

Identifying the Imprint of Climate Change on Low-Arctic Rivers from Planform Changes of the Colville River, Alaska

by

Pedro Valentin Serrano

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

The undeniable effect of climate change is prevalent in countless number of natural processes occurring across our planet, particularly within the circumpolar region. These climatic shifts have had an impact on internal and external forces that drive river movement. Hence, channel activities within these regions would, presumably, also change in response. Using the Colville River, situated in northern Alaska, USA, as a study site, the research first identifies the climatological trends occurring within the region. Temperature, precipitation, and discharge from the year 2002 to 2019 are examined to identify how these internal and external factors have changed throughout the years. Additionally, channel activities of two reaches within the river are also calculated within the same period using Landsat data. These variables are then correlated amongst each other to identify how one factor influences the other. Trends are captured on both a continuous (short-term) and a yearly (long-term) timeframe, whereby the continuous timeframe presents the data in a monthly sequential period from 2002 to 2019 while the yearly timeframe compares the data of each month across the years. Finally, the same approach was completed using Planet satellite imageries, where data is available, to verify the result. The findings show an overall increase in temperature primarily during the winter months, increase in frequency of precipitation towards the more recent years, and both an increase and decrease in discharge during the freezing and thawing period, respectively. Furthermore, the calculation shows a strong positive correlation between discharge and temperature ($r = 0.63$, $r^2 = 0.39$, $p\text{-value} = 4.64\text{e-}17$) for the continuous, short-term, timeframe and a relatively strong negative correlation ($r = -0.57$, $r^2 = 0.32$, $p\text{-value} = 1.88\text{e-}5$) for the yearly, long-term, timeframe. The positive correlation between the two variables in the short-term timeframe shows the seasonal relationship between temperature and discharge, whereby as the temperature increases, discharge also increases in response. Interestingly, however, the long-term timeframe suggests that as the temperature increases, discharge decreases in response. This was identified as the effect of climate change that is caused by the increase in temperature during the freezing months. Discharge is starting to take place throughout the year, therefore it is hypothesized that during the thawing months most ice have already melted which results in an overall decrease in discharge during the freezing months. And given the relatively strong positive correlation of discharge and channel activity for the short-term timeframe (Reach A: $r = 0.62$, $r^2 = 0.62$, $p\text{-value} = 1.02\text{e-}16$ and Reach B: $r = 0.68$, $r^2 = 0.46$, $p\text{-value} = 2.65\text{e-}19$), it is expected that channel movement will soon follow such decrease in discharge trend in the long run. These findings suggest that semi-arctic braided rivers, the Colville River in particular, are transitioning to river movements more similar to rivers situated in temperate climate, whereby activity is not only prevalent during the thawing months but will soon be identifiable throughout the year.

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CHAPTER 1

INTRODUCTION

Rivers are natural conduits for one of the most powerful forces on our planet's surface. They can divide huge landmasses and generate complex landscapes as the water carves through the earth's crust. Landscapes such as the Grand Canyon, U.S., Yosemite National Park, U.S., and Jiuzhaigou Valley, China (National Park Service 2023; National Park Service 2023; New World Encyclopedia 2022) were once massive rivers, that today serve as remnants and evidence of the powerful force of water. Through weathering, erosion, and sediment transport, these hydromorphological shifts are governed by time and the river's water discharge, which allows mobility and migration across the floodplain by transporting water and nutrients along its path to sustain life for animals and vegetation dependent on them (Li et al, 2017). However, despite rivers' significance and formidable ability to carve landscape, they remain highly sensitive and susceptible to changes that could affect their formation and direction (Jiang et al, 2022).

The highly mobile and sensitive nature of rivers results in their intricate patterns and movements that are often difficult to understand and predict. A slight change in the internal and/or external forces that are exerted on rivers could result in irreparable change in water movement and affect erosional and sedimentary deposits within the system (Esfandiary and Rahimi, 2019). And since the environment is constantly changing, river morphology would then respond to these movements to compensate for such alterations and reach equilibrium (Dai and Liu, 2013). In other words, rivers are constantly changing and moving along with their environment – a process that is highly implicated by climate change. As the climate shifts into unprecedented extreme weather and climatic patterns, river movements and morphology are bound to adjust in response (Gain, A. K. et al. 2011; Kopytkovskiy, M. et al. 2015; M. Hoerling et al. 2019; Palash, W. et al. 2023). Unusual flooding, massive hurricanes, and prolonged droughts are a few examples of climate-change-related events that are happening on our planet that exert significant impact on rivers and their morphology (Gain, A. K. et al. 2011; Palash, W. et al. 2023). Furthermore, drastic temperatures changes are also being experienced across the globe. In fact, the arctic and subarctic regions that were once deemed uninhabitable due to their freezing climate are now becoming more promising for vegetation and wildlife to grow and prosper as the temperature continues to increase (Marcot et al, 2015). Activities, like these, would then have an impact on arctic watersheds and rivers that flow through them (Jiang et al, 2015).

The low arctic region is an area where the average temperature ranges between -30°C to -10°C at its coldest time and 0°C to 10°C at its peak warmest season within its coastal areas. Recent studies suggest that these averages are at a continual rise due to the impact of climate change (Overland et al, 2019; Cook et al, 2019).

The warmer climate has resulted in vegetation increase (Wilson and Nilsson, 2009), human and animal migration (Heleniak, 2014; Moore, 2011), and urban sprawl (Heleniak and Bogoyavlensky, 2015) as well as permafrost melts (Schuur et al, 2015), glacial retreats (Li et al, 2019), and sea water rises (Gain, A. K. et al. 2011; Moon et al, 2018). Particularly, affecting factors that have severe consequential effect on the arctic's watersheds and streams within them (Deb et al, 2015). For example, the prolonged warmer temperatures result in an increase in meltwater, water that is normally only present during the summer months. Therefore, water discharge and current remain relatively strong throughout the year, encouraging erosion and sediment transport during times when rivers are generally frozen solid (Box et al, 2019). In further studying these processes, we can better understand the effect of climate change and its impact on northern rivers and landscapes. Thereby, piloting further river-related research in the arctic and preparing for the future growth and development of the area.

