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Assessment of Present and Future Water Security of the Kettle River at Grand Forks in Southeastern B.C.

httpscommons.wikimedia.org/wiki/File:%E2%80%A6along_the_Kettle_River_near_Grand_Forks_(8124250213).jpg

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1. Executive Summary

The simultaneous occurrence of warm spring temperatures and a large snow water equivalent at high elevations in the Kettle River Basin caused a rapid snowmelt event, creating the Kettle River flood at Grand Forks in May 2018. This flood represents an acute isolated event. No long-term trends were observed in the Kettle River's hydrology and climate data. Yet, cumulative effects from decades-long forest land use changes have made the basin more vulnerable to floods. Hence, the 2018 flood resulted from the pairing of climate effects and forest land use changes in the headwaters.

The Kettle River is largely driven by snowmelt given that the majority of this watershed lies above 1,200 meters. Forest removal and road networks have increased open surface area for snow accumulation. Melted snow is likely to run off these surfaces, given changes in soil infiltration that resulted from conventional and pine infested tree harvesting, combined with wildfires. This melt greatly amplifies the Kettle River's streamflow.

Climate change is impacting the watershed. Melting events will occur earlier in the spring. Given the likelihood of warmer than average temperatures in the longterm, flood risk may diminish as snow falls less at higher elevations. Wildfires, the mountain pine beetle, and more dramatic infestations of western spruce budworm are likely to continue with climate change–dead stands potentially increasing the severity of fires.

Continued forest removal will cause a greater impermeable surface area for snow accumulation. If a heavy snowfall were to occur, such open exposure is likely to lead to an even larger snowpack. Should this heavy snowfall coincide with warm spring temperatures again, another devastating flood is likely.

High summer temperatures will produce more droughts. Grand Forks' water security for surface water extraction is likely to be precarious in the summertime – exactly when most licenses along the Kettle River extract water for agricultural irrigation.

Therefore, forest rehabilitation, spring flood protection, and summer water conservation will become crucial for the health of the Kettle River watershed and its communities in the 21st century.

2. Introduction

i) Overview of Environmental Concern

The City of Grand Forks in Southeastern British Columbia has had a precarious existence in recent years. In May 2018, the Kettle River peaked 60 centimetres over record levels and flooded portions of the watershed, including Grand Forks itself (Kettle River Watershed Authority, 2019). The flood forced about 3,000 people out of their homes; two years on, many of these British Columbians live a precarious economic existence. Uncertainty exists over government handouts and the fiscal future of their ruined property (Smart, 2019). In May 2020, Grand Fork residents experienced the alarm of another potential flood. Thankfully, no flood occurred and the Kootenay Boundary Regional District rescinded their evacuation warning (CBC News, 2020). Ironically, in the same period, Grand Forks has also suffered from too little water. During the summer of 2015, a severe drought affected the region.

Given this startling contemporary environmental history, the security of these rural folk in the Kettle River basin feels uncertain (Parfitt, 2019). Such extreme events are likely to increase as climate change continues to impact British Columbia (Regional District of Kootenay Boundary, 2014). Since the Kettle River is a bounded watershed, this basin provides an excellent case study for investigating why extreme environmental events are affecting local areas in the BC interior. This assessment can be achieved through hydrologic, climatic, and land use data analysis.

ii) Aim of the Study

This report investigates why environmental extremes have occurred in the Kettle River watershed. The major questions this report asks are:

- Firstly, why did the May 2018 flood occur? The working theory this report begins with is that rapid snowmelt led to an excessive discharge in the spring of that year.
- Secondly, is the Kettle River experiencing an increase in extreme hydrologic events driven by climate change? Can long-term trends be identified and attributed to climate change?
- Thirdly, how is land use change affecting the basin's hydrological behaviour? How much did land use change contribute to the 2018 flood?
- Fourthly, should residents on the Kettle River and in Grand Forks expect this precarious existence to continue, anticipating more floods and more droughts? How is their surface water security being affected? Or, were the May 2018 flood and 2015 drought singular events?

iii) Geography of Grand Forks and the Kettle River Watershed

Grand Forks is built at the confluence where the Granby River merges with the larger Kettle River in Southeastern British Columbia. Urban, rural, and agricultural land use in Grand Forks rely on the Kettle River for their water security (City of Grand Forks, 2020).

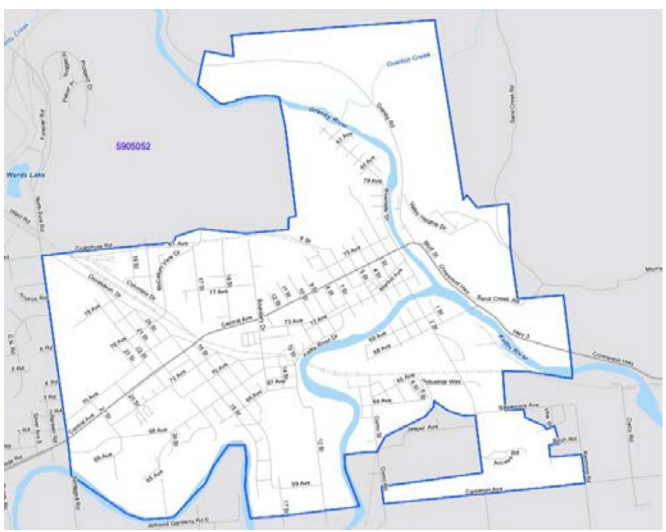

Figure 1: Map of Grand Forks with boundaries (Statistics Canada, 2016).

"The Kettle River Basin is located […] between the Monashee Mountains in the West, the Okanagan Highlands in the East and the US border in the South" (Harker, Hutcheon, and Mayer, 2014, p. 339). One of its tributary basins is in the United States, but the vast majority lies in British Columbia: about 75% of a roughly 11,000 square kilometre catchment area (Summit, 2012). The Kettle River forms part of the larger Columbia River basin not far after entering Washington State (Kootenay Boundary Regional District, 2014; Climate Impact Groups, 2009).

The Kettle River basin forms the majority of the Kootenay Boundary Regional District, as well as the Boundary Timber Supply Area (Government of BC, 2020).

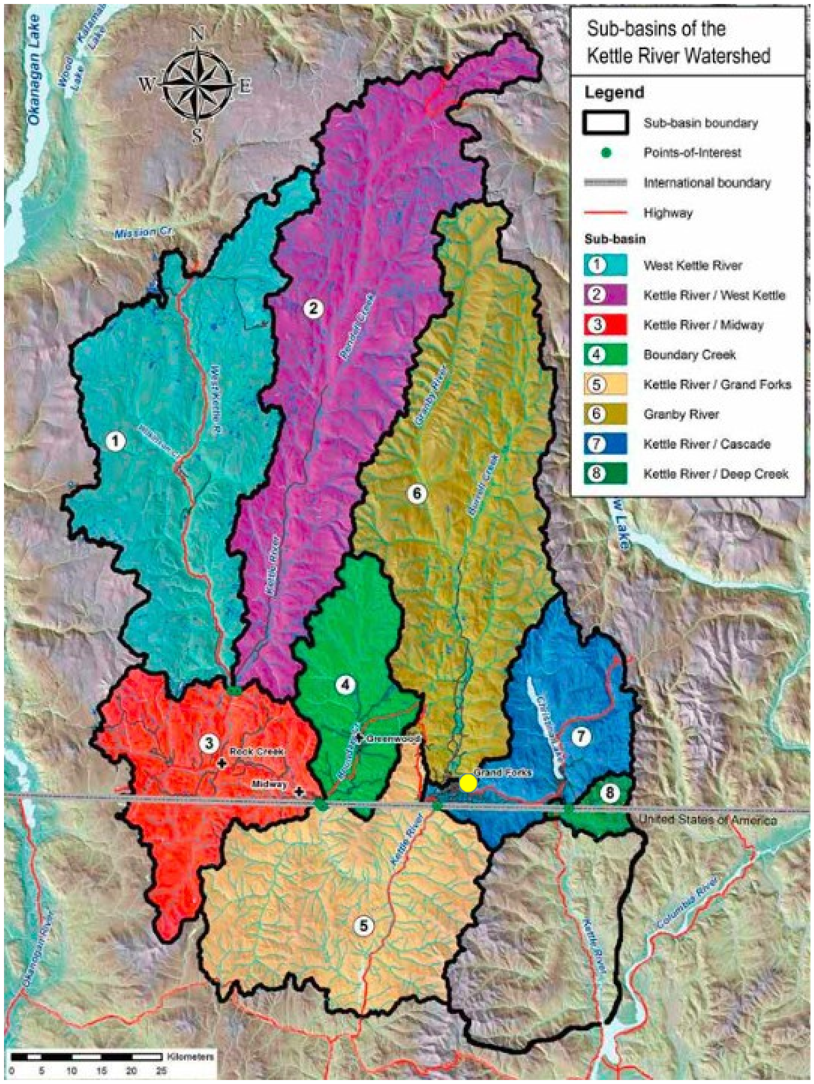

Figure 2: Map of the Kettle River basin; an indicator has been drawn to show Grand Forks's location (Kootenay Boundary Regional District, 2014).

<u>iv) Pertinent Literature</u>

- Hydrological Data

Two hydrological data stations are of significance for tracking data of the Kettle River near Grand Forks: the downstream station at Laurier and the upstream station at Westbridge (Kootenay Boundary Water Tool, 2020).

The Laurier station is located just on the Canadian side of the US-Canada border opposite the American town, Laurier. Here, the Kettle River crosses the border. The station number is 08NN012 and the elevation is about 504 meters. The Laurier data is accessed through Environment Canada (2020).

The Westbridge station is located much further North, upstream in British Columbia at the community of the same name, which is at the confluence of the West Kettle and Kettle Rivers. The Westbridge station number is 08NN026 and is located at 763 meters (Mapcarta, 2020). This data set is published by the Water Survey of Canada (2020) and accessed through BC Water Tool (2020).

Discharge levels will be taken from the downstream station at Laurier. By looking at the downstream flow of the Kettle River, a more accurate picture of the amount of water flowing through Grand Forks can be seen because the Granby River joins the Kettle in town. Therefore, flooding in Grand Forks will be a product of the combined streamflow of the Kettle and its tributary. To observe this discharge, data from the downstream station is more relevant.

- Snow Data

As will be discussed in the next section, inadequate snow data is a limitation of the report. However, snow data that is used in this report comes from the Province of British Columbia's Ministry of Environment and Climate Change Strategy (2020), accessed through BC Water Tool (2020). Monashee Pass snow water equivalent (SWE) data is from station 2E01 at 1,761 meters. Big White SWE is from station 2E03 at 1,337 meters (BC Environment, 2020).

- Climate Data

Grand Forks climate data is retrieved from station 1133270 at 531 meters (Environment Canada, 2019). Midway climate data is from station 1135126 at 578 meters and was used where data at Grand Forks is missing (Environment Canada, 2019). Midway is a town East of Grand Forks along the border. Monashee Pass climate data is from station 34091 at 1,221 meters (BC Environment, 2020).

- Land Use Data

Reports on forest harvesting in the Boundary Timber Supply Area (TSA) will be necessary to observe land use change in the watershed. The Province of British Columbia's Ministry of Forests, Lands, and Natural Resource Operations, and Rural Development (2020) is able to provide this type of information. Data catalogues from DataBC (2020) and iMap BC (2020) will also be useful in assessing this land change visually through their online interactive maps.

Since the Grand Forks flood, a civil society group called the Boundary Forest Watershed Stewardship Society (2020) was created. They advocate for better forest and river management. They present through their website and YouTube channel several independent logging studies. For example, professional foresters Herb Hammond (2019) and Fred Marshall (2019) have researched logging in the Kettle River watershed and argue that over-harvesting is changing its hydrological regime.

v) Limitations of the Report

This report is limited to the Kettle River watershed within British Columbia. It concerns the population centre at Grand Forks specifically since it was the location of the 2018 flood. Hence, towns along the Kettle River other than Grand Forks will not be surveyed.

The main limitation will be exact information on snow accumulation and snow water equivalence at the watershed's higher elevation and headwater. Given that this watershed's headwater is in the Monashee Mountains and that 60% of the watershed is above 1,229 meters, snowmelt is an import influence in the watershed (Hammond, 2019). To appreciate a clear picture of the hydrologic regime, comprehensive data on snow is crucial. However, the exact information of this kind is not as extensive. Snow accumulation data is available from Big White's ski resort. Since the resort requires good snow accumulation to be successful, they advertise the snow accumulation on the mountain; however, their available records exist only for the 2010s (Big White, 2020). An international ski group has useful records on snow levels (Snowpak, 2020). Data on Big White and the Monashee Mountains exists for snow water equivalence only–not snow accumulation. The SWE sets do not have extensive data for both April and May in the last few decades (BC Water Tool, 2020; Kootenay Boundary Water Tool, 2020).

Despite these limitations, the bounded nature of the Kettle River provides an excellent case study for investigating why and how hydrologic regimes may be changing. Should extreme events such as floods continue to occur more frequently throughout BC, exploring hydrologic, climatic, and land use data to observe if and why trends exist will become increasingly important for the security of communities.

vi) Objectives

- Assess the relationship between the Kettle River's climate data and hydrologic data to determine any long-term trends in the Kettle River's behaviour near Grand Forks.

- Explore data sets to determine potential reasons behind the Kettle River's environmental extremes – notably the May 2018 flood.

- Assess land use changes in the Kettle River basin which could be contributing to changing hydrological behaviour.

- Appraise future climate scenarios in the Pacific Northwest to assess how hydrologic and climatic regimes will be affected and how this may contribute to more extreme events like floods and droughts.

- Survey the demography of Grand Forks to determine water demand and appraise the present and future water security for surface water extraction from the Kettle River at Grand Forks.

3. Methods

The main methodological feature of this report will be the exploration, analysis, and interpretation of data sets. These data sets will be attained from Environment Canada (2020), BC Water Tool (2020), and Kootenay Boundary Water Tool (2020) for hydrology data of the Kettle River and climate data at Grand Forks; for land use changes, from a variety of governmental, academic, and professional reports.

I. Assessment of climate and hydrology regimes of the Kettle River at Grand Forks

- Graph May 2018 discharge data to observe what occurred during the month of the flood.
- Analyze discharge data on a mean seasonal spring, mean April, and mean May scale. Create trend lines to show correlation trends to determine if the Kettle River's behaviour shows any statistically relevant long-term trends.
- Show respective maximum and minimum points over time and highlight any data points of interest to assess the history of the Kettle River's behaviour.
- Analyze precipitation and temperature data on a mean seasonal spring, mean April, and mean May scale. Create trend lines to show correlation trends to determine if the climate around the Kettle River at Grand Forks is changing in a statistically relevant way
- Graph available snow data for April and May to observe how snowmelt influence streamflow.

