Hydrological Analysis for Great Slave Lake 2020

Dec 15, 2020

ECCC-led Report
with modifications by the Government of the Northwest Territories

1. Executive Summary

At the request of the Deputy Minister of the Department of Environment and Natural Resources of the Government of the NWT (GNWT) and after consultation with the Governments of Alberta and British Columbia, a decision was made by the Associate Deputy Minister of Environment and Climate Change Canada (ECCC) to create a technical working group to better understand and explain the high-water levels on Great Slave Lake (GSL) in the summer and fall of 2020, as well as the potential for the duration of these high waters. There is a need to understand attribution of the high-water levels so that contributing conditions are understood and that causality is evidence-based.

A technical working group was formed on September 15, 2020 to gather information from the ECCC networks, models and production systems that are readily available. This group was comprised of staff from ECCC, and the Governments of Alberta, Saskatchewan and the Northwest Territories, as well as BC Hydro. The current status of the science-based efforts is summarized below. Further to this work, we will collectively develop an agreed upon understanding of the system and communicate these findings between partners.

As stated below, we are looking at a suite of methods to gain an understanding of the high water levels on Great Slave Lake this year. Findings to date show the following:

1. Based on the provisional hydrometric observations provided by the National Hydrological Service/Water Survey of Canada, the water levels observed on **GSL reached an all-time high level** since gauging commenced in the 1930s **with all major tributaries reaching higher than normal levels, including:**
    a. **Lake Athabasca**, where water levels reached the second highest peak on record;
    b. **Peace River**, where flow has exceeded the 75th percentile for much of the summer of 2020;
    c. **Athabasca River**, where flow has been much higher than normal throughout the summer of 2020, and the total volumetric discharge on the Athabasca River in 2020 will very likely be the largest of the 62-year record;
    d. **Fond du Lac, Tazin and Taltson Rivers**, where flows have been at or near record highs for much of the summer of 2020; and
    e. **Lockhart River**, where flow has been the highest on record through the late summer and fall.
2. The **precipitation computations** revealed:
    a. **Alberta** Environment and Parks' **anomalies map for 2019-2020** shows excess precipitation **(200% above normal)** in the northern part of Alberta in the Peace-Athabasca Delta region for the Sept 1 2019 to Aug 31 2020 period;
    b. Canadian Meteorological Centre (CMC) **annual precipitation analysis** to date shows **significant positive precipitation anomalies for the Mackenzie River drainage basins that feed GSL and equal to the highest on record for the hydrological year spanning September 2019 – August 2020** when compared to climatology for the 2000 to 2018 period;

   c. **Seasonal Precipitation analysis** shows **record summer precipitation** for Athabasca watershed in 2020; and
   d. **Monthly Precipitation analysis** shows record high input locally within the GSL region in 2020 for the month of August.
3. Two different methods were used to attempt to calculate a basin water balance for Great Slave Lake. The methods included a **residual analysis** and a **component analysis**:
   a. The **residual analysis** revealed:
      i. **Inflows were consistently larger than outflows for most of 2020, particularly in July;**
      ii. **Slave River discharge** was close to average for the start of the calendar year, but **exceeded the 75th percentile during summer and into fall;**
      iii. **Peace River had the second highest contribution amount** compared to other hydrological years between 1979/80 and 2019/20;
      iv. **Athabasca River had the highest contribution amount** over the same period;
      v. **Local gauged inflows to GSL** (defined as all inflows excluding the Slave River) **had the third highest contribution amount** over the same period;
      vi. **Lake Athabasca and the Peace Athabasca Delta contributions were lower than average**, but not significantly so (possibly due to hydraulic damming by high water levels on the Peace River); and
      vii. **Other tributaries contributing directly to GSL,** including the Hay River, Lockhart River, Taltson River and Snare River, **all experienced well above normal summer flows with many peaks at or near record levels being reached at seven of the minor inflow gauges**. This suggests significant ungauged local inflow into GSL over the summer period.
   b. The **component analysis** confirmed that:
      i. There were very high inflows to GSL from the local basin and from the Slave River; and
      ii. It is an infrequent occurrence that both of these inflows exhibit this behaviour over the same period.
4. Even if inflows decrease significantly, the **time required to reduce water levels on Great Slave Lake is quite long because of the large storage capacity of the lake**.
   a. Based on the **residual analysis** and an outflow model, we anticipate that **Great Slave Lake water levels** will not return to **normal historical levels of 156.61 m** for an extended period of time based on statistical modelling analysis.
5. By examining derived **inflows and outflows around the Williston Reservoir** (the reservoir which is impounded by the W.A.C. Bennett Dam), we were able to set the context for reservoir operations. It was determined that **the summer of 2020 represented the highest inflows into the Williston Reservoir system since 1979.** When both the derived Williston inflow and outflow volumes are routed to GSL and compared to 2020 observed GSL data, it is observed that the water levels on GSL may have been almost 0.5 m higher if the W.A.C. Bennett Dam did not impound the high inflow volumes from spring and summer. This scenario does not, however, include proper routing through the Peace Athabasca Delta and Lake Athabasca complex and as a result, this estimation is likely somewhat overestimated.

6. Water levels over the course of the winter and spring freshet conditions are difficult to predict at this time as they will be dependent on a number of variables, including:
    a. Winter river recession curves;
    b. Over-winter rain (in southern parts of the basin);
    c. Volume and density of snow received over-winter;
    d. Timing of snowfall;
    e. Thickness of river and lake ice;
    f. Timing and rate of spring melt; and
    g. Site-specific biophysical characteristics.

    Furthermore, given that there is no historic analogue for the current conditions, we cannot make predictions based on recession rates from previous years.

In summary, the analysis has shown that inputs from the Slave River into Great Slave Lake have been much higher than normal for the duration of the summer. It appears that the Peace and Athabasca rivers both contributed significantly to these flows, with strong contribution from the Lake Athabasca region helping to sustain these high flows. Furthermore, we have observed very high inflows from local rivers around Great Slave Lake, especially to the east and southeast of the lake. We attribute this to exceedingly high precipitation over the hydrological year in the much of the basin. Looking ahead, winter water levels and spring freshet conditions are difficult to predict, as recent and current conditions are unprecedented, and will be dependent on many variables, such as timing and amount of precipitation over winter.

2. Science Questions

The first major task of the working group was to examine the total inflows into GSL and attempt to attribute the flows to regional and temporal change that may have occurred in the basin over the spring and summer this past year.

- *What are the historical estimates of the Net Basin Supply and Net Total Supply (NBS/NTS) of Great Slave Lake thus far in 2020 and how have any potential changes to the water balance components affected the level of the lake?*
- *Given the current water level conditions, is it possible to determine how long the lake will remain at these levels and project changes in water levels over the near future?*

The science questions are being extensively investigated and the report provides a summary of the efforts to date. The report is an ECCC-led effort in partnership with the Government of the Northwest Territories. It has been circulated to the scientists and engineers in Alberta, BC and Northwest Territories for additional insights. A phase I draft report was completed on Friday Oct 2. This phase II final report is the culmination of the efforts.

3. Analytical Framework

At the request of the Associate Deputy Minister (ADM) of ECCC, and after consultation with the Governments of the Northwest Territories (GNWT), Alberta and BC, a decision was made to develop a technical working group to try to understand the above-noted science questions.

In order to expedite the analysis, an ECCC technical working group was formed on September 15 to gather information from the ECCC networks, models and production systems that are readily available. In addition to ECCC studies (e.g., Northern Rivers Ecosystem Initiative, 2004) and operational models, ECCC also reached out to the Global Water Futures (GWF) programme for their assistance given their comprehensive study of historical analyses. The Working Group (WG) met again on September 23rd to share the efforts to date and identify work to be carried out over the following weeks.

The technical working group is made up of the following members.

- MSC-NHS (Evan Friesenhan, Aaron Thompson, Malcolm Conly, Derek Forsbloom, Daniel Princz, Dave Hutchinson, Al Pietroniro, Scott Palfreyman, Megan Garner)
- MSC-CCMEP (Dorothy Dunford)
- STB-ASTD (Étienne Gaborit, Vincent Fortin)
- STB-WSTD (Daniel Peters, Daqing Yang, Chris Spence, Ram Yerubandi)
- Global Water Futures (Mohamed Elshamy, John Pomeroy)
- Alberta Environment (Carmen de la Chevrotiere)
- BC Hydro (Martin Jasek, Heather Matthews)
- GNWT (Shawne Kokelj, Ryan Connon)

The purpose of this meeting was to look at possible ways to estimate Net Basin Supplies and Net Total Supplies into GSL historically for context and to examine the 2020 conditions with respect to these supplies. The challenge is that much of the basin is ungauged and that precipitation gauges in the region are limited, therefore there is a need to use models to infer the Net Basin Supply (NBS) and Net Total Supply (NTS).

Given the short time frame requested by GNWT and ADM to initiate initial examination of the science questions, the team used existing products and services, as well as published studies, to develop the context. To that end, we are aware of three separate initiatives that will allow for these calculations with a quick turn-around.

Component NBS-NTS

1. Dorothy Dunford will use the operational NSPRS system at a high resolution to calculate NBS and NTS with streamflow substation for gauged regions from possibly 2008 to present but more likely 2018 to present.
2. Etienne Gaborit will use an open loop coarser resolution version of the same model with re-analysis from 2008 to present to estimate NBS and NTS components.
3. Mohamed Elshamy will extract NBS/NTS from historic Mackenzie GWF runs using WATCH forcing from 1979 - 2018

Residual NBS/NTS

1. NHS team, led by Evan Friesenhan will calculate residual NBS and estimate lake drawdown using observations and change in lake levels.

4. Understanding the Water Balance of Great Slave Lake

The first task of the hydroclimatic analysis was to assess the validity of existing methodologies used to determine contemporary estimates of the GSL water balance. Although the existing conventional methodologies used for estimating water balance components have proven relatively successful in the past (*e.g*., Gibson *et al*, 2006a), questions remain regarding measurement uncertainties associated with the principal components of the GSL water balance (*i.e*., precipitation, evaporation and runoff). To address these questions, the Study sought to improve accuracy and consistency in NBS estimates, including the modification of existing models, development of new models, collection of new data, and improvement of a range of methodologies that have been used for lake level estimation. These analyses were also fundamental to ensuring that any potential future climate outcomes could be understood and attributed to past changes. This attribution required historical estimates of the water balance elements to be as bias-free as possible and to have uncertainty bounds associated with each element.

Geography

Great Slave Lake (GSL) located in the Northwest Territories is one of the deepest freshwater lakes in the world (614 m) and is hydrologically dynamic due to large inflows from 949 000 km^2 drainage area comprised of mountain, boreal forest – plains - shield areas that feed the Mackenzie River (Figure 1). Roughly 65% of the contributing areas drained by the Slave River are supplied by the Peace-Athabasca Delta – Lake Athabasca system (606 000 km^2).

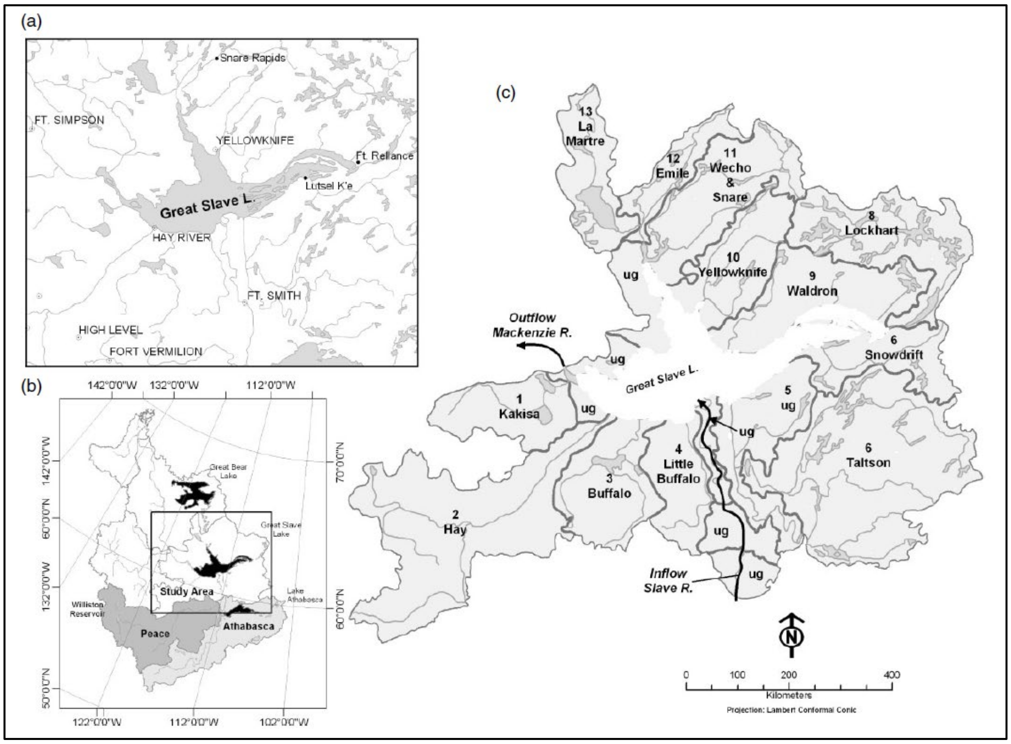

Figure 1 - Maps of (a) Great Slave Lake and water level and precipitation monitoring sites, (b) the Mackenzie Basin showing major sub-basins and large lakes, (c) catchments tributary to Great Slave Lake. Note that catchment numbers refer to Table I; ug is ungauged (Gibson et al., 2006a).

Water Balance

The mean annual water balance of GSL can be expressed as follows:

$$I + P – E - O = dS/dt +/- G +/- error$$

where:

I is the collective riverine inflow to the lake ($m^3\ s^{-1}$);
P is the precipitation on the lake surface ($m^3\ s^{-1}$);
E is the evaporation from the lake surface ($m^3\ s^{-1}$);
O is the riverine outflow ($m^3\ s^{-1}$);
G is the unknown groundwater inflow/outflow from the lake bottom;
S is the lake storage change over time t ($m^3\ s^{-1}$) which at this point is ignored.

Surface area of GSL is assumed to be 28 568 km^2.

Up to ~85% of the contributing areas to GSL have been gauged as part of the National Hydrometric Service (NHS), with this percentage varying over the historical period. Select inflows are shown in Figure 2, highlighting the importance of the Slave River to the water balance of GSL.

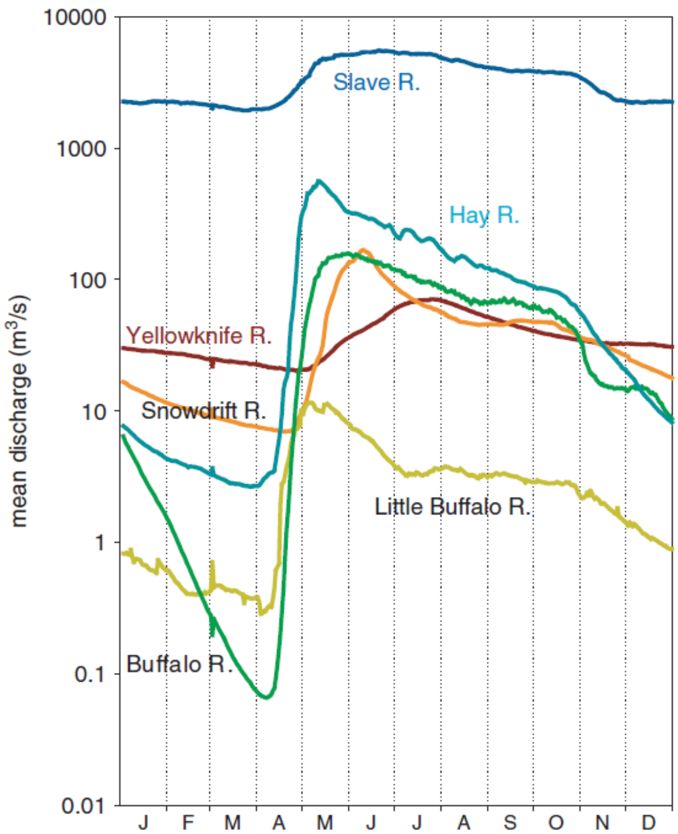

Figure 2 - Mean flow regime of inflows to Great Slave Lake. (Gibson et al., 2006a)

5. Historical Inflows and Current Water Levels and Flow

Based on the real time provisional data available from the ECCC HYDAT online database, the 2020 water levels observed on GSL reached an all-time high level since gauging commenced in the 1930s (Figure 3). The daily water level regime of GSL has been influenced by flow regulation since 1968 when construction of WAC Bennett Dam was completed (Figure 4). Noteworthy, the end of summer 2020 water level on GSL was higher than the 1962 natural flow regime generated peak, as well as the high level in 1996 when substantial volume of water was released from Williston Reservoir, combining with above normal downstream runoff. The 2020 water levels on Lake Athabasca are above normal and reached one of the highest levels on record, fed by above normal spring and summer inflows into the LA-PAD from the Athabasca River and Fond du Lac River. Outflow from the LA-PAD combines with the Peace River to make up Slave River flow into GSL.

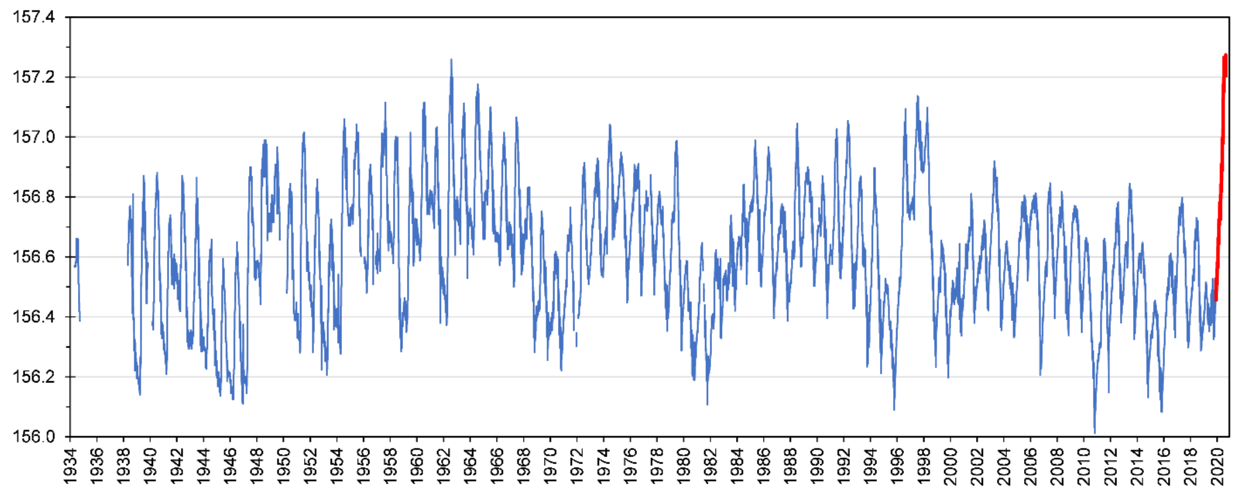

Figure 3 - Historical mean daily water level on Great Slave Lake at Yellowknife Bay (station 07SB001). Note that 2020 data in red are provisional.

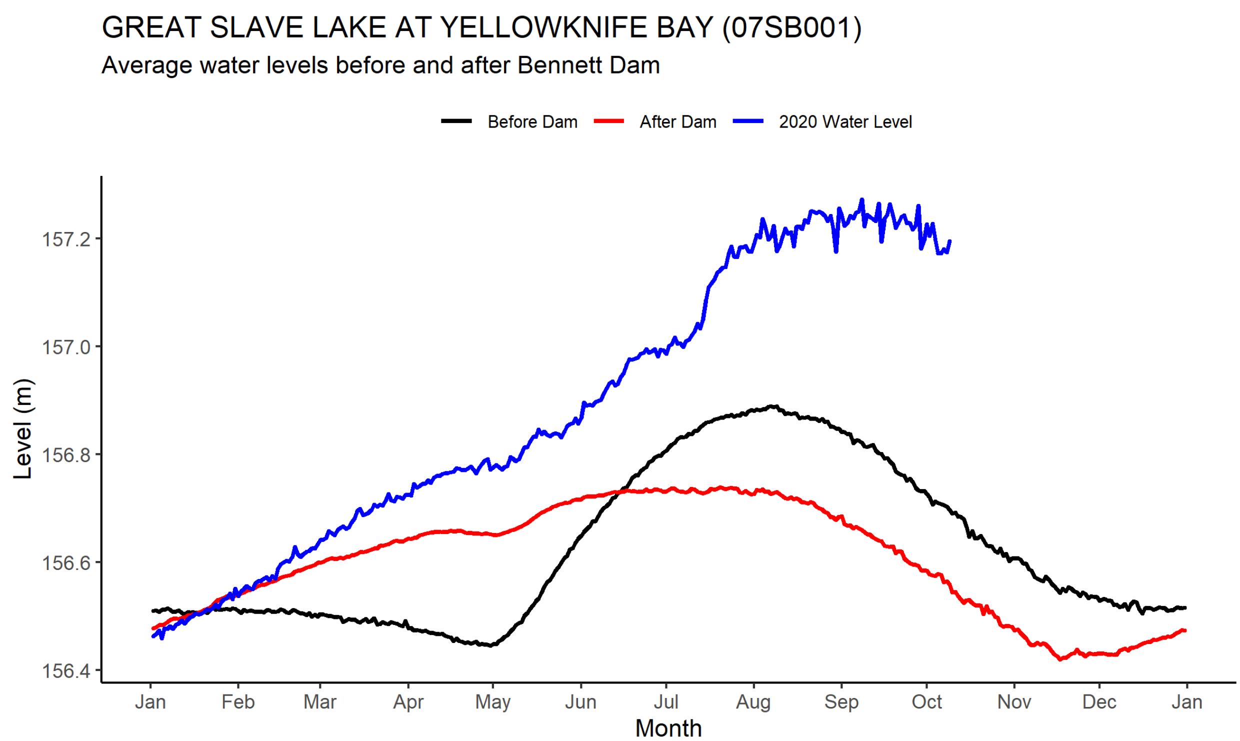

Figure 4 - Average daily water levels on Great Slave Lake before and after the Bennett Dam began operations. Also includes provisional water levels for 2020.