CHAPTER 2

THESIS MOTIVATION, OBJECTIVES & STRUCTURE

2.1 Motivation

A vast number of river-related literature is focused on warmer climate rivers. Scientists have thoroughly studied forces that affect rivers both on smaller and grander scales (Lane et al, 2007). Forces such as erosion (Henshaw et al, 2013), sediment transport (Syvitski et al, 2019), and water discharge (Van Vliet et al, 2013) have been a topic in numerous literatures focused on temperate or tropical rivers. Particularly, the Amazon River, Mississippi River, and Nile River are a few examples that have served as study areas in examining river movements (Yamazaki et al, 2012), migration (Shen, 1988), spatial patterns (Mertes et al, 1995), chemical concentrations (Abdelhafiz et al, 2021), etc. In general, it seems that tropical and temperate rivers are substantially well-explored in comparison to rivers located in colder climates. Perhaps this is due to data availability, site accessibility, and/or its direct impact on urbanized areas surrounding it. Nevertheless, cold region rivers serve as a critical component of circumpolar landscapes, which have their own complexities, dynamics, and annual patterns. Understanding these processes would bring forth a clearer foresight with regards to the future of our world, especially in the area that is primarily responsible for cooling our planet and holds a large volume of our freshwater.

Climate change has had major impacts in various patterns and phenomena across the world. It has exacerbated factors that can be linked to river movements and migration. In fact, Retrogressive Thaw Slump, ground instabilities and collapse due to melting permafrost, has been rampant in the arctic. This would likely introduce more sediments in the northern watersheds. The introduction of more sediments may drive changes in sediment transport and deposition in channel banks, which facilitates in the formation of rivers' inner banks and overall shape and form of the river. Furthermore, annual average temperatures have risen in the arctic region, causing glaciers to recede at a much faster rate since the late 1900s (Overland et al, 2019; Cook et al, 2019). This results in an increase in meltwater, which would eventually percolate and make its way downstream, thereby increasing the water discharge even during the winter months, when water in cold-region rivers is generally steady and scarce (Dzhamalov et al, 2017). Given the undeniable effect of climate change in colder regions, it is likely that the region's river patterns and movements would also be impacted by these rapid changes. Identifying the effects of climate change on cold-region rivers would be beneficial in discovering the greater impact of climate change on northern landscapes and land cover.

Finally, communities in the northern region have also undergone expansion as transportation improves, technology develops, and climate changes (Hamilton et al, 2016). In fact, the human population of Nunavut, Canada has steadily increased from ~27,000 in 2000 to ~40,500 in 2022 (Statistica, 2022). Hence, urbanization would presumably occur in response to the population growth in these areas. In identifying river movements and their future migration, urban planners and engineers could develop settlements and cities that would have little to no impact on nearby rivers for generations to come. Furthermore, most northern populations belong in the Aboriginal community where rivers are not only valued for their environmental function but also pose as a significant part of their cultural and spiritual livelihood (Gibson, 2016). Therefore, understanding the movements and migration of arctic rivers could provide decision-makers with information to better protect and preserve these natural resources.

2.2 Research Questions and Objectives

As the climate continues to change around the globe, several natural phenomena start to take place, particularly in the semi-arctic region. Namely, vast permafrost and glacial melt are now being noticed in the arctic and subarctic area. Along with these, comes ground instabilities causing thermokarsts and thaw slumps across the landscape. Thereby introducing massive influx of meltwater and sediments within the watershed that is bound to change the dynamic of rivers in this region. The Colville River is a highly mobile river located in Alaska, U.S. that is likely affected by such changes. Therefore, using this river as an initial attempt to study more about the relationship between cold region rivers and climate change, the research aims to answer the question: *How does climate change affect cold region rivers' discharge and activity, particularly the Colville River's?* In answering this question, the paper shall (1) determine the prevalence of Climate Change in the Area by examining Temperature, Precipitation, and Discharge, (2) analyze Channel Activity of specific reaches within the river, and (3) Identify the relationships between the Temperature, Precipitation, Discharge and Channel Activity, thereby providing evidence for identifying the implications and significance of climate change on the river's water discharge and activity.

2.3 Thesis Structure

The thesis will be structured as follows: background, study area, methodology, results, discussion, conclusion, and bibliography. *Chapter 3: Background* shall explore fundamental concepts of river dynamics, particularly highlighting internal and external factors that affect river movement. Additionally, this section will then integrate these concepts and determine the effect of climate change on these factors, thus suggesting the probable implications climate change would have on river movement. *Chapter 4: Study*

Area will introduce details regarding the Colville River, Alaska, and reasons why this river was selected for the study. *Chapter 5: Methodology* will specify the steps taken to acquire the findings of the study, highlighting the data collection method and processing steps performed on the data. *Chapter 6: Results* will present a summary of all the collected data, trends, and correlations of the study. *Chapter 7: Discussion* speaks about the results, highlighting the thesis objectives, and answering the research question of the study. Furthermore, this section identifies the limitations and shortcomings of the research and potential future work that could be done to supplement the findings of the research. *Chapter 8: Conclusion* summarizes the thesis findings and implications of the research. Finally, *Chapter 9: Bibliography* lists the sources and literature used in this research paper.

CHAPTER 3

BACKGROUND

3.1 River Forces

River dynamics and morphology are impacted by internal and external forces (Church, 2015). Internal forces are processes that occur inside an active channel without external potency (Parasher, A. 2022). Water discharge, erosion, and sediment transport are perhaps the most well-recognized internal forces that dictate the rate at which rivers move and migrate across the floodplain (Alekseevskiy et al, 2008). Moreover, these forces are highly interconnected so much so that a slight change in one factor can trigger shifts in other internal pressures (Chang, 2008). External forces, on the other hand, are large-scale stresses that occur outside of the river systems. They are an indirect control that impacts channel formation regardless of the processes occurring within the active river system. The weather (Yilmaz, 2021), nearby vegetations (Oorschot et al, 2016), animal and human activities (Elosegi et al, 2010) are examples of external pressures that either exacerbate or weaken internal forces, causing the river movement to change. Because there is abundance and variability of external pressures, river movements and morphology are often complex, volatile, and difficult to predict. To summarize, external forces highly influence internal forces, which, in turn, drive river movement and morphology.