- Assess likely reasons behind the May 2018 flood.

II. Assessment of Land Use Changes in the Kettle River Basin

- Determine the types of land use changes impinging on the Kettle River watershed.
- Assess the geographical scale of these land use changes.
- Assess how the cumulative effects of these land use changes are related to climatic and hydrological conclusions concerning extreme environmental events.

III. Survey of Future Climate Scenarios

- Assess IPCC and academic reports on future climate scenarios to determine how hydrologic and climatic regimes will be affected in the 2020s, 2040s, and 2080s.
- Interpret climate change projections in relation to future land use changes to appraise how the Kettle River will be affected.

IV. Appraisal of Domestic and Surface Water Use in Grand Forks

- Determine the present population and domestic water use per person per day.
- Calculate the present total annual domestic water use and the distribution of water sourcing.
- Create population projections to observe how much water demand will be increasing.
- Determine the number of water licenses on the Kettle River and the amount per license.
- Assess how conclusions from data analysis and climate projections will affect domestic and surface water use.
- Suggest water conservation strategies for the Grand Forks population.

4. Results & Discussion

I. Environmental Extremes in the Kettle River Basin at Grand Forks

i) Daily Flood Event

A graph of the Kettle River's discharge for May 2018 is provided below:

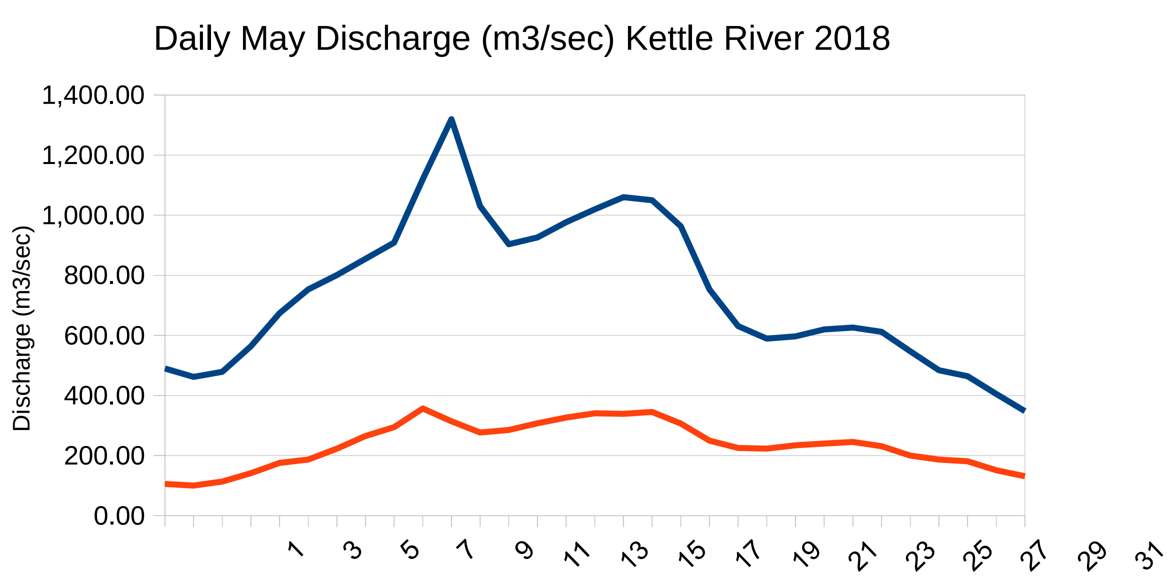

Figure 3: Stream discharge of the Kettle River in May 2018 at downstream (blue) and upstream (red) monitoring stations (Environment Canada, 2020; Water Survey of Canada, 2020)

Grand Forks began flooding on May 10th. Peak flood level occurred on May 11th with a discharge of 1,320 m3/sec at the downstream station at Laurier. At the upstream station, Westbridge, the peak discharge for May was a day earlier on May 10th with a discharge of 356.12 m3/sec. Given the large difference in upstream and downstream flows, the flood event may have been driven by acute rapid snowmelt at higher elevations of the Kettle River and its many small tributaries.

This idea of rapid snowmelt being the driver behind the flood will be the working hypothesis for this report; data exploration will observe if this theory holds.

Data exploration of the Kettle River's discharge, precipitation, and temperature at Grand Forks will be performed. This data exploration is intended to observe if any trends in these hydrological and climate phenomena can be determined; and, to test the idea that the 2018 flood was driven by snowmelt. Furthermore, data concerning the 2015 drought will be noted as this report is concerned with climatic extremes.

II. Discharge Trend Analysis

i) Monthly Discharge

Since peak flow usually occurs in late spring, analysis of April and May data will be conducted to observe the Kettle River's behaviour at this time. Monthly mean values for these months will be taken from available years and graphed to determine if discharge trends exist.

- April

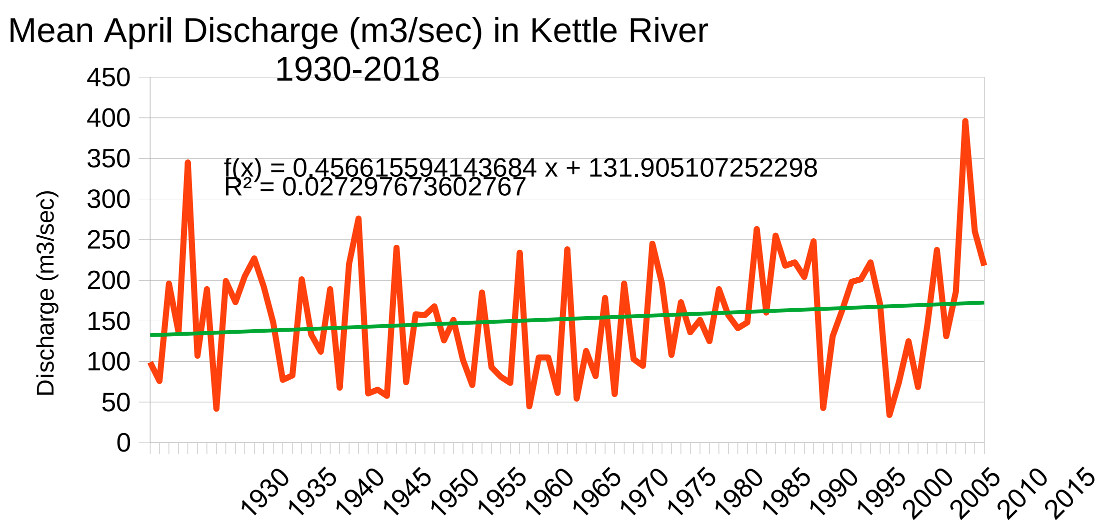

Figure 4: The month of April's mean discharge (m3/sec) from each year between 1930 to 2018 at the Laurier station downstream of Grand Forks (Environment Canada, 2020).

In the past century, April discharge has varied greatly. 2016 was the year of greatest April discharge with 396 m3/sec. 2008 had the lowest April discharge at 34.62 m3/sec. 1930 is also a year with very low discharge, which suggests that 1930 was a dry year.

During the flood year, 2018, the Kettle River's April discharge was 218 m3/sec. Available data for the Kettle River's discharge ends with 2018. April 2018 discharge is middling in the data set; this middling value suggests that a large input of snowmelt had yet to occur.

- May

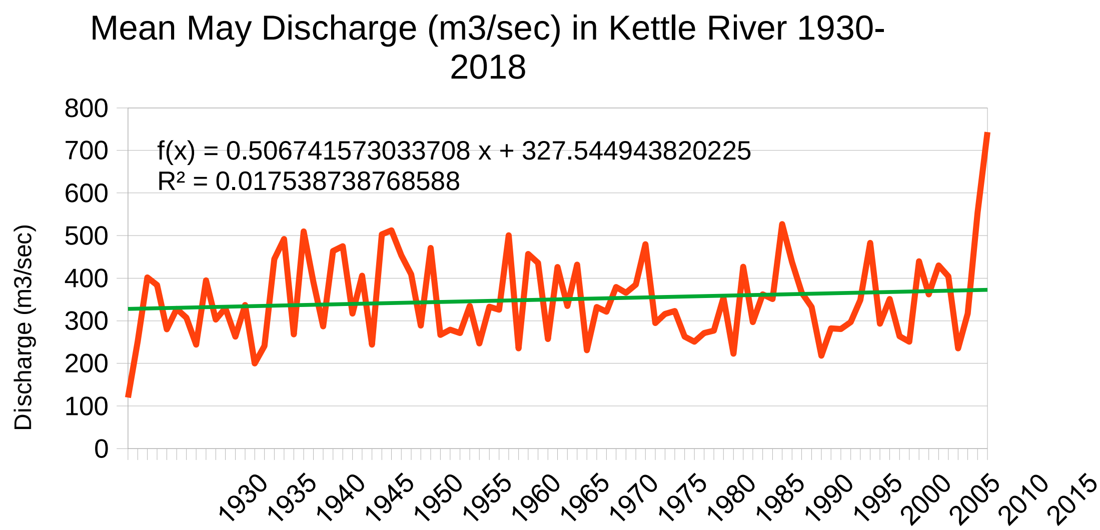

Figure 5: The month of May's mean discharge (m3/sec) from each year between 1930 to 2018 at the Laurier station downstream of Grand Forks (Environment Canada, 2020).

Since 1930, the year with the greatest May discharge has been 2018–the same year as the flood. As said earlier, May 2018's greatest daily discharge was 1,320 m3/sec. Taking the average of that month, May 2018's mean monthly discharge was 743 m3/sec. This data makes sense given that the flood occurred in 2018. The huge jump between April and May 2018 suggests that a large input of water amplified the streamflow–an input likely from rapid snowmelt.

The second maximum is 1997 – 527 m3/sec, which suggests the idea of 1997 as a wet year and a particular year of note, which this report will continue to monitor. The minimum discharge during this period occurred in 1930 with 120 m3/sec. Given that April and May both experienced the lowest mean monthly discharge during this year, this suggests 1930 was a year with very low precipitation and snowfall.

Since 2015, each consecutive May has had increasing discharge: 2015, 235m3/sec; 2016, 317 m3/sec; 2017, 554 m3/sec; and 2018, 743 m3/sec. This consecutive increase in May's mean discharge synchronizes with 2015 being one of the hottest and driest years on record. Does it also suggest that precipitation, particularly snowfall, has been increasing each year between 2015 and 2018? That would suggest that snow accumulation may have been building over a few years before a rapid melt event in spring 2018. This question will be examined in the precipitation analysis in the next section.

April showed the opposite pattern between 2016 and 2018: each consecutive April has experienced decreasing discharge. During the 2015 drought, April showed a low discharge, but nowhere near the lowest discharge value for April.

ii) Seasonal Discharge

- Spring

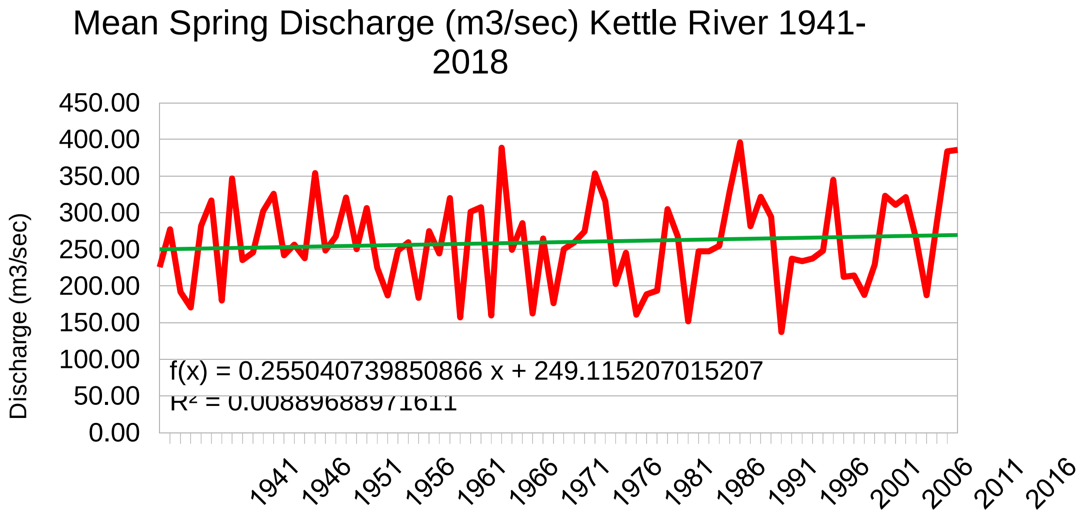

Figure 6: The mean discharge (m3/sec) of the Kettle River near Grand Forks during the spring between 1941 and 2018 (Environment Canada, 2020).

Spring discharge was taken by averaging the mean monthly discharges of April, May, and June for each year between 1941 and 2018.

June was selected over March, in this instance, for the definition of "spring;" because, discharge in June was comparable to May and this seasonal analysis intends to observe trends in discharge during the spring melt. Seasonal flow is greatest during this melt. July discharge sharply drops and has values resembling March. Hence, the three months with the highest discharge are April, May, and June. These months will, therefore, be used for the Kettle River's spring seasonal discharge analysis.

As for potential trends in the Kettle River's spring discharge, the trend line shows that discharge has increased slightly on average during the time frame; however, the correlation coefficient illustrates that the data is not linked together in a statistically significant way.

1997 experienced the highest seasonal discharge during the spring with a mean discharge of 395.33 m3/sec. The lowest discharge occurred in 2001 with 136.57.

On the other hand, 2018 offered the third maximum point with 385 m3/sec (1974 was higher). Hence, while 2018's May discharge is dramatically highest, its seasonal spring discharge was not concomitantly dramatic. This pattern suggests that an acute event occurred at the end of April or beginning of May to shoot up the Kettle River's discharge in 2018 between April and May; this event was likely driven by rapid snowmelt.

