland degradation scenarios have a smaller influence on streamflow, while forest disturbances have a larger effect. This is likely due to the fact that higher elevation sites have both higher precipitation (and therefore a larger effect by changing forest interception rates) and more forest cover (averaging that a percentage change has a larger absolute footprint). Overall, the relative effect of forest disturbance and wetland degradation scenarios is tied to the land cover composition of each sub-basin, where high-relief basins typically contain more forest cover, while lower-relief typically have large wetland coverage.
Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

Figure 10. Percent change in average annual runoff relative to percentage change in land cover. Note: the percentages of land cover change are negative, while the average annual runoff response is positive.

4.4.1 Streamflow Contributions from Wetlands

In all Lesser Slave Watershed tributaries upstream of Lesser Slave Lake, between 21 and 56% of the annual streamflow was produced in wetland areas. In all sub-basins the percentage of contribution was highest in flat, lower-elevation tributaries, such as the Driftwood (45%) and South Heart Rivers (56%), where wetlands cover a large portion of the sub-basin. Conversely, higher elevation and largely forested sub-basins such as the Swan (22%), Sakwatamau (24%), and Driftpile (22%) Rivers had relatively low contributions from wetland areas.

Seasonally, wetland percent contributions were highest during winter low flow periods from November to April (Figure 9). During this period, very little snowmelt occurred and precipitation fell predominantly as snow, averaging streamflow was generated mostly through soil water reserves and stored water in wetlands. In the Driftwood River, these winter contributions made up 70 - 95% of daily streamflow. During freshet (April to July), wetland contributions were relatively low due to streamflow generated mainly through snowmelt in forested and open areas, as well as summer rainfall. In sub-basins with higher elevation reaches and thus greater winter snowpack, such as the Swan, Sakwatamau, Freeman, and East Prairie Rivers, wetland contributions were as low as 10 - 15% during this period.
Figure 11: Average daily streamflow contributions from wetlands for all sub-basins in the study area that are not downstream of Lesser Slave Lake.
4.5 Climate Scenarios

4.5.1 Historical and Future Climate

Under historical conditions, air temperatures were colder (Appendix A). The difference was greatest during the winter months, where air temperatures were 3 – 4°C colder than the present baseline. Conversely, summer (June - September) air temperatures were less than 0.5°C colder than present, while some scenarios had months warmer than the current baseline. In general, air temperatures have increased approaching present day, particularly during the winter and spring months. In general, summer precipitation increased approaching current day. Precipitation was approximately 10 mm/month higher during the winter months, and 8 - 15 mm/month lower during the rest of the year under all historical climate scenarios relative to current-day conditions.

In general, climate in the Lesser Slave Watershed is projected to be warmer and wetter under all future climate scenarios (Appendix A). Air temperatures are expected to increase more over time; average basin-wide temperatures are expected to increase approximately 2°C between 2010 and 2040, and an increase of 4 – 6°C is projected by 2070 – 2100. Precipitation is projected to increase substantially relative to historical conditions. These changes are projected to increase over time, with average monthly increases of 2 - 3 mm/month in 2010 – 2040, and 6 - 8 mm/month by 2070 – 2100. Increases are generally most dramatic in the winter and fall, while mid-summer (June - July) increases are negligible.

4.5.2 Range of Natural Variability

Overall, variability in average Lesser Slave Lake water levels between 30-years periods is modest. Lake levels during spring freshet (May - July) exhibit only modest variability between 30-year periods (Figure 12). Late-summer and winter water levels (September - April) were higher during the 1971 - 2000 period while late-April lake levels were higher during the two most recent periods (1971 - 2000 and 1986 – 2015) relative to the rest of the 20th century. This less-pronounced seasonality is likely due to warmer mid-winter weather would have contributed to episodic snowmelt, depleting the snowpack and leading to less seasonal variability in water levels, but yielding higher winter water levels. The earliest period (1901 – 1930) had lowest average lake levels; approximately 0.15 m lower than the Baseline period, and 0.05 m lower than the median for the entire 100-year reconstruction. It should be noted that there were no changes in the weir at the outlet of Lesser Slave Lake during these simulations; therefore, all scenarios represent weir levels that would be consistent with current conditions.
Streamflow exhibited larger inter-period variability than lake levels (see Appendix E). Spring flows show the largest change, where more recent periods have substantially lower freshets. The decrease in spring runoff was largest for sub-basins with higher elevation reaches, such as the Freeman, West Prairie, and Swan River. Conversely, changes were more modest in low-relief sub-basins such as the South Heart and Driftwood River. This is likely due to warmer winter weather, which would have depleted the deeper snowpack at higher elevations, thereby lessening water available during spring snowmelt. Conversely, summer and fall flows were lower under more recent periods, likely due to the fact that earlier freshet and snowpack depletion led to less water storage for late-summer baseflow.