3.1.1 Internal Dynamics

3.1.1.1 Water Discharge

Water discharge drives internal movement within the river system. It is responsible for the transport of water, nutrients, and sediments across the watershed, that is guided by the direction of the river's *primary flow* (Ji et al, 2020). As its name suggests, primary flow is the general direction towards which an unobstructed current flow (Kauffman, R. 2018). It is generally based on the landscape's elevation and the channel's gradient, moving water from higher to lower elevation. On the other hand, *secondary flow* also plays a major role in river morphology. In fact, most theories suggest that this flow triggers rivers to bend and meander. Secondary flow is any component of flow that moves irregularly and is unaligned with the primary downstream water movement (Asfari, A. 1968). This can occur due to wall-effects in straight channels (Bathurst et al, 1979) or in response to existing bank and bed morphology (Thompson, 1986). When a slight imperfection exists along the bank or bed of a channel, flow can be forced to move irregularly. This expends energy and affects the pressure gradient within the channel, which results in secondary flow. If a consistent secondary flow exists, water movement can take the form of an alternating helicoidal current due to its superposed motion on the stream's primary flow (Secondary Flow. n.d.; Asfari, A. 1968). In

particular, the helical cell circulates towards the shore opposite to the bed or bank imperfection, which focuses bank-erosive power on the alternate wall and sediment-depositing motion on the other (Azpiroz-Zabala, M. et al. 2017). Over time, this leads to changes in the river's depth, which, in turn, leads to changes in the channel's geometry and stream's internal velocity (Chant, 2002).

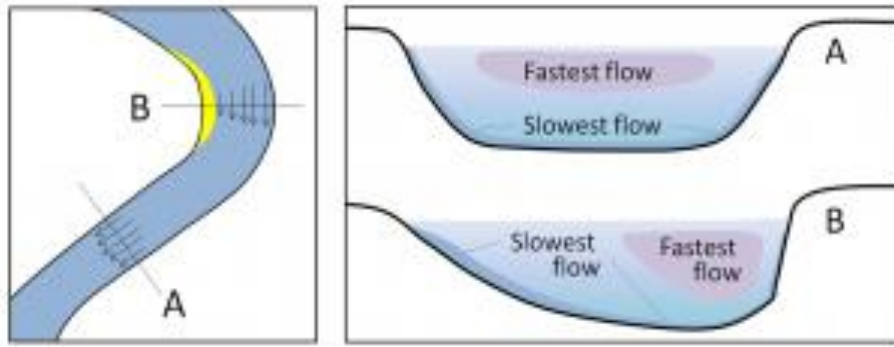


Figure 1: Difference in flow velocity (taken from Earle, S. 2015)

Channel geometry and gradient are strongly correlated to the river's internal velocities (Earle, S. 2015). From a cross-sectional point of view, rivers are generally faster at the centre, where the water is deep and far from debris and rocks that may create friction against the water flow (Earle, S. 2015; Kauffman, R. 2018; CN 2022). Moreover, water tends to move slower closer to the river's edge due to the friction created between the shallower waters and the riverbank and riverbed (Earle, S. 2015; Kauffman, R. 2018; CN 2022). Likewise, stream velocity tends to be the slowest near the bottom due to friction against the riverbed, and gradually increases in speed moving up just below the top surface of the water (Earle, S. 2015; Kauffman, R. 2018). Water surface is slightly slower than the water right below the surface as friction is created between the water and the air above (Earle, S. 2015; Kauffman, R. 2018). Figure 1 depicts such differences in velocity depending on the location of the waterflow. Therefore, field data collection literatures, such as the *Manual of British Columbia Hydrometric Standards* (2009), regard a generic vertical velocity curvature that is associated with depth, when reviewing procedures on measuring rivers' discharge. Hence, field-collected velocities are normally averaged for any calculations where the variable is integrated (MBCHS, 2009). This is critical in river dynamics as the difference in velocity within the channel drives power variability and its ability to exert energy on constituents within the system.

Stream power (Ω) is the rate of energy at which the water flows downstream (Allaby, M. 2018). It is the river's ability to perform work such as erosion and sediment transportation (Allaby, M. 2018). As shown in Equation 1, the stream power (Ω) is calculated by multiplying water density (ρ), acceleration due to gravity (g), hydraulic discharge (Q), and the channel's slope (s), where Ω is a unit of W/m, ρ is typically

1000kg/m³, g is 9.8m/s², Q is a unit of m³/s, and s is the riverbed's gradient, which is normally measured in the field (TW 2014).

$$\Omega = \rho g Q s \quad (1)$$

Hydraulic discharge (Q) is the amount of water moving in a reach per unit of time, which is calculated by multiplying the channel's wetted area (A) and water velocity (v), as shown in Equation 2 (Vert, J. 2021). Q is a unit of m³/s or ft³/s, A is m² or ft², and v is m/s or ft/s.

$$Q = A v \quad (2)$$

Hence, stream power has an explicit relation to the channel's: (1) slope, (2) wetted area, and (3) water velocity. Firstly, there is a positive correlation between the slope (s) and stream power. In most cases, the higher the riverbed's elevation, the stronger the stream power exerted by the river (Bizzi and Lerner, 2015). For example, since braided rivers tend to flow on steeper topography near mountains, they generally hold more stream power than a meandering river that normally forms on flatter landscapes (Michael, A. and Saffer, D. n.d). This is due to the extra gravitational energy found in steeper slopes (n.a.n.d.). It is important to note, however, that although slope heavily influences stream power, the channel bed also degrades over time (Whipple, K. and Tucker, G. 1999). This process is known as stream incision, where the stream power downcuts the riverbed, reducing its slope gradient (Whipple, K. and Tucker, G. 1999). Therefore, although steep slope increases stream power, it has a reversal effect whereby the increase in stream power gradually levels the riverbed surface (Whipple, K. and Tucker, G. 1999). Secondly, the wetted area (A) is the perimeter of the cross-sectional region that is in direct contact with the water (Vert, J. 2021). Therefore, a large river would generally have a strong stream power in comparison to a smaller river. Flooding is a prime example of the relationship between the wetted area and stream power. Welber, M. and colleagues (2011) suggests that an increase in a wetted perimeter has a direct effect on planform configuration, which in turn affects discharge and stream power. This study was done on the braided river of Tagliamento River, Italy, where repeated flooding induced constant changes in the morphological features of the river (Welber, M. et al. 2011). Finally, water velocity (v) is the speed at which the water flows (Flomatic Corporation 2022). As mentioned earlier, this variable differs depending on the channel's geometry and position within the internal river. Hence, stream power varies internally, which results in power dynamics, difference in work performed by water, and unequal shear stresses exerted on elements inside the river system.

Shear stress is a measure of the force of friction that is parallel to the direction of flow (VT Agency of Natural Resources, 2004). In rivers, this force is constantly exerted on elements within the channel.