Flow rates on the Peace River in 2020

Flow on the Peace River was above average between November 2019 and April 2020, and much higher than average between July and September 2020 (Figure 5, Figure 6). According to various sources, these high flows were due primarily to high winter and summer precipitation. Northern British Columbia and

Alberta received between 115 – 200% more precipitation than normal, impacting regulated and unregulated river basins across a broad region. The average flow rate for the month of August on the Peace River above Pine River was 1020 $m^3 s^{-1}$ (1972-2020). In 2020, the August average flow rate was 2275 $m^3 s^{-1}$, more than double the average for the period of record.

High precipitation is likely the primary reason for higher than normal August average flow rate downstream of the Bennett Dam (which is inferred through the July and August sections of the hydrograph for Peace River above Pine River, Figure 5). It should be noted that flows in tributaries downstream of the dams (i.e. unregulated systems; Smoky River) are also very high this year, although these systems exhibit more of a natural (flashy) hydrologic regime with steeper peaks and shorter recession limbs (Figure 7). Water levels in Williston Lake (the reservoir above Bennett Dam) dropped from slightly lower than average to below average over the winter 2019-20 (Figure 8). Water levels began to rise at the end of April as snowmelt runoff added substantial volume to the reservoir. Between June and September 2020, water levels remained within the interquartile range (25th to 75th percentiles) of the historic record.

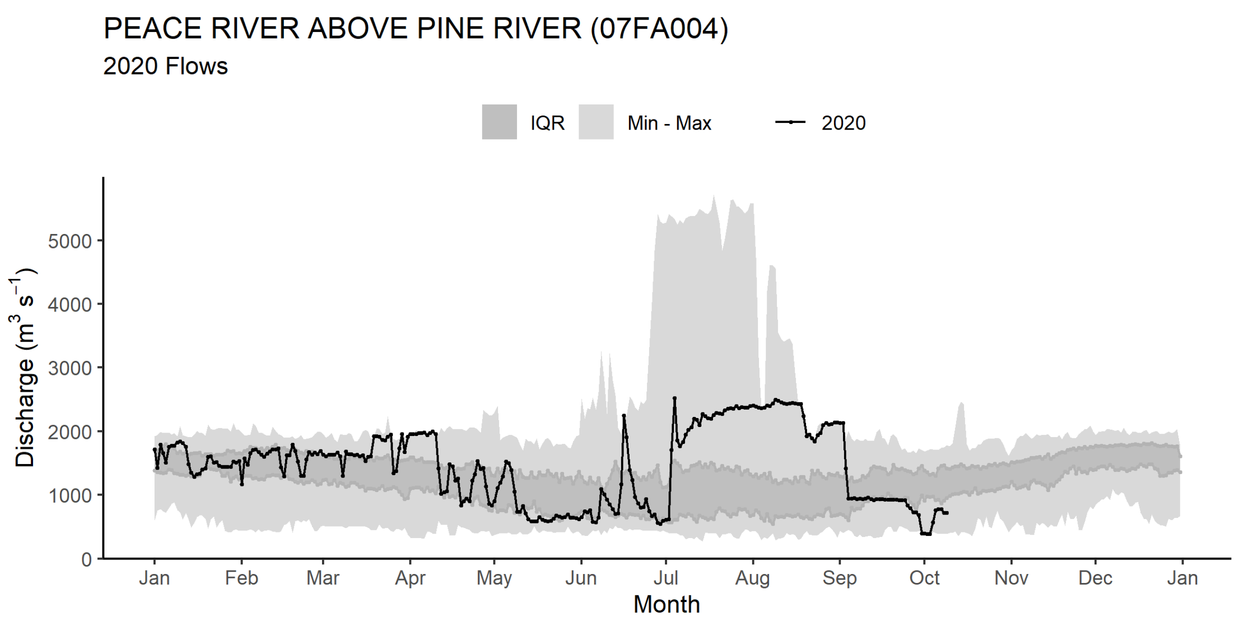

Figure 5 - 2020 flows on the Peace River above Pine River. This is the closest WSC gauge to the Bennett Dam and the best approximation of outflows using publically-available data. The gauge is 110 km downstream of the Bennett Dam and the hydrograph contains inputs from tributaries between the Dam and the Pine River.

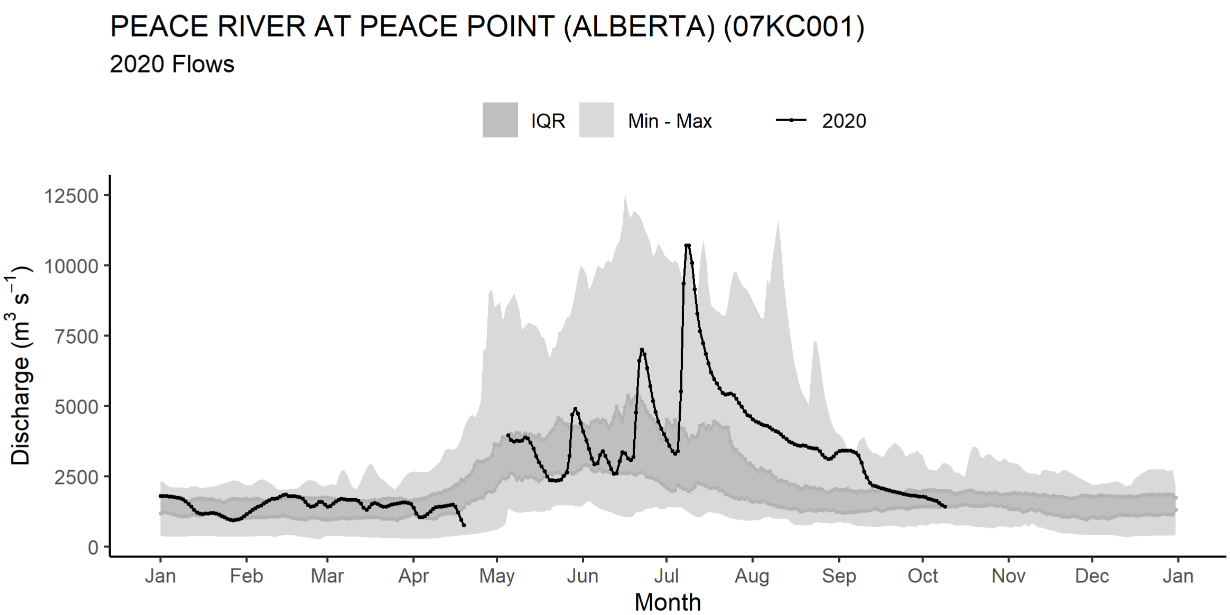

Figure 6 - 2020 flows for the Peace River at Peace Point. This is the closest WSC gauge to the Peace-Athabasca Delta on the Peace River

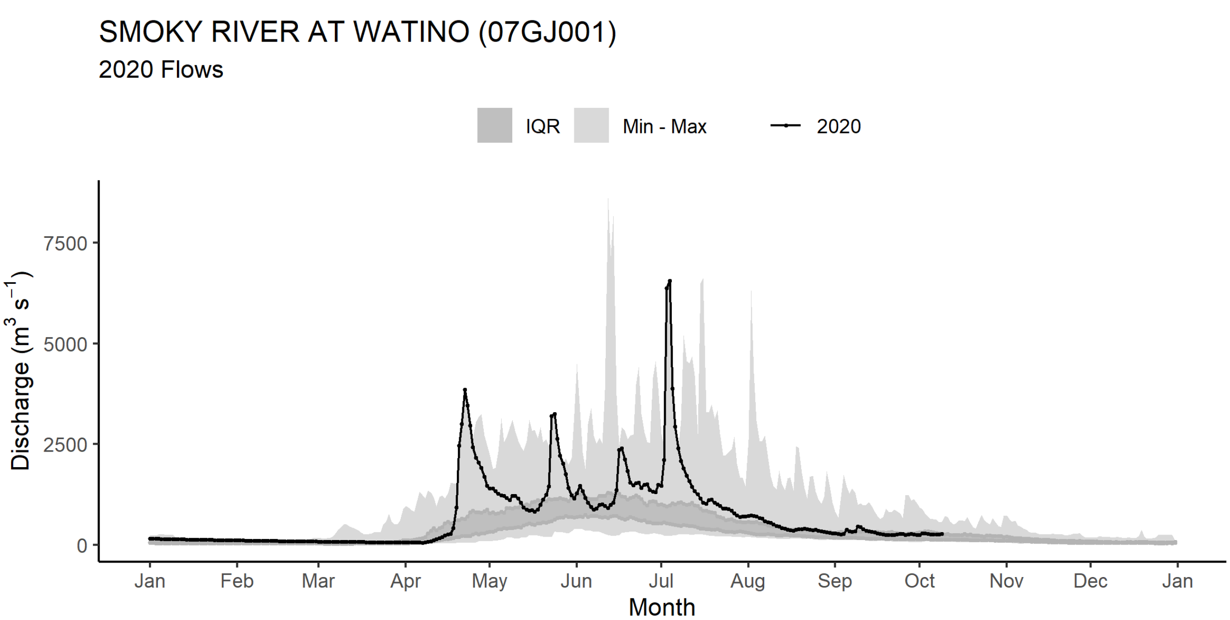

Figure 7 - 2020 flows on the Smoky River at Watino. This gauge, located in Alberta, is on the Smoky River which flows into the Peace River and is unaffected by regulation.

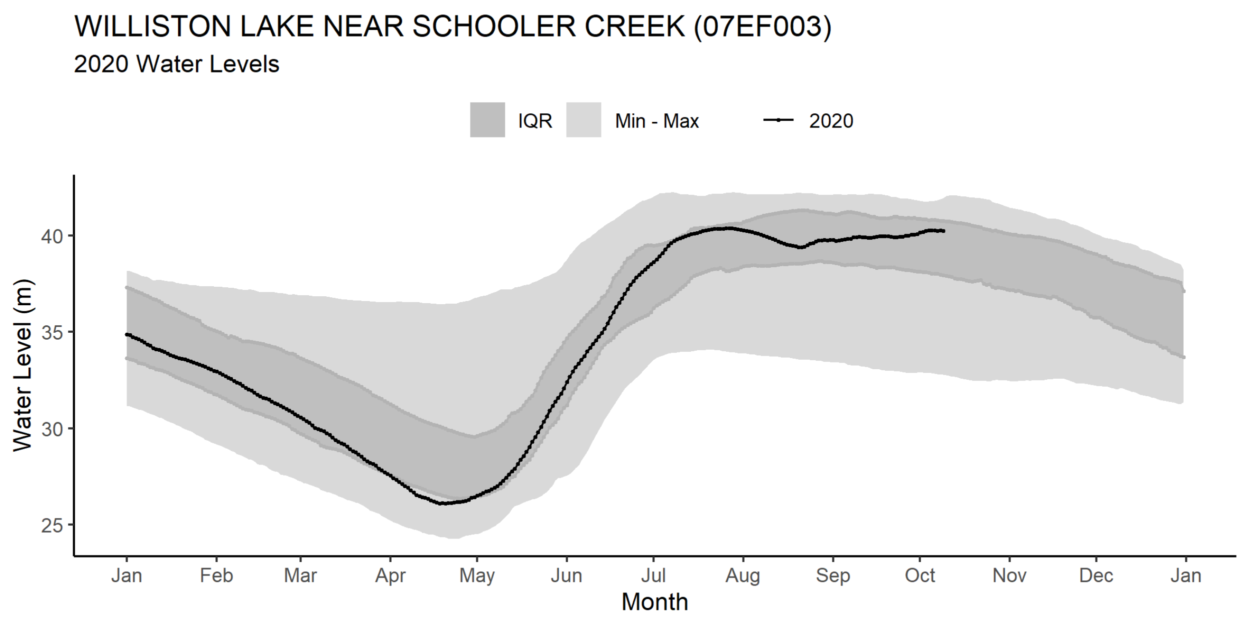

Figure 8 - 2020 water levels at the Williston Reservoir

Flow rates on the Athabasca River in 2020

Flow on the Athabasca River has been much higher than normal throughout the summer of 2020 (1958-2020; Figure 9). Although flow has diminished since summer peaks (~ 4000 m^3 s^{-1}), it is still well above the longer-term average. The total volumetric discharge on the Athabasca River in 2020 will very likely be the largest of the 62-year record.

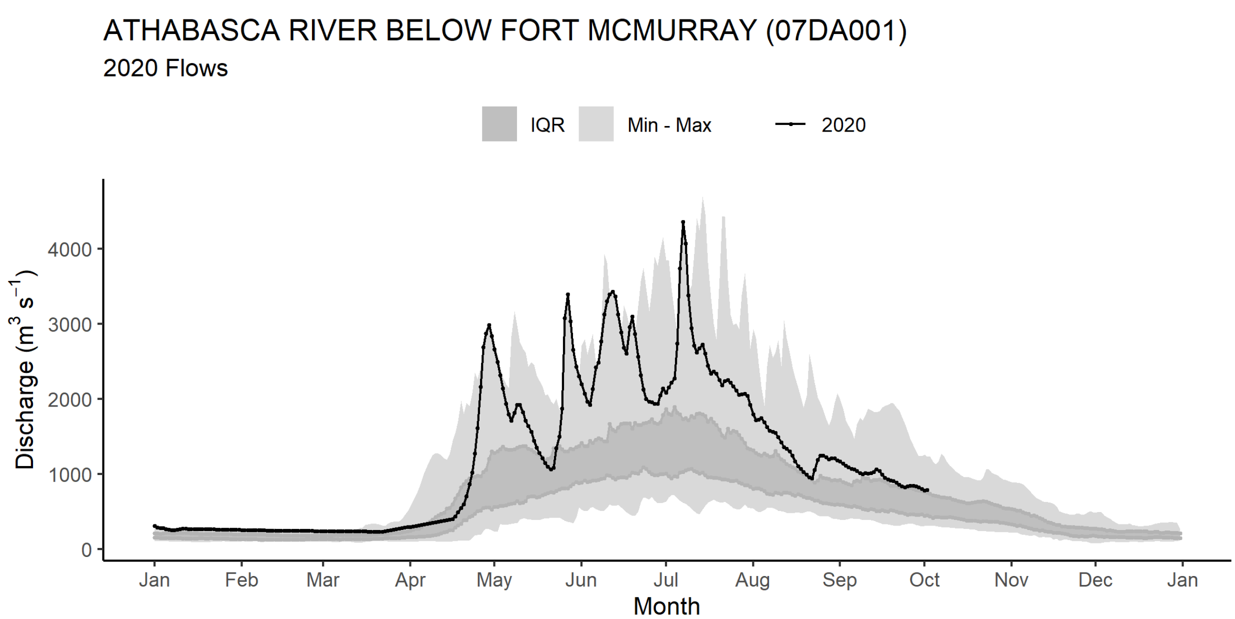

Figure 9 - 2020 flows on the Athabasca River below Fort McMurray. This is the most downstream gauge on the Athabasca River (i.e. closest to the Peace-Athabasca Delta) with a long continuous record.

Flow rates on the Slave River

Due to Covid-19 restrictions on hydrometric site visits, no flow data are available for the Slave River for most of May and June 2020. When data collection resumed in mid-June, flow rates were above the 75th percentile. Flow has been steadily decreasing since a large rain event in early July, however the rate of decline slowed through the month. Flow on the Slave River is currently much higher than normal (Figure 10). The median flow rate on the Slave River in August 2020 was 6850 $m^3 s^{-1}$, whereas the median flow rate during August is 3840 $m^3 s^{-1}$ over the period of record 1972 - 2018.

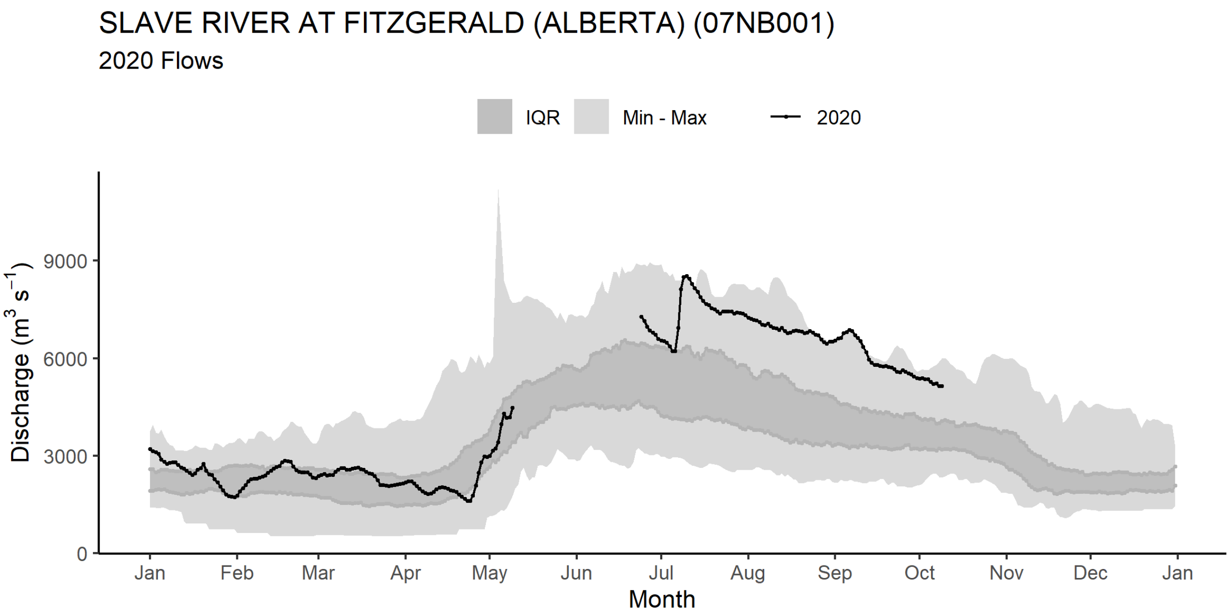

Figure 10 - 2020 flows on the Slave River at Fitzgerald.

Lake Athabasca and Flow Contribution to the Slave River

The Peace River typically contributes between 50-70% of flow to the Slave River in the summer, whereas the Athabasca River contributes between 20-25% of the flow (Figure 11). In July 2020, the residual component of the proportional flow calculation was negative (-21.4% of Slave River flows; Table 1). This was the only time there has been a negative residual in July since completion of the Bennett Dam in 1972. A negative residual implies a backwater/dam effect as a result of high water on the Peace River. This suggests: (i) a diversion of flow to Lake Athabasca and the Peace-Athabasca Delta (PAD) from both the Peace and Athabasca Rivers; and (ii) a reduction in outflow from Lake Athabasca into Slave River. In August 2020, the Peace River contributed about 4% more flow than normal, while the Athabasca River appears to have contributed about 5% less than normal. It should be noted that water levels on Lake Athabasca are currently the highest for the period 1961-2020 and second highest on record (Figure 12). Flow on the Fond du Lac River was at or near the highest on record for the summer of 2020 (ca. 600 $m^3 s^{-1}$; Figure 13) which also contributed to high water levels on Lake Athabasca. Also, the high flow on the Peace River may have impeded the outflows of the Lake Athabasca and the Peace-Athabasca Delta (LA-PAD) into Slave River. The high-water levels on Lake Athabasca may lead to an increase in over-winter inputs to the Slave River, should flows on the Peace River recede sufficiently to allow outflow from Lake Athabasca and the PAD.

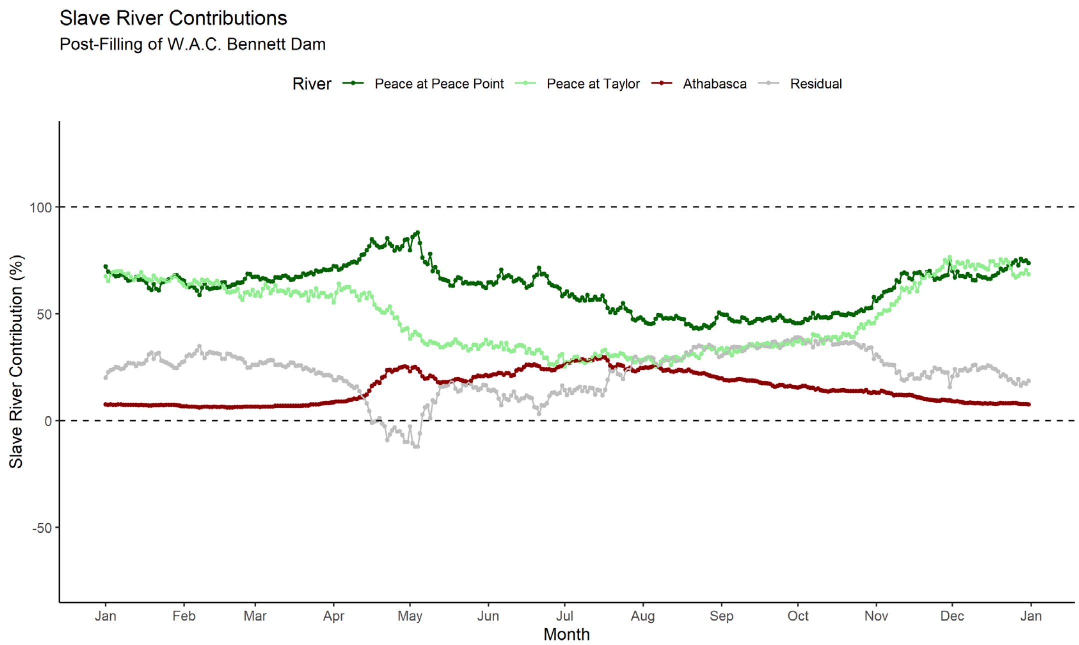

Figure 11 - Relative contributions to the Slave River (Slave River at Fitzgerald) of the Peace River (Peace River at Peace Point) and the Athabasca River (Athabasca River below Fort McMurray). The residual is calculated as the difference between Slave River flows and the sum of the Athabasca and Peace River flows.