4.5.3 Future Projections

Under all future climate scenarios, water levels on Lesser Slave Lake were projected to increase substantially throughout the year (Figure 13). This increase is projected to be largest during the spring runoff, and all future simulations project a more marked peak in water levels during the spring, coinciding with snowmelt. This peak in water levels was larger and occurred earlier in the spring under the higher greenhouse gas emissions scenario (RCP 8.5). For the period of 2070 – 2100, lake levels are projected to increase by approximately 0.8 m. Even under more conservative climate scenarios (RCP
4.5), lake levels are projected to reach 577.0 m in at least one out of every five springs; approximately 0.5 m above rate and level for the range of natural variability.

In general, simulated changes in streamflow were greatest along the lower reaches of the Lesser Slave River (see Appendix C). Increases in spring flow were up to two to three times higher during the spring at Lesser Slave River at Slave Lake. Changes were less severe at higher-elevation sub-basins in the study area such as the Sakwatamau, Freeman, and Swan Rivers, where only moderate increases in spring flow were observed under most climate scenarios. In all cases, changes were largest under the higher greenhouse gas scenario and further-into-the-future climate scenario (RCP 8.5, 2070 – 2100). In all tributaries, under all climate scenarios, late-summer flows were projected to be lower than the current baseline, while winter flows were projected to be higher. This is likely due to projected warmer winters, which will deplete snowpack and stored water earlier in the spring, while warmer winter weather will provide occasional snowmelt and rain events that will increase mid-winter streamflow.

4.5.4 Temporal Variability

Overall, average water levels for Lesser Slave Lake increased approximately 0.2 m from 1915 to 1985, with levels varying by approximately 0.4 m in four out of five years (Figure 14). Simulated average lake
levels under climate scenarios were projected to increase by 0.4 - 0.5 m by 2085, with lake levels varying as much as 1.8 m in four out of five years. On average, annual lake level variability was likely to double or triple by the end of the century, with higher variability (and higher average lake levels) under the higher greenhouse gas emissions scenario (RCP 8.5).

Figure 14: Lesser Slave Lake average annual lake levels by overlapping 30-year normals from 1901 to 2100. Observed period is referenced as 2000 and encompasses 1986 – 2015. Shaded areas correspond to 10 and 90% quantiles of annual average lake levels.

Average annual streamflow increased in all Lesser Slave watershed tributaries from 1900 to 2000 (Appendix D). In general, this increase was relatively uniform; however, increases were higher in lower elevation tributaries such as the Driftwood, East Prairie, and Lesser Slave Rivers. Future climate scenarios suggest large increases in average annual flow over the coming century. Increases were projected to be greater and relatively uniform under the RCP 8.5 scenario, with larger increases in higher elevation tributaries such as the Sakwatamau, Freeman, and Swan Rivers.

Simulations suggest annual average maximum daily flow increased in all Lesser Slave Watershed tributaries from 1900 to 2000 (Appendix D). In most tributaries, this increase was relatively uniform;
however, increases were much more variable in the upper Swan River and Sakwatamau River. In all tributaries, maximum daily flows were projected to increase by the end of the 21st century. While maximum daily flows in lower-elevation tributaries were projected to increase linearly through the coming century, flows in higher-elevation tributaries such as the Sakwatamau and Swan were projected to decrease until 2055 under the RCP 4.5 scenario.