However, sufficient force must be applied for sedimental movement to occur. The energy necessary for such mobilization is called critical shear stress. For non-cohesive sediments (e.g., coarse silt, sand, and gravel), grain size, shape, and density are some factors that heavily influence their critical shear stress (Kamphuis, J. 1974; Wilberg, P. and Smith, D. 1987; Petit, F. 1990; Wilcock, P. 1993; Shvidchenko, A. et al. 2001; Chen, D. et al. 2021). Several investigative reports (e.g., Berenbrock, C. and Tranmer, A., 2008 and VT Agency of Natural Resources, 2004) present a classification of non-cohesive sediment size and the required power to mobilize each respective class. Their findings suggest that larger particles require stronger critical bed shear stress for sediment mobilization (VT Agency of Natural Resources, 2004; Berenbrock C. and Tranmer, A. 2008). Moreover, the composition of the riverbed's surface, whether mixed- or uniformly- sized sediments, plays a significant role. For mixed-sized sediments, Wilberg, P. and Smith, D (1987) highlight that their motion is dependent on the protrusion of the non-cohesive sediment and its angle of repose. Whereas, for well-sorted riverbeds, coarser materials require larger critical shear stress than riverbeds that are composed of finer sediments (Wilberg, P. and Smith, D. 1987). On the other hand, for a more cohesive sediments (e.g., fine silt and clay) its electrochemical properties have more significant impact on its critical shear stress (Berlamont, J et al.1993; Chen, D. et al. 2021). Compact substances like these consist of smaller void spaces and stronger bonds between particles, which generally requires more energy to break it apart (Berlamont, J et al. 1993; Chen, D. et al. 2021). To summarize, the mobilization of sediments is determined by their size, shape, density, and level of cohesion. Depending on the velocity and sediment type, water discharge may either erode, transport, or deposit sediments within the river.

3.1.1.2 Erosion

Erosion is the gradual degradation of rocks or soil materials from natural forces like water, air, and ice (Collins, n.d.). In river systems, there are four internal types of erosion: (1) hydraulic action, (2) abrasion, (3) attrition, and (4) solution (Hooke, J.M. 1979; BBC 2020; Chassiot, L. et al 2020). Firstly, hydraulic action is the degradation of riverbank and riverbed caused by the force of moving water (BBC 2020). As water permeates through the soil's air pockets, it loosens the ground's cohesiveness by increasing the void spaces between each granule. With sufficient force from the river's stream power, the water slowly disassociates the ground into finer particles (Mehri, A. et al. 2018). Thereby creating further ground instabilities which may lead to more abrupt and large-scale erosions (Osman and Thorne, 1988). Secondly, abrasion is a similar type of erosion caused by rocks, pebbles, and other solid materials grinding and scraping the river walls. In contrast to hydraulic action, abrasion is an erosion caused by other sediments carried by the channel, whereas hydraulic action scours the ground mainly through the sheer force of water. Over time, both types of erosion occurring on the riverbed results in deeper entrenchment (vertical river

movement), whereas erosion on the riverbank results in wider channel (lateral river movement) (Malatesta et al, 2017; Hickin et al, 1984). Therefore, these two types of erosion are heavily integrated in studies related to material engineering. Specifically, research on reducing the negative impact of hydraulic force and abrasion on infrastructures submerged under moving water (Xu, Liqun, et al. 2019; Wang, H. et al. 2020). These are studies proved useful in river management for controlling the natural migration of river to balance their socio-economic impact of its setting (Davechand, R. 2020). Thirdly, attrition is an erosional type occurring in already broken-down sediments, whereby rocks within the river further break into finer sediments as it collides and smashes into the river walls and other solid materials (BBC 2020). Sediments then continue to break apart until it reaches a soluble size for water to dilute (Attal and Lave, 2009). This is the final erosion type called solution, where water chemically dissolves sediments disintegrating it further until it is fully amalgamated with the water (BBC 2020). Unlike the first listed types of erosions, attrition and solution are erosion not responsible in widening river channels. Instead, they produce sediments necessary in forming new riverbanks.

In river systems, erosion may occur through mechanical or thermal processes (Walker, J. et al. 1987). Thermal process is erosion occurring because of temperature fluctuations. A prime example of this is the retrogressive thaw slump (RTS) mentioned earlier. Happening in colder climates, RTS is a result of permafrost melting due to the increase in temperature (Lantz and Kokelj, 2008). Hence, frozen ground that stabilizes and holds sediments together is thawing which results in erosion and sediments being introduced into the watershed. Mechanical process, on the other hand, is the erosion occurring within the riverbanks involving a physical force applied on the surface (Harrison, 2000). A review done by Chassiot, L. and colleagues (2020), have categorized and summarized different forms of mechanical erosion based on numerous field studies conducted in U.K. rivers. Their categorization includes: (1) fluvial entrainment, (2) mass failure events, and (3) subaerial weakening and weathering process (Chassiot, L. et al 2020). Firstly, hydraulic action and abrasion are the main erosion type responsible for fluvial entrainment. As mentioned, this mechanism involves the actual scouring of riverbanks due to the sheer power of water velocity and the sediments that it carries (Whipple et al, 2000). They generally occur slowly and steadily, whereby the erosion performed is generally unnoticeable in the short term. Secondly, mass failures can be an extension to fluvial entrainment. These may occur due to the collapse of a structure holding sediments in place (Rinaldi and Darby, 2007). Perhaps a more common and natural occurrence of these is the toe-bank erosion, whereby the stream flow undercuts the riverbank bottom. This often occurs in streams where the river walls are steep and highly elevated from the water surface (Duong and Do, 2019). In fact, a commonly used streambank stability model, Bank Stability and Toe Erosion Model (BSTEM), had incorporated toe erosion and bank stability modules in its version 5.2 (Midgley, T. et al. 2012; Klavon, K et al. 2017; Stryker, J. and

Bomblies, W. 2017). Since then, the model has been used in several literatures to predict streambank retreat caused by fluvial erosion and geotechnical failure (Midgley, T. et al. 2012; Klavon, K et al. 2017; Stryker, J. and Bomblies, W. 2017). Another example of mass failure events are dam breaks. When a dam breaks, a massive accumulation of sediments is released into the river. Thereby affecting the overall waterflow, erosion rate, and sediments within the channel downstream (Amini et al, 2022). These would occur on either man-made dam structures or natural dams such as beaver dams or ice jams. Thirdly, subaerial weakening and weathering refers to the “processes ... that do not have a direct link with river flow” (Chassiot, L. et al 2020). In other words, these are power exerted by environmental and/or external factors that results in erosion and added sediments within the river system. Examples of these include rain, vegetation, human and animal activities, etc. These will be further elaborated and discussed in the external dynamics of this literature review in *Section 2.2.2*. Performed either by mechanical or thermal erosion, streambank retreat is part of the process of rivers’ lateral migration. Whereby, the channel’s outer bank typically serves as the benchmark and boundary when measuring the rate of erosion (Nanson and Hickin, 1986).