Table 1- July 2020 flow rates in the Slave River basin

River	**July 2020 Average Flow ($m^3 s^{-1}$)**
Peace River at Peace Point	6 226
Athabasca River below Fort McMurray	2 566
Slave River at Fitzgerald	7 455
Residual	-1 337 (storage in LA-PAD)

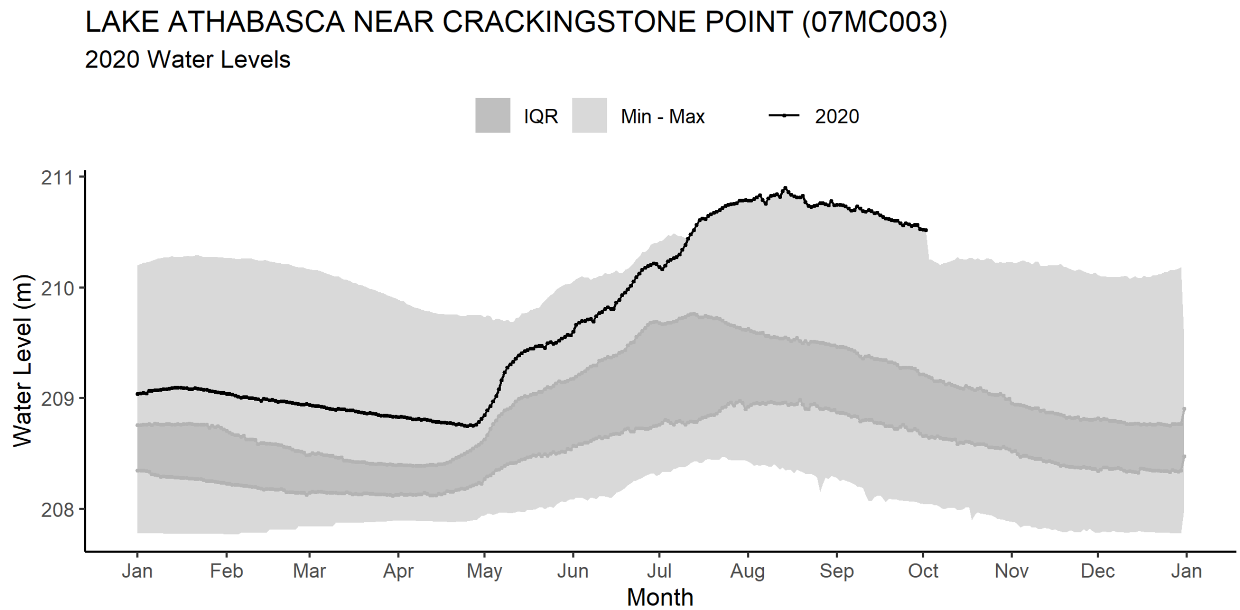

Figure 12 - 2020 water levels on Lake Athabasca near Crackingstone Point, SK.

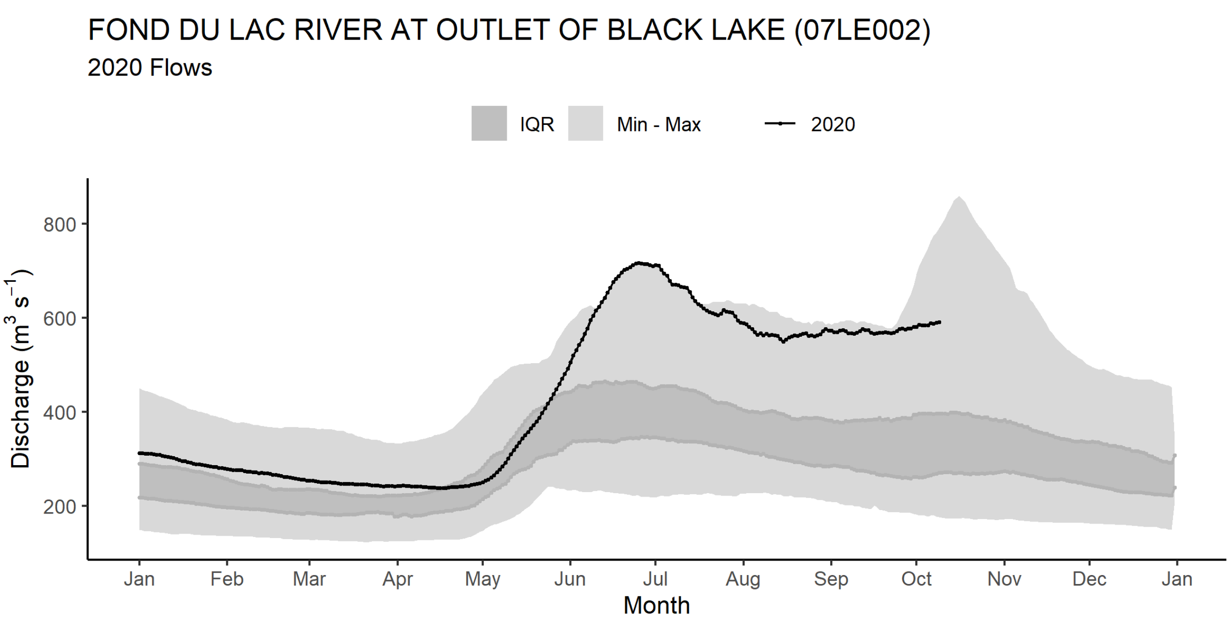

Figure 13 - 2020 flows on the Fond du Lac River at outlet of Black Lake, SK

Great Slave Lake water levels

Water levels on GSL have been at a record high since mid-July 2020 (Figure 14). Recession of seasonally high-water levels usually begins in early-mid August and continues until late November when water levels begin to rise again as a result of sustained releases from the Bennett Dam. As of early November, water levels on GSL are ~50 cm higher than average.

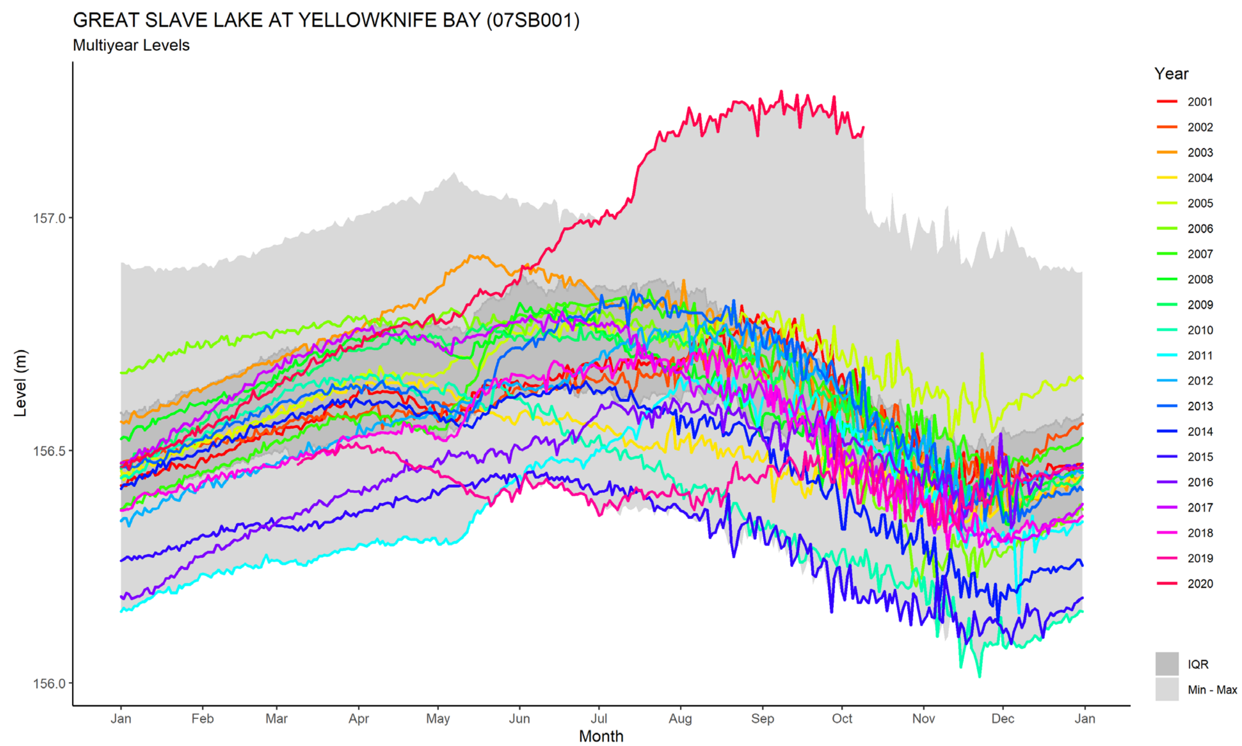

Figure 14 - Water levels on Great Slave Lake at Yellowknife Bay between 2001 and 2020. 2020 is denoted by the red line at the maximum level.

6. Precipitation Analysis of Contributing Basin

In order to understand the context of the observed water supplies into GSL, it is important to understand what precipitation patterns over this past year looked like in comparison to other years. It is important to understand that precipitation that falls on the ground may not make its way into GSL over a month or season. This water can be stored on the landscape for years as LA-PAD are major storage features that drain into GSL, and have an overall impact on the timing and amount of water flowing into the Slave River. During that time, water can also end up back in the atmosphere through evaporation of surface water or transpiration of vegetation.

Precipitation anomaly maps for the hydrological year made available by Alberta Environment and Parks highlight some important features in the overall precipitation amounts (Sept 1, 2019-August 31, 2020) for the past hydrological year.

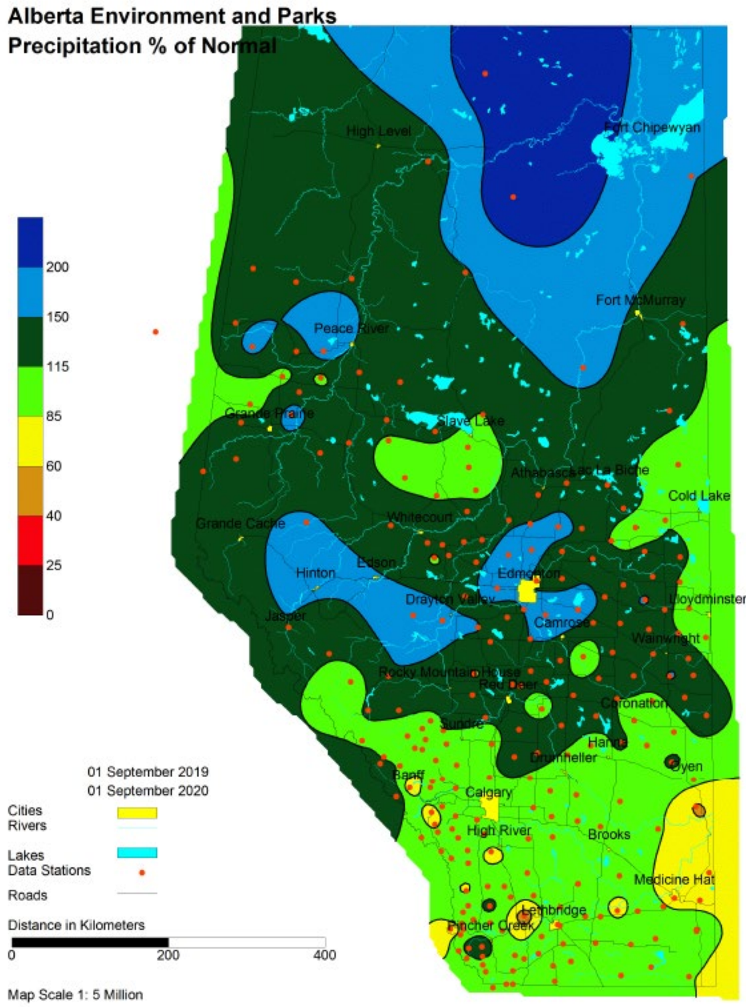

Figure 15 – Alberta precipitation map for Sept 1, 2019 to Sept 1, 2020. Note the exceedingly high precipitation rates above 200% in the Peace and Athabasca river regions downstream of the WAC Bennett Dam.

A second data set was used and made available from ECCC Numerical Weather Prediction System. This dataset and analysis combine data from the 2000-2017 CMC reanalysis and CaPA RDPA for 2018-2020. Both products have a horizontal resolution of 10 km, combine gauge data with a short-term forecast from the GEM atmospheric model, and are able to provide reasonable estimates of areal precipitation even in regions with sparse gauge networks due to the contribution of the atmospheric model.

To proceed with the analysis, following discussion with the Technical Working Group (TWG), the watershed was regionalized into three major sub-basins:

PEACE: Peace River Basin at Peace Point (station 07KC001) covers an area of 300 000 km^2, and constitutes 31% of the total watershed.

ATHABASCA: This corresponds mainly to the inputs of the Athabasca River and Lake Athabasca, and also constitutes 31% of the total watershed.

LOCAL GSL: Great Slave Lake Intermediate Sub-Basin, defined as the Mackenzie River Basin at Strong Point (Station 10FB006) minus the Slave River Basin (Station 07NB001). Its area is 375 000 km^2 or 38% of the total watershed.

Combining these sub-basins creates the Great Slave Lake Total Basin (GSL TOTAL), defined as the Mackenzie River Watershed at Strong Point (Station 10FB006). The three sub-basins have comparable sizes, which facilitates analysis. The total area is 976 000 km^2. The area of the lake itself is large (over 27,000 km^2) but is less than 3% of the total basin. The lake area is included in the GSL LOCAL sub-basin.

The contribution of each sub-basin to the average precipitation over the whole watershed is obtained by multiplying the average precipitation of the sub-basin by the fraction of the total watershed that it represents, *i.e.*, by multiplying average precipitation by the area of the sub-basin and dividing by the area of the whole watershed. The three sub-area contributions to the GSL TOTAL precipitation are plotted below using a stacked area chart (the contribution of each sub-basin being displayed on top of each other), so that the GSL TOTAL monthly precipitation corresponds to the upper limit of the gray area.

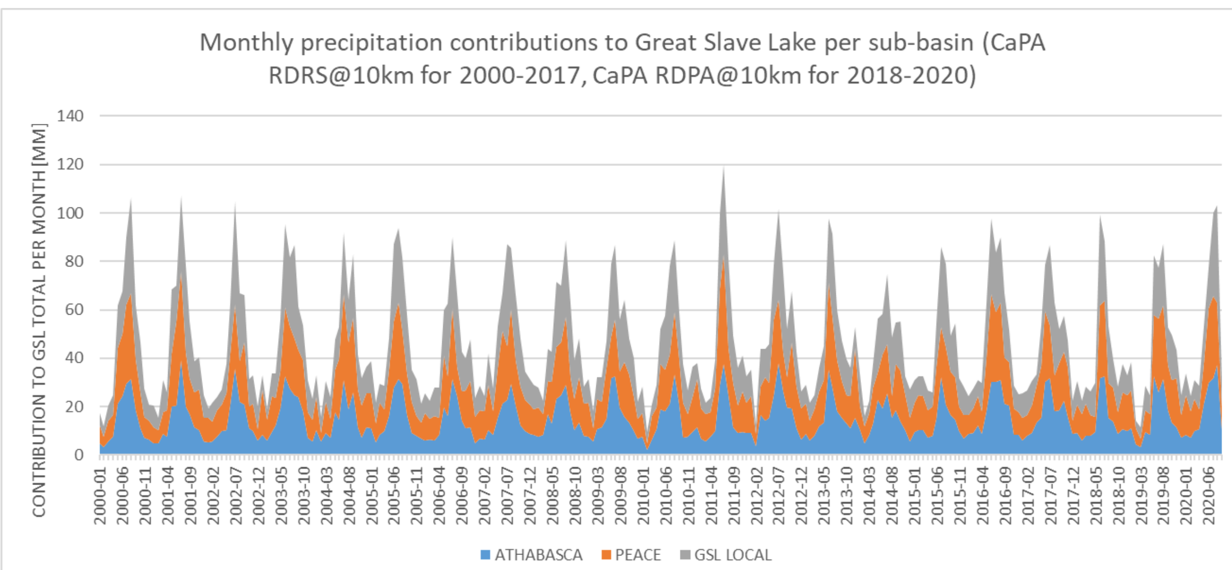

Figure 16 – Monthly precipitation estimates for the upstream and local contributing areas of Great Slave Lake using the regional re-analysis and real-time estimates for summer 2020 at 10 km resolution.

A clear annual cycle is observed for precipitation in this basin, with monthly maximums reached during the summer season. We can also see that the monthly maximums for GSL TOTAL have declined throughout the decade 2000-2010, and increased more or less regularly since 2014. In August 2020, a value of over 100 mm for GSL TOTAL was observed for the first time since 2012, and a record was also set for the contribution of the GSL LOCAL watershed during the month of August, which may have contributed to rapidly raising the lake level, as these inputs arrive faster at the lake. The summer of 2020 was also exceptional for the ATHABASCA sub-basin, where a record amount of precipitation was observed for the total of the June, July and August months. However, when you look at the behaviour of each of the three sub-basins for 2020, it is not clear which of the three sub-basins contributed the most to precipitation over the year. Indeed, monthly precipitation totals are difficult to interpret in terms of their impact on water levels, since storage and evapotranspiration within the basins can impact substantially the timing and magnitude of inflows into GSL. In order to eliminate as best as possible this issue when considering only precipitation, we can examine annual totals as a context to make some comments on attribution. The table below presents the calculated annual contributions to annual GSL (GSL Total) watershed precipitation based on the hydrological year defined as September 1 to August 31.

Table 2 – Hydrological Years analysis of average contributions to annual precipitation (in mm) for the contributing areas of GSL. The table highlights in bold highest values of each column in black, and the lowest values in red. Annual precipitation is obtained for each sub-basin by dividing the value by the percentage of the total basin that it represents (provided in parenthesis below the sub-basin name)

Contribution to GSL TOTAL annual precipitation				
Year	ATHABASCA (31% of total)	PEACE (31% of total)	GSL LOCAL (38% of total)	GSL TOTAL
2001	169	199	204	573
2002	161	176	185	522
2003	188	197	204	589
2004	170	204	155	529
2005	195	219	208	**622**
2006	**159**	**161**	209	528
2007	162	214	193	569
2008	182	194	200	576
2009	184	178	199	561
2010	165	178	196	539
2011	178	**233**	198	609
2012	188	196	**211**	595
2013	186	220	188	594
2014	175	172	176	524
2015	161	195	182	538
2016	197	214	201	611
2017	191	190	191	571
2018	186	192	180	558
2019	170	183	**150**	**503**
2020	**207**	221	193	**622**
Max	207	233	211	622
Min	159	161	150	503
Mean	179	197	191	567
Dev.	14	19	16	36

The statistics show that 2020 is a record year over the period 2000-2020 for the Athabasca sub-basin and a very high amount for the Peace Basin. Although it had a monthly record in August 2020, the GSL LOCAL sub-basin has an annual total close to the average. The record contribution from the PEACE and ATHABASCA sub-basins led to volume that equaled the record 622 mm of precipitation for the total GSL Basin. The standardized precipitation analysis for the period 2000-2020 is also plotted in Figure 17 and clearly support the above findings. Interestingly enough, Table 2 shows that record low precipitation was observed for both GSL LOCAL and GSL TOTAL in 2019. Hence, the contrast between 2020 and 2019 is by far the largest over the 2000-2020 period for GSL TOTAL watershed.

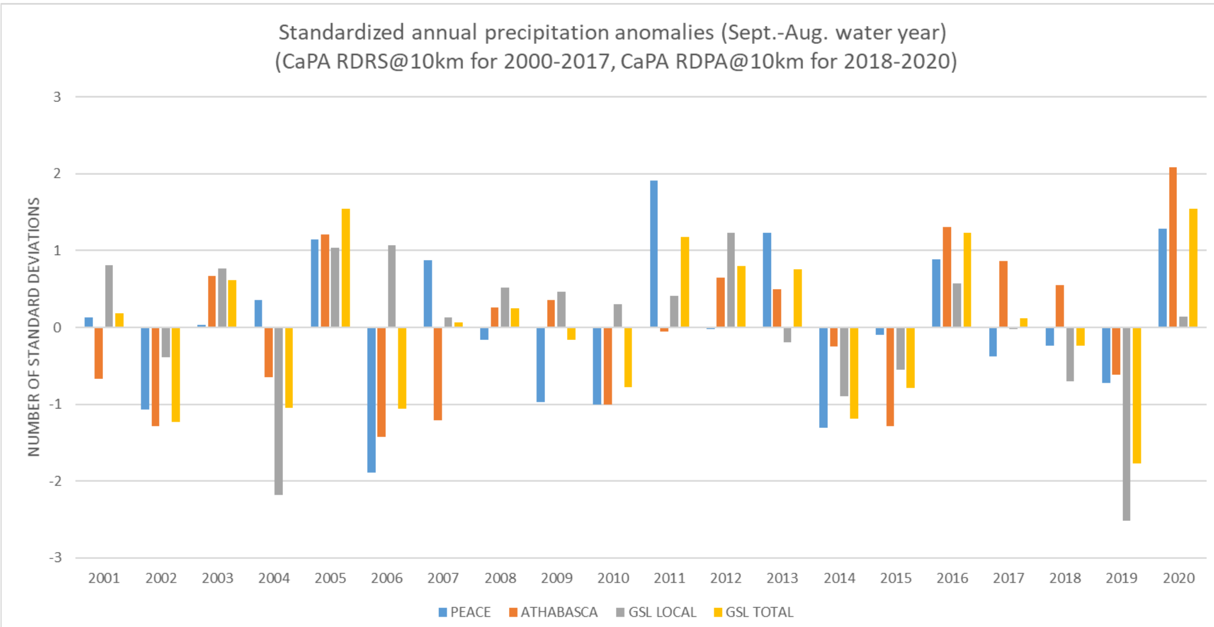

Figure 17 – Standardized Precipitation Anomalies for the Mackenzie Basin Drainage basins feeding Great Slave Lake.