During the 2015 drought, seasonal spring discharge is comparatively low, but not in the top three minimal points. This comparatively, moderate, minimum discharge suggests that it was the combination of this lower discharge combined with high summer temperatures and/or low precipitation which meant soil moisture couldn't be maintained.

iii) Upstream-Downstream Discharge

- April

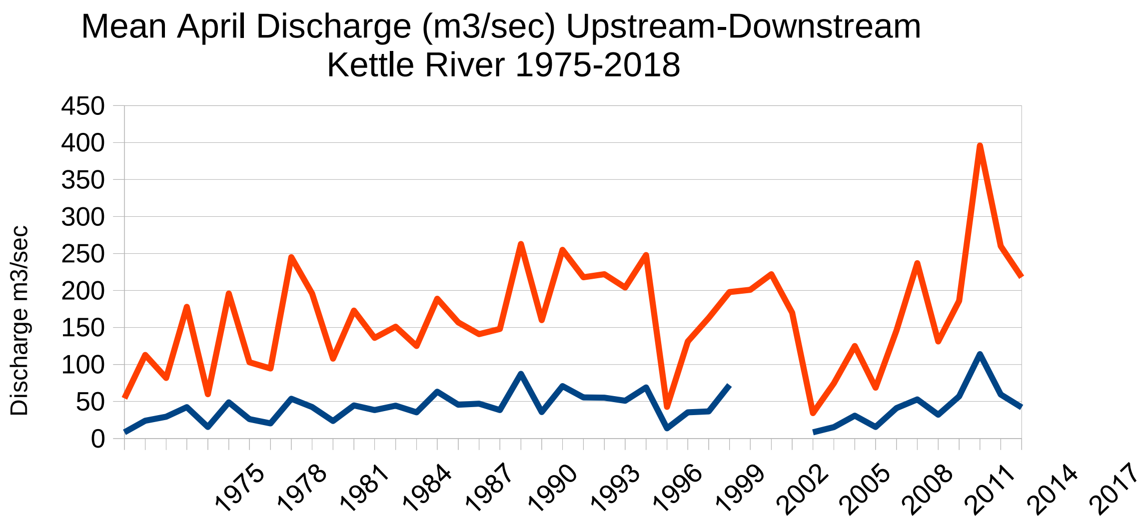

Figure 7: Upstream discharge at Westbridge (blue) and downstream at Laurier (red) (m3/sec) between 1975 and 2018 (Environment Canada, 2020; Water Survey of Canada, 2020).

The large difference between upstream and downstream discharge reflects the inputs from the Kettle River's tributaries. The West Kettle River joins the Kettle just below the Westbridge station and the Granby River before the Laurier station, both of which significantly amplifying the Kettle River's streamflow.

The difference between these stations reflects how spring snowmelt has an enormous influence on the Kettle River's streamflow. As a result, heavy snowfall and higher temperatures leading to rapid melting are primary influences affecting the Kettle River's discharge.

- May

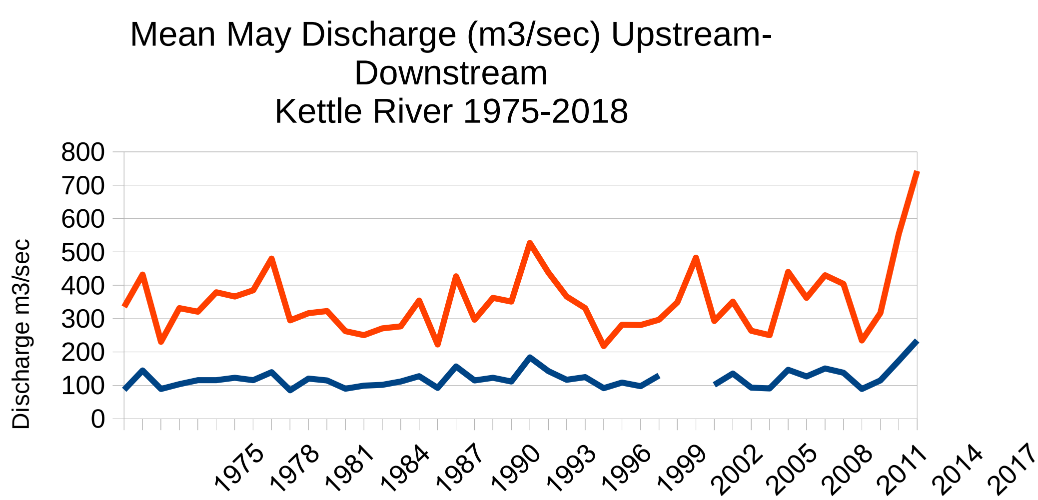

Figure 8: Upstream discharge at Westbridge (blue) and downstream at Laurier (red) (m3/sec) between 1975 and 2018 (Environment Canada, 2020; Water Survey of Canada, 2020)

The peaks at Laurier in 1997 and 2018 suggest rapid melt caused downstream streamflow to be high in the spring of those years. The difference between upstream and downstream stations in May corroborates the idea that rapid snowmelt explains why downstream flow is so much greater.

iv) Conclusion of Discharge Trend Analysis

The greatest seasonal discharge occurred in 1997–not 2018, the year of the flood. Data reveals a recurring trend of maximum points in 1997. These phenomena suggest that 1997 was either a very wet year in the Kettle River around Grand Forks and/or upstream at the Kettle River's headwaters. Yet, why did the flood occur in 2018 and not 1997?

The year 2018's remarkable feature is only the monthly mean discharge in May of that year. 2018's annual discharge is not particularly high, nor is the monthly mean discharge in April. Yet, May 2018's discharge is significantly higher than May 1997's discharge.

However, given that the flood occurred in May 2018 and not May 1997, some other phenomenon (or more) must explain why May 2018's discharge was so high. Comparing April and May 2018 discharge shows that some acute input events occurred. Therefore, May 2018's flood could be explained by more, rapid snowmelt occurring at the headwater's of the Kettle River during 2018 than in 1997.

Possible reasons for 2018's faster and greater snowmelt than 1997's could be because 2018 had a hotter spring than 1997's and/or because more snowfall occurred in the winter of 2017/2018 than in 1996/1997. Land use changes since 1997 could also be an underlying reason why 2018 was more vulnerable to a rapid snowmelt event.

III. Precipitation Trend Analysis

i) Monthly Precipitation

- April

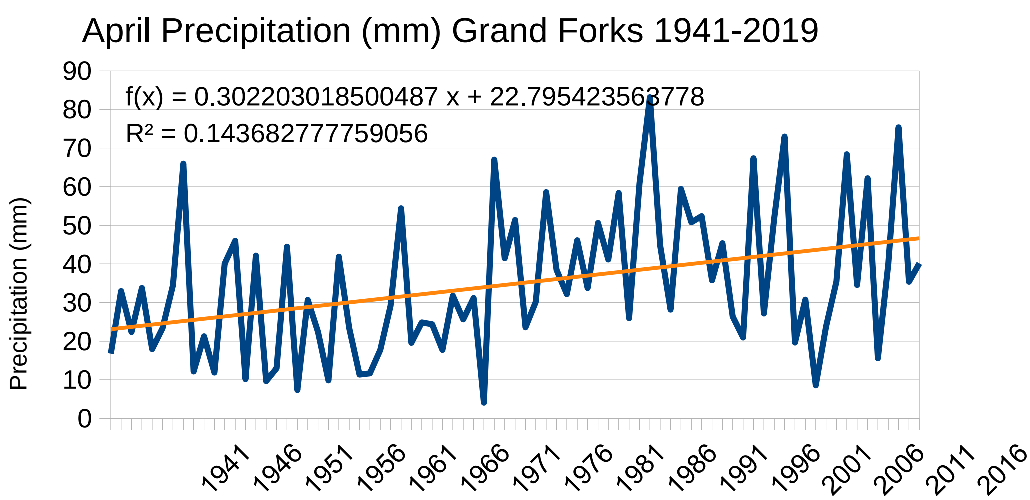

Figure 9: Total precipitation (mm) for April in Grand Forks between 1941 to 2019 (Environment Canada, 2020).

April precipitation has been trending upward; however, the correlation coefficient remains near zero and so a conclusive trend for April precipitation cannot be defined.

The maximum point was in 1993 with 83.2 mm; the lowest was 1977, with 4.1 mm.

April precipitation in 1997 was 50.8 mm; 2018, 35.4 mm; and 2015, 15.6 mm.

1997's higher April precipitation suggests that the high discharge during the spring of that year was a combination of precipitation and snowmelt; on the other hand, since 2018 spring precipitation was not as high, 2018's spring discharge looks like it was driven more by rapid snowmelt.

- May

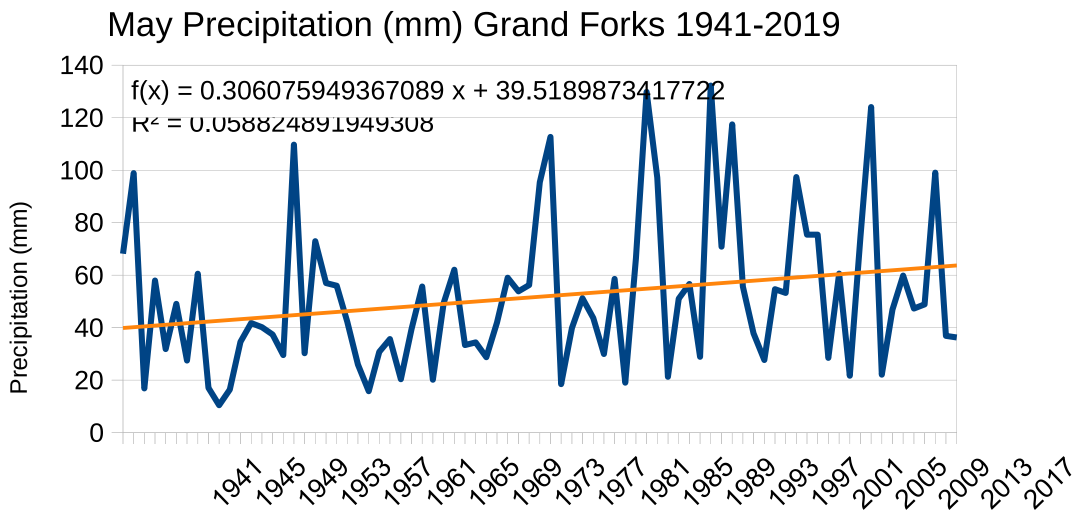

Figure 10: Total precipitation (mm) for April in Grand Forks between 1941 to 2019 (Environment Canada, 2020).

While the levels for 1997 and 2018 are not particularly high, the precipitation for the immediately preceding years are noteworthy: 1996 as the maximum point and 2017 with 99 mm. Presumably, if precipitation is high around Grand Forks, this may mean that snowfall upriver at the headwaters was also high.

This note is particularly relevant for 2018. The lack of heavy precipitation during May 2018 – yet the presence of enormous discharge during that same month – suggests that the acute spike in discharge from April to May must have come from rapidly melting snow upriver in the Kettle River Basin.

The May 2015 precipitation was middling once more at 47.2 mm.

ii) Seasonal Precipitation

With correlation coefficients continuing to reflect an absence in statistically significant trends, yet reinforcing the theory that the 2018 flood was driven by rapid snowmelt, an examination of the seasonal precipitation around the Kettle River's peak flow will be done as part of this data exploration to observe if these themes continue.

- Spring

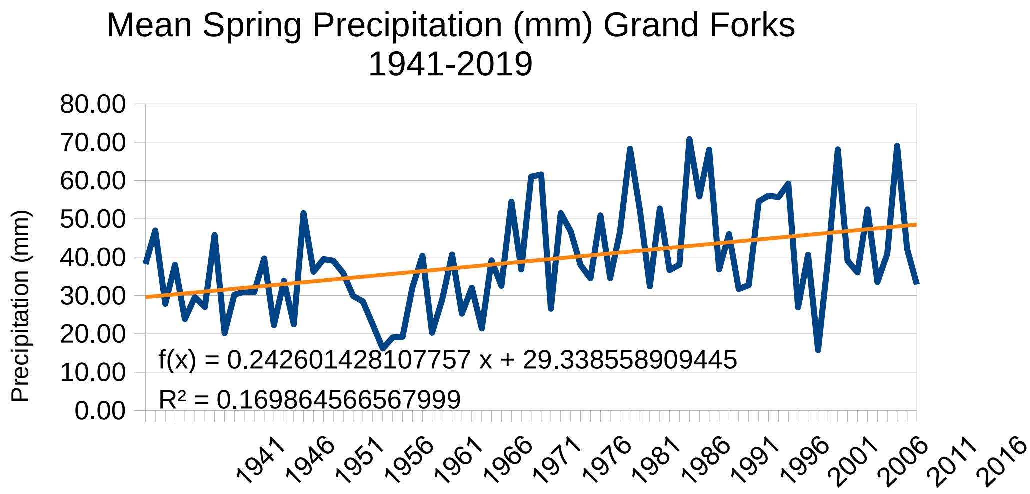

Figure 11: Mean precipitation (mm) for the spring season in Grand Forks between 1941 and 2019 (Environment Canada, 2020).

The year with the greatest spring precipitation was 1996 with 70.80 mm; the lowest was 2009 with 15.73 mm. Neither 1997, the year with the greatest discharge, nor 2018, the year with the devastating flood in Grand Forks, experienced a high precipitation level during the spring – 55.80 mm and 42.07 mm respectively. These low levels of spring precipitation suggest that the Kettle River's high discharges during those years – and especially 2018 – was indeed driven by snowmelt at its headwaters. Spring precipitation in 2015 was 33.47 mm. This suggests that the 2015 drought was driven by temperature extremes which would have evaporated this middling amount of precipitation.

- Summer

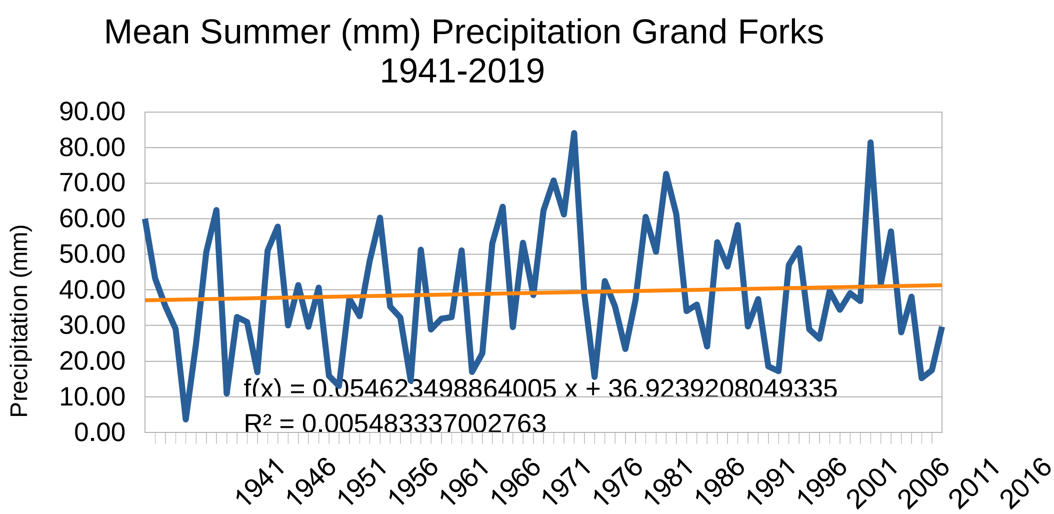

Figure 12: Mean summer precipitation (mm) for Grand Forks between 1941 to 2019 (Environment Canada, 2020).