Riverbanks’ erosion rate is the displacement of channels’ shoreline over a unit of time (Hooke, 1980). This is one of the main parameters measured when determining lateral migration rates of rivers. Researchers focus on a specific river reach, typically a bend, and measure the bank retreat over a pre-determined time range. This is, of course, quite difficult to measure for the entirety of a river as erosion rates are dependent on several factors (e.g., soil properties and vegetation) that may vary across the floodplain (Randel, T. 2004). Hence, measurement samples are generally taken across the river being studied. Lawler, D. M (1993) summarizes the different techniques for measuring lateral channel change from the 1800s to late-1900s. In his list, data collection varies but all tries to measure riverbanks’ erosion rate and lateral channel changes (Lawler, D. M 1993). For a more predictive studies, scientists still aim to create a more accurate model for channel migration, which is proven to be difficult as erosion rate is governed by the unpredictable and complex soil-water interaction (Randel, T. 2004; Saadon, A. et al. 2021). Channel parameters such as water level, water velocity, bank geometry, and bank composition that are constantly changing both spatially and temporally, which is difficult to measure and predict throughout the river system (Randel, T. 2004; Saadon, A. et al. 2021).

3.1.1.3 Sediment transport and deposition

There are several ways sediments are transported depending on the size of the particle and water velocity. Sediment modes of transport within a river channel are summarized into four types of movements: (1) Bed load, (2) Suspended load, (3) Wash load, and (4) Dissolved load (Babinski, 2005). Bed loads are movements where the sediment remains consistently and regularly in contact with the riverbed. This could happen

either through traction, whereby the material is rolled along the channel bed, and/or saltation, whereby the sediment may bounce along the riverbed (“leap-frog” motion) (Turowski et al, 2010). These generally occur on larger sediments such as rocks and pebbles that require stronger flow for mobilization (Turowski et al, 2010). However, when water velocity is high, larger particles could also be transported through sediment load. Suspended load are sediments that remain above the channel bed and are carried by turbulent water flow. Particle size like sand is typically transported in this manner (Turowski et al, 2010). In fact, sediments that are transported by either bed load or suspended load make up the sediments that initially form the inner banks of a river (Turowski et al, 2010). Wash loads and dissolved loads are sediments that are carried and amalgamated with water. Wash loads, in particular, are typically <63µm in size like clay and silt (Kayvantash et al, 2017). They generally only separate from water, if the water becomes stagnant (0 velocity) or when it evaporates, whereby sediments carried through the wash load would settle at the bottom of the channel (Kayvantash et al, 2017). Finally, dissolved loads are water solutes that stay in the water once introduced as it chemically bonds with the river’s water (Babinski, 2005). These are generally chemicals or organic materials not visible to the naked eye like phosphorus or nitrogen that can only be parted from the water through chemical or bacterial breakdown (Babinski, 2005). In general, larger sized sediments transported through bed load, suspended load, and wash loads make up most of the sediments found within a river which ultimately forms its morphology.

Lane balance is an integral part of all river movement and migration especially in meandering rivers. It refers to the balance between sediment transport, water discharge, and channel slope. A general expression introduced by E.D, Lane (1955) presents such a relationship in Equation 3 (Lane, E.D. 1955).

$$Q_s \times D = Q_w \times S \quad (3)$$

Whereby, Q_s refers to sediment discharge (m^3/s), D is sediment size, Q_w is the water discharge (m^3/s), and S is the channel slope (Lane, E.D. 1955). This idea suggests that for a river to be ‘balance’ sediment discharge and water discharge must remain consistent (Lane, E.D. 1955). A change in sediment discharge without an equivalent change in water discharge may result to changes on the river’s slope; An overpowering water discharge would cause erosion and channel incision, whereas a surplus in sediment supply results in sediment aggradation and deposition. This is related to stream power and its ability to perform work (Bizzi and Lerner, 2015). When stream discharge increases stream power also increases in response. Hence, the river can transport more sediment. However, insufficient amount of sediments could then lead to erosion due to excess stream power, thus leading to vertical (i.e., channel incision) and/or lateral (i.e. channel movement) migration (Simon and Rinaldi, 2006). Once lane balance is reached the river system reaches the state of equilibrium.

Stream equilibrium is a wholistic state that rivers try to maintain. Whereby, erosion and sediment transport are approximately equal to the sediments the channel deposits (Dai and Liu, 2013). Therefore, the stream would have little to no morphological change unless an external force affects the system once again. As the rivers' internal and external forces continue to be active, so does its equilibrium. A small change in the condition of the river would result in a new equilibrium to compensate and adapt to such a difference (Dai and Lui, 2013). In other words, equilibrium is not a static state but rather is dynamic, that constantly transforms throughout a rivers' lifespan. Once a channel has reached equilibrium, it is then referred to as a *graded stream*, whereby the channel is 'mature' and has reached a, somewhat definitive, 'graded' channel bed morphology (Hoover, 1948). Typically, these rivers follow a laminar flow, whereby the river bottom is smooth with a gentler slope and has an upward concave formation (Strahler, 1952). Examples of which are meandering rivers like the Amazon River in South America and the lower Mississippi river located in the United States. On the other hand, *ungraded streams* are rivers that have not yet reached equilibrium and is still in the process of downcutting its riverbed (Blom et al, 2016). Such rivers generally follow a more turbulent flow like rapids and waterfalls, whereby the riverbed consists of irregularities with knickpoints, terraces, and potholes (Blom et al, 2016). Examples of which are braided rivers formed in steeper slopes with high sediment loads like streams that forms on mountain sides as well as waterfalls like the Niagara Falls which borders the United States and Canada. Ultimately, this is likely why rivers are in constant movement and morphological shifts: they try to reach or maintain a steady equilibrium state, whereby incoming sediments are equal to the amount being transported and deposited across the river channel.