7. Residual and Component Analysis

The two most commonly utilized methodologies for water balance accounting are:

- the *residual method*, which is more indirect and is based on change in storage of the lake; and,
- the *component method*, which directly computes Net Basin Supply/Net Total Supply by calculating the water balance through a quantification of the components of the hydrological cycle for each lake, and accounting for all inflows and outflows.

Residual NBS and NTS

The residual method estimates NBS indirectly by accounting for the inflow to the lakes, the outflow, and the net change in storage or water level for a period. Recorded amounts of the diversions into and out of the lake and estimates of consumptive use can also be factored in when calculating NBS.

The errors inherit in the residual method are primarily from estimations in change-in-storage, inter-basin inflow and outflows, and diversions, and ignoring thermal volumetric changes, consumptive use and groundwater.

Equation for Calculating Residual NBS for GSL

NBS = O – I + ΔS
with the TOTAL supply to the GSL
NTS = O+ ΔS

Where:
O: the outflow from GSL;
I: inflow from Slave River; and
ΔS: change in water storage of the GSL.

Understanding Component Supplies

The component method estimates NBS/NTS directly from its component contributions (*i.e*. over-lake precipitation, basin runoff, lake evaporation and groundwater). Component supplies are calculated using modelling methods since direct estimates of lake evaporation, precipitation and local runoff are not comprehensive enough or possible in such a large domain.

Calculating Component NBS/ NTS

NBS = P + R – E
and
NTS = P + R – E + I

Where:
P: overlake precipitation;
R: basin runoff to GSL;
E: evaporation from the lake surface; and
I: inflows from the Slave River

Residual Supply Investigation into High Water Levels on Great Slave Lake 2020

The locations of the hydrometric gauging stations surrounding GSL are shown in Figure 18. Inflows to the lake are measured at eleven locations, including the major source of inflow via the Slave River, as well as ten lesser tributaries. At the time of this assessment, data for 2020 were available from eight of these gauges, while the remaining three were impacted by reduced field operations in 2020.

Downstream from the lake, the hydrometric gauge Mackenzie River at Strong Point (10FB006) has been operational since October 1991. Two small tributaries, the Trout River and the Jean-Marie River, flow into the Mackenzie River between this station and the outlet of Great Slave Lake. Additionally, flow of the Kakisa River, although located closer to the body of GSL, has been demonstrated to only move downstream into the Mackenzie River, and thus is not considered as an inflow to the lake. Using data available from these gauges, outflow from GSL is estimated by subtracting the flows from Jean-Marie River at Highway 1 (10FB005), Trout River at Highway 9 (10FA002) and Kakisa River at Outlet of Kakisa Lake (07UC001) from the recorded flow of the Mackenzie River at Strong Point.

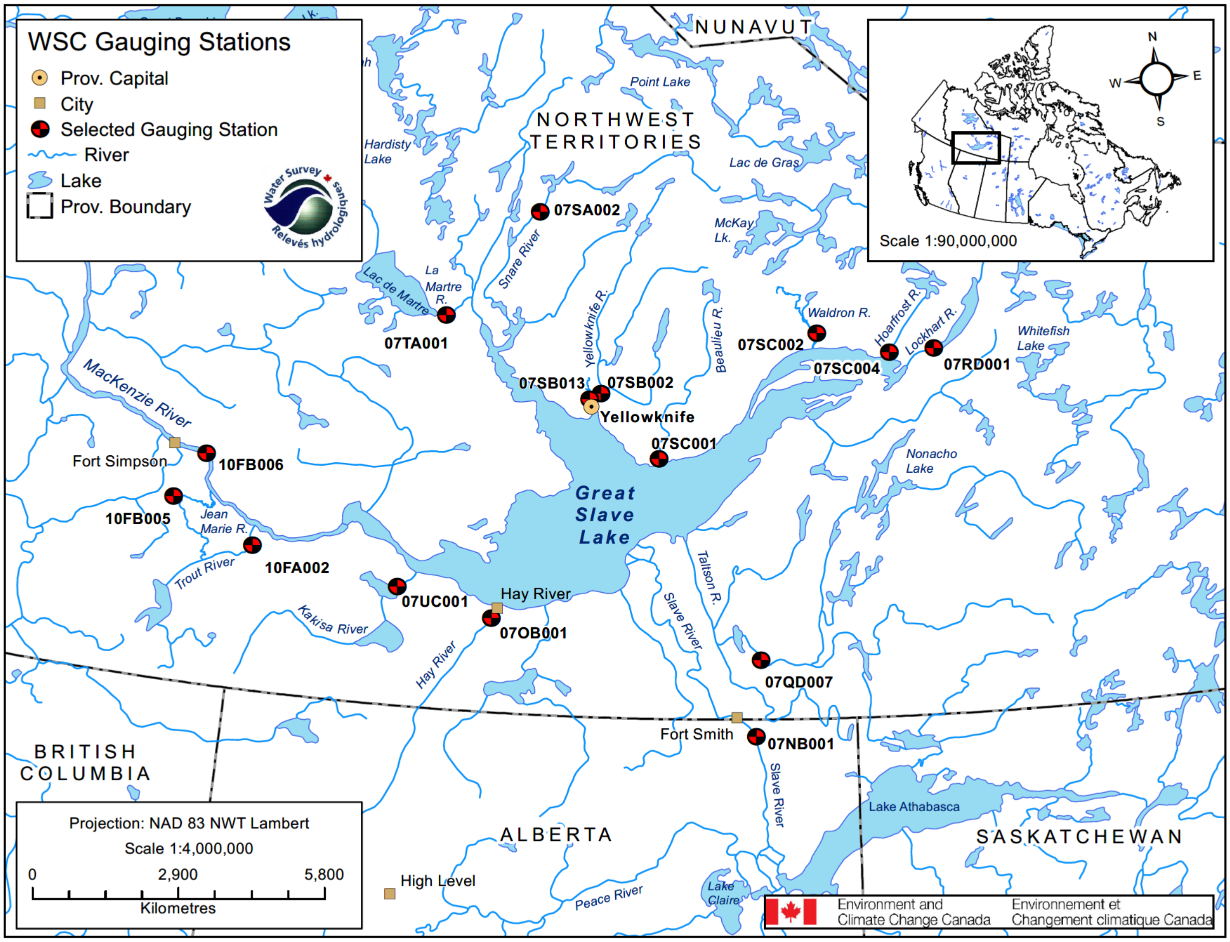

Figure 18 - Location of Water Survey of Canada hydrometric gauges used for NBS residual supply calculations.

The surface area of Great Slave Lake is 28 568 km^2 with a total volume of over 1 070 km^3. Given the surface area and volume of the lake, it is possible to estimate the change in storage of the lake by multiplying the change in water level with the surface area of the lake. A more accurate change in storage could be calculated using a stage-volume relationship determined from bathymetric and topographic data for the lake, but required information was not available at the time of this analysis.

Great Slave Lake Residual Net Total Supply

The first part of this analysis was an assessment of the inflows to the lake in 2020 based on the residual net total supply as described previously in this report. Not all of the streams and contributing area to Great Slave Lake are gauged; thus, it is difficult to estimate the contributions of the ungauged areas and over-lake precipitation directly. However, by looking at the outflows of the lake, a residual estimate of the total supplies to the lake can be determined.

NTS is the "net" inflow, which represents the total amount of water coming into the lake minus all losses, such as evaporation. This calculation is sensitive to the accuracy of lake level measurements, since a small error in level change can produce a large error in inflow estimate due to the large surface area of the lake. The calculations were conducted using a daily time step but results are presented using a 7-day average for clarity. The resulting NTS are shown in Figure 19 along with the estimated outflows and water levels for Great Slave Lake. It is evident that inflows were consistently larger than outflows for most of 2020, particularly in July.

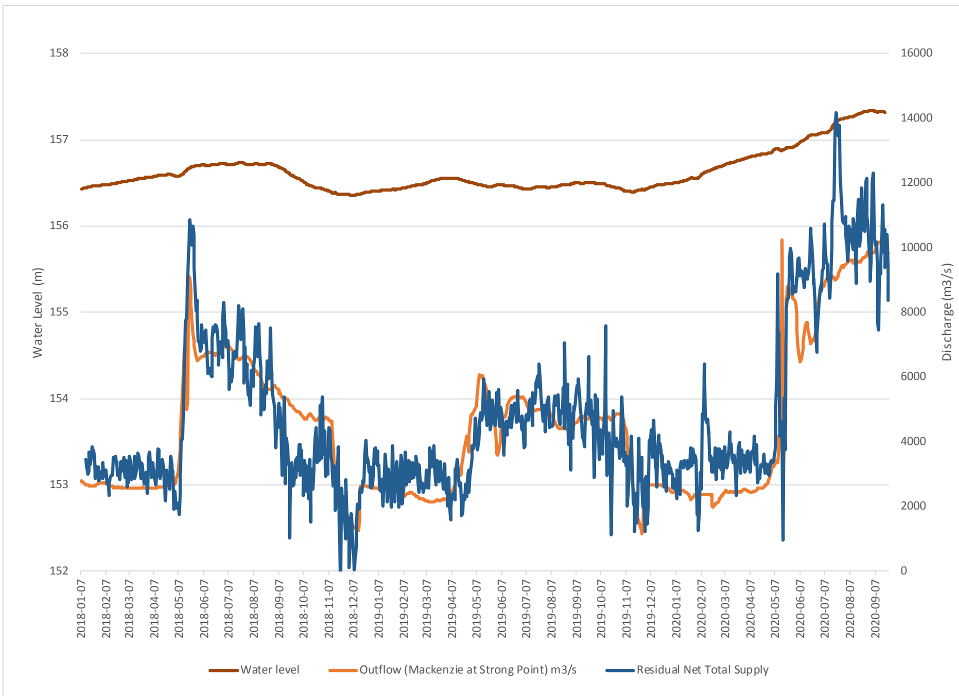

Figure 19 - 7-day average Great Slave Lake Residual Net Total Supply

2020 Residual Net Total Supply in Historical Context

In order to examine the difference between conditions experienced on GSL in 2020 compared to recent history, the same residual net total supply analysis as described above was completed for the period of October 1991 to present, based on a monthly timestep, as shown in Figure 20. The results clearly confirm the inflow volumes experienced in 2020 well surpass that of any of the previous 28 years. The recorded data from 1991-2020 were also used to calculate monthly mean net total supply for GSL, with the results as shown in Figure 21 where the inflow volumes are expressed as depth over the surface area of the lake. Again, this supports the findings above that, although the spring saw slightly above normal inflows to the lake, it has been the conditions experienced since about the start of July that have been exceptional in the context of the previous 28 years.

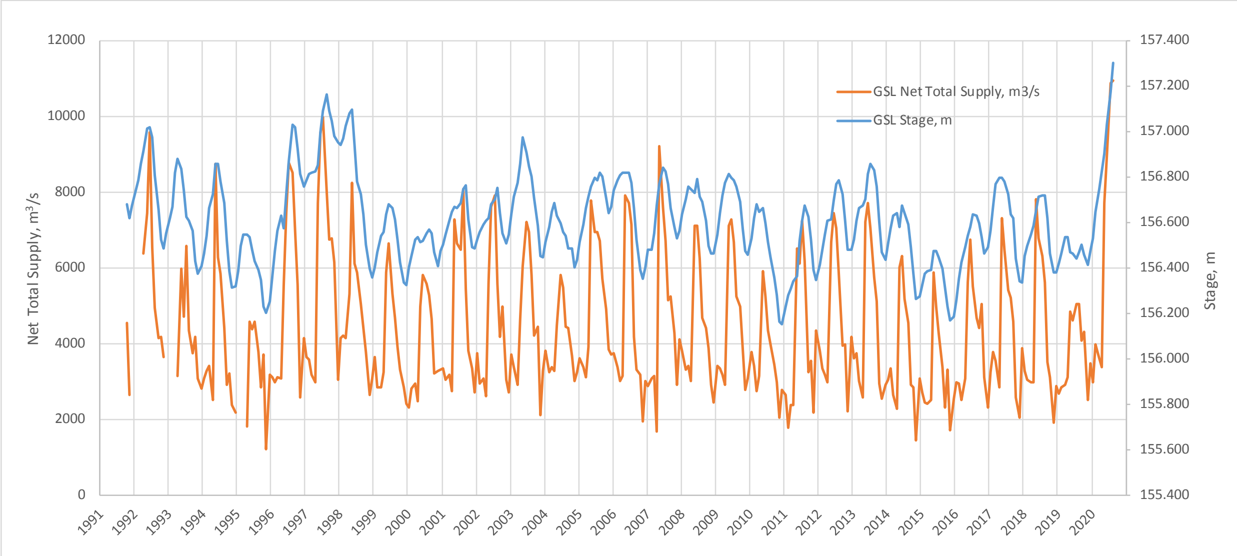

Figure 20 - Residual Net Total Supply (monthly) for the period from 1992-2020 for Great Slave Lake.

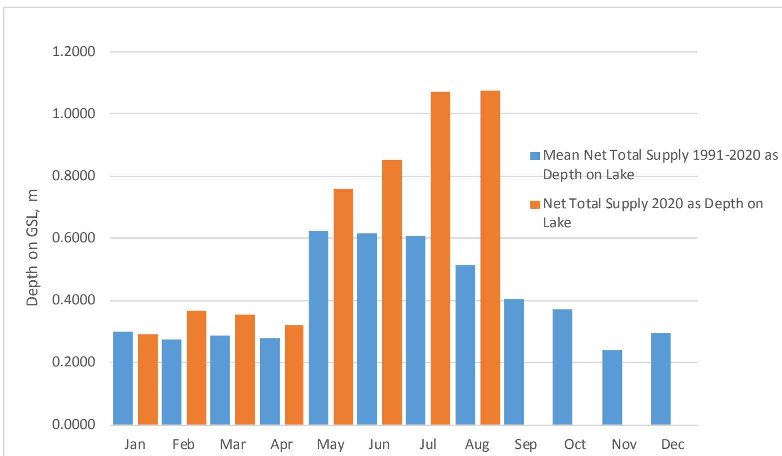

Figure 21- Monthly Mean Residual Net Total Supply for the period from 1991-2020 for Great Slave Lake in contrast to 2020, expressed as depth on the lake (assumed 28,586 km^2 surface area).

WSC Gauged Inflows and Outflows

As discussed above, for the purposes of this analysis, outflow from GSL has been estimated based on the recorded flow at four WSC gauges in the Mackenzie River basin downstream of GSL. In addition to estimating the lake outflow, provisional data from eight WSC operated gauges were used to approximate inflow to the lake (from the gauged portion of the basin). Those gauges are: 07NB001 Slave River at Fitzgerald, 07SB013 Baker Creek at Outlet of Lower Martin Lake, 07SC001 Beaulieu River near Great Slave Lake, 07RD001 Lockhart River at Outlet of Artillery Lake, 07SC002 Waldron River near the

Mouth, 07SC004 Hoarfrost River near the Mouth, 07OB001 Hay River near Hay River and 07SA002 Snare River below Ghost River.

Figure 22 compares the total gauged inflow, estimated outflow and recorded lake level on GSL. Similar to the previous figures, it shows the water level of GSL has increased steadily since the beginning of the year. Early in the year, it appears that the estimated outflow was relatively close to the gauged inflow, with the ongoing increase in the lake stage attributed to ungauged inflows and precipitation directly on the lake. Both gauged inflows and estimated outflow from the lake increased sharply through May and June. The gauged inflows to the lake peaked in the middle of July, while estimated outflow from the lake continued to increase, peaking around early September. Figure 23 illustrates the relative magnitude of recorded discharge at the gauges surrounding Great Slave Lake for 2020.

In order to better understand the conditions experienced in 2020 on GSL, the provisional WSC data for this year were compared to historical flows for the period of record for each gauge used in this analysis. The results are shown in Figure 24 to Figure 35 (below). Inflow to Great Slave Lake from the Slave River was not far off average for the start of the year, while summer saw discharges exceeding the 75th percentile, based on the period of record. The other, minor contributors to the lake, including the Hay River, Lockhart River and Hoarfrost River, all experienced well above normal summer flows, with many peaks at or near record levels being reached at seven of the minor inflow gauges. This would be indicative of significant ungauged local inflow into GSL, which would have contributed to the ongoing rise in lake levels through the summer period. Downstream of Great Slave Lake on the Mackenzie River, the gauges on the Kakisa River, Trout River and Jean Marie River have also experienced well above normal discharge from the late spring through to present.

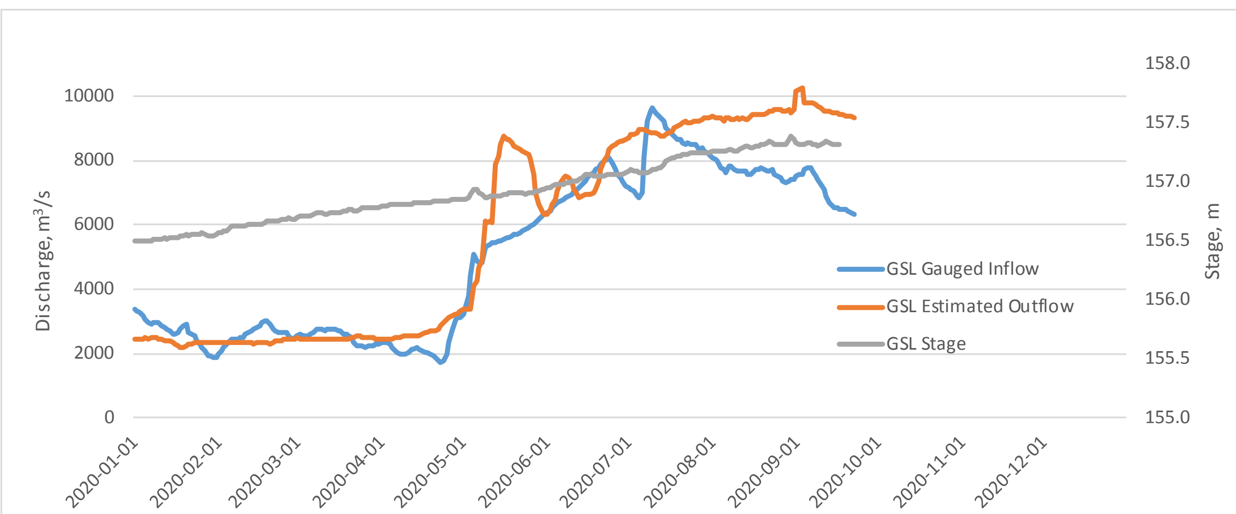

Figure 22 – Comparison of Gauged Inflow vs. Estimated Outflow from Great Slave Lake and associated lake levels (based on WSC Provisional data).

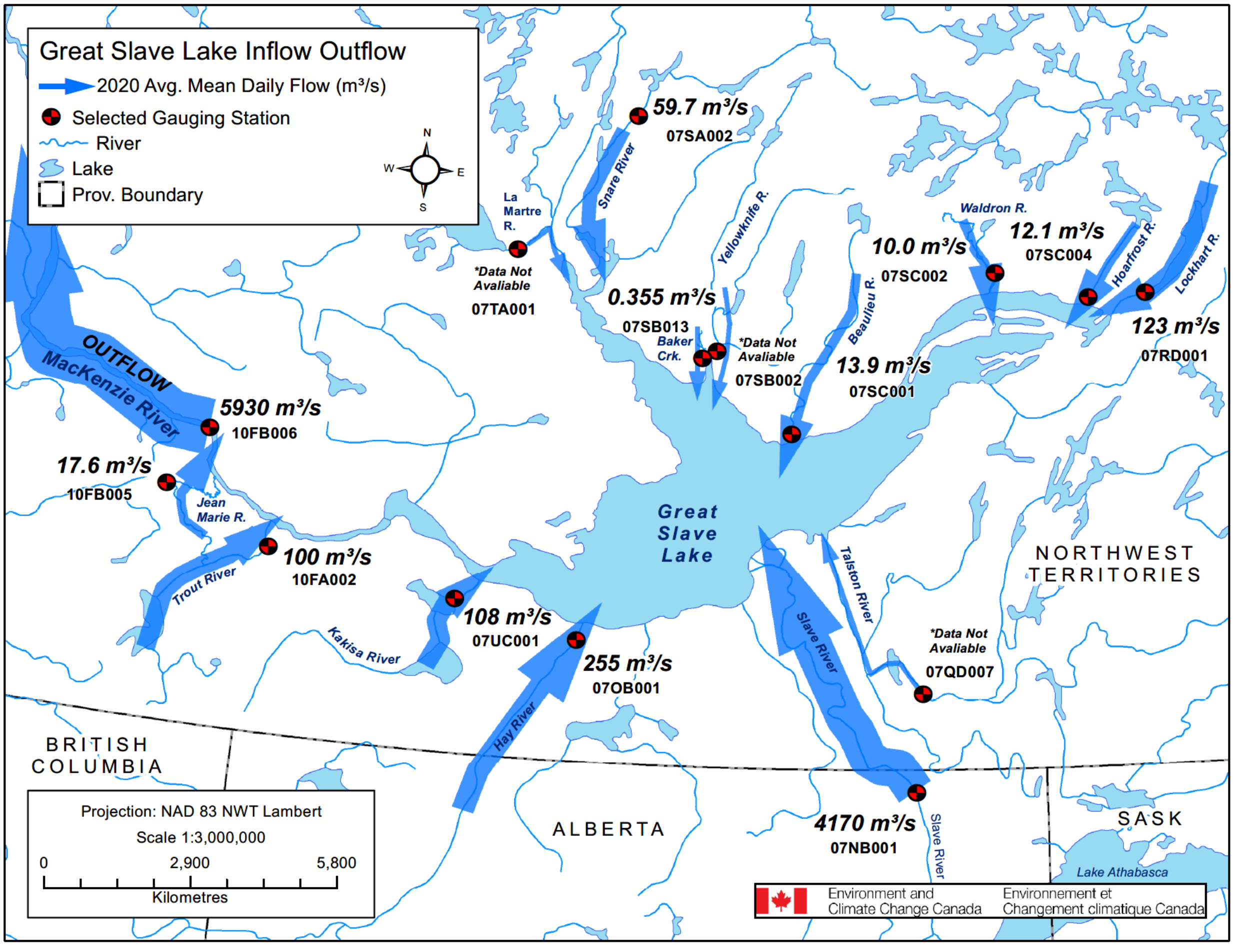

Figure 23- 2020 (Jan to present) mean daily discharge at WSC hydrometric stations.