Given that 1997 and 2018 had lower precipitations – 53.27 mm and 17.40 mm respectively – yet both years experienced notable discharge events, this data continues to support the idea that discharge in those years was mainly driven by rapid snowmelt.

Summer precipitation for 2015, the year of the drought is not devastatingly low; rather, it was 28 mm. Since precipitation in spring and summer were moderate, the drought must have been caused by extreme temperatures, making this precipitation evaporate rapidly.

iii) Conclusion of Precipitation Analysis

Precipitation data continues to reinforce the idea that the 2018 flood occurred because of heavy, rapid snowmelt. Since annual and seasonal precipitation for 2018 are not remarkable – especially in May 2018 when the flood occurred – the remaining explanation for the acute spike is high levels of rapid snowmelt that occurred between April and May causing a jump in streamflow between months.

Given that the preceding year, 2017, had high precipitation this may suggest that snow had been building up between 2015 and 2018. Indeed, every month, precipitation between these years had been increasing, which squares with the increasing discharge between these same years on a spring seasonal basis. With a buildup of snow at the headwaters and higher elevations in the watershed, snow levels were high for an extreme snowmelt event.

Something similar could have occurred in 1997, which has the highest annual and seasonal spring discharge. 1996 shows the highest monthly precipitation; so, snow could have also been building up for 1997's snowmelt. However, this snowmelt would not have been as dramatic as that of 2018.

Concerning the drought in 2015, precipitation data do not reflect dramatically low levels as may be expected. Hence, the drought was likely due to extreme temperatures meaning that any rainfall would have evaporated.

IV. Temperature Trend Analysis

i) Monthly Temperature

- April

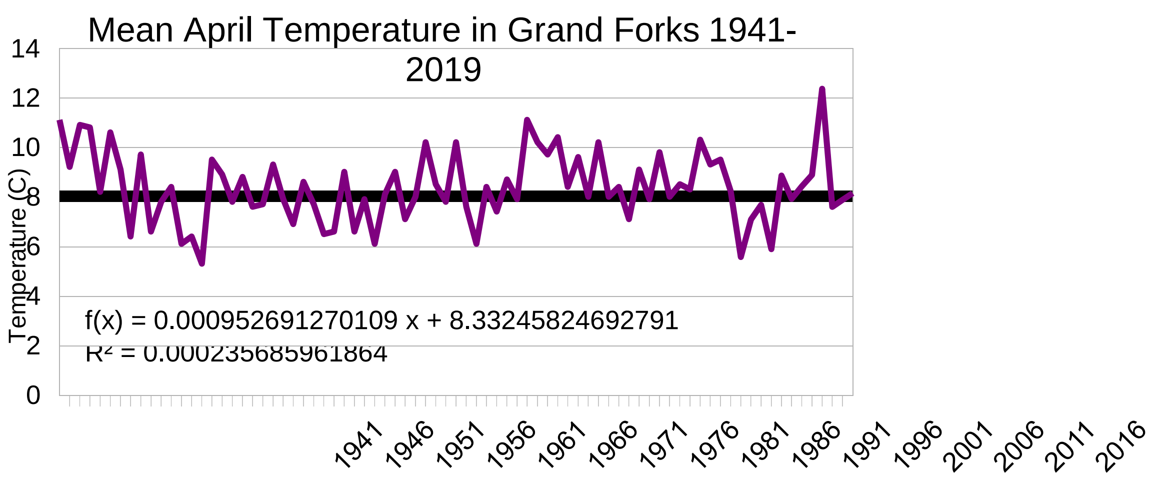

Figure 13: Mean April temperature © from 1941 to 2019 in Grand Forks (Environment Canada, 2020).

Taking the mean temperature for each April between 1941 and 2019 reveals that no temperature trends for this month exist. Neither the trend line nor the correlation coefficient showed any significant changes for April temperatures.

On this local scale, April temperatures do not appear to be rising though a report on temperature trends in the larger Columbia River basin has shown that spring temperatures have increased, which is leading to early peak discharge (Climate Impacts Group, 2009; Hanspeter Schreier, personnel communication, July 9th, 2020).

The year with the highest mean temperature for April was 2016 with 12.36 C; the minimum point was 1955 with 5.3.

Once more, 1997 and 2018 bear similar temperatures for April – 7.1 C and 7.88 C.

2015 has a higher April temperature at 8.88 C.

- May

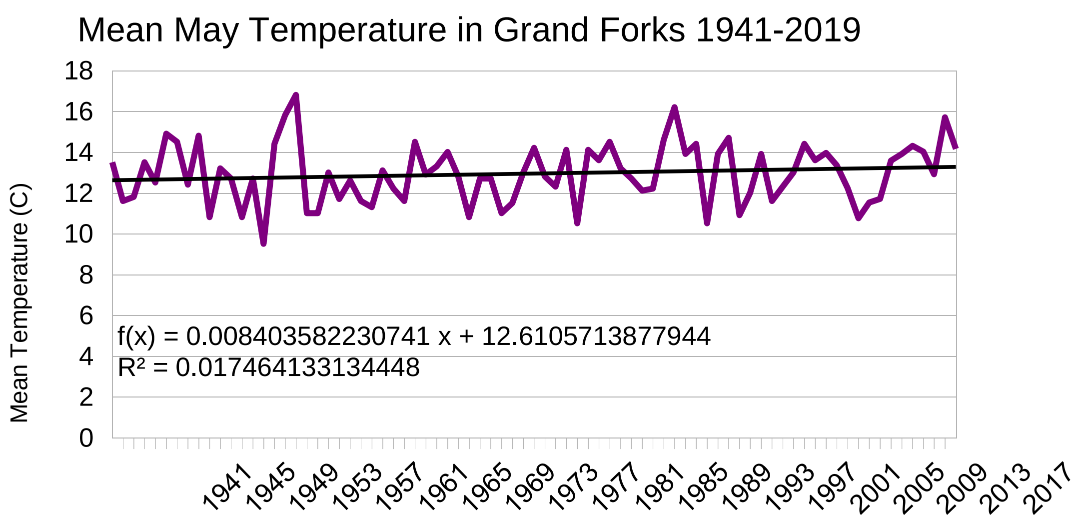

Figure 14: Mean May temperature © from 1941 to 2019 in Grand Forks (Environment Canada, 2020).

Taking the mean temperature for each May between 1941 and 2019 reveals that no temperature trends for this month exist. Neither the trend line nor the correlation coefficient shows any significant changes for May temperatures.

The maximum and minimum points for mean May temperatures occur in the 1950s – the maximum in 1958 with 16.8 C; the minimum with 9.5 C during 1955.

May 2018 had the third-highest mean temperature in the data set at 15.7. This high temperature in May supports the idea that snowmelt would melt rapidly in the Kettle River Basin and amplify the Kettle River's streamflow during that month. This rapid snowmelt would have led to the acute spike in May 2018 discharge, leading to the flood in that month.

May 1997 was not as hot at 13.9 C. While that year did have the highest mean annual discharge, its lack of extreme temperatures in the spring supports the idea that snowmelt in that year was not as high as in 2018, which is why the flood occurred in 2018 and not 1997.

May 2015 temperature is in between these two values with 14.3 C.

Similar to April, on this local scale, May temperatures do not appear to be rising though in the Columbia River basin spring temperatures have been increasing, leading to early peak discharge (Climate Impacts Group, 2009; Hanspeter Schreier, personnel communication, July 9th, 2020).

ii) Temperature vs. Precipitation

- April

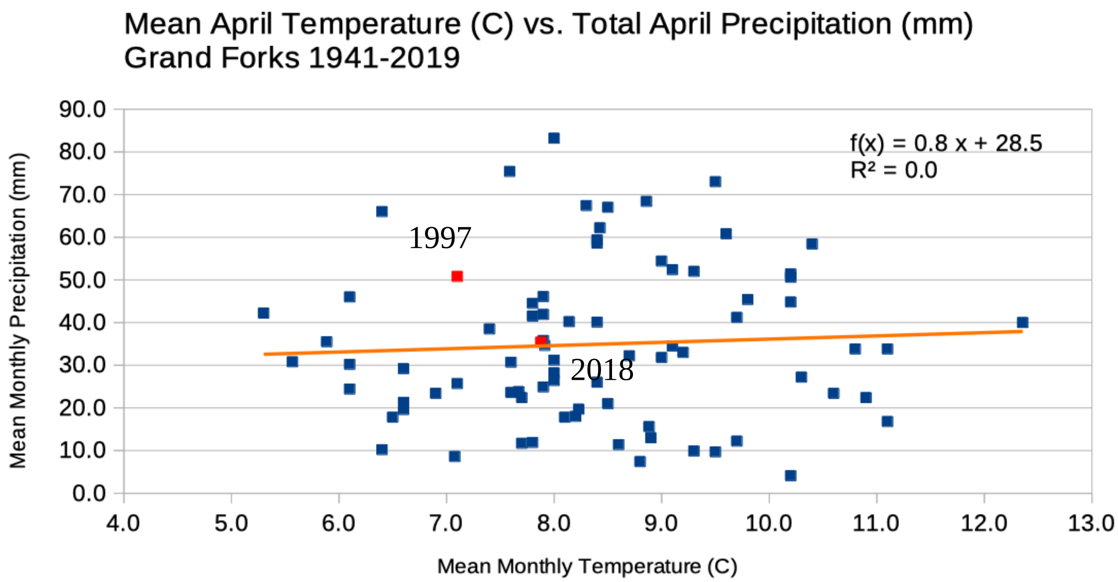

Figure 15: Mean April temperature © versus precipitation (mm) in Grand Forks 1941 to 2019 (Environment Canada, 2020).

Graphing mean April precipitation versus April temperature reveals a trend line that demonstrates no statistically significant trend in the relationship between precipitation and temperature between 1941 and 2019.

Values for April 1997 and 2018 have been labelled and highlighted in red.

- May

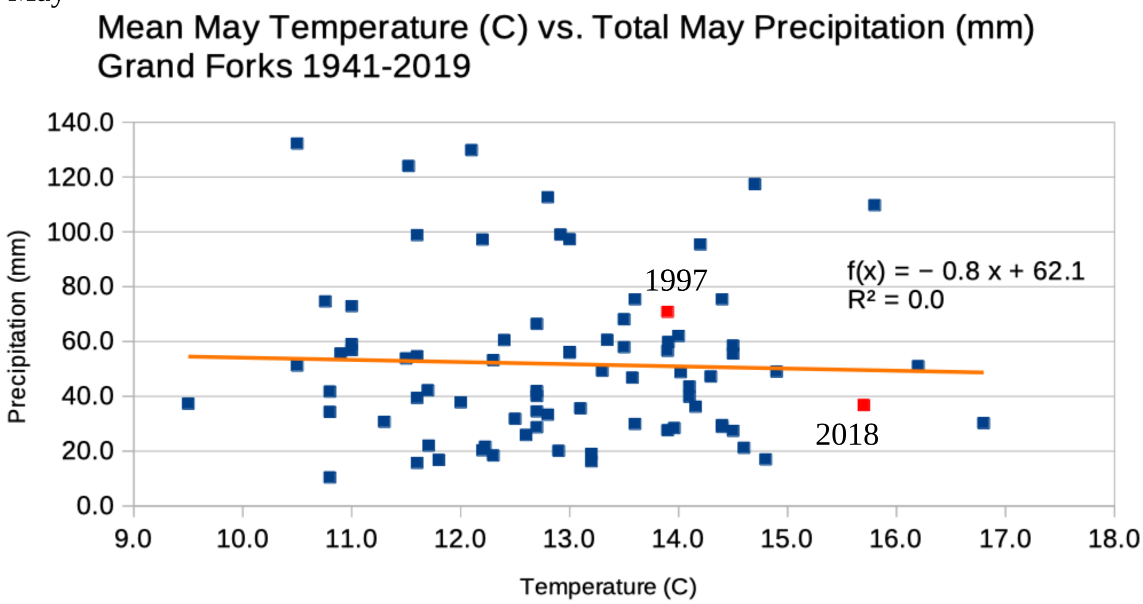

Figure 16: Mean April temperature © versus precipitation (mm) in Grand Forks 1941 to 2019. (Environment Canada, 2020).

Graphing means May precipitation versus May's temperature reveals a trend line that demonstrates no statistically significant trend in the relationship between precipitation and temperature between 1941 and 2019. Values for May 1997 and 2018 have been labelled and highlighted in red.

V. Snow Data Analysis

i) Snow Water Equivalent at Headwaters

- April

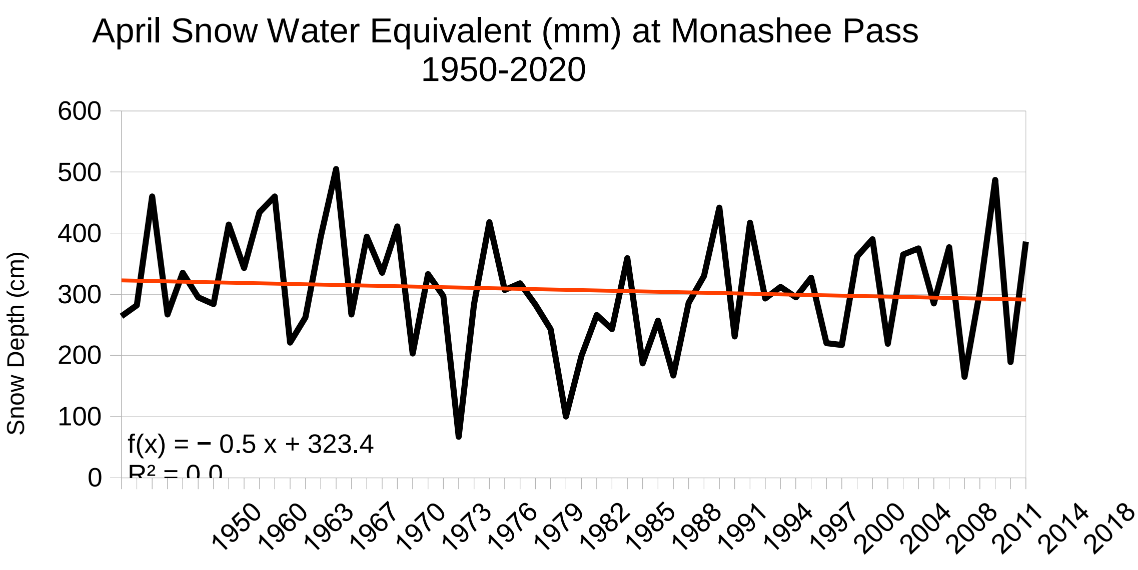

Figure 17: Level of snow water equivalent (mm) at the Monashee Pass at the Kettle River's headwaters in April for years available between 1950 and 2020. (BC Environment, 2020).