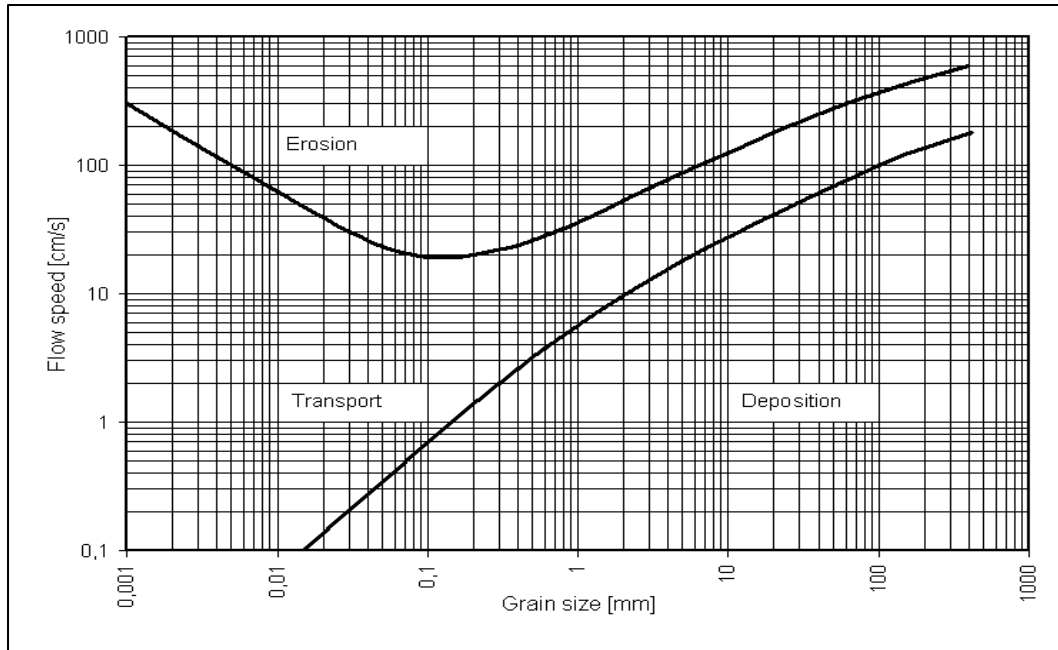


Figure 2: Hjulström Diagram (Hjulström, 1935)

The Hjulström diagram presents curve lines that determine the necessary water velocity to perform sedimental movements within the channel (Hjulstrom, 1935). The graph was first presented by Filip Hjulström for his doctoral thesis, “Studies of the morphological activity of rivers as illustrated by the River Fyris” back in 1935. Today, the diagram developed from his research is being used by hydrologists, geologists, and researchers globally (Khosrojerdi et al, 2015). Shown in Figure 2, the graph shows zones of average stream velocity required to either erode, transport, or deposit particles based on their size. In general, larger particles size requires stronger entrainment velocity. Entrainment velocity is the speed at which the river must flow in order to pick up a sediment particle (Ferguson, 2012). However, for materials composed of clay and fine silt, it requires a stronger force for erosion because of the electrochemical bond the particle holds between each other, as mentioned earlier. For materials composed of sand, gravel, pebbles, and boulders the average velocity threshold required for its erosion generally increases proportional to its size (Wilcock et al, 1996). Similarly, the margin for deposition also increases based on the sediment size, whereby clay particles are in constant transport due to it being dissolved by water, moving along with its flow (Wilcock et al, 1996). This diagram remarkably explains the critical linkage between water velocity, erosion, sediment transport and deposition which, as mentioned earlier, drives the internal processes and forces occurring within the channel. It depicts a strong summary of how these processes work together to carve, shape, and move rivers across the landscape.

3.1.2 External Dynamics

In addition to internal processes, external forces are also highly influential to river movements. Vegetation, soil properties, human and animal activities as well as weather and natural phenomena are a few examples of independent external systems that may alter rivers' internal processes which indirectly affects their movement.

3.1.2.1 Vegetation, soil properties, animal, and human activities

The absence or presence of vegetation may contribute to changes in river's morphology depending on where they are located within the area of study: (1) on riverbanks, (2) within the river, or (3) within the watershed. In fact, Hickin, E. (1984) have summarized and classified the influence of vegetation in fluvial geomorphology as 'flow resistance', 'bank strength', 'bar sedimentation', 'formation of logjams', and 'concave-bank bench deposition' in their dissertation (Hickin, E. 1984). Firstly, vegetation on the riverbanks can prevent erosion (bank strength), encourage sediment deposition (bar sediment and concave-bank deposition), and vary the river's water movement and velocities (flow resistance) (Hickin, E. 1984). Vegetation is generally known to withhold and reduce the rate of erosion by fastening sediment with their roots (McMahon, J. et al. 2020). Their presence on riverbank provides the same support on banks' structure to inhibit mass erosion. Moreover, their roots may also act as flow resistance for the water movement and capture sediments being transported to form new innerbanks. Secondly, vegetation and its by-products (i.e., fallen leaves, logs, and branches) within a river may stir up morphological variation by encouraging erosion and impeding water movement (formation of logjams). To elaborate, logs and other residue from vegetations could promote erosion as it abrades through the river walls especially during stronger currents (Sear et al, 2010). Furthermore, logjams may act as dams which may change the water current and velocity, thus affecting the transport of sediment and water's erosive capability (Montgomery and Abbe, 2006). However, once the log jam breaks free, sudden surge of water may result in greater erosion and release of accumulated sediments (Montgomery and Abbe, 2006). This is particularly similar to dams and ice jams and their effect on rivers' movement. Finally, vegetation inland, within the watershed, may also pose impacts on water discharge and sediment transport. Particularly, on their ability to percolate and make its way down towards the catchment basin. The presence of canopy creates a barrier for water to fall directly onto the ground (Sear et al, 2010). With trees and shrubs covering the landscape, water is retained as it goes through their leaves and branches along its path (Sear et al, 2010). Moreover, fallen leaves covering the ground may prevent liquid to percolate directly underground. Thus, generating a longer lag time for water, and sediments that it carries, to move across the landscape. Therefore, creating an overall impact on water discharge and sediment availability within the river, especially during rainfall and thawing events.