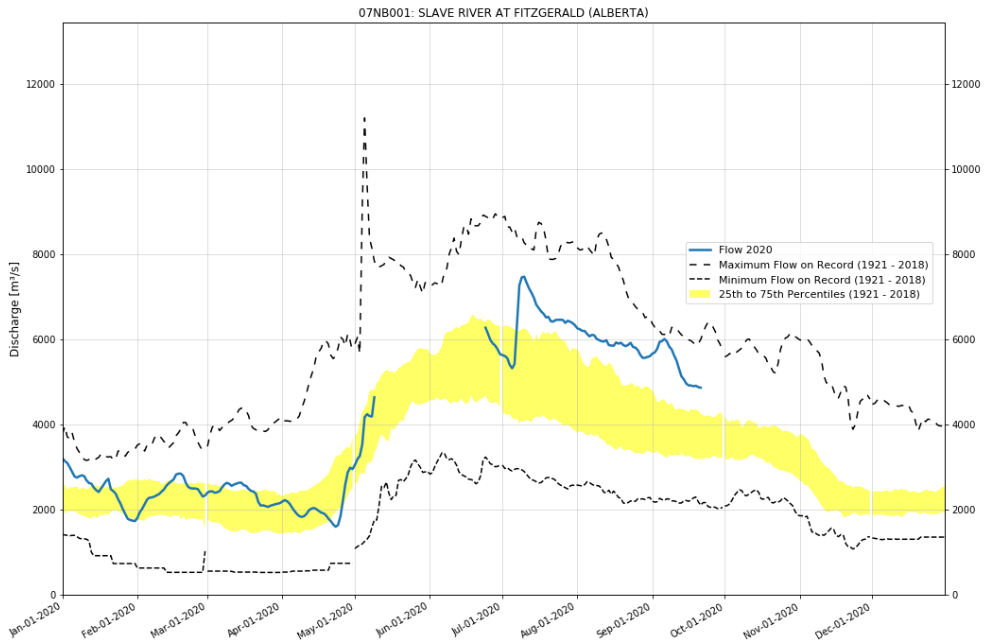

Figure 24 - 2020 Provisional WSC data in comparison to period of record for gauge 07NB001.

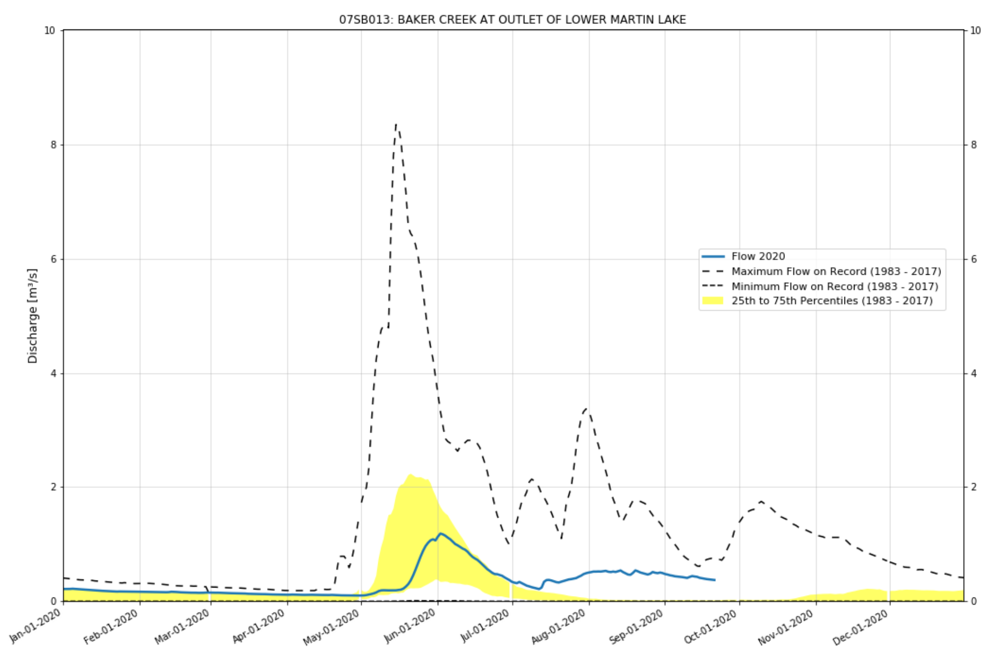

Figure 25 - 2020 Provisional WSC data in comparison to period of record for gauge 07SB013.

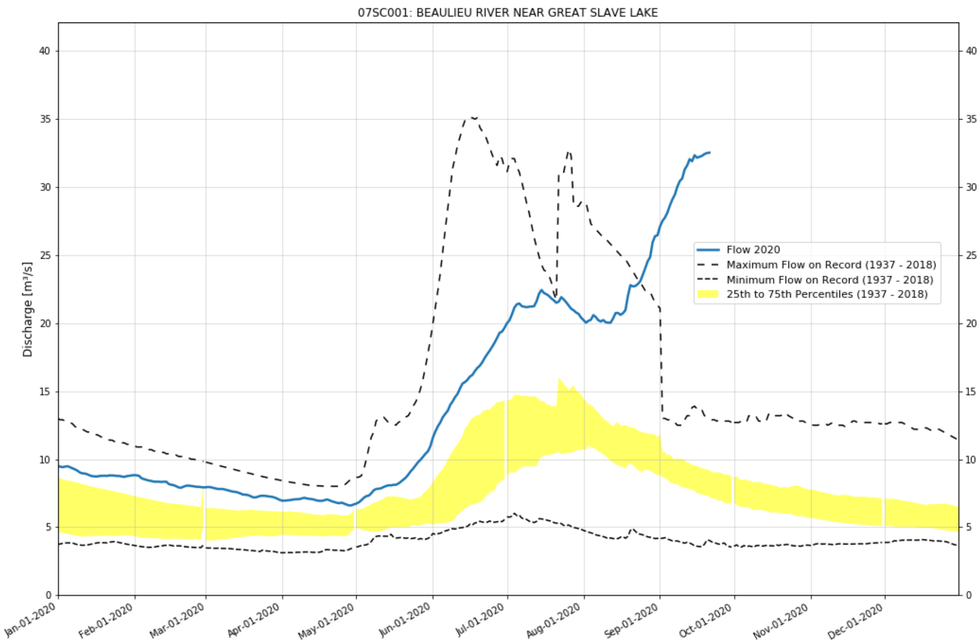

Figure 26 - 2020 Provisional WSC data in comparison to period of record for gauge 07SC001.

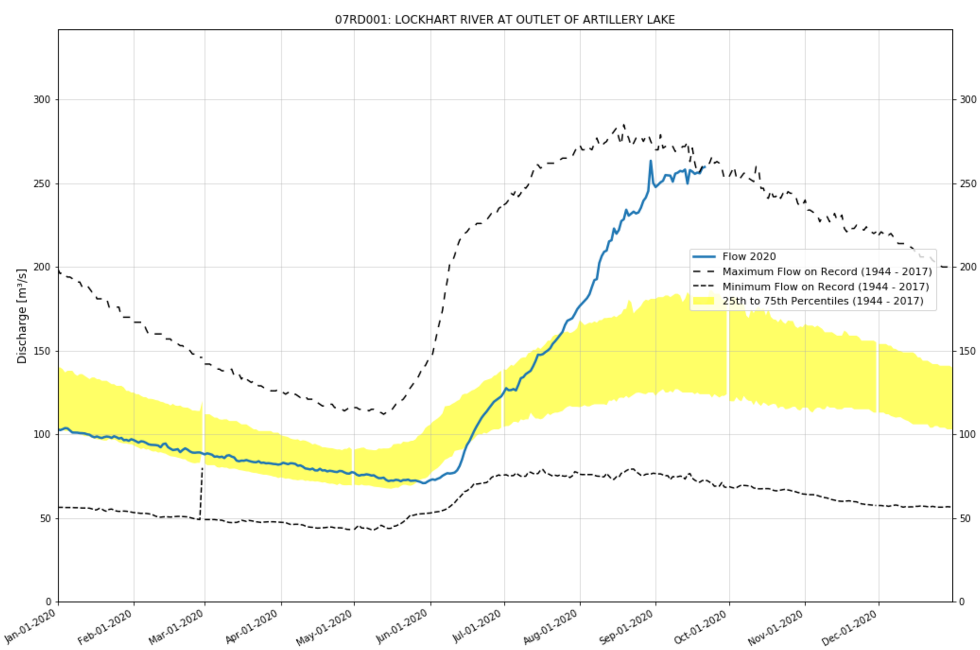

Figure 27 - 2020 Provisional WSC data in comparison to period of record for gauge 07RD001.

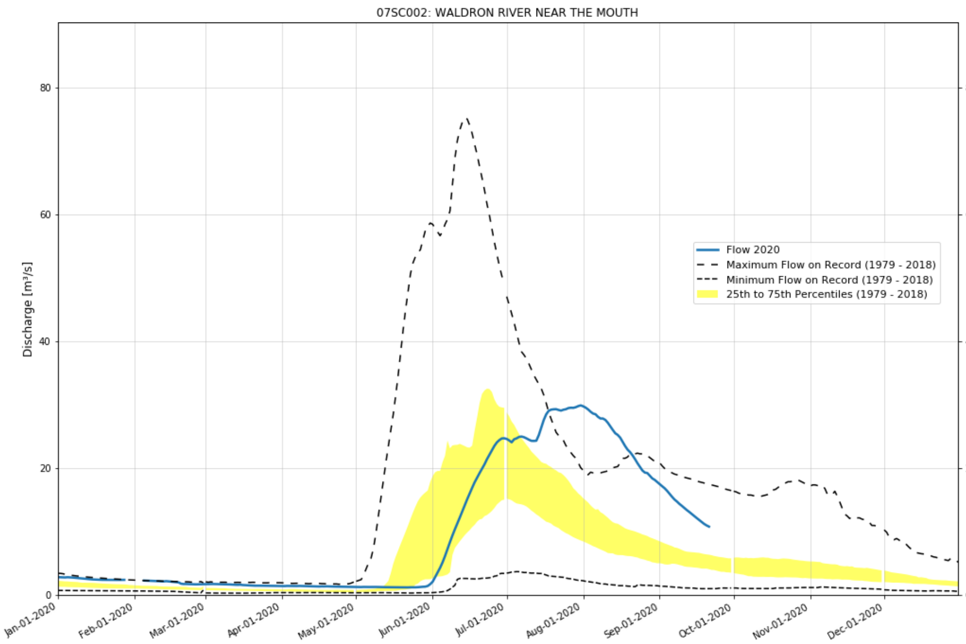

Figure 28- 2020 Provisional WSC data in comparison to period of record for gauge 07SC002.

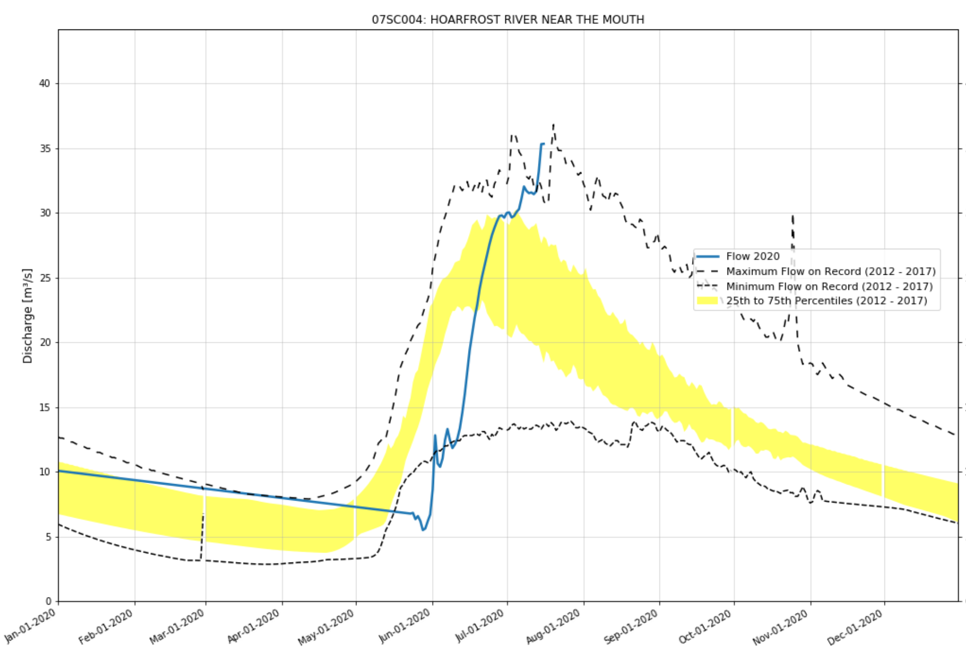

Figure 29- 2020 Provisional WSC data in comparison to period of record for gauge 07SC004.

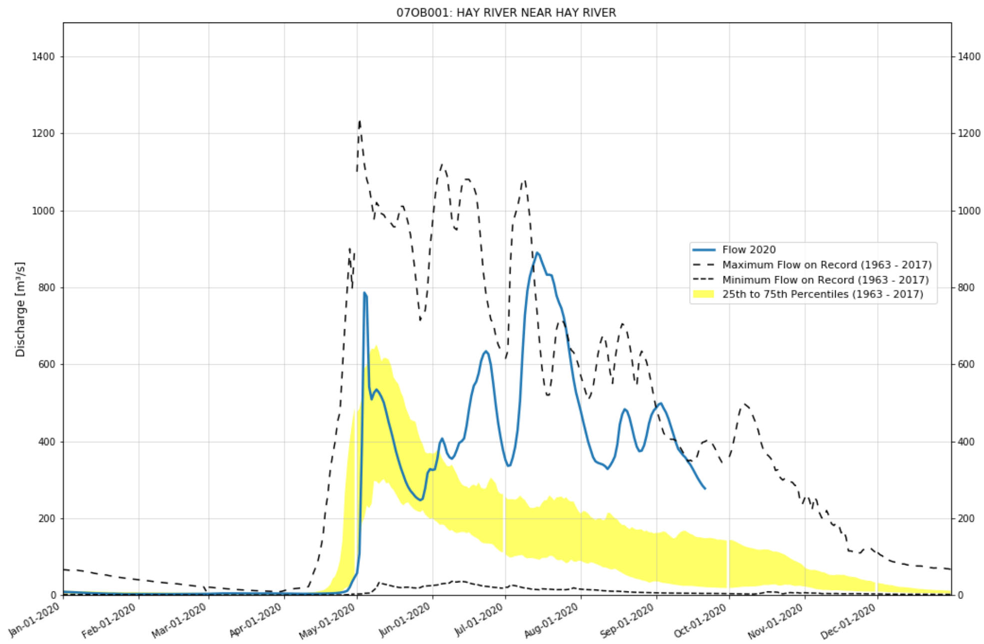

Figure 30 - 2020 Provisional WSC data in comparison to period of record for gauge 07OB001.

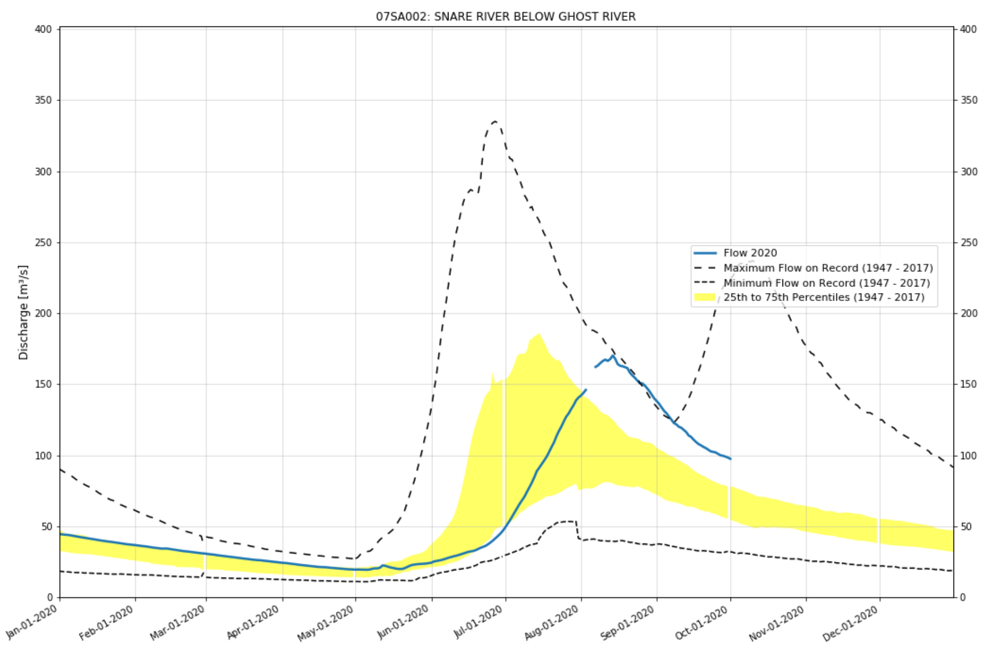

Figure 31 - 2020 Provisional WSC data in comparison to period of record for gauge 07SA002.

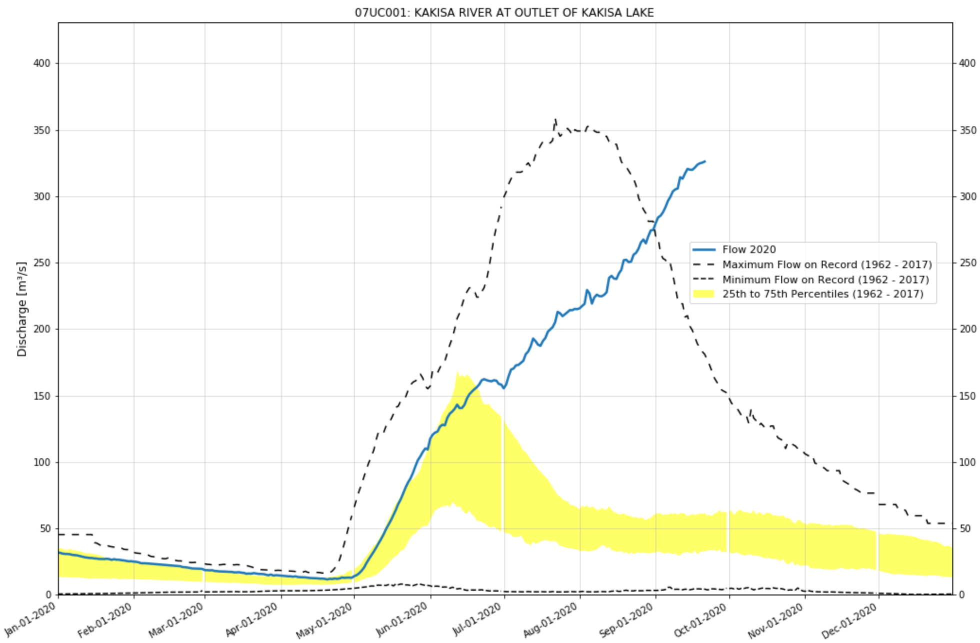

Figure 32- 2020 Provisional WSC data in comparison to period of record for gauge 07UC001.

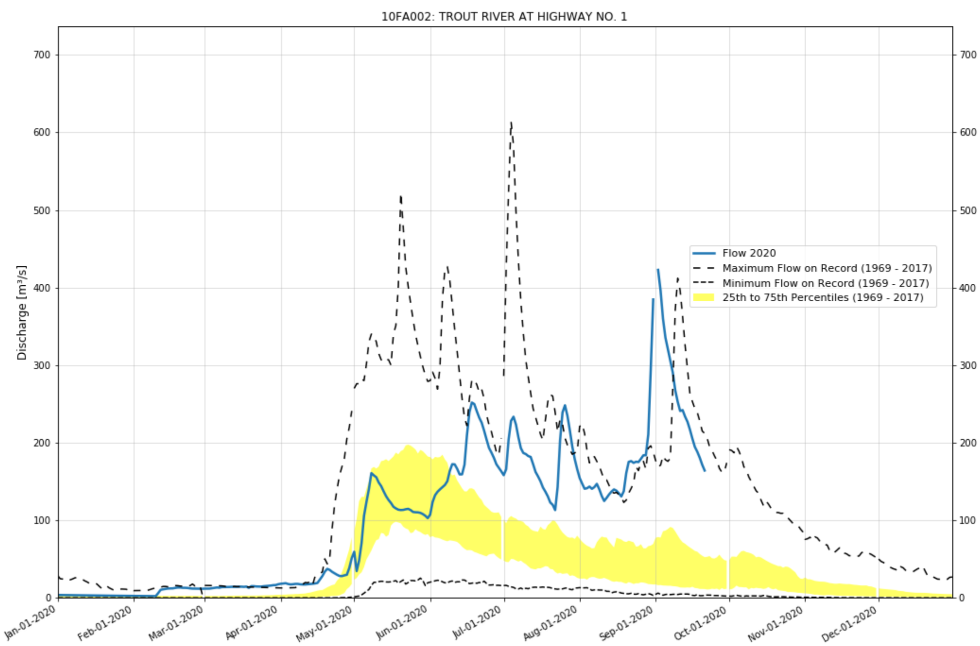

Figure 33- 2020 Provisional WSC data in comparison to period of record for gauge 10FA002.