Snow data at the headwater continues to confirm the idea that the May 2018 flood was driven by rapid snowmelt. Snow water equivalent (SWE) in April 2018 is the second-highest in recent years – significantly above that of April 1997. SWE in 1997 was quite high. Combined with greater precipitation than 2018, it explains why annual and spring discharge were higher than discharge values in 2018. Yet, the greater SWE in April 2018 explains the acute spike in May 2018's discharge when this snow melted, amplifying the Kettle River.

SWE in 2015 was very low, which fits the pattern that would be expected for that drought year. This low SWE was likely driven by higher temperatures rather than low levels of precipitation since spring 2015's precipitation levels were not dramatically low.

ii) Snow Data at Big White Ski Resort

Given the geographic proximity to the West Kettle and Kettle Rivers, Big White Mountain is an influential tributary of the Kettle River catchment. As such, observing the 2017/2018 ski season of Big White will reveal snow conditions on mountains in this northern region of the Kettle River basin.

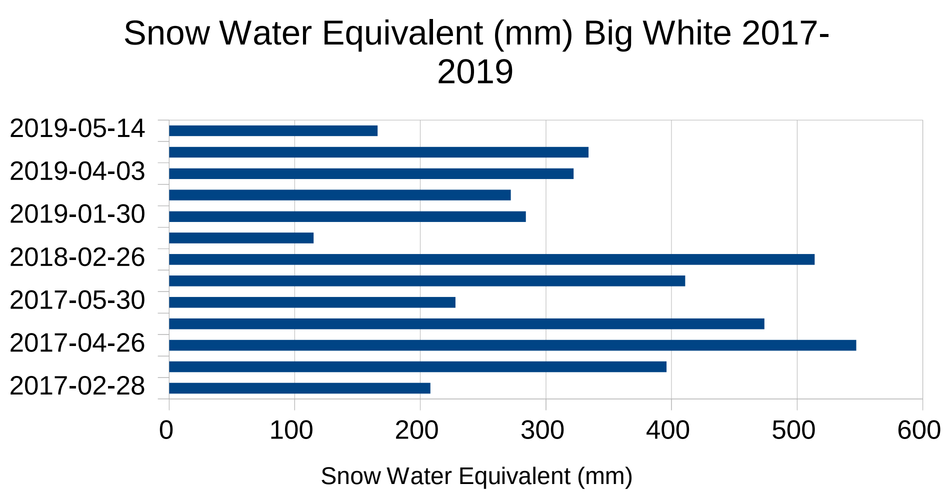

Figure 18: Snow water equivalent (mm) at the Big White ski resort in recent years (BC Environment, 2020).

While the apex of SWE is unrecorded for 2018, the data point for February 26th suggests that SWE in April would be substantially higher than the other years. Given that March, April, and May are when the ski season is best (Big White, 2020; Snowpak, 2020), more snow would have fallen past February. Yet, February 2018's SWE is already approximate to April 2017's. Hence, SWE a few months later in April 2018 would presumably have been even greater by a large margin.

Big White (2020) confirms snow continued to fall past February 2018, leading to a terrific season for winter sports. For example, in the week after February 26th, 77 cm of snow fell (Snowpak, 2020).

Snowpak (2020) has data on Big White snow depth, showing that Big White depth between 2016 and 2018 ski seasons has increased slightly. This slight increase in snowpack fits with conclusions derived during precipitation analysis. Precipitation between 2015 and 2017 had been increasing (see Figure 11).

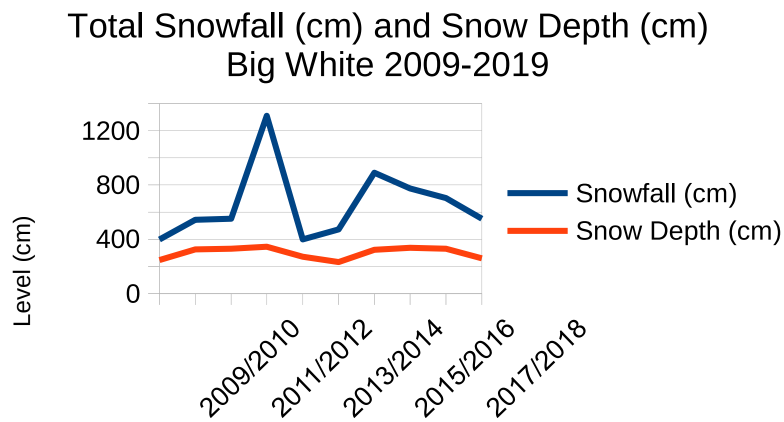

Figure 19: Total snowfall (cm) and snow depth (cm) for the Big White ski resort for each season between 2009 and 2019 (Snowpak, 2020).

Despite the similarity in the snow in the decade, Big White SWE values still differ. SWE since February 2018 would have continued increasing till April since the ski season was just beginning; this increase would have led to a much greater SWE by April 2018. When melted, this SWE amplified the discharge of the Kettle River leading to the 2018 May flood (BC Water Tool, 2020).

May 2018's high temperature would have been the ideal climatic event to have this large input of SWE melt and amplify discharge for May 2018 (see Figure 14).

iii) Spring Mean Minimum Temperature near Headwaters

Given that snowmelt is greatly influenced by mean minimum temperatures being warmer and that minimum temperature is more likely to have increased as averages warm, monthly mean minimum temperatures will be explored (Hanspeter Schreier, personal communication, July 14th, 2020).

However, climate data at Monashee Pass is limited between 2015 and 2019 (BC Environment 2020). Climate data is better slightly downstream at the Kettle li station, numbered 388 at 1,391 meters (BC FLNRORD, 2020). This station has daily climate data between 1987 and 2020.

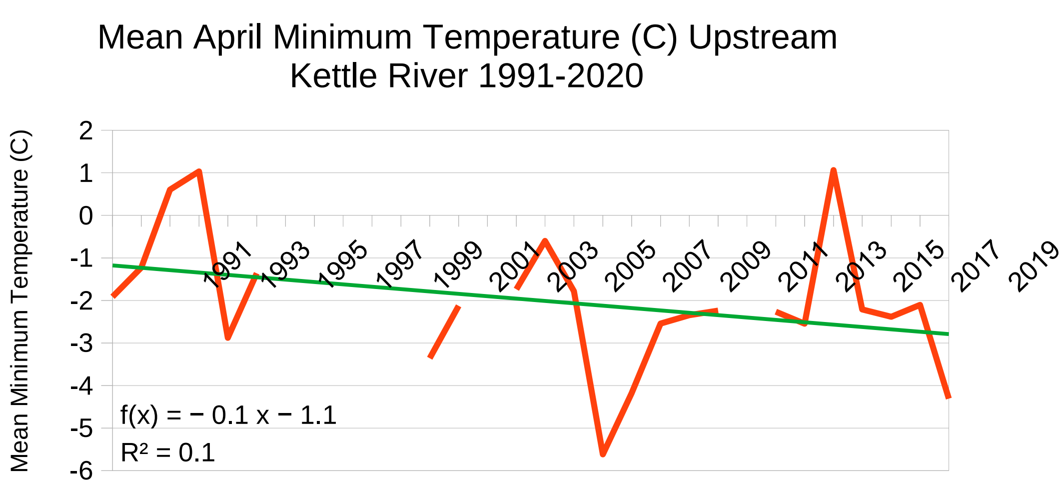

Figure 20: Mean April minimum temperature © for the Kettle River far upstream in the watershed near the headwaters (BC FLNRORD, 2020).

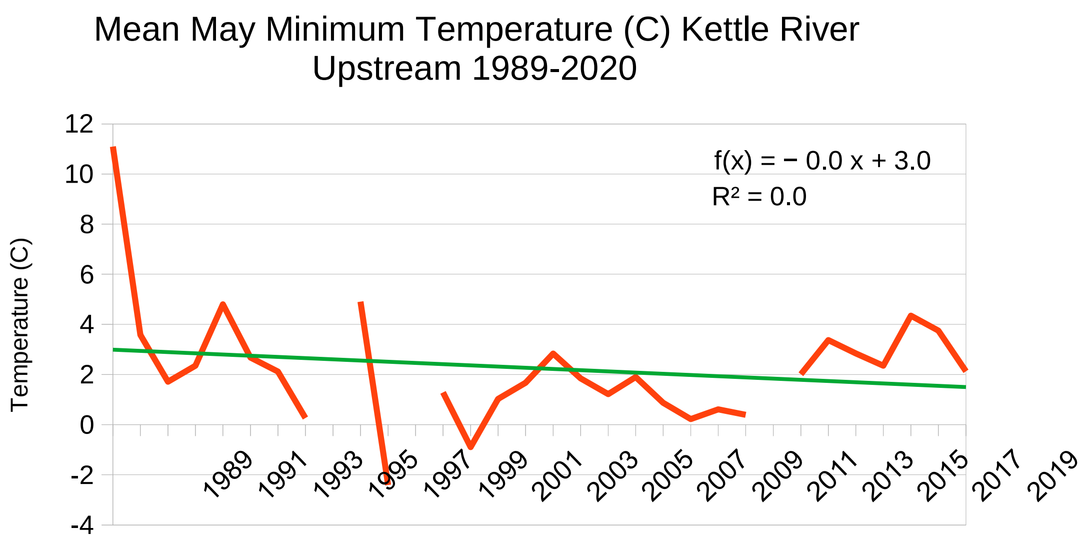

Figure 21: Mean April minimum temperature © for the Kettle River far upstream in the watershed near the headwaters (BC FLNRORD, 2020).

While no seasonal trend is evident in these limited data sets, the April and May 2018 values are still meaningful. April 2018 had a very cold mean minimum, which illustrates that the SWE for the snowpack would be great. Melting would not have occurred. Then, with the mean minimum of May 2018 being very high, a considerable amount of that snow would have melted rapidly. The high spring 2018 SWE would have gone into the Kettle River. Therefore, the jump in discharge between April and May 2018 was an acute event driven by rapid snowmelt containing a high SWE.

VI. Conclusion from Data Analysis

While reports on climate change's effects in Washington state and the Columbia River catchment have been trending upward in the springtime, seasonal data on this tributary river at Grand Forks does not show this trend on a local scale (Climate Impacts Group, 2009; Motte *et al.*, 2014; Mote and Saranthé Jr., 2010). This data exploration is unable to determine conclusively any increasing or decreasing trends in the Kettle River's discharge nor in Grand Fork's precipitation and temperatures between 1941 and 2019 because of the ubiquity of correlation coefficients at or near zero.

Yet, ample evidence exists to eliminate certain reasons behind the environmentally extreme events in the Kettle River Basin near Grand Forks and make the case that the May 2018 flood is likeliest to have been driven by an acute incident of rapidly melting snowmelt.

The discharge of the Kettle River in 2018 was only extraordinary during May. April discharge was not high. This acute spike in discharge between April and May was not caused by a dramatic increase in precipitation during that year since 2018 precipitation levels were moderately low.

However, in the preceding three years, precipitation levels are increasingly led to a very slight increase in snow depth at higher elevations in the Kettle River Basin. In the 2017/2018 winter, a large SWE existed at the headwaters and in the surrounding mountainous northern region of the watershed.

Then, with hot temperatures in 2018 – especially high May mean minimum temperature near the headwaters – this would have led to the rapid snowmelt of this high SWE snowpack. Given how influential snowmelt is to the Kettle River's streamflow, as illustrated by comparing upstream and downstream flows, the spike in May downstream discharge is most likely caused by excessive and rapid melting during May 2018. Therefore, a simultaneous occurrence of climate events occurred to cause the flood: large SWE present in the northern basin and a high mean minimum May 2018 temperature at high elevations caused a rapid and larger than normal snowmelt.

This combination of factors in 2018 did not occur in 1997. While 1997 had the greatest spring discharge between 1941 and 2018, an acute melting event on the same scale as May 2018 did not happen. Different circumstances explain why 1997 had the greatest spring discharge, but not the flood.

Precipitation levels are higher in 1997 than in 2018; moreover, 1996 had the highest precipitation level in that data series; hence, a similar accumulation of snow at higher elevations in the Kettle River could have taken place. The high discharge in 1997 was likely caused by a combined precipitation and snowmelt event in that year likely driven by that year experiencing a major El Nino event (Canadian Columbia Basin Glacier and Snow Research Network, 2020) – though with the absence of 2018's acute surge in snowmelt in May of that year. Hence, 2018's accumulation of SWE was greater than 1997's water input from snow and rain despite 2018 not experiencing warmer winters from El Nino.

Concerning the drought in 2015, that event was caused by extreme temperatures rather than low levels of precipitation. Discharge levels of the Kettle River during 2015 are very low on an annual and spring level; yet, precipitation levels in 2015 are of middling values. This means that snowmelt would not have been high in the Kettle River; as well, temperatures were hot enough to evaporate the precipitation that did fall such that enough evaporation occurred for a drought.

In addition, could land use changes be a contributing factor to the 2018 flood? Are there underlying conditions caused by land use changes that made this simultaneous occurrence of climatic events more severe? Have land use changes caused the watershed to be less resilient to synchrony of high snowfall and high temperatures? If land use is changed and more open spaces are revealed with removing tree cover, then snowpack will increase. The next section explores these questions.

VII. Land Use Changes

i) Types of Land Use Changes in Kettle River Watershed

- Forest Harvesting

Grand Forks is the biggest community in the Boundary Timber Supply Area (TSA), which roughly overlaps with the Regional District Kootenay Boundary. The Boundary TSA covers 656,000 hectares, of which 272,286 hectares are considered harvestable, known as the Timber Harvesting Land Base (THLB) (Nicholls, 2014). Lodgepole Pine and cedar are the two main trees harvested in the Boundary.

Established in 1982, the Boundary TSA's Annual Allowable Cut (AAC) has changed little over time; the AAC has typically been 700,000 cubic meters. Between 1993 and 1995, the AAC was increased to 900,000 cubic meters in response to the mountain pine beetle's surge in the area. As of 2016, the current AAC is 670,142 cubic meters (Nicholls, 2014).

According to the Boundary TSA Timber Supply Review (2011), "92% of the area is harvested using clear-cut methods" (p. 23).