Another criterion that affects rivers' morphology is the nearby ground composition. The ground is composed of different soil types distributed unevenly across space, whereby their erodibility is highly dependent on the sediment condition and properties (Jepsen R. 2006). As discussed earlier, depending on the soil type (clay, sandy, silty, loamy, and chalky soil) a ground could produce a highly erodible surface or a solid and impermeable bedrock whereby water must move around it (Prasannakumar, V. et al. 2011). This is due to the soil's complex properties related to texture, organic matter, and permeability that are often considered in studies calculating soil erodibility factor (K) (Van Kesteren 1994; Prasannakumar, V. et al. 2011). In studies predicting erosion risk, for example, the K factor is an influential variable that cannot be overlooked as modelled by Prasannakumar, R. and colleagues (Prasannakumar, V. et al. 2011). Additionally, obstructions such as rocks and vegetation that are generally randomly scattered around an area add to the unique morphological arrangements of river. Due to their solid and impermeable composition, these substances can often resist strong erosional pressure from water, ice, or air (Chassot and Lajeunesse, 2020). Therefore, vegetation and rocks are commonly used to impede bank erosions and prevent water surges respectively (Chassot and Lajeunesse, 2020). Artificial levees, for example, are commonly used on riversides to mainly prevent flooding on nearby communities, but also pose as a resistance to eroding the riverbank (Knox et al, 2022). Although beneficial for settlements located near river shores, these infrastructures prevent rivers' natural meandering and movement patterns. Overall, such differences in ground compositions, riverbank infrastructures and material, can therefore create a unique formation of one reach compared to another that is composed of different compounds within the same river system. Such differences explain the unique morphology of rivers and their unpredictable movement across the floodplain.

Animals unavoidably interact with the river in one way or another, as it houses both water and food that can be directly linked with all species' ecological footprint. Therefore, their activities could also impact rivers' morphology and migration patterns both directly and indirectly (Naiman and Rogers, 1997). Their general movement inland already adds erosion and sediment supply within the watershed which eventually makes its way down to the river. Furthermore, their interaction with the river itself could also directly change the internal dynamic of the river system within. Beavers with their dams and lodges, for example, have changed river courses across north America as they create infrastructures that affect water movements and discharge (Naiman et al, 1988). Additionally, the mere existence of a single species could influence channel morphology and characteristics as studied by Beschta, R. and Ripple, W. (2006). In their study, they've identified the effect of the extirpation of wolves' population in Yellowstone National Park, USA and its direct linkage to streamside vegetation and water discharge (Beschta, R. and Ripple, W. 2006). Whereby, their studies suggests that the decline in wolf population resulted in the increase in elk's

population, which in turn caused an over consumption of a particular riparian vegetation that generally envelops the riverbank (Beschta, R. and Ripple, W. 2006). Thereby causing a visible morphological shift on the upper Gallatin River as the bankfull discharge continued to increase over the years (Beschta, R. and Ripple, W. 2006). It is evident that rivers' morphology can be associated to countless number of both implicit and explicit links on activities occurring inland. Therefore, human activities and development would also have some obvious implications and disruptions on rivers, especially near settlements.

Human footprints have made an undeniable effect on river systems and their morphology. The infrastructures and development we have built have both indirectly and directly influenced rivers and their forces. Particularly, the building of dams for water storage, hydroelectric power, flood control, industrial use, etc. as well as the construction of bridges to sustain human connectivity, movement, and transportation have vastly intervened with rivers directly (Gregory, 2006). A well-known example of such development is the construction of Glen Canyon Dam in Arizona, US back in 1963 that dramatically altered the course of the Colorado river downstream. A vast number of studies have shown the implications it had on the transport of sediments (Topping, D. et al, 2000) and water flow (Webb, R.H et al. 1999; Melis, T. 2011). Furthermore, humans have indirectly influenced rivers in the development of urban settlements via creating impermeable land surfaces, stormwater drainage, and sewage systems that have affected the percolation and transport of water downstream. Thence, water movement has become more restricted and focused on specific areas of the river, rather than a generally more evenly dispersed and gradual movement down current (Gregory, 2006). This has resulted in the increase of water runoffs but a decrease in the deposit of natural sediment transported into the river (Chin, 2006). Overall, these are a few examples of how human movements and developments have altered river courses and movements across the planet.

3.1.2.2 Weather and Climate

Weather and climate are highly influential in almost every natural aspect or process that takes place within the planet. To specify the difference between the two, weather are natural events that takes place in a short-period and small-scale environment that may constantly vary from day to day and from one place to another (i.e., rain events, snowstorms, sunny days, etc.) whereas climate is a long-term and large-scale environmental condition that typically averages weather conditions that is observed within a larger geographical region (i.e. tropical climate, dessert climate, etc.) (Parishat, 2014). Undoubtedly, both weather and climate would pose impacts on rivers' internal forces, which could affect a rivers' activity, stagnation, or overall presence.

Although short-term and small-scale, weather poses obvious and observable disturbances within a river system. Rainfall events, in particular, are perhaps the most obvious weather conditions that could stir up variability within a river's typical activity. Not only do they supply additional water within the stream which increases water discharge (as shown in most hydrographs after a rainfall event) but they also promote sediment transport and erosion within the watershed (Deng et al, 2008). More observable in natural and pristine environments, small-scale rivers become murkier during rainfall events due to the mobilization and additional supply of sediments (i.e., mud) in the river (Coppus and Imeson, 2002). These are alluvium stirred up within the channel perimeter and sediments carried by rainwater from inland erosion. Furthermore, the sheer force of constant water droplets on any surface could form small depression holes, which are eroded surfaces caused by the kinetic energy gained by a single raindrop from gravity as they fall onto the ground. This process is called "splash erosion". Although miniscule in small-scale, constant, and heavy rainfall could cause noticeable splash erosion over time. Whether this occurs on the river shorelines or inland, eroded materials will eventually make their way downstream, which indirectly affects internal forces in the river. On the other hand, some rivers would have an opposite effect when hot and sunny seasons take place, whereby the water discharge subsides or even completely dissipates during this time span. These ephemeral rivers, rivers that do not always have waterflow all year round, would only flow once again at times of rainfall or snowmelt events. Thereby affecting the rivers by having little to no movement during this period. These are several examples of how weather could affect river movement (or the lack thereof). Weather's shorter temporal scale generally affects rivers in the same manner, in which the changes it generates are small and (often) temporary until the river reaches its new equilibrium. Whereas climate, on the other hand, could pose a longer term and more permanent changes on a river's dynamic.