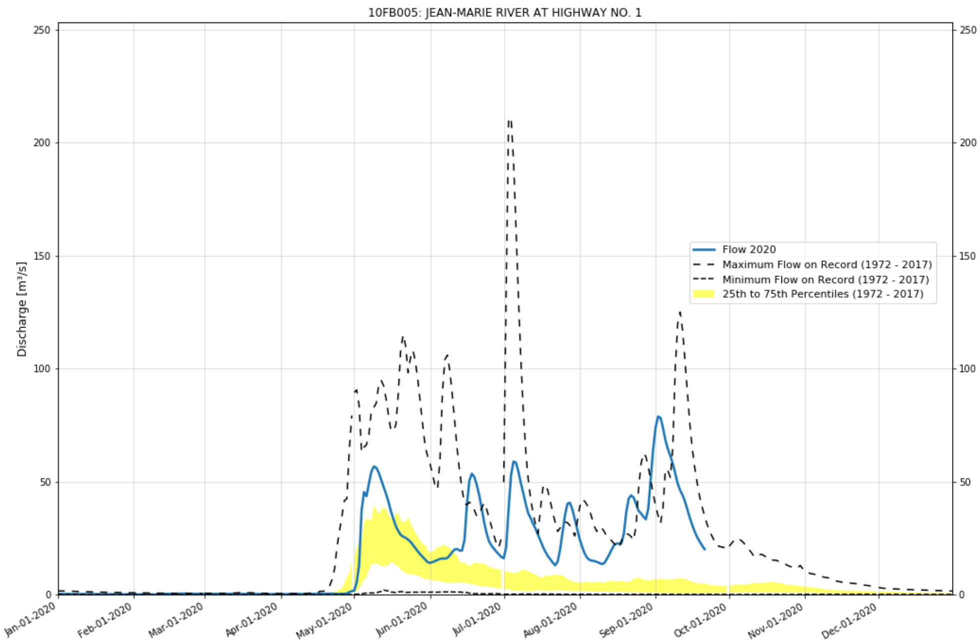

Figure 34 - 2020 Provisional WSC data in comparison to period of record for gauge 10FB005.

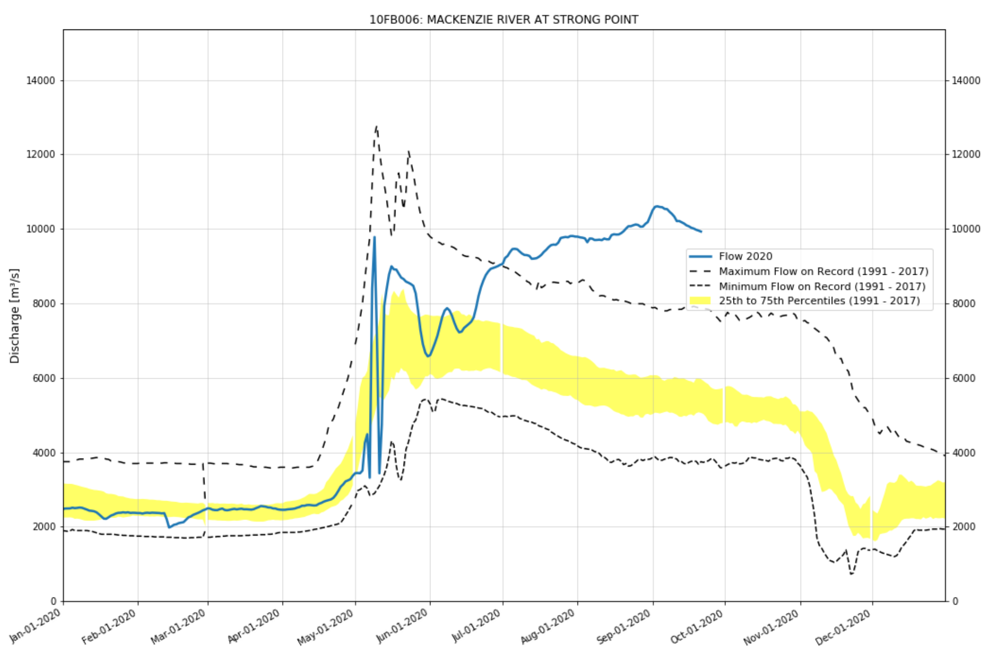

Figure 35 - 2020 Provisional WSC data in comparison to period of record for gauge 10FB006.

Residual Net Total Supply - Historical Analysis

The Annual (hydrological year: October 1 – September 30) Net Total Supply (NTS) for Great Slave Lake (GSL) and its contributors were calculated using monthly data from Water Survey of Canada gauging stations. The annual totals are expressed as depth (mm) over the lake assuming a surface area of 28 586 km^2 for GSL (Figure 36).

Total Annual NTS = Total Annual Outflow + Total Annual Change in Storage on GSL, where:

-*Total Annual Outflow = Mackenzie R. at Strong Point - Jean Marie R. - Trout River - Kakisa River*

For years prior to the Mackenzie River at Strong Point gauge coming online, the data from Mackenzie River at Fort Simpson minus the Liard River near the Mouth were used. The flow data from the Peace River at Peace Point and Athabasca River below Fort McMurray were converted to total annual depths over the lake to represent the contributions of the Peace and Athabasca rivers, respectively. The contribution of Lake Athabasca and the Peace-Athabasca Delta (LA/PAD) combined was estimated by:

-*LA/PAD = Slave River at Fitzgerald - Peace River at Peace Point - Athabasca River below Fort McMurray*

The residual Net Basin Supply (NBS) was used to represent the local inflow as a significant portion of the local inflow into GSL is ungauged. The Residual NBS determined by:

Total residual NBS = Total Annual Outflow + Total Annual Change in Storage on GSL - Slave River at Fitzgerald

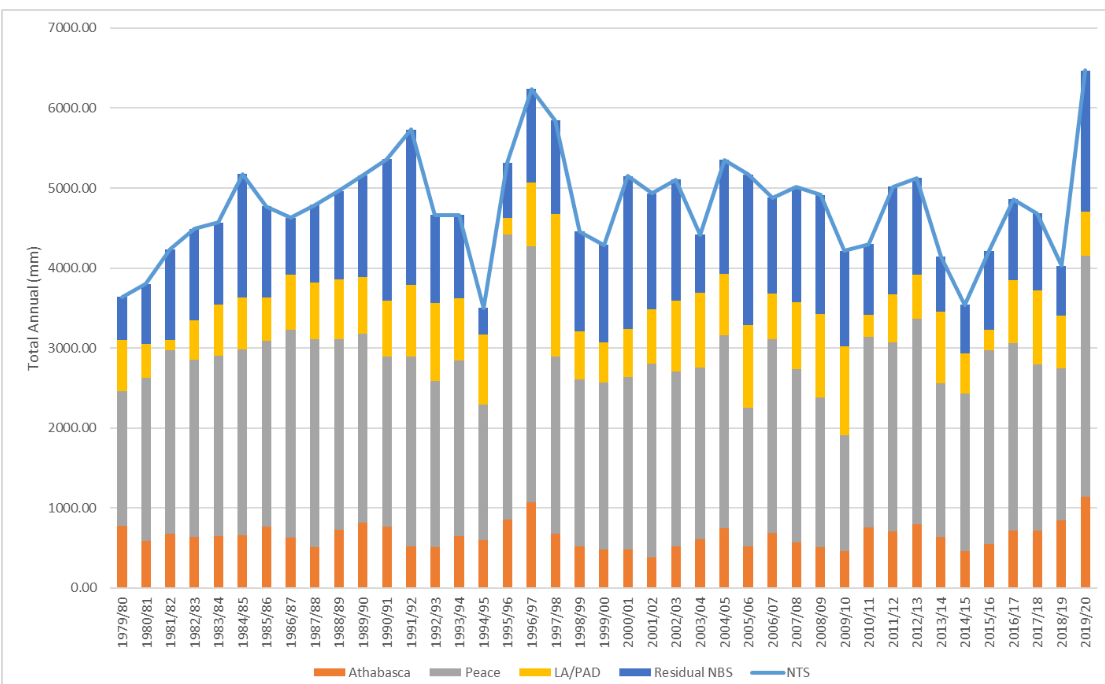

Figure 36 Total Annual (hydrological year) NTS and its contributors as depths over the GSL

The anomalous years that stand out from Figure 38 are 1991/92, 1996/97, 1997/98, and 2019/20. The relative contributions of each contributor expressed as a percentage of the annual NTS was calculated and plotted in Figure 37.

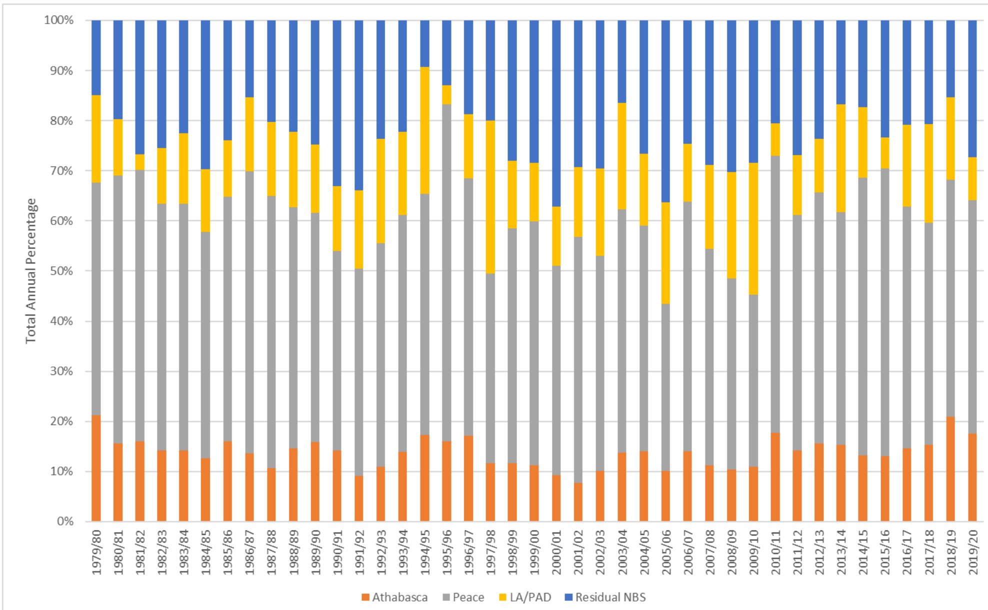

Figure 37 - Total Annual (hydrological year) contributions as a percentage of NTS

A closer look at the attribution for the anomalous years shows that:

- 1991/92: the percent contribution of the direct local inflow (represented by the residual NBS) accounted for approximately one third of the total annual NTS whereas in most over years it accounts for one quarter. In comparison, the percent contributions of both the Peace and Athabasca rivers is lower than compared to most other years; and the percent contribution of the LA/PAD region is comparable to most other years.
- 1996/97: the total contribution of the Peace River is third highest amount compared to other hydrological years between 1979/80 and 2019/20, the Athabasca River is the second highest amount contributor within the same time period, and their percent contributions are above most other years.
- 1997/98: the LA/PAD contribution seems to be driving the anomalous condition as it represents the highest total amount between 1979/80 and 2019/20, and also the highest percent contribution within that same time period. The Athabasca and Peace river totals and associated percentage contributions are lower than most other years, and the residual NBS totals and percentage contribution is comparable to most years.
- 2019/20: regarding the total amounts contributed, the Peace River has its second highest contribution amount compared to other hydrological years between 1979/80 and 2019/20, the Athabasca River has its highest contribution amount for the river over the same time period, the

residual NBS is its third highest amount over the period examined, and the LA/PAD is lower than most other years but not significantly so. The percent contributions show that the Peace River and the residual NBS are similar to most other years, whereas the Athabasca is providing a larger percent contribution than is typical, and the LA/PAD percent contribution is lower than most other years.

8. Component Net Basin and Total Supply Analysis

Three estimates of Monthly Net Total Supplies to Great Slave Lake were obtained as part of an effort to understand the cause of extreme water levels observed in Great Slave Lake in 2020:

Method	Model	Main inputs	Provider	Period
Residual method	Mass-balance equation	Water levels of GSL and outflow observations	NHS (Evan Friesenhan)	1991-2020
Component method	GEM-Hydro (SVS land-surface scheme)	GEM+CaPA as well as WSC gauges	RPN-E (Étienne Gaborit)	2008-2020
Component method	MESH (CLASS surface scheme)	WFDEI dataset	U. Saskatchewan (Mohamed Elshamy)	1980-2016

Data were provided by email during the last week of September 2020. Daily data were provided for the residual method and GEM-Hydro, and monthly averages were provided for MESH. Two simulations were provided for GEM-Hydro: one where the model is run in open-loop mode, and one in which WSC gauge data are inserted in the routing scheme. Monthly averages of daily outputs were computed for GEM-Hydro and the residual method in order to compare them to MESH outputs and to reduce the magnitude of the observational error for the residual method that is prone to random fluctuation due to the sensitivity of the method to errors in observations of water level. However, by considering a monthly time step, we are also smoothing out timing errors from the hydrological models used for the component method.

In order to speed up simulations, GEM-Hydro was implemented using the same low-resolution routing scheme used by MESH, rather than the operational configuration of the routing scheme at 1 km. Hence, the results from GEM-Hydro in open-loop mode and MESH differ mainly in terms of land-surface scheme and forcing data. Since the accuracy of WSC gauge data is superior to simulated values from GEM-Hydro, better results are expected for the configuration of GEM-Hydro in insertion mode, and this configuration should be preferred when it comes to analyzing past years. It was thus selected for the following analysis. However, it remains important to evaluate the skill and bias of GEM-Hydro in open-loop mode in order to have confidence in the model when it comes to forecasting as well as for what-if scenarios, such as climate change studies or studies aimed at evaluating the impact of regulation. Figure 388 compares the residual method, MESH and GEM-Hydro in insertion mode over the period 1980-2020. It is clear from this figure that better agreement is obtained between the residual method and GEM-Hydro than between the residual method and MESH, but it is a limited time series. This agreement may be due to precipitation forcing, however both models are useful in understanding relative changes from year to year. Furthermore, it can be seen that both the residual method and GEM-Hydro point to a record year in 2020 when it comes to monthly NTS.

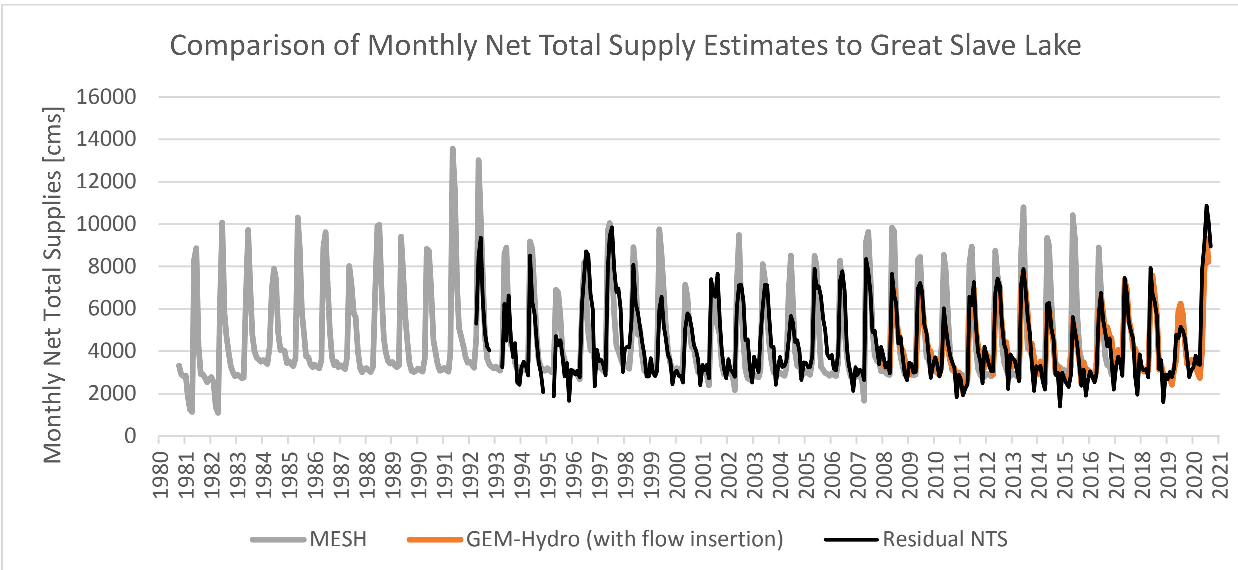

Figure 38- Comparison of monthly NTS to GSL from three different methods over 1980-2020

The GEM Hydro results were encouraging for the simulation period and are used here to try to determine the impacts of the various components for the 2020 high water levels. NBS simulations have been performed with two different simulations: with the insertion of observed flow data whenever available for a list of selected stations, or without any observed flow insertion at all, in order to produce NBS and NTS simulations as accurately as possible (insertion), and to have an idea of the simulation quality (no insertion), which will govern simulated values when observed data are missing. Over the simulated period from 2008-2020 (2007 used as spinup), Great Slave Lake (GSL) direct watershed is gauged at about 65% up to the end of 2017, while the GSL total watershed (including Slave River watershed) is gauged at more than 80% up to the end of 2018. As can be seen in Figure 39, GSL NBS simulated values without any observed flow insertion are in quite good agreement with the simulations including observed flow insertion, despite a tendency for simulations with no insertion to overestimate NBS compared to simulations with insertion.

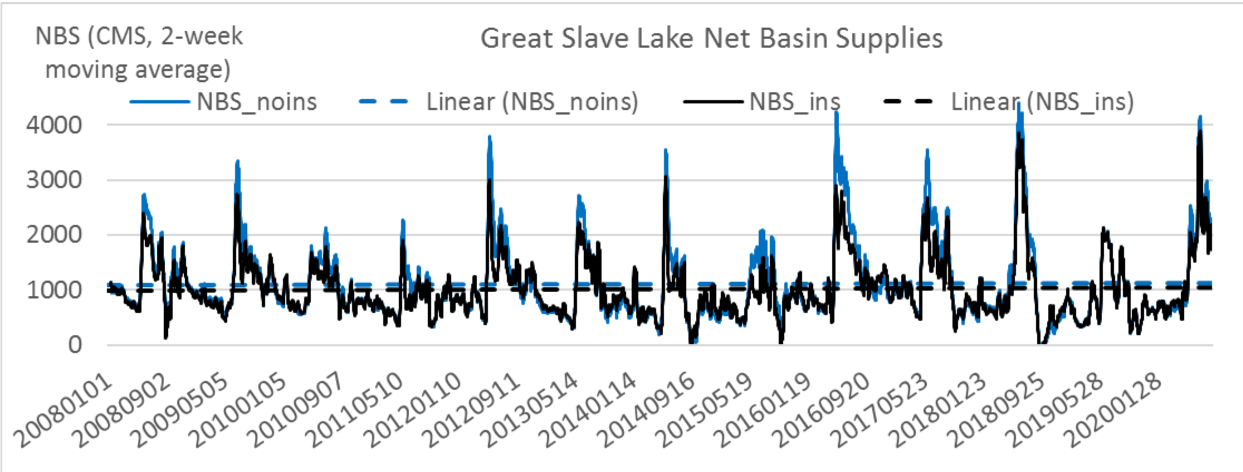

Figure 39- GSL NBS simulations when inserting observed flow data (black) or without inserting observed flow data (blue). Dashed lines represent the linear tendency of the two time-series. CMS = m3 s-1

Figure 40 shows the different components of the NBS simulations when using flow insertion. Note, however, that the three NBS components (streamflow from direct watershed, over-lake precipitation and evaporation) were adjusted after the simulations in order to correct for the GSL area error in the low-resolution routing model, based on the ratios between simulated and observed areas. It can be seen on Figure 40 that NBS for 2020 were quite high, which can be explained by strong flows from the direct watershed and a strong over-lake precipitation event in July 2020. However, the GSL NBS solely cannot explain the GSL level records observed in 2020.

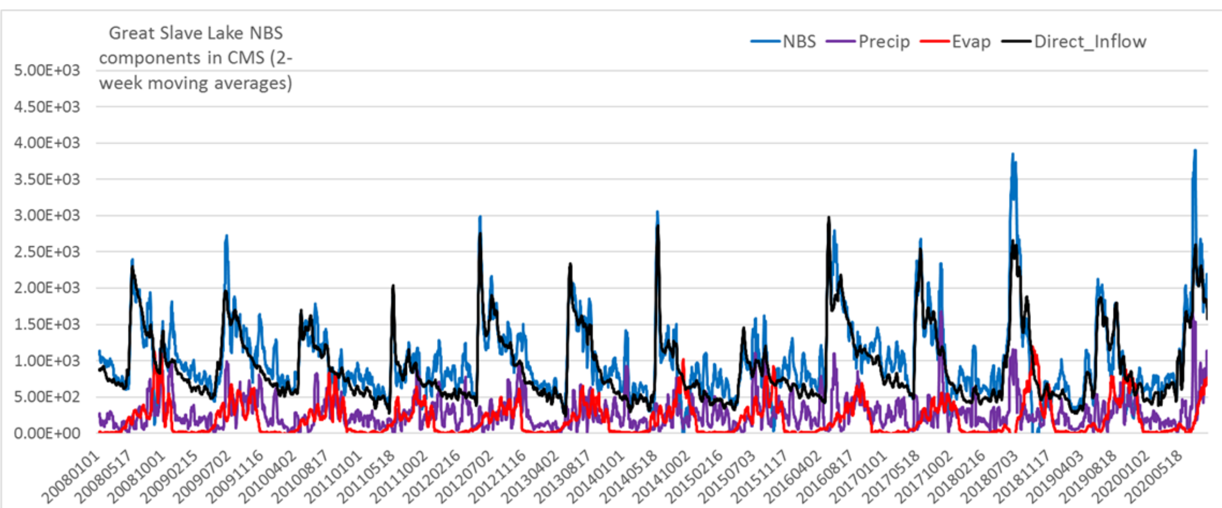

Figure 40 - GSL NBS simulations (with observed flow insertion) decomposed into its three components.

Figure 41 illustrates simulation quality for the Slave River (GSL main tributary). Despite the fact that flow dynamics are not perfectly simulated, the simulation represents well the overall water balance, with an underestimation of less than 5% compared to observations, which allows for trust in the simulated volumes in general.