Professional forester, Herb Hammond (2019), retrieved harvest data for consolidated cut blocks in the Kettle River watershed. That cut block data, which he kindly shared with me, is graphed below:

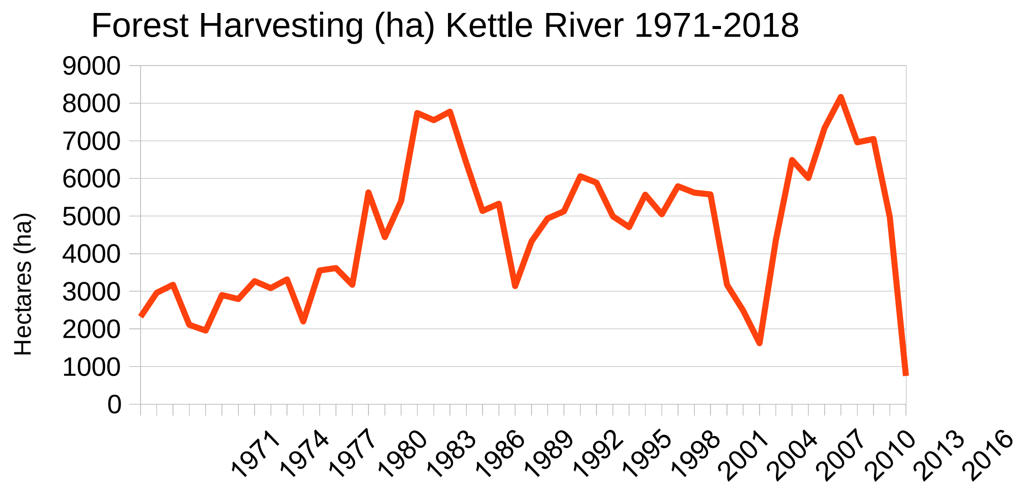

Figure 22: Forest harvesting (ha) by year in the Kettle River watershed between 1971 and 2017 (Hammond, 2019).

Recalling that 1997 witnessed the highest annual and spring discharge; May 2018, the highest peak flow causing the flood; both discharge events occurred immediately succeeding a rapid rise in deforestation. This trend demonstrates the relationship between forest harvesting and hydrology.

Given that clear-cutting is the dominant method of silviculture, these harvested land represents an enormous surface area where snowpack can accumulate and provide a large input in the Kettle River's hydrology.

- Distribution of Harvesting

The elevation and size of harvesting influence snow accumulation. For example, larger clear-cuts are less effective at increasing snow accumulation than smaller cuts because snow in larger cuts tends to melt faster (Hanspeter Schreier, personal communication, July 9th, 2020). Moreover, the higher elevated a cut is, the likelier the land will experience snowfall given weather is colder at higher elevations.

The H60 line of a catchment is that elevation above which 60% of the catchment lies. For the Kettle River watershed, The H60 is 1,229 meters (Hammond, 2019).

The average elevation of forest harvesting is slightly above the H60 line, representing 44% of all clear-cuts (Hammond, 2019). The majority of logging occurring at elevations where snowfall would be ubiquitous in the winter times demonstrates the likelihood of greater snowpack.

According to Hammond's (2019) analysis, recent logging distribution has been varied. In the lower half of the Kettle River basin, logging is mostly along the tributaries; in the upper portion, logging is both along the tributaries and along the main-stem.

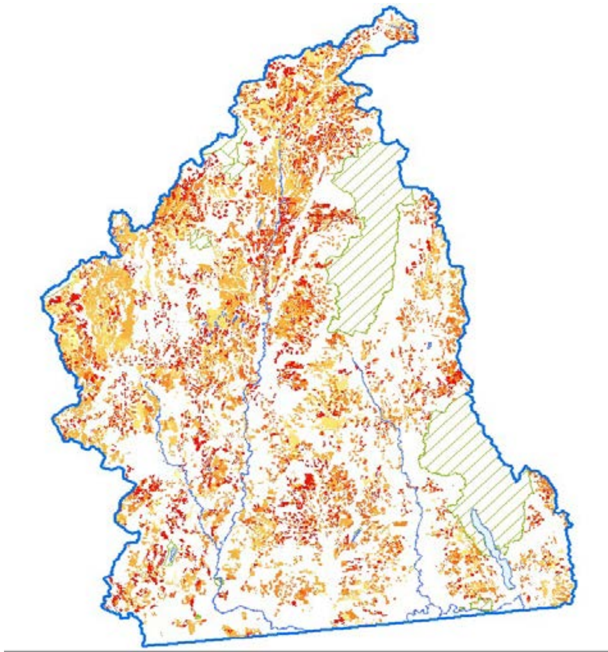

Figure 23: Harvesting in the Kettle River basin. Areas are temporally represented based on redness: the more red a block is the more recent the harvesting is (Figure from Hammond, 2019)

Focusing on the red areas, one can see that an area of focus has recently been along the main-stem in the upper portion of the watershed; concurrently, recent harvesting has also occurred throughout the whole watershed in the tributaries.

Zooming into harvesting maps of these tributary watersheds like Granby River, Hellroarer Creek, Christensen Creek and Boundary Creek, one sees that harvesting blocks are mixed in size. For example, Hellroarer Creek has mostly large cut-blocks and others like Christensen and Boundary have more small cut-blocks.

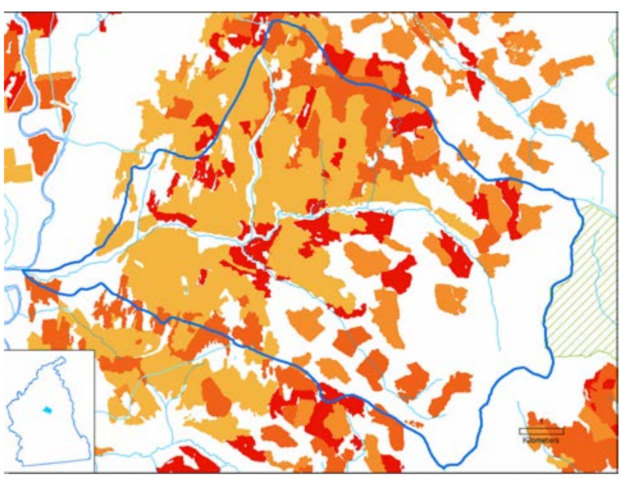

Figure 24: Hellroarer Creek harvesting distribution (Figure from Hammond, 2019)

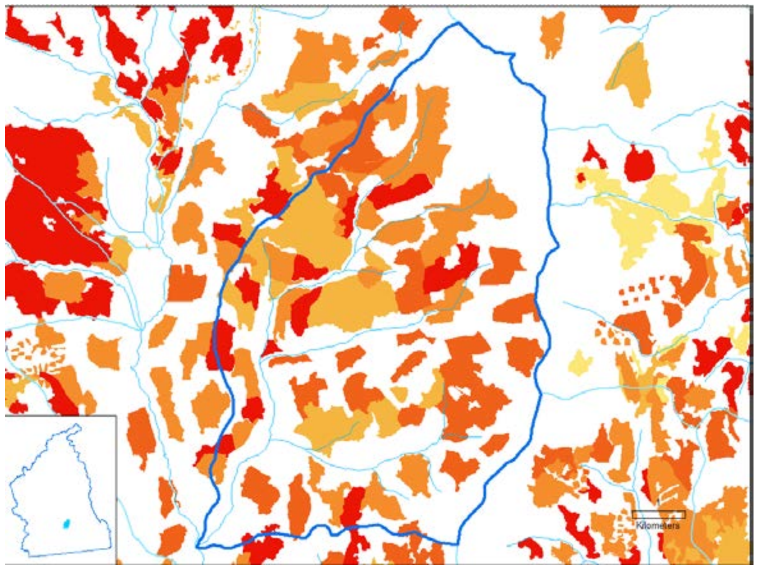

Figure 25: Christensen and Boundary Creek cut-blocks (Figure from Hammond, 2019)

From these maps, one can see the extent to which the watershed has been logged. There appears to be no pattern to this harvesting. The amalgamation of small and large cut-blocks appear to be randomly distributed across the entire watershed.

Furthermore, to achieve the high rate of logging in the Boundary TSA, professional forester, Fred Marshall (2019) has calculated that over 15,000 kilometres of logging roads have been created. These roads zigzag throughout the THLB with ditches at either side, providing additional surface area for snowpack to accumulate.

- Mountain Pine Beetle

Given that 54% of trees in the Boundary TSA are pine, the mountain pine beetle (MPB) has been particularly virulent in the regional district (Nicholls, 2014). The outbreak in the 1990s was the reason the AAC was increased to salvage some of the damaged wood. While this practice continues, an estimated 24,090 cubic meters of trees are lost due to MPB (Timber Supply Review, 2011). The MPB infestation is exacerbated by reforestation efforts, which typically plant lodgepole pine as part of their forest management (Hammond, 2019).

MPB has become a persistent and pernicious infestation because warmer summers have accelerated the life cycle of beetles – creating adults earlier in the summer, which then fly to more and more stands (Strain, 2012); moreover, milder winters lack the extremely cold temperatures necessary to kill off large percentages of the population to keep the infestation in check (Environment Canada, 2020). These dead pine stands affected by MPB then become excellent fuel for forest fires.

- Wildfire

In the Timber Supply Review (2011) for the Boundary TSA, 614 cubic meters of forest are burned each year.

According to the manager of Interfor, Jeff Becker, before a Grand Forks city council meeting in 2019, 24,000 hectares of forest in the Kettle River watershed burned in wildfires between 2014 and

2018 (Parfitt, 2019). More than twice the amount of land burned in the 2010s than in the preceding 30 years according to Becker (Parfitt, 2019).

ii) Cumulative Effects of Land Use on Hydrology

In a study completed in 2012, Kim C. Green and Younes Alila at the UBC Department of Forestry quantified how deforestation affects forest hydrology. Their findings "illustrate how forest harvesting has substantially increased the frequency of the largest floods in all [their] study sites" (Green and Alila, 2012, p. 1). Not only did the frequency of large floods increase by a rate of two and sometimes four, but their peak flow also experienced a similar rate of increase (UBC Faculty of Forestry, 2012). Green and Alila write (2012):

> "A frequency-based meta-analysis reveals that moderate levels of forest harvesting (33% to 44%) have affected the entire flood frequency distribution including the largest floods on record in all four study catchments, irrespective of sample size. In two of the four catchments (240 and Redfish) harvesting has resulted in increases in both the mean and the standard deviation of the post-treatment series of flood peaks compared to the pre-treatment." (p. 13)

The Kettle River watershed unfortunately provides a real-world example of a catchment whose intensive forest harvesting has resulted in less stable hydrology – a phenomenon heightened by cumulative effects of land use changes resulting in larger runoff from rapid snowmelt into the watershed. Since the average elevation of logging is above the H60 line of 1,229 meters, it is unsurprising that snowpack will accumulate given this elevation (Hammond, 2019).

Removing trees affects forest hydrology through various mechanisms. When snow falls, trees are able to transpire 500-700 ml of that precipitation per year (Chapman, as quoted in Parfitt, 2019). Hammond's (2019) estimation is that logged areas accumulate 40% more snow because the removal of forest canopy eliminates these trees' sublimation effect on snow, which blocks some snow and evaporates it before reaching the ground.

Snowpack accumulates under an open sky and its rapid melting leads to increased and less predictable forest hydrology. As Green and Alila (2012) write, "The dominant process responsible for these newly emerging insights is the increase in net radiation associated with the conversion of long-wave-dominated snowmelt beneath the canopy to short-wave dominated in harvest areas" (p. 1). In other words, rather than the heat from the surface melting the snow over time (heat manifested through the earth's surface's long-wave radiation), the sun's short-wave radiation reaches the snow and is able to melt it more rapidly. Given how local weather is variable day to day, this snowmelt, dominated by short-wave radiation, will be capricious and may occur suddenly as the May 2018 flood suggests.

This snowmelt is more likely to run off and amplify streamflow because the removal of tree roots diminish the soil's ability to accept, hold and release water.

Tree roots improve infiltration and drainage. The network of tree roots provides mechanical vectors for water to infiltrate the soil surface and to drain down through the soil matrix. Moreover, these roots increase organic matter in the soil over time as roots die and are regrown. This soil organic matter improves soil water holding capacity. Older forests, one-quarter of which have been lost in the Kettle River watershed, are able to generate more organic matter and hence have the greatest soil water-holding capacity (Brown, 2019; Brown and Krjic, 2020; Hammond, 2019). Changes in land use from forests will therefore decrease a soil's physical quality with regard to this process of accepting, holding, and releasing water.

Given the reduction in the infiltration capacity of the soil, snowmelt is likely to runoff. When water impinges on the soil surface and the soil's infiltration rate is less than the amount of water trying to enter the soil within the same temporal scale, the water will runoff. This excess of water greater than the soil's infiltration rate leads to Hortonian overland flow (Beven, 2004).

Runoff is likely to increase also because of degradation in soil structure. Given the prevalence of heavy lorries in forest harvesting sites, this weight will compact soil. Soil porosity will reduce and water will be less likely to infiltrate and move through the soil (Brown, 2019; Brown and Krjic, 2020).

Furthermore, when snowpack accumulates on impermeable road surfaces and compacted ditches at the side of these roads, the result inevitably is a surge in runoff (Marshall, 2019).

Lastly, when wildfires burn, the soil's surface can become impermeable from hydrophobicity (Schreier, 2015). As professional geoscientist and hydrologist, Allan Chapman, explains, "For some period of time after a hot fire occurs, the upper levels of soil have a waxy layer that is hydrophobic and a decreased volume of water enters the soil" (Chapman, as quoted in Parfitt, 2019).

Conditions were perfect for rapid snow melt leading to a devastating flood. Given the elevation of logging, the rate of forest harvesting, and these cumulative effects on forest hydrology and soil, snowmelt was enabled to accumulate and melt rapidly, causing a spike in the Kettle River's May 2018 discharge. The substantial logging since the 1990s provides an underlying reason for why an acute event of rapid melting was able to occur in 2018. With more land in the Kettle River still forested in 1997, less snow was able to accumulate. By 2018, much more open surface area and logging roads existed. Hence, forest harvesting provides an underlying condition that made the acute jump in discharge between April and May 2018 possible from rapid snowmelt, which led to the flood.

This case is a warning of how Green and Alila's 2012 findings can occur in the real-world. Rather than the flood occurring because of long-term trends in hydrology or climate, the flood was enabled because of pernicious cumulative effects resulting from forest management, which did not take into account how each component of the system influences the other.