Average annual runoff increased in all Lesser Slave Watershed tributaries from 1901 to 2015, and in all future climate scenarios (Appendix E). Spatially, runoff was highest in the higher elevation tributaries located south of Lesser Slave Lake along the peak of the Swan Hills. Increases in runoff were projected to be largest under the RCP 8.5, 2070 – 2100 climate scenario, with average annual runoff projected to roughly double.
5.0 Discussion

5.1 The Current and Future Hydrological Regime of the Lesser Slave Watershed

Tributaries in the study area can be grouped into two separate sub-basin types, which reflect varying levels of water production and the processes that drive streamflow in each sub-basin. One group consists of higher elevation, high relief sub-basins and includes the Swan, Sakwatamau, Freeman, and East Prairie Rivers. Streamflow in these tributaries originates along headwater reaches in the Swan Hills above 1000 m and encompass 500 - 800 m of relief. These sub-basins generally have higher runoff and streamflow occurs predominantly during the spring freshet. Runoff is mainly driven by the deeper snowpack found at higher elevations in the study area due to colder air temperatures and higher precipitation. These factors lead to a typical nival streamflow pattern characterized by high flows during spring snowmelt and lower summer and winter flows.

The second group consists of low-elevation and low-relief sub-basins, characterized by variable flows, lower runoff, and a less seasonally dominant pattern. These tributaries include the Driftwood, Driftpile, West Prairie, and South Heart Rivers, as well as lower reaches of the Lesser Slave River. Given the lack of high elevation reaches in these sub-basins, the snowpack is generally low due to less winter precipitation and episodic winter snowmelt. This leads to the lack of a pronounced spring freshet and less annual runoff. Streamflow in these sub-basins are less seasonal and more variable than in the high-elevation group as increases streamflow are generally ephemeral and largely driven by episodic summer storms.

Streamflow contributions from wetlands in the watershed follow a strongly seasonal pattern while their overall contributions to streamflow vary by sub-basin. In all cases, wetlands were primarily responsible for flow occurring during low-flow periods from November to April. During periods where there was limited snowmelt and rainfall, streamflow was generated by baseflow. Much of this water is stored in wetlands and accompanying deep soils during the spring and summer and is released slowly. The percentage of contribution from wetlands varies by sub-basin, generally proportionally to the total area covered in wetlands and the size of the winter snowpack. These two factors are related and generally correspond to the two major sub-basin types: higher elevation reaches typically see moderate contributions to streamflow from wetlands during low-flow periods and minor contributions during high flow periods, while low-elevation and low relief sub-basins are more reliant on wetlands for streamflow.

Changes in hydrologic regime and streamflow timing due to projected climate change were greater for the low elevation, low relief sub-basins than for the high relief sub-basins. Since air temperatures are warmer at lower elevations and more often close to the melting point during the winter, additional warming generates episodic winter snowmelt at lower elevations. Lower elevation sub-basins were more prone to these events and, therefore, on average end up with lower winter snowpack. Conversely, higher elevation sub-basins had cooler air temperatures, fewer episodic winter melts, and more stable winter snowpack, providing a reliable spring runoff, more a more seasonal streamflow pattern, and a
more resilient hydrologic regime in response to changing climatic conditions. This is in contrast to lower elevation sub-basins where the lack of a reliable winter snowpack averages that streamflow is more reliant on ephemeral summer storms.

The stability of winter snowpack in each sub-basin is threshold-based; that is, basins that have winter temperatures more often near the melting point (0° C) are more susceptible to episodic melt. Under both climate change scenarios, air temperatures are predicted to increase, which is likely to affect the hydrologic regime of these currently stable higher elevation sub-basins. This is evident in both the predicted earlier onset of spring freshet and in more variable summer, fall, and winter flows (Appendix D). While the annual runoff is expected to increase for all sub-basins in the Lesser Slave Watershed, the change in timing of flows is expected to exhibit a larger relative change.

5.2 Water Resources in the Watershed and Drivers of Hydrologic Change

Within the Lesser Slave Watershed, water demand is relatively modest and has a minimal impact on water levels in Lesser Slave Lake. Water use is predominantly on the Lesser Slave River, Lesser Slave Lake, and the South Heart River, while many of the sub-basins in the study area have little or no water use. Even a doubling of water use is unlikely to be detected anywhere upstream of Lesser Slave Lake.