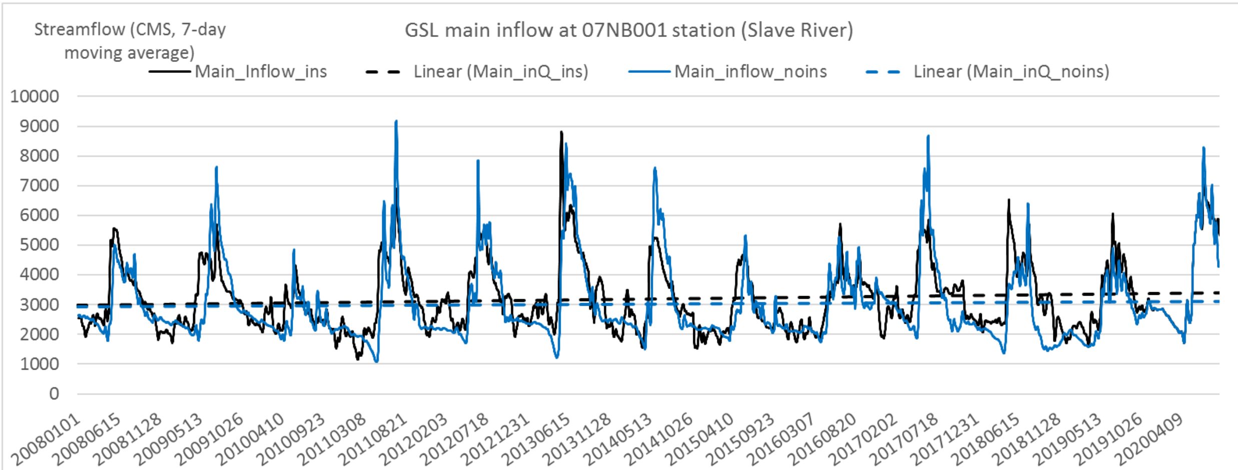

Figure 41- Streamflow for Slave River at station 07NB001 (GSL main tributary). Black: flow observations or (when missing observations) flow simulations but still with upstream flow insertion. Blue: flow simulations without any flow insertion. On this figure, flow observations for station 07NB001 are considered missing from February to May 2020 because suspicious.

Figure 42 below represents the GSL main water fluxes and highlights the fact that the main GSL input water flux consists of the inflow from its main tributary, the Slave River, which was unusually high in 2020 and added on top of the high GSL 2020 NBS. When looking at flows for the Peace and Athabasca watersheds (not shown here), both basins displayed unusually high values for 2020.

Looking at the limited time series below, there seems to be exceedingly high flow in from the local basin (NBS) and also from the Slave River contributions. This seems like a fairly rare occurrence to have both local and Slave River flows exhibit such behaviour. Further analysis and longer time series are required.

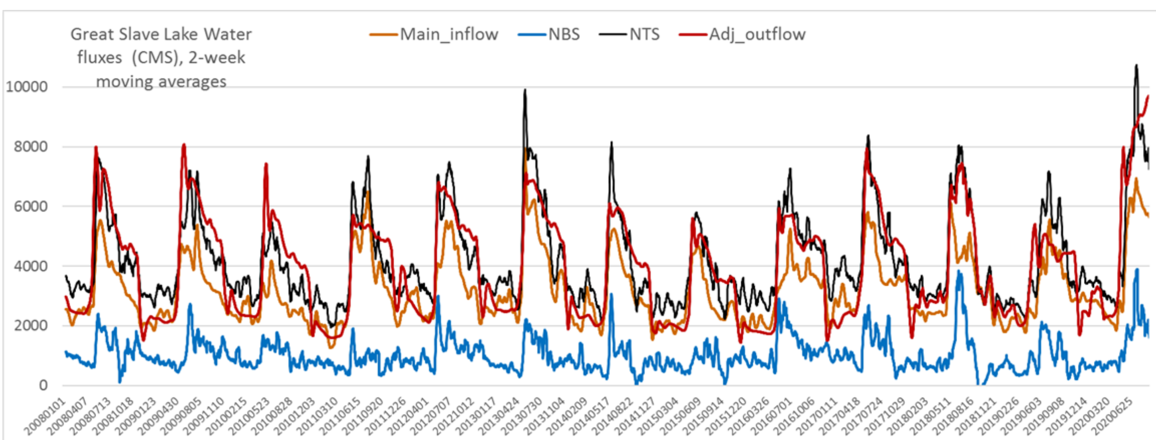

Figure 42- GSL main water fluxes (main tributary inflow, NBS, NTS and adjusted outflows) with observed flow insertion. Outflows at station 10FB006 were adjusted with the area-ratio-method to correspond to the total watershed area of GSL, because station 10FB006 is more downstream than the real GSL outlet.

9. Great Slave Lake Water Level – Looking Forward

In terms of making projections of what the future holds for GSL, even if the inflows decrease significantly, it will take a while for the levels to fall because of the large surface area of Great Slave Lake. Based on the surface area of the lake, the weekly average discharge of the lake would need to be greater than total inflows by 472 $m^3 s^{-1}$ to drain one cm off of the lake. For example, if outflows are 2 362 $m^3 s^{-1}$ greater than inflows over a week, the lake level would fall by 5 cm.

Statistical Projection of Levels Using Residual Net Total Supply

The 25th, 50th and 75th percentiles of weekly net total supply (NTS) were calculated from the observed record (described earlier). Daily historical data were used from October 1, 1991 to September 30, 2020. Pietroniro *et al* (2011) previously fit a curve for the stage/outflow relationship of GSL, which the report notes is valid up to 157.18 m, when outflow of approximately 11 000 $m^3 s^{-1}$ would be observed.

When tested using data from recent months, the curve has a tendency to overestimate outflows at high levels. To derive an updated curve for stage/outflow, an optimization was performed to fit a 2nd-order polynomial to observations from the months of August and September in excess of a reference level where the previous curve remains effective. This reference was identified as the level where the difference between outflows generated by the two curves was minimal. The iterative analysis determined that outflow should be calculated using the updated curve when stage of the lake is at 155.45 m and higher (Figure 43).

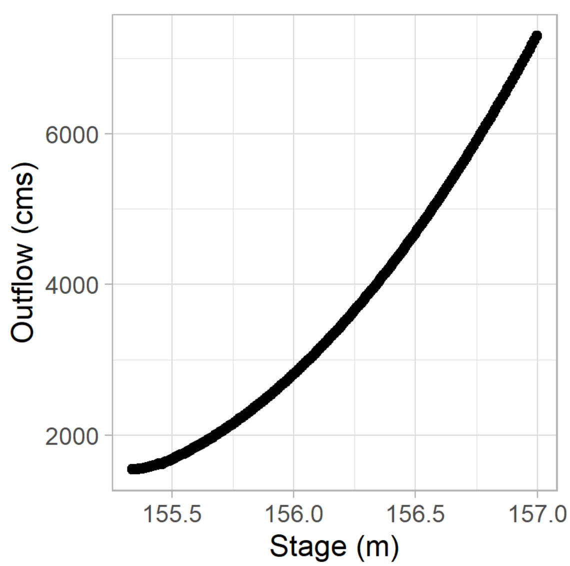

Figure 43- Relationship derived between stage and outflow using the approximation derived by Pietroniro *et al* (2011) at levels below 155.45 m and using a 2nd-order polynomial for levels above the reference level.

The derived approximation is as follows:

$if\ (z \geq 155.452492709345):$
$\quad q = 1492.887 \cdot z^2 - 462775.6 \cdot z + 35864911$
$else\ if\ (z \geq 155.337873865431):$
$\quad q = optimize(fn(q_0, z)\ \{$
$\qquad f = 1931.51407508514 \cdot z^2 - 600074.574299946 \cdot z + 46607692.6223807$
$\qquad y = {}^{q_0}/_{f}$
$\qquad q = 12064.0527933766 \cdot y^2 - 61248.0593570564 \cdot y + 77913.2974158042\ \},$
$\qquad where: 1000 < q_0 < 12000)$

Where z is the current stage of the lake, q is the calculated outflow, q_0 is a first guess for outflow in the iterative derivation using the Pietroniro *et al* (2011) approach for stage less than 155.45 m. The lower limit of the approximation is 155.34 m.

A simple water balance model was used to estimate water level based on historical NTS and lake outflow, estimated as described above. The model was conditioned using current observations and driven forward in time using weekly statistics of the NTS record. The weekly NTS for future dates was estimated as a weighted function of the residual NTS calculated for September 22, 2020 and the value of the 25th and 75th percentiles on that date. The historical record shows outflows from Great Slave Lake generally stabilize to approximately 2 500 $m^3 s^{-1}$ by winter (Figure 44), so the weighting of the percentiles in calculating NTS becomes 100% by January 15, 2021. The calculation for the assumed daily NTS is as follows:

$$NTS_i = NTS_p + \left(NTS_{i-1} - NTS_p\right) \cdot \frac{d_i - d_R}{d_0 - d_R}$$

Where NTS_p is the NTS of the respective percentile, NTS_{i-1} is the NTS from the previous day, d_i is the current date, d_0 is September 22, 2020, and d_R is January 15, 2011.

The water balance itself is calculated on a weekly time-step. The equivalent volume of water of the NTS is added to lake storage, the stage is updated and the equivalent volume of the calculated outflow is removed. The stage of the lake is calculated using an assumed surface area of 28 568 km^2.

In this scenario, NTS is forced to return to normal levels by January 2021. The NTS contribution to the lake by this function this is illustrated below (Figure 44).

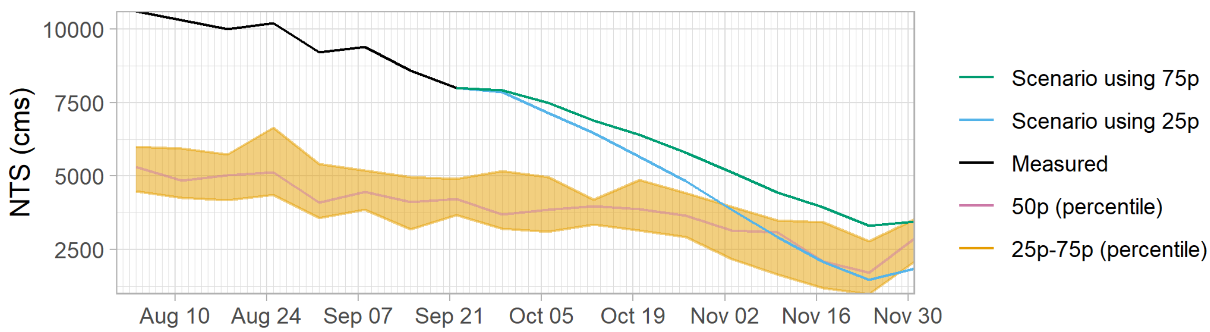

Figure 44 - Assumed NTS contributing to the lake as a function of current conditions and the 25th and 75th percentiles. The reference 25th and 75th percentiles of NTS for this period under normal conditions are shown in the yellow band. The black line is the NTS calculated from observations until September 22, 2020, which were used to initialize the model.

The outflow and stage (level) generated from this model are illustrated in the figures below.

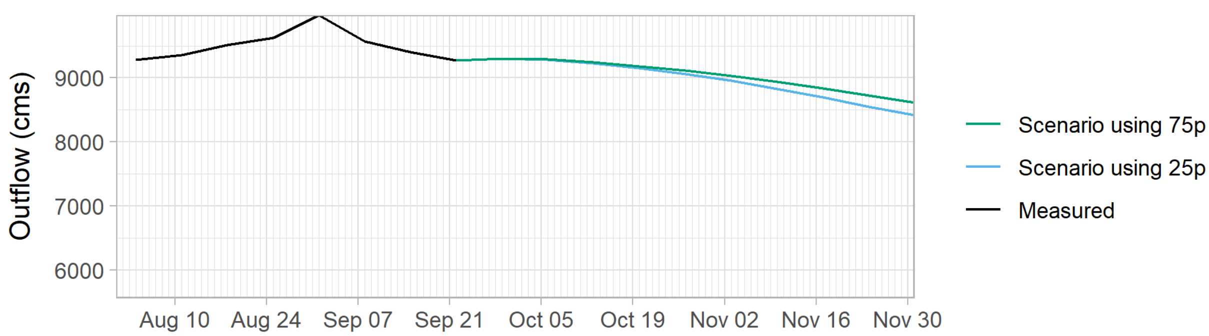

Figure 45 - Outflow generated from the simple water balance model using NTS. “25p” and “75p” are representative of the 25th and 75th percentiles.

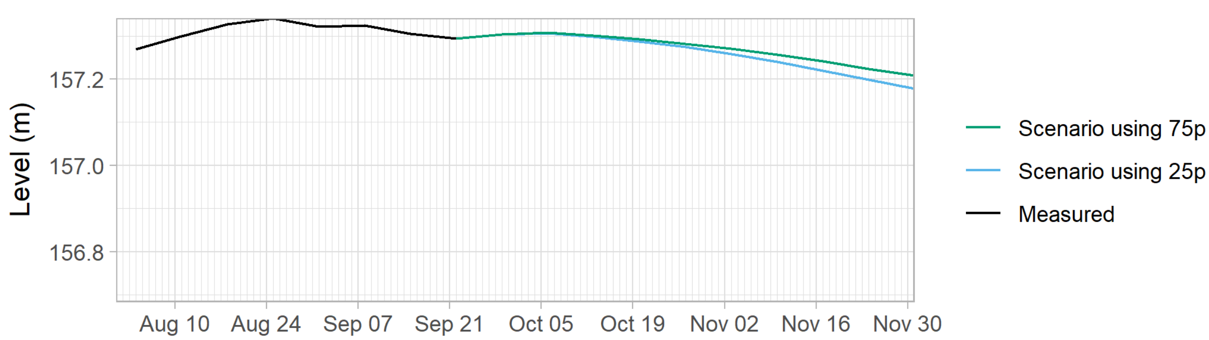

Figure 46 - Level (stage) of the lake from the simple water balance model. “25p” and “75p” are representative of the 25th and 75th percentiles.

As it is unlikely current flows will return to normal in the coming months, a second scenario was run where the weekly NTS for future dates was estimated as 80% and 120% of normal flows (50th percentile) offset to conditions observed on September 22, 2020. This scenario assumes that outflows from Great Slave Lake will remain generally higher than the historical normal for an extended period. The rationale behind this scenario is that higher inflows from the Peace River have prevented Lake Athabasca and waters in the Peace-Athabasca Delta regions from draining, which will contribute to sustained higher inflows from the Slave River to Great Slave Lake for longer. The NTS contribution to the lake under this scenario is illustrated below, where "CC" stands for "Current Conditions" from September 22, 2020.

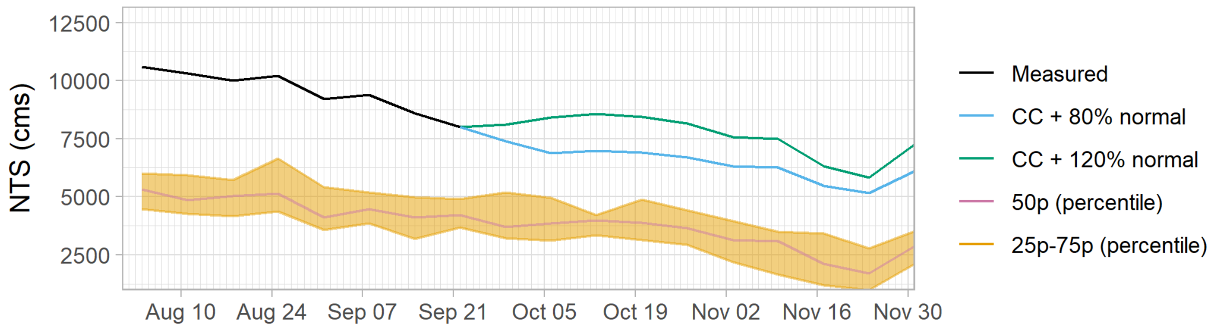

Figure 47 - Assumed NTS contributing to the lake as a function of 80% and 120% of normal flows (50th percentile) offset to the current conditions (CC). The reference 25th and 75th percentiles of NTS for this period under normal conditions are shown in the yellow band. The black line is the NTS calculated from observations until September 22, 2020, which were used to initialize the model.

The outflow and stage (level) generated from this scenario are illustrated in the figures below.

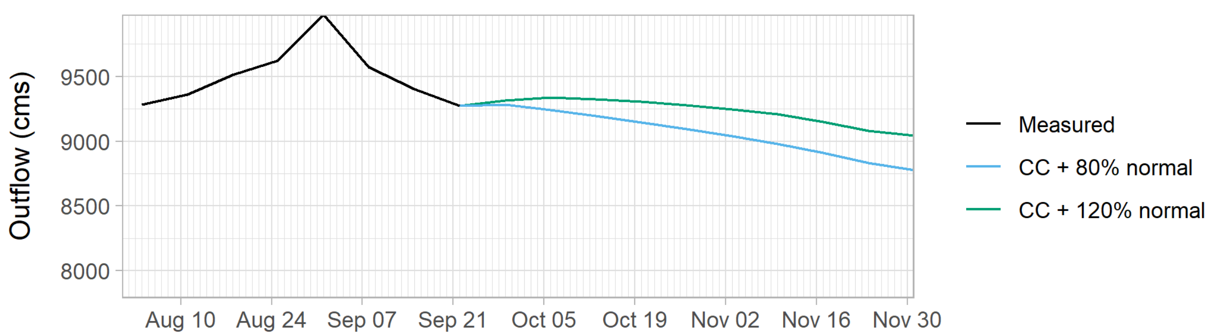

Figure 48- Outflow generated from the simple water balance model using NTS. "CC + 80% normal" and "CC + 120% normal" are representative of 80% and 120% of normal offset to the current conditions (CC).

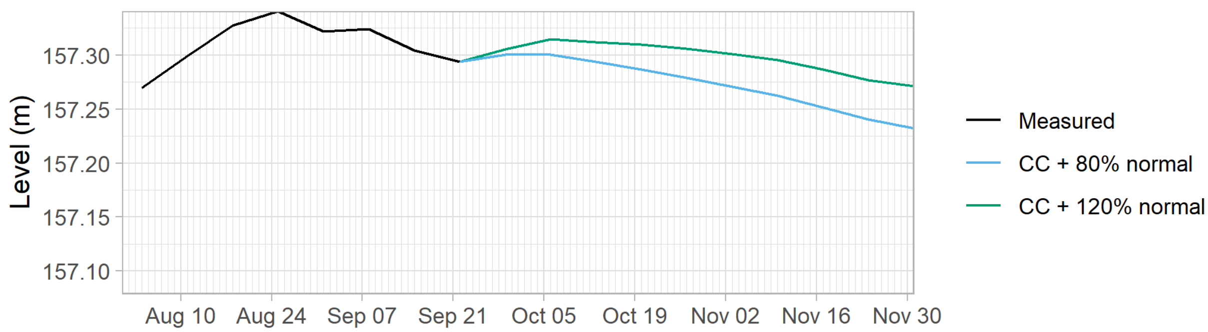

Figure 49 - Level (stage) of the lake from the simple water balance model. "CC + 80% normal" and "CC + 120% normal" are representative of 80% and 120% of normal offset to the current conditions (CC).

In the above scenario, higher than normal lake levels are expected to persist for an extended period.

10. Influence of Peace-River Flows and WAC Bennett Dam

The major inflow to GSL, the Slave River, has been influenced by regulation of the flow emanating from the headwaters of the Peace River since 1968 with the operation of the WAC Bennett Dam and Peace Canyon Dam for the generation of hydroelectricity. On average, the storage in and release of water from the large Williston Reservoir have led to higher winter flows and lower peak summer flows reaching the lower Peace River, and subsequently, Great Slave Lake (Figure 4). Noteworthy is that the Peace River can act as a "hydraulic dam" to outflow from the LA-PAD, impeding LA-PAD outflow and facilitating the storage of water within the connected lakes when the Peace River level is near to Lake Athabasca levels. During extremely high-water levels, the Peace River can contribute reverse flow south into the LA-PAD as well as north to the Slave River (Peters and Buttle, 2010).

The main purpose of the Williston Reservoir and the Bennett dam infrastructure is to harness energy from the flowing water of the Peace River, and that all water released from the dam (termed "water releases") is controlled. The Bennett Dam was constructed on the Peace River to impound a reservoir where water is stored. The water then flows through penstocks in the dam and causes turbines to turn, generating the electricity. BC Hydro controls when water is released through the dam (termed "normal generation discharge"). When the reservoir is full, water flowing into the reservoir must be released. The general operation of the reservoir is to draw down the reservoir across the late summer, fall and winter and then fill the reservoir during the spring. When more energy is needed, the penstocks to the turbine-intake system are opened, and water flows through them. When less energy is needed, some of the penstocks will be closed and less water will flow through the dam. The process used to control this outflow is referred to as dam operations and they are based on a number of factors including the amount of electricity being consumed by BC Hydro customers, reservoir water levels, hydrological forecasts and the uncertainty in those forecasts, dam safety considerations, water license and water license order requirements, and import/export opportunities to Alberta and the U.S. During periods with high inflows to the Reservoir, the turbine-intake system is supported by a spillway to manage excess water. A spillway is a structure that allows water to flow directly into the river below the dam, bypassing the turbines and generators (defined as “spill”) to prevent the reservoir from overfilling, potentially damaging the dam and the downstream communities, or for other operational needs.

Inflow conditions into the reservoir must be monitored closely, and projections of possible future inflows into the reservoir are an important consideration to operate the dam efficiently and safely. Because inflows are dependent on future weather conditions, there is considerable uncertainty in predicting inflow volumes to a reservoir more than five days in advance. These future conditions cannot be accurately predicted and therefore BC Hydro uses probabilistic forecasting based on decades of historical weather sequences in order to estimate a range of possible future outcomes to manage the operations and to determine when to generate and when to spill. This process occurs months in advance and before it is too late to take corrective action within the operating limits of the generation and spilling facilities. To manage risk in the short term (one week), there are 11 hydrometric gauges that monitor inflows into the reservoir, and one outflow gauge downstream of the dam that provides information on releases. Staff from the Global Water Futures (GWF) program carried out an analysis of inflows to and outflow from the Williston Reservoir from 1979 to present using observed records obtained from the Water Survey of Canada, in parallel with MESH model results for over-lake rainfall and evaporation. The schematic below (Figure 50) shows the WSC gauges used in this analysis and the development of the inflow-outflow GWF time-series. Gauge 07EF001 (Peace River at Hudson Hope) is used as the outlet of the catchment and it has a continuous record until September 2019. Due to preparation of Site C construction site, the gauge was discontinued and the record of the next downstream gauge (07FA004 – Peace River above Pine River) can be used to infer outflows (*i.e.* flows at 07EF001) after subtracting the flows of two small tributaries (Moberly and Halfway). This was done to extend the Gauge 07EF001 (Peace River at Hudson Hope) record to 2020.