VIII. Climate Change Projections

Given the vulnerability of the Kettle River watershed to rapid snowmelt and the threat of flood that derives from that vulnerability, evaluation of climate projections is relevant. Climate scientists in Washington state have been modelling climate change in the Pacific Northwest for over a decade (Climate Impact Groups, 2009; Mote *et al.*, 2014; Mote and Salanthé Jr., 2010; US Global Climate Change Research Program, 2009). Washington models look at the state as well as areas of Southern British Columbia because many Washington watersheds begin just North of their border with BC. Given that the Kettle River is a major tributary of the Columbia River and that the Southern Okanagan the Kettle runs through is topographically and climatically similar to eastern Washington State, these climate models are pertinent to this case study.

Although the IPCC (2004) report that is used for the Washington projections used multiple warming scenarios, two scenarios are treated as more important: B1 and A1B, the former which is an optimistic scenario where emissions begin tapering off by 2030, the latter where emission reduction is much slower and occurs in the second half of the 21st century.

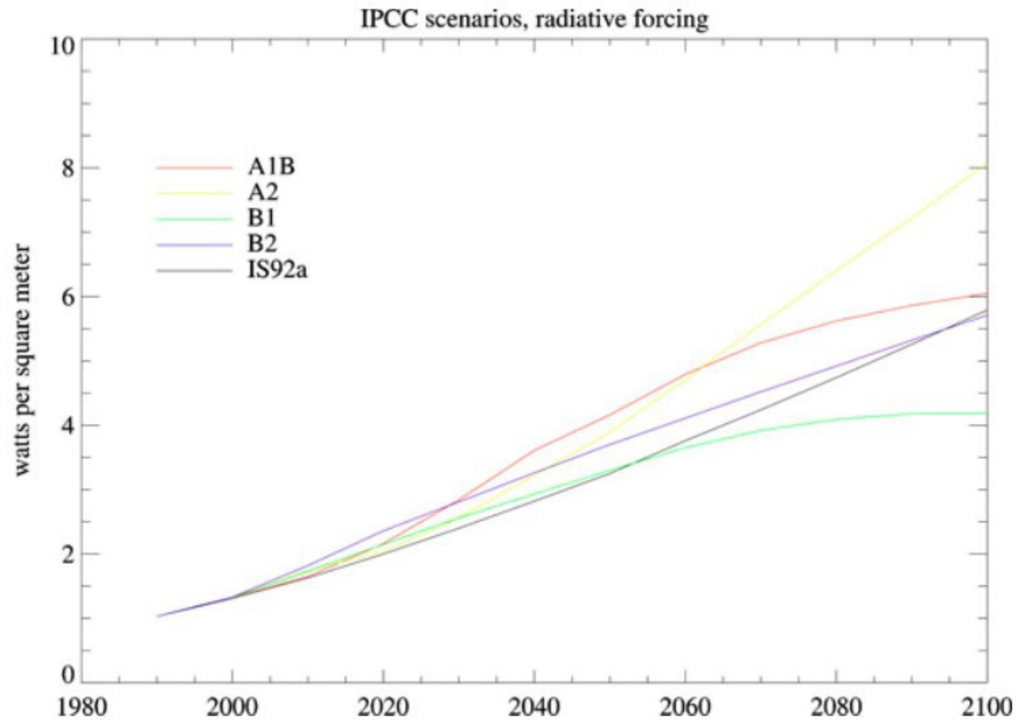

Figure 26: Different IPCC scenarios based on how much CO2 is emitted and the relative increase in atmospheric warming. For this climate projection section of the Kettle River case study, B1 and A1B will be examined, which is the same method as these Washington reports because they are the likeliest (Figure from Motte and Saranthé Jr., 2010)

<u>i) Changes in Snow Conditions</u>

Mote *et al*. (2014) write, “Observed regional warming has been linked to changes in the timing and amount of water availability in basins with significant snowmelt contributions to streamflow” (p. 489). Hence, the Kettle River falls within such a catchment category because as this report has shown that May 2018 was driven by rapid snowmelt. Furthermore, according to a climate change impact assessment by the Climate Impacts Group (2009) of the University of Washington, “In snow-melt dominated watersheds that prevail in the higher altitude catchments and in much of the interior Columbia Basin, flood risks will likely decrease” (p. 13).

Hence, if flood risk was viewed purely in isolation, a warming climate would be beneficial for the town of Grand Forks. Given the ubiquity of open surfaces at a higher elevation and land use change’s cumulative effects, the watershed is particularly vulnerable to a repeat of 2018 snow conditions and the flood risk that comes with its melting if a simultaneous occurrence of high May temperatures occurs. Therefore, reduced snow water equivalent and snow levels will diminish flood risk.

- April

According to the Washington Climate Change Impact Assessment (2009), “April 1st snowpack is projected to decrease by 28% across the state by the 2020s, 40% by the 2040s, and 59% by the 2080s compared with the 1916-2006 historical average.” These percentage reductions were calculated by averaging across all climate models (Climate Impacts Group, 2009). While calculated for snowpack, this percentage reduction will be applied to SWE data at Monashee Pass.

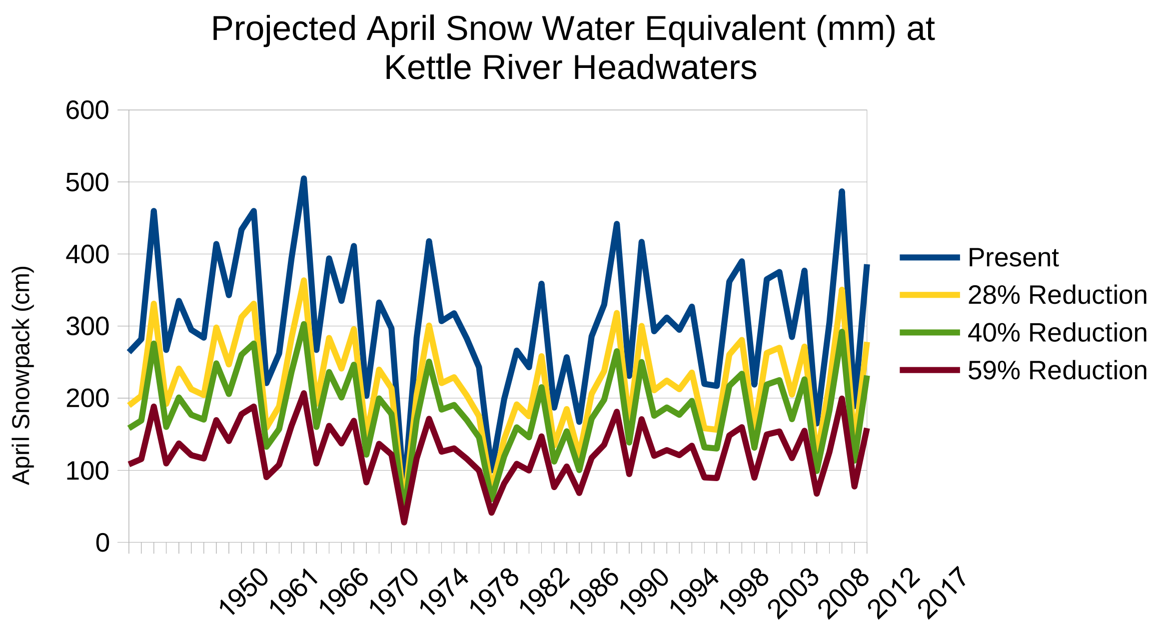

Figure 27: Projected April snow water equivalent (mm) using the three future reduction scenarios. (Government of Canada, 2020; Mote and Saranthé Jr., 2010).

Even within the first projected reduction of 28%, the large April 2018 SWE that contributed so devastatingly to the May flood of that year is within a prosaic range. From this estimation, a repeat of a large melting causing a sudden spike in May discharge is unlikely.

ii) Seasonal Changes

In their report, Mote and Saranthé Jr. (2010) focus on seasonal changes in terms of temperature and precipitation for two specific scenarios: B1 and A1B. They argue that seasonal modelling is particularly relevant because some seasons will be more affected than others (Mote and Saranthé, 2010). For example, summer has the most dramatic change in temperature and precipitation than other seasons (Climate Impacts Group, 2009).

- Spring

Although Mote and Saranthé Jr.'s (2010) projections have error bars, their averages for the B1 and A1B scenarios will be taken. For March, April, and May, the B1 and A1B scenarios are tabulated below:

Spring Temperature © Changes in Two Climate Scenarios

	B1	A1B
2020s	+ 1 C	+ 1 C
2040s	+ 1.4 C	+ 1.7 C
2080s	+ 2.1 C	+ 2.8 C

Figure 28: Temperature (C) changes (i.e. projected radiative forcing) for the two likeliest climate scenarios during the springtime in Washington state and the Columbia River catchment (Mote and Saranthé Jr., 2010)

“Though B1 is the lowest of the IPCC illustrative scenarios, it still produces changes in climate that many scientists call dangerous” (Mote and Saranthé Jr., 2010, p. 3). Written five years prior to the Paris Agreement, which aimed to limit global averages warming to 1.5 C, the B1 scenario will breach that target in the second half of this century.

Differences between B1 and A1B temperature changes is measurable, but not very high. This pattern is not the case for precipitation.

Spring Precipitation Changes (%) in Two Climate Scenarios

	B1	A1B
2020s	+ 1.3%	+ 2%
2040s	+ 5.8%	+ 5.1%
2080s	+ 5.5%	+ 9.8%

Figure 29: Precipitation changes (%) for the two likeliest climate scenarios during the springtime Washington state and the Columbia River catchment (Mote and Saranthé Jr., 2010)

The divergence between these precipitation scenarios increases dramatically in the 2080s. Given that with warming temperatures, precipitation is likeliest to fall as rain and not snow, melting snowpack into the Kettle River would substantially decrease. Floods will likely occur due to lengthy, sustained, and heavy rainfall rather than rapid snowmelt from a large seasonal snowfall as the case was in May 2018.

- Summer

Averaging out the projections for June, July, and August reveals why approaching climate projections from a seasonal lens is crucial to grasping a better visualization of how life will be affected.

Summer Temperature © Changes in Two Climate Scenarios

	B1	A1B
2020s	+ 1.3 C	+ 1.7 C
2040s	+ 1.9 C	+ 2.7 C
2080s	+ 3 C	+ 4.5 C

Figure 30: Temperature (C) changes (i.e. projected radiative forcing) for the two likeliest climate scenarios during the summertime in Washington state and the Columbia River catchment (Mote and Saranthé Jr., 2010)

In the 2020s, even with the most optimistic scenario, the summertime increase is dangerously close to exceeding the Paris Agreement; in the A1B scenario, this decade will exceed the agreed benchmark of trying to limit warming to below 1.5 C.

Going into the 21st century, both scenarios’ warming in the Pacific Northwest shows a pessimistic reality, which, if realized, would be dangerous for salmon spawning and agriculture (Mote *et al*., 2014; Climate Impacts Group, 2009).

Summer Precipitation Changes (%) in Two Climate Scenarios

	B1	A1B
2020s	- 3%	- 8%
2040s	- 5%	- 11.2%
2080s	- 11.2%	- 14.4%

Figure 31: Precipitation changes (%) for the two likeliest climate scenarios during the summertime Washington state and the Columbia River catchment (Mote and Saranthé Jr., 2010)

Summertime precipitation is expected to decrease and accelerate as the century goes on. Where spring precipitation's increase is expected to be potentially hazardous if heavy, sustained rainfall occurs, riparian drought is the risk posed in the summer.

As Steward, Cayan, and Dettinger (2004) writes, "Consistent with these advances are decreased spring and early summer (AMJJ) fractional flows and increasing fractions of annual flow occurring earlier in the water year" (p. 1152). In other words, streamflow is likely to be skewed towards early spring, leading to a period of dangerously low summer flow (Mote *et al*., 2014). As Mote *et al*. (2014) write, "Warming increases winter flows and advances the timing of spring melt […] Summer flows are projected to be substantially lower, even for an emissions scenario that assumes substantial emissions reductions (B1)" (p. 489-490).

<u>iii) Effect on Land Use</u>

- Pest Infestations

Overall, future mountain pine beetle (MPB) infestation is unlikely. In the last couple of decades, the supply of pine trees has reduced substantially (Hanspeter Schreier, personal communication, August 1st, 2020).

In areas where enough pine supplies still exist, a pine beetle outbreak could occur in the short term with drier, hotter summers expected. As Mote *et al*. (2014) write, "Between now and the end of the century, the elevation of suitable beetle habitat is projected to increase as temperature increases, exposing higher-elevation forests to the pine beetle" (p. 495). However, as temperature averages continue to increase, the MPB expanded niche will contract. Temperature rises and dry climates will diminish the MPB habitat, which had been increasing. This contract is expected to occur by the 2040s (Mote *et al*., 2014). Reduced winter severity will also cause make more habitat favourable to MPB in the short term (Murdock, *et al*., 2013).

Therefore, "As a result, the proportion of Northwest pine forests where the mountain pine beetle is likely to survive is projected to first increase (27% higher in 2001 to 2030 compared to 1961 to 1990) and then decrease (about 49% to 58% lower by 2071 to 2100)" (Mote *et al*., 2014, p. 495).

In addition, a more pernicious problem could be new pest infestation occurring targeting new tree species. As climate change continues to alter temperature and precipitation regimes, different pest ranges will expand either with shifting latitudes north or at higher elevations (Murdock *et al*., 2013).

The western spruce budworm is one such critical pest whose range will expand as warmer winters occurs in British Columbia (Régnière and Nealis, 2018; Murdock *et al*., 2013). In their models, Régnierre and Nealis (2018) show that the budworm's "ability to complete its life cycle before the killing frosts limits its range to the North and at higher elevations" (p. 228). As a result of baselines in climatic averages shifting to warmer winters and higher elevations not experience the same level of cold, the budworm's fitness will increase (Régnierre and Nealis, 2018). In addition to increased fitness, the synchrony between larvae emergence and the swelling of spruce buds will be ideal. Larvae eat these buds and penetrate them to hide from predators. When this synchrony is off, a high larvae mortality occurs; however, climate projections predict that this synchrony will improve and lead to greater spruce mortality (Murdock *et al*., 2013).

Similarly with MPB outbreaks, if warm temperatures are too high, an outbreak of western spruce budworm will collapse (Thomson, Shepherd, Harris, and Silversides, 1984).