Forest disturbance and wetland degradation scenarios have modest effects on streamflow patterns and moderate effects on Lesser Slave Lake water levels. Both land use changes increase flow, particularly during spring freshet, but their effects are larger at local scales and in sub-basins with larger areas that are converted. For instance, forest disturbance has a discernible effect on peak and spring flows in the Swan River sub-basin where a large portion of the sub-basin is forested, while flows in the Driftwood River sub-basin are largely unchanged since the sub-basin is mostly composed of agriculture and wetland land cover. Conversely, replacing wetlands with an impervious surface leads to overall increases in streamflow due to reduced interception from vegetation, evaporation, and infiltration to soils. However, increases in streamflow were seen almost entirely immediately following rain and snowmelt events, while baseflow did not change markedly, and in some cases decreased.

While changes in forest disturbance, wetland degradation, and water use affect sub-basin and watershed-scale hydrology, projected changes in future climate dwarf these effects. In this region, increases in air temperature and precipitation have relatively large effects on the consistency of winter snowpack at higher elevations and on the magnitude of summer storms. While climate scenarios project higher streamflow and water levels, hydrologic modelling in this study also suggests increase flow variability. Earlier freshets and depletion of the winter snowpack leave many of the Lesser Slave Lake Watershed sub-basins more reliant on summer storms to supplement their flow during the fall and winter - typically periods when more water shortages could occur.
6.0 Conclusions

To quantify the effects of climate change, land use, and water allocations on the hydrology of the Lesser Slave Watershed and Lesser Slave Lake, the hydrology of the region was simulated using a refined version of the hydrological model designed as part of the Athabasca Integrated Regional Model. Simulated results show that runoff was greater in higher elevation sub-basins where winter snowpack was larger and less prone to episodic winter melts. Simulated water levels in Lesser Slave Lake have risen only modestly over the last century. However, much larger increases are expected in the coming century due to increased precipitation.

Land use scenarios demonstrate that both forest disturbance and wetland degradation increase streamflow on an annual timescale. The magnitude and timing of these effects depends on the location and type of the disturbance. Sub-basins with large areas of forest or wetland are more prone to changes, since a larger proportion of the sub-basin can be altered. Additionally, forest disturbances typically lead to larger changes in spring snowmelt and freshet and modest increases in low flows, while wetland degradation typically results faster streamflow response to storm events and small increases or decreases in baseflows. Current water allocations in the watershed have a relatively minor effect on water quantity and any discernible effect was limited to the South Heart River, Lesser Slave Lake, and Lesser Slave River. In these sub-basins, a doubling of usage leads to annual changes in streamflow of approximately 1%.

Wetland contributions were both seasonally and annually variable. Wetlands predominantly contributed to streamflow during the low flow periods, suggesting they play important roles in sustaining baseflows during periods in which water shortages are typically observed. On an annual scale, the contributions of wetlands to streamflow vary by sub-basin, mainly as a function of the relative percentage of the sub-basin covered in wetlands. In high relief sub-basins, which are primarily forested, wetlands contribute little to streamflow, while low relief sub-basins with high wetland coverage are very reliant on them for water production.

Changes in climate are likely to drive the most significant alterations to the regional hydrology. Under all tested climate scenarios, the projected changes were large enough to not only increase flows, but also to change the hydrologic regime of much of the watershed. For instance, while many of the sub-basins, particularly those with higher relief, currently do not experience frequent winter warm spells that melt much of the snowpack, these events are projected to occur more often and be more severe in the future. These changes, in turn, are likely to affect the reliability of spring freshet and alter the flood risk. Overall, while changes to land use and water allocations will have important local effects on sub-basin hydrology, changes in climate are likely to be the primary driver of future hydrologic change by disrupting the timing and reliability of flows over the entire watershed.
6.1 Key Messages

6.1.1 Hydrologic Regime
- Runoff is higher in high elevation sub-basins.
- High elevation sub-basins follow a largely snowmelt-dominated streamflow pattern, while low elevation sub-basins are less seasonally variable.

6.1.2 Water Usage
- Water use accounts for less than 1% of annual runoff in the Lesser Slave Watershed.
- Usage is primarily concentrated in the lower Lesser Slave and South Heart Rivers.