The inflow record has been constructed from the gauged sub-catchments noted in Figure 50. The catchment of the Peace River at Hudson Hope has an area of 73 149 km^2, and 70% of it has been gauged since 1981. Provisional WSC records are used for the last 18 months. Using the gauged area ratio, the inflows are estimated from the sum of gauged flows and then scaled to match the long-term outflow. This independently constructed series (referred to as GWF-WSC Inflows) can be used to assess the approximate inflows into the Williston reservoir. BC Hydro’s data on inflows and outflow are not publically available.

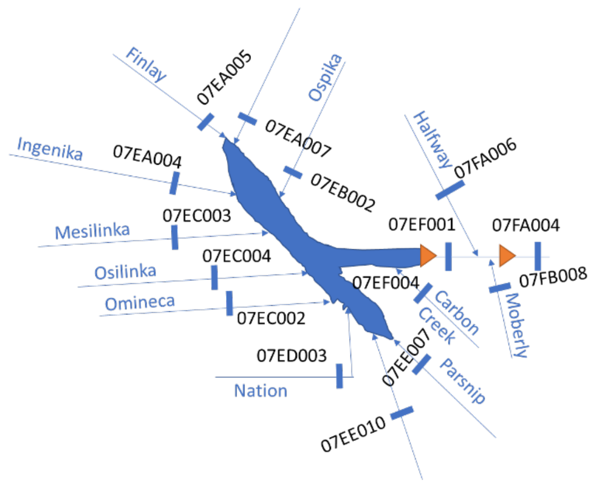

Figure 50 - Water Survey of Canada gauges used in the Williston Inflow-Outflow analysis

In order to understand events of the summer of 2020, it is important to understand the context under which the operators were making decisions. The factors that affect dam operations were described above and BC Hydro has provided a description of dam operations and further context in the following paragraph to describe operations over the summer of 2020.

At the start of June, the Williston Reservoir was 61 cm (2 ft.) below normal and the Water Supply Forecast for the freshet period (for Feb – Sep) was just below normal at 97%. Heavy rainfall events in the Williston basin in June and early July caused the July Water Supply forecast to increase to 109% of normal. By mid-July it became apparent that releasing more water than what can pass through the turbines would be required to manage the filling of the reservoir. A minimum 1.5 m (5 ft.) of storage in the reservoir was being maintained to be able to attenuate large rainfall events and route floods for the construction of Site C downstream of the Williston reservoir. Maximum flow that can be released through the turbines is approximately 1980 $m^3 s^{-1}$. BC Hydro spilled additional water from the Williston Reservoir above the turbine maximum flow from July 17 to August 18 and from August 25 to September 1. The additional water spilled during the prolonged release ranged from about 100 to 400 $m^3 s^{-1}$. Heavy rain continued in July causing the August Water Supply Forecast to increase to 120% of normal. Precipitation in August was the highest in the historical record and resulted in the highest August peak inflow into the reservoir.

In examining Figure 51, we can see that the outflow matches the description provided above by BC Hydro. Flow releases out of the Williston reservoir in 2020 were higher than normal at times, and there was a spill of water (flows over 1982 $m^3 s^{-1}$) for a period noted in BC Hydro's text above.

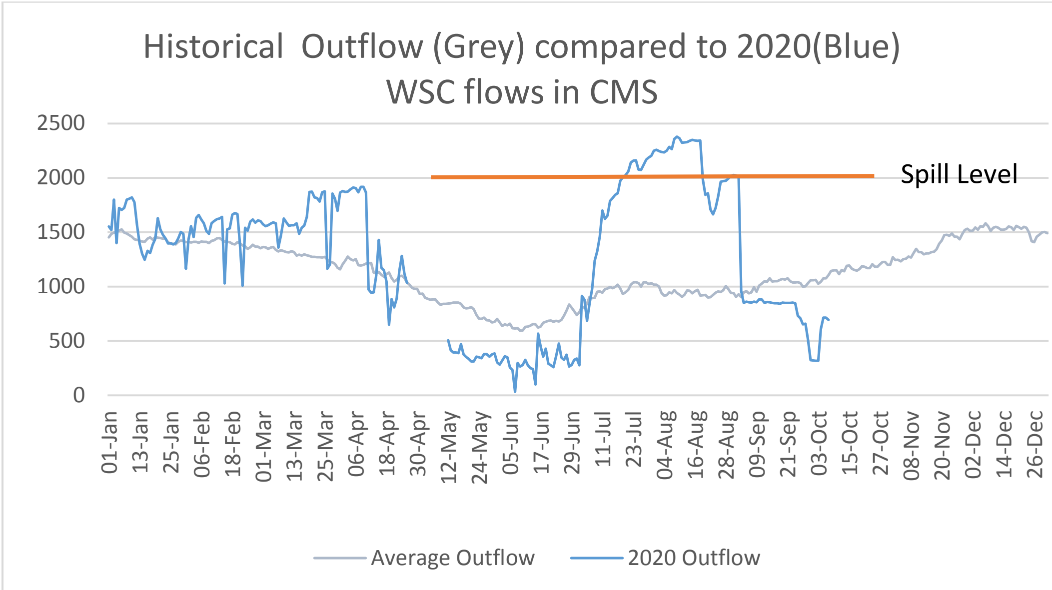

Figure 51- Inflows for Williston Reservoir with historic estimates (1979-2020) in gray and the 2020 estimates shown in blue. The orange line indicates the approximate threshold of outflow where spillway operations occur.

The outflow information presented in Figure 51 indicates the volume of water leaving the reservoir, but as mentioned above, outflows are heavily dependent on inflow volumes, particularly during high water years. In order to assess this, the GWF-WSC derived time-series of inflows are plotted as an anomaly for the April 1 to September 30 period for 1979-2020. This plot indicates that there are a few positive anomalous years, specifically, the summer of 2020 and the summer of 2007.

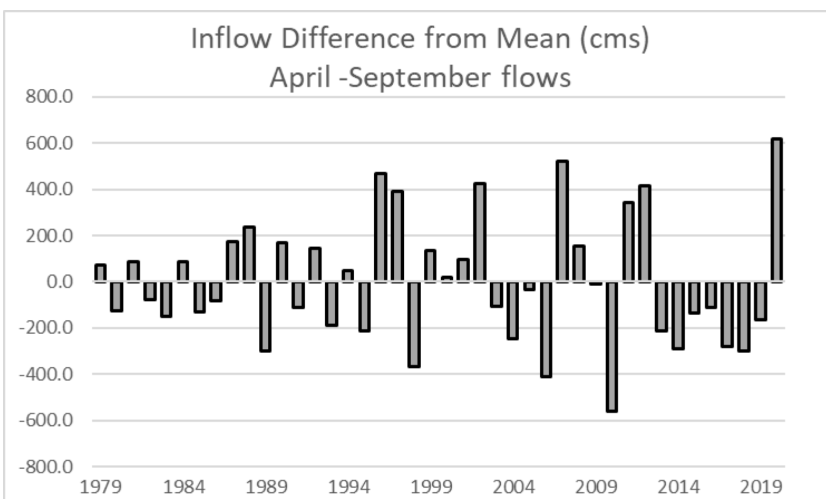

Figure 52- Summer average flow anomalies from 1979 to 2020. The plot represents the deviation from the mean average summer flow for the GWF inflow time-series derived from Water Survey of Canada measurements and MESH model estimates. The largest positive anomaly since 1979 is 2020 with the second highest occurring in 2007.

Examining the details for 2020 as compared to other years, Figure 53 shows daily average Williston inflow from 1979-2020 for each day of the year as compared to the inflows during summer 2020. The total area under the curve represents the volume of water passing through the system and is represented by the summer flow average. The years 2007 and 2020 represent very similar average inflow volumes; however, as can be seen in the figure, the inflow hydrographs represent two very different timing scenarios. In 2007, there is an exceptional spring and early summer inflow event where the peak in early June is attributable to late spring runoff and high snowpack in the mountains combined with record breaking temperature in the region peaking around 30°C on June 3rd. The 2020 inflows are different in that there is a steeper and earlier spring melt that levels off in early June. It is clear, however, that wet conditions persist over the entire summer. The numerous peaks are reflective of persistent rainfall-driven conditions and the high runoff response in mid-August was due to an unusual late summer rainfall event.

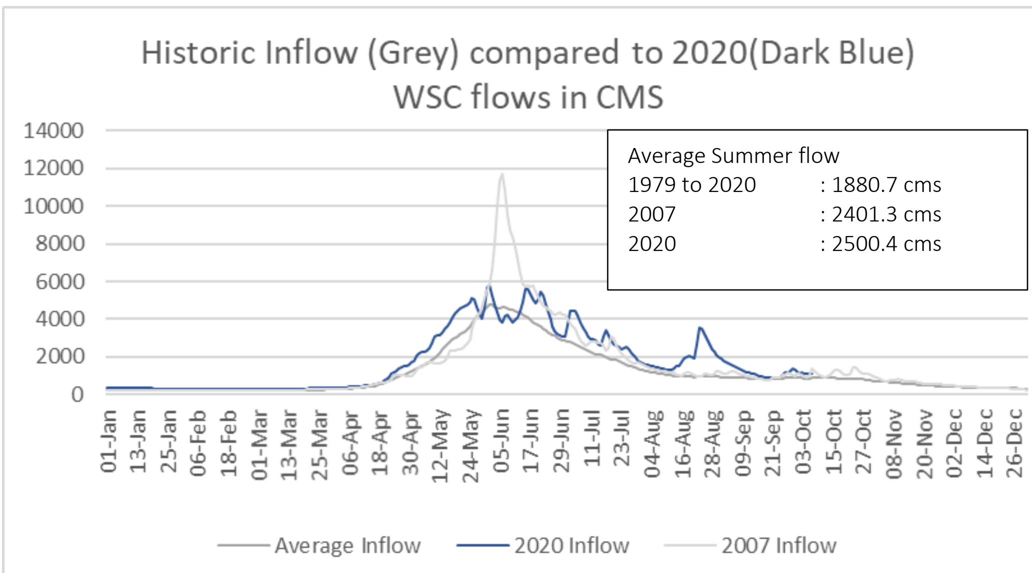

Figure 53 - Average summer inflow hydrographs for Williston Reservoir based on the GWF inflow series. The plot also highlights the two largest anomalous year inflows as compared to the average.

In further examining the 2020 summer sequence of flows, we compare inflows and outflow of the GWF time series for Williston Reservoir. The GWF inflow time-series represent a close approximation of the natural flow that would have occurred in the Peace River downstream of the Bennett Dam. This is analogous to the flow rates that would have occurred had the Bennett Dam not been constructed. To demonstrate the impact that naturalized flows (*i.e.* no attenuation by the Bennett Dam) would have on water levels on Great Slave Lake, we modelled two different scenarios using a daily timestep: 1) routing the inputs to the Williston Reservoir as direct inputs into the Peace River; and 2) routing the outputs from the Bennett Dam as direct inputs into the Peace River. We ran these scenarios through a simple lag of 10 days and then routed the flows through GSL routing models described in the previous section. Scenario 1 (Figure 54) demonstrates that water levels on GSL may have been up to 50 cm higher in July/August than they were in reality. This is due to the attenuation of high flows by the Bennett Dam. It should be noted that this simple modelling exercise does not include proper routing through the Peace-Athabasca Delta and Lake Athabasca systems, so actual water levels would likely be lower than the modelled predictions.

Figure 55 shows derived outflows from the Bennett Dam in 2020, relative to minimum and maximum operational discharge, as well as the typical operating range, defined by 25th to 75th (dark grey) and 5th to 95th (light grey) percentile envelopes. When releases are outside of these ranges, they can be assumed to represent non-normal operations. Figure 53 demonstrates the exceptionally high inflows into the Williston Reservoir in 2020. Because of these, water levels in the Williston Reservoir approached the maximum volume that the reservoir could hold in the summer of 2020, while maintaining the 1.5 m buffer needed to attenuate high flows during river diversion for Site C construction anticipated in the fall (Figure 55). It appears that the higher-than-normal releases (discharge generation + spills) in July and August 2020 were necessitated by the high inflow volumes received in the early spring and through the summer. In a hypothetical situation that does not involve the construction of Site C, the Williston Reservoir may have been able to retain another 1.5 m of water to further attenuate flows, but spilling may have been required during the large rainfall event in August regardless. The presence of the Bennett Dam likely attenuated high flows during the summer of 2020 and water levels on Great Slave Lake may have been higher without flow regulation. The impact of Site C construction and flow diversion required BC Hydro to release a higher-than-normal volume in July and August, but this release may have been necessary regardless following the high August rainfall event.

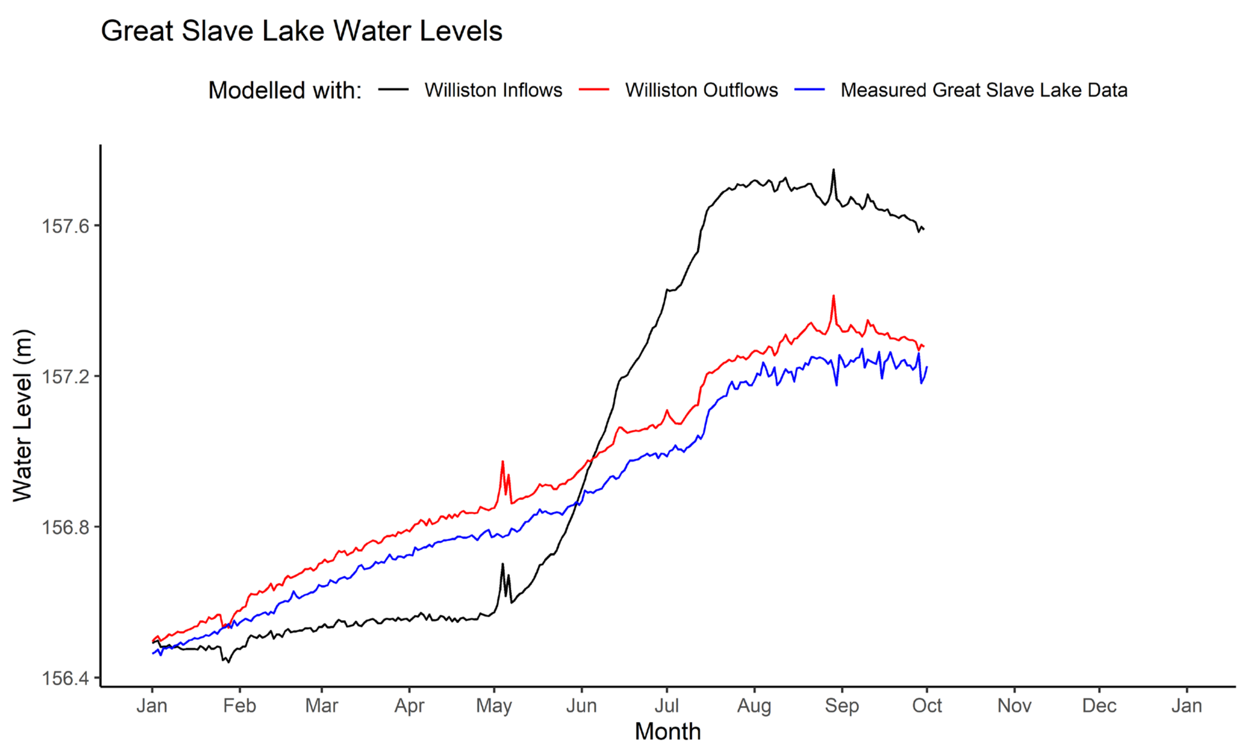

Figure 54 Modelled water levels on Great Slave Lake

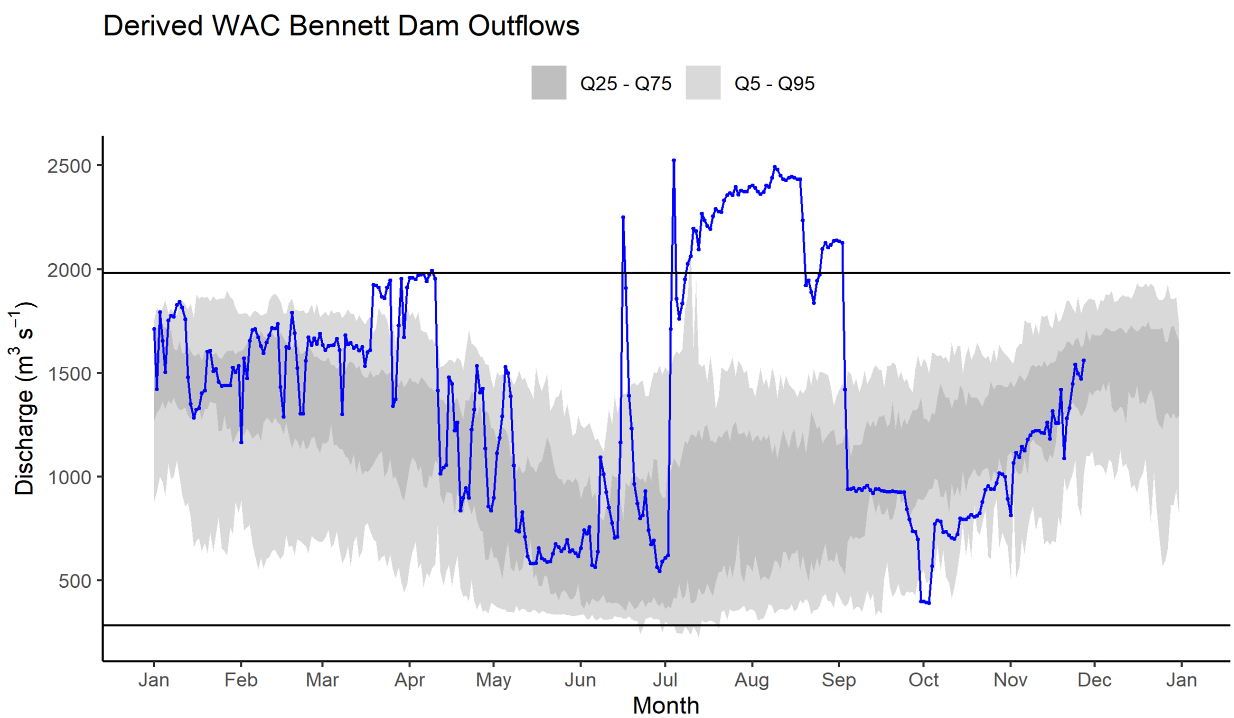

*Figure 55 - Derived Bennett Dam Outflows. Outflows were calculated using: 07AF004 – ((07FB008 + 07FA006) * 1.18). Horizontal lines represent minimum (283 m^3 s^{-1}) and maximum (1982 m^3 s^{-1}) normal generation discharge. Black horizontal lines represent minimum and maximum operational limits.*

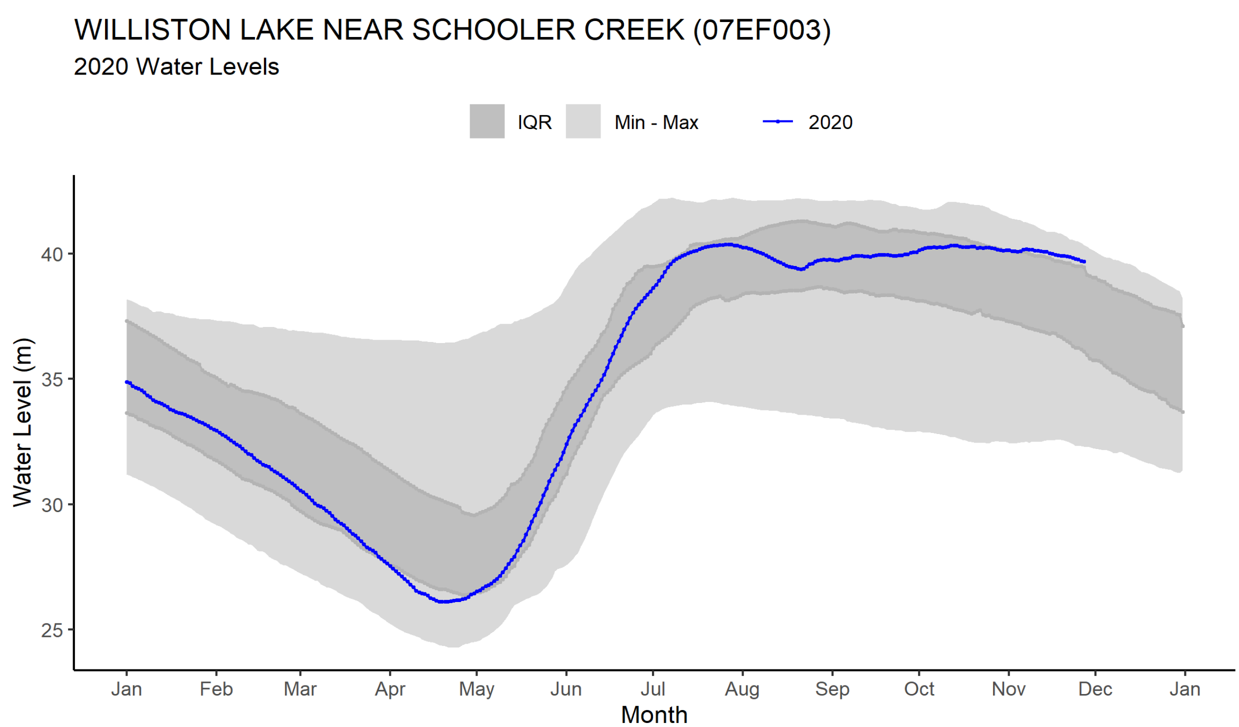

Figure 55- Williston Lake Water Levels in 2020

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