- Wildfires

With more standing, dead wood, fuel for forest fires will increase. With hotter, drier summer, and given added fuel, the cumulative effect is the expected increase in forest fires. As Climate Impacts Group (2009) warns, “Due to increased summer temperature and decreased summer precipitation, the area burned by fire regionally is projected to double by the 2040s and triple by the 2080s” (p. 2).

iv) Conclusion from Climate Change Projections

Climate change will affect the hydrology of watersheds differently based on whether streamflow is driven by melting glacial water, snowmelt, or rainfall (Schreier, 2015). With the Kettle River, which is driven by snowmelt, this snowmelt is expected to be skewed towards earlier in the spring with peak flow occurring in March as opposed to April or May (Schreier, 2015).

Yet, climate change has been measured as more felt at higher elevations especially during the winter season (Schreier, 2015). From the climate assessments and peer-reviewed articles on climate change in Washington state, the upper basin of the Columbia River, of which the Kettle River is a part, is expected to be driven more by spring rainfall than by rapid snowmelt. Snowmelt will become less relevant to the Kettle River’s streamflow; spring rain will be the cause behind peak flow. As a result, future floods are likely to occur either much earlier in the spring/late winter or because of heavy, sustained rainfall earlier in the spring season (Climate Impacts Group, 2009).

On the other hand, the risk of drought will increase as summers become hotter and drier. Summer precipitations will sharply decrease even in the most optimistic climate scenarios (Mote and Saranthé Jr., 2009). In addition to drought risk, MPB and wildfires will increase in the Kettle River watershed, both phenomena amplifying the other.

The reduction of forest stand will also amplify the deterioration of the soil’s process of accepting, holding, and releasing water. With forest cover removed, rainfall will hit the soil and dislocate topsoil surface particles (Pennock, 2019); given that this rainfall will runoff just as with melting snow for the same reasons (as detailed in the previous section), soil erosion is expected and will likely deteriorate the Kettle River’s water quality as more sediment will be suspended in the water.

Given the dramatic seasonal variability between the risk of too much water in springtime and not enough in the summer and deterioration on water quality, the water security of communities relying on the Kettle River becomes precarious. The next section will examine this potential precariousness.

IX. Water Security of Grand Forks

i) Population

The Census Profile of 2016 reveals that the population of Grand Forks in 2016 was 3,953 – up from 3,892 in 2011, representing a 1.6% growth rate; in all, 1,902 dwellings exist in Grand Forks (Statistics Canada, 2019).

Grand Forks Population in Southeastern British Columbia

	2011	2016	2020	2050
Population	3,892	3,953	4,490	7,228

Figure 32: Population of Grand Forks at present and projected population values using the 1.6% growth rate from the Census Profile of 2016.

ii) Water Use

According to the Government of Canada (2017), the average daily water use per Canadian is 251 litres in 2011. However, the City of Grand Forks (2016) has a metering system that was installed in 2016. From this metering, Grand Forks (2020) reports "The average Grand Forks resident uses about 720 litres per day – that's more than 3,000 cups of water a day. That's also one-third more than the average British Columbian" (para. 4). As the tone of the city suggests, this domestic water use is unbelievably high. In 2008, all businesses and industries were equipped with water meters (Grand Forks, 2020). Hence, it does seem like this high daily residential use is for purely domestic consumption.

This domestic use typically increases between May and August with warmer, drier temperatures (Hanspeter Schreier, personal communication, July 14th, 2020; Grand Forks, 2020). As the city warns, "We face drought and water supply issues during hot summer months and very high cost for pumping water during high demand" (Grand Forks, 2020, para. 1).

With the caveat that demand is skewed higher in the summer, the daily average of 720 litres will be used. Using this figure, the annual domestic water use for each year in the population table above can be calculated.

Domestic Water Use (m3/y) Grand Forks for Present and Projected Populations

	2011	2016	2020	2050
Water Use per day per person	720	720	720	720
Water use per year per person	262,800	262,800	262,800	262,800
Water Use per year for population (L)	1,022,817,600	1,038,848,400	1,179,890,119	1,899,559,067
Water Use per year for population (m3)	1,022,817.6	1,038,848.4	1,179,890.1	1,899,559.1

Figure 33: Domestic water use (m3/y) of the Grand Forks population across all the years this section is considering.

- Groundwater

The main source of water use is groundwater. According to the Water Conservation page of the City of Grand Forks (2016), "All of our drinking water (or water for household use) comes from groundwater sources, and like many communities in southern BC, we face drought and water supply issues during the hot summer months" (para. 1).

Given the climate projections treated in the previous section, the hotter, drier summers will exacerbate the water security of Grand Forks; with streamflow peaking earlier in spring and the diminishment of snow melting as a relevant input into the Kettle River, the water security derived from the aquifer is precarious given the recharge of the aquifer is undermined.

While groundwater analysis is beyond the scope of this case study on the Kettle River, an evaluation of Grand Forks' main drinking water was assessed by Wei, Allen, Carmichael, and Ronneseth (2010). Moreover, the impact of climate change on this aquifer was looked at by Scibek, Allen, Cannon, and Whitfield (2007). In the future, the Kettle River's contribution to the aquifer's recharge should be assessed (Hanspeter Schreier, personal communication, August 1st, 2020).

Rather than observe groundwater extraction and recharge, the next section will look at surface water extraction from the Kettle River itself as it flows through Grand Forks

iii) Surface Water Licensing

While groundwater is extracted for domestic water use, water is privately extracted from the Kettle River for irrigation purposes (Kootenay Boundary Water Tool, 2020).

Seventeen water licenses on the Kettle River presently exist within Grand Forks (Kootenay Boundary Water Tool, 2020). Three are for municipal use; the others, irrigation. A table of the water licenses with how much is extracted per license is tabulated below:

Water Extraction Licenses on the Kettle River

License Number	Quantity (m3/y)
C001685	6,167.00
C038168	37,004.40
C038168	1,245.35
C113288	1,542.00
C113287	12,335.00
C045331	17,269.00
F057153	1,233.00
C053179	50,326.00
F017207	24,670.00
C133745	365.00
F056374	5,427.31
C133745	365.25
C123362	24,670.00
F055758	493.39
F055746	1,295.15
C025664	4,964.00
C004489	829,661.00
Total	1,019,032.85

Figure 34: (Kootenay Boundary Water Tool, 2020).

As both water consumption tables show, the domestic groundwater use and mostly agricultural surface water use are comparable – both about a million m3/y.

However, domestic and agricultural water use is understood to be uneven throughout the year – that is, the rate of use is usually higher in the summertime (Hanspeter Schreier, personal communication, July 14th). This unevenness is especially true for surface water use, which is skewed towards the agricultural season.

As climate change analysis reveals, this summer demand for the Kettle River's surface water coincides with the lowest streamflow–streamflow that will become even more precarious as climate change continues in the 21st century.

iv) Conclusion from Water Security Assessment

The Kettle River at Grand Forks is likely, in this decade and in the future, to experience too little water during the summertime when agricultural and municipal water demand is highest.

Solutions to the precariousness of Grand Forks' water security from low summer streamflow are a diminishment in non-agricultural irrigation such as from License C004489, which is for the Grand Fork's municipal park downtown (Kootenay Boundary Water Tool, 2020). This license alone extracts over 800,000 m3 per year – presumably mostly in the summer to water the grass.

Considering the likelihood of future summer water shortages, a more detailed analysis of surface water extraction for agricultural use is recommended.

5. Conclusion of the Kettle River Report

The first question this report focused on was: Why did the May 2018 flood occur at Grand Forks? It possessed two corollary questions: Is the Kettle River near Grand Forks experiencing an increase in extreme hydrological events driven by climate change? And, how much is land use change contributing to hydrologic behaviour? Such long-term trends would provide underlying reasons for the 2018 flood.

An assessment of climatic and hydrologic data revealed no long-term trends to explain why the 2018 flood occurred. Rather, the hydrologic data showed that 1997 was a more significant year concerning overall seasonal flow; yet, 2018 bore the flood in May. The data showed that a sudden jump in discharge occurred between April and May.

The May 2018 flood likely occurred because of simultaneous climate events leading to sudden rapid snowmelt. The first event was the accumulation of the snowpack at high elevations containing a high snow water equivalent (SWE); the second was warm May temperatures especially high mean minimum temperatures at these high elevations. Therefore, one is able to determine with a high degree of certainty that May 2018 was driven by rapid snowmelt from high elevations in the watershed.

However, these climate events do not reveal the whole picture. Precipitation for the winter 2017-2018 was not extreme as may have been expected. Hence, a new question arose: Why was the 2018 snowmelt so severe if the winter precipitation was not concomitantly extreme? While the precipitation was substantial, the hydrologic response of a devastating flood did not seem congruous with the data.

Assessing land use change explained this incongruity. The question became: How much did land-use change contribute to snow accumulation and runoff?

Forest harvesting, pest infestation, and wildfire have dramatically altered the Kettle River watershed's natural hydrology. Less forest canopy meant greater open surfaces. More snowfall could accumulate in the watershed. Shortwave radiation from the sun drove a rapid snowmelt event during May as the mean minimum temperatures were high. Conventional logging, harvesting infested pine trees, and fires have disturbed the soil; poorer soil infiltration contributed to high runoff.

The most significant change has been the removal of forest cover because of traditional logging and the harvest of infested pine trees. Forest harvesting of the Kettle River watershed has been poorly and unsustainably managed: numerous small and large cut blocks exist throughout the watershed especially above the H60 line. The contribution of wildfires and mountain pine beetle outbreaks amplified a cycle of cumulative effects altering the hydrology of the watershed by an amplifying feedback loop of negative cumulative effects.

This removal of forest cover at higher elevations has increased surface area for snowpack to accumulate. When snow falls in the watershed, rather than having a large percentage intercepted by the forest canopy, snow has more surface area on land to accumulate. Moreover, surface area from forest road networks and ditches contribute to greater snow accumulation as well.

The cumulative effects are a change in the hydrological relationship between snow, soil, and forests. Rather than smaller snowpacks melting and having some portion of it drain into the forest soil, a larger amount of melted snow is running off the surface. The soil's water-holding capacity has been reduced. Runoff from snowmelt has therefore increased, augmenting the risk of spring floods. Given these observations, winters of medium to high levels of snowfall now pose a serious risk to spring floods which is precisely what has occurred in May 2018.

This situation was different in 1997. The discharge was driven by precipitation due to a significant El Nino event. The watershed's resilience in 1997 was still intact. By 2018, much more land had been clear-cut. By 2018, when a moderately high amount of snowfall fell, the response to the snowmelt was dramatic. Given the degree of forest removal by harvesting, MPB, and wildfires, the snowmelt had a disproportionately severe response. The high degree of runoff amplified the Kettle River in an acute instance causing levels to break the banks of the river.

From these results, the fourth question this report posed was answered with a high level of certainty. Residents on the Kettle River and in Grand Forks can expect this precarious existence to continue, anticipating more floods and, likely, more droughts because of increased climatic variability, changing forest cover, and poor soil water-holding capacity. It seems likely that the environmentally extreme events like the May 2018 flood and the 2015 summer drought were not one-time events.

These land use changes as well as climate change have made the watershed more sensitive. Domestic and agricultural water security is threatened.

Reports of climate change in the Columbia River basin have shown that snowmelt will occur earlier in spring (Climate Impacts Group, 2009). Snowfall will be reduced as warm winter and spring trends increase. At the same time, hotter and drier summers are guaranteed to exacerbate estival low streamflow. A likely future scenario is too much water in the spring and too little in summer.

Hotter, drier summers are likely to produce more tree stress. Pest infestations will generate more fuel; wildfire risks will increase. The mountain pine beetle will diminish as temperatures warm, but the western spruce budworm damage may increase in severity.

Faced with the potential of this precarious scenario, the water security of Grand Forks residents is of concern. While domestic water consumption uses the aquifer, many agricultural permits extract water from the Kettle River's surface water. Seasonal surface water demand is greatest in the summertime when streamflow is lowest. A future report would be able to analyze the long-term water security of surface water extraction for agriculture in and around Grand Forks.

The answers to this report's questions reflect how concerning water issues are to Grand Forks. Sensible policies on forest harvesting, water consumption and conservation, and fire safety measures can be followed by the Kootenay Boundary Watershed. With a bit of effort, a sustainable remedy is possible to prevent a repetition of the loss of home that occurred in May 2018. Hopefully, no one in the future becomes a flood refugee.

6. Recommendations

The bounded nature of the Kettle River watershed within the Columbia Basin makes this analysis a terrific case study for an assessment of climate change and land-use change impacts on a local scale. The combination of climate events and land use changes resulted in the May 2018 flood. Hence, the explanation for the flood cannot refer to one part of the environmental system alone because each component affects the behaviour of the others. Cumulative effects from all the components taken together need to be considered. This holistic explanation incorporates a systems-thinking approach, which shows surface-level and underlying reasons for environmental events. Future rehabilitation efforts should also incorporate this holistic approach.

i) Policy Measures

From this report's findings, below is a list of policy measures to consider in an effort to manage the watershed more sustainably:

1. Monitoring snowfall is crucial for determining if flood warnings for the spring are necessary. With flood risks deriving from rapid snowmelt, a close watch on this dimension of climate is highly recommended for the Kootenay Boundary Regional District. More collection of snow water equivalent data, snowfall, and snow depth are highly advisable.

2. Awareness of large-scale climatic patterns that will influence snowfall and winter temperatures will be useful in predicting future floods. Wetter winters during La Nina events could mean large accumulations of snowfall, which if coinciding with early spring warm spikes will lead to a potential flood. Conversely, warmer winters from El Nino would mean that glacial melt from the Monashee Mountains could lead to amplified spring discharge (Canadian Columbia River Basin Glacier and Snow Research Network, 2020). Warmer winters could also lead to more drought conditions (Hanspeter Schreier, personal communication, August 1st, 2020).

3. An effective flood protection response is necessary to avoid the destruction of private property and the forced evacuation of residents from their homes given the likelihood of a repeated scenario where rapid snowmelt drives the April or May discharge to dangerous heights.

4. Since forest activity is changing the hydrological process, more attention to harvesting and tree planting's impact on the water cycle needs to be given. The importance of Interfor in the local economy(Parfitt, 2019) means that consultation with this economic stakeholder as well as those in Grand Forks employed in forestry is important to consider to find a sustainable compromise to all the stakeholders in the watershed.

5. Domestic water use is able to be reduced to diminish stress on groundwater. Planting water-efficient crops and using an efficient irrigation system can diminish stress on surface water extraction. The City of Grand Forks can also increase its environmental education programs to create a psychological reorientation prioritizing water conservation in the summer.

6. With the western spruce budworm likely to become a more serious pest, the experience from dealing with the mountain pine beetle can serve as a template for spruce budworm management.

7. A further assessment should be done on surface water extraction for agricultural use given the water issues in the summertime.

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