6.1.3 Land Use Change
- Forest disturbances lead to an increase in runoff. The effects of this are larger in higher elevation basins, where precipitation and winter snowpacks are greater. Streamflow increases are most pronounced during spring runoff due to higher winter snowpacks in non-forested areas.
- Wetland degradation leads to an increase in runoff and makes Lesser Slave Lake more prone to high water events. The effects of this are larger in lower elevation basins, near Lesser Slave Lake, where most wetlands are located. Streamflow increases substantially immediately following rain or snowmelt events, but there are minimal increases or decreases in baseflows.
- For both wetland degradation and forest disturbance, increasingly large levels of disturbance lead to linearly proportional increases in runoff at an annual timescale. For low relief sub-basins, wetland degradation has a larger effect, while conversely forest disturbance has a larger effect in high relief forested sub-basins.

6.1.4 Wetland Contributions to Streamflow
- Streamflow contributions from wetlands are highest in low relief and low elevation sub-basins.
- Streamflow from wetlands are highest during low-flow periods, predominantly during the winter months, suggesting they are effective at attenuating flows and storing water to be subsequently released later in the year.

6.1.5 Climate Change
- Future climate conditions are projected to be wetter and warmer under the scenarios used, particularly during the winter months.
- Simulated water levels for Lesser Slave Lake show only modest changes, and a relatively low range of natural variability. Streamflow in sub-basins occurred earlier and was larger relative to the current-day baseline.
- Under all future climate scenarios, projections indicate large increases in water levels and streamflow, well above the range of natural variability.
- Freshet is projected to occur earlier in the spring and winter flows are projected to increase
under all climate scenarios.

- Runoff, average annual flow, and peak flows are all projected to increase under future climate scenarios.
- Overall, while changes to land use and water allocations will have important local effects on sub-basin hydrology, changes in climate are likely to disrupt the timing and reliability of flows over the entire watershed to a more substantial degree.
7.0 References


Daly, C. (2002a). Western Canada average monthly or annual average temperature, 1961-90. Spatial Climate Analysis Service at Oregon State University, Corvallis, Oregon, USA.

Daly, C. (2002b). Western Canada average monthly or annual precipitation, 1961-90. Spatial Climate Analysis Service at Oregon State University, Corvallis, Oregon, USA.


Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

Appendices

A. Lesser Slave Lake Storage Curves

Table 4: Lesser Slave Lake stage-discharge-volume-area curve derived for AIRM (Alberta WaterSMART, 2017)

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### B. Water Usage Data

Table 5. Average Monthly Water Usage ($m^3/s$) used in AIRM. Tributaries with no water usage are excluded.

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<th>Jul</th>
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C. Climate Scenarios

Figure 15: Average changes in air temperatures and precipitation under historical climate scenarios used in this study
Figure 16: Average changes in air temperatures and precipitation under future climate change scenarios used in this study
D. Water Demands

**Lesser Slave Lake Water Use Simulations**

![Graphs showing average daily streamflow for major tributaries in the Lesser Slave Watershed under different water usage scenarios.](image)

**Figure 17:** Average daily streamflow for major tributaries in the Lesser Slave Watershed under Water use scenarios.
Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

E. Climate Change Scenarios

Lesser Slave Watershed Natural Range of Variability

Figure 18: Average daily streamflow for major tributaries under historical climate scenarios.

Lesser Slave Watershed Future Projections

Figure 19: Average daily streamflow for all tributaries under future climate scenarios.
F. Time Series Variables

Figure 20: Average average annual flow by overlapping 30-year normals from 1901 – 2100.
Figure 21: Average annual maximum daily flow by overlapping 30-year normals from 1901 – 2100.
Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

Figure 22: Average Julian date of peak annual flow by overlapping 30-year normals from 1901 – 2100.
G. Runoff Maps

Historical Climate Scenarios

Figure 23: Map of average annual runoff for all historical climate scenarios in this study.
Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

Figure 24: Map of average annual runoff for all future climate scenarios in this study.
H. Land Use Scenarios

Figure 25: Average daily streamflow for all major tributaries under forest disturbance scenarios.
Quantifying the effects of climate change and land use on streamflow and lake levels in the Lesser Slave Watershed

Figure 24. Average daily streamflow for all major tributaries under wetland degradation scenarios.
Figure 26. Average daily streamflow for all tributaries under cumulative effects scenario.