As the climate may alter the general intensity and patterns of weather, temperature, or atmospheric conditions, this too could pose a significant change in rivers' internal forces. A strong example of such changes is the lack of precipitation and an increase in temperatures in several places around the world. In a reservoir in Upper Colorado River Basin, US, for example, shows a predicted overall decline in water level of more than 70% as simulated in a study done by Kopytkovskiy, M. and colleagues. (2015). This is attributed to the consistent lack of precipitation and the increase in temperature during the summer months. In fact, this is supported in a separate publication done by M. Hoerling, et al. (2019) whereby their findings also suggest that the primal cause of decline in Colorado river is due to the same changes in climate which resulted to a decline in streamflow of approximately 20% over the last century. On the other hand, the increase in temperature has resulted in the opposite effect in some rivers in other parts of the world, resulting in an overall increase in water level as the climate continues to change. The Brahmaputra River Basin in Asia, for example, has experienced an increase in water level due to vast glacial melt and increase in

variability of rainfall event during the monsoon season as studied by Palash, W. et al. (2023). This presents a similar finding in models done by Gain, A. K. et al. (2011) projecting a strong likelihood of higher streamflow of the river in the future, causing problematic issues to countries downstream like Bangladesh. Evidently, climate change has shown its varying impact on warmer region rivers. Similar to its scale, river changes caused by the changing climate would likely pose a more permanent and irreversible impact on the rivers affected by these climatic shifts.

3.2 Cold Region Rivers versus Temperate Rivers

Cold region rivers generally function similarly to temperate rivers. Whereby, the internal factors which dictate rivers' movements (i.e., erosion, water discharge, sediment transport and deposition) continue to operate the same way. However, the external forces prevalent in these region presents additional complexity to the rivers' dynamics. In particular, the difference in season, environment, and the presence of ice enables rivers to move differently from their temperate river counterparts.

3.2.1 Seasonal and Environmental Difference

The latitudinal difference across the planet exposes rivers to completely different conditions from the difference in seasonality. Rivers closer to the tropical areas consist of only wet and dry climate, while rivers near the temperate zones experiences summer, spring, autumn, and winter (Syvitski et al, 2014; Boulton et al, 2008). Moving closer towards the circumpolar regions, frigid zones rivers are primarily exposed to harsher climate that is commonly referred to as the freezing and thawing cycles (Laidler and Ikummaq, 2008). During the freezing cycle, rivers' surfaces are generally frozen solid where little to no water discharge and sediments are moving its way down from the watershed (Ma and Fukushima, 2002). On the other hand, the thawing period generates a massive influx of water discharge and sediments from the watershed produced from the meltwater and the particulates it carries respectively (Wang et al, 2021). Therefore, rivers in these areas generally only have a small annual window for movement and morphological shifts to take place. In the arctic region, the thawing period normally occurs between late-May to early-September and the rest of the year remains within the freezing phase (Akerman and Johansson, 2008). Hence, precipitation also reflects such impact on the rivers accordingly. For example, heavy snow or hail does not have much effect on these rivers during the freezing season, as they only accumulate and rest on top of the land surface and very little water movement occurs within the watershed. Only over the melting months will its effect manifest on the river when meltwater and sediment finally move towards the stream (Laidler and Ikummaq, 2008). Such difference in lag time between natural events (i.e., precipitation) and its effect on rivers, are one of the things that sets cold region rivers apart from temperate and tropical

rivers; frigid zone rivers' peak discharge only takes place during the melting period, whereas other rivers' highest discharge occurs typically not long after a major rain event. These are some of the direct impacts of the freezing climate in cold region rivers that may not be as evident on rivers in other parts of the world. Differences in other external forces (i.e., vegetation, animal, and human activities) in these regions may not be as directly linked with the rivers' internal dynamic but may also pose a significant effect on rivers within this region.

Vegetational availability and diversity slightly differ within the earth's frigid zones. The arctic region is primarily composed of low-lying vegetation such as moss, shrubs, lichens, and grasses that carpet the landscape (Boulton et al, 2008). They function like vegetation in other parts of the globe, whereby they withhold sediments from flowing directly into the river by fastening them into the ground, as well as holding on to water during precipitation and runoff period. However, due to the lack of diversity and density of vegetation in arctic zones, they are not as effective as the vegetative landscape in a warmer area of the planet. On the other hand, their presence provides a unique contribution in the arctic through their interaction with ice and ground permafrost. Depending on the season (freezing or thawing), the vegetation generally moderates the ground temperature for ice and biomes that reside within the soil layer (Heijmans et al, 2022). In the freezing months, shrubs act as barriers for the ground from the cold air to penetrate deeper into the soil, hence preventing permafrost from forming deeper underground (Ma and Fukushima, 2002). Conversely, they also act as insulation for permafrost and ice to prevent them from melting quickly during the thawing months (Heijmans et al, 2022). In preventing the formulation of permafrost and meltwater during each respective period, the presence of vegetation implicates the amount and the rate at which the sediment and water reaches the arctic river. Although their effect may be minimal, their presence (or the lack thereof) still poses impact on internal forces acting within the watershed.

Finally, the lack of terrestrial movement and development have also generally allowed the rivers to move unhindered. Human settlement and infrastructure dramatically alter rivers' internal pressures. By contrast, in the absence of nearby settlements, internal forces within the watershed such as water movement, sediment transport, and erosion occur naturally and unimpeded by such external forces. Furthermore, the river is free to migrate as there is generally no structures developed to inhibit river movement (i.e., man-made levees or bridges). In the absence of human intervention, rivers and their internal dynamics are the primal force that sculpt the watershed's landscape. Likewise, a similar effect can be observed with the lack of animal activity within the region. Due to the scarcity of animals in the arctic, fewer animals interact with the river and less movement occurs inland that would otherwise lead to an increase in erosion and sediment

deposit. Therefore, arctic rivers flow largely undisturbed by nearby human and animal activities and movements.

3.2.2.3 Present of Ice and Permafrost

Perhaps the most significant difference between cold region rivers and their temperate or tropical counterparts is the presence of ice all year-round. Ice adds a new dynamic to river movement and its migration as it directly affects the internal forces acting on the river: (1) water discharge, (2) sediment transport, and (3) erosion:

- (1) During the freezing period, the formation of ice on the water surface increases the river's hydraulic pressure. The ice acts like an enclosed pipe conduit that speeds up the flow of water as the confined space prevents the water from moving in other directions apart from moving forward. Thus, increasing the water velocity of the river during this period. Furthermore, the movement of water supply also varies when the property of ice is considered. Ice does not melt instantaneously; hence water only percolates and moves towards the river as the temperature continues to increase. Therefore, water steadily flows downstream throughout the warmer season and becomes more dependent on the temperature rather than precipitation events. Finally, ice jams are also prevalent in these regions during the thawing period. Similar to dams, these natural phenomena generally change the water level and velocity interfering with the natural flow and discharge of the river.
- (2) Beyond the transport of sediment through meltwater, the ice itself can trap and carry sediments across the river. As the ice forms during the freezing period, sediments become entrapped within the ice matrix which could then be carried as it detaches itself from the bank or other ice during the thawing months (Turcotte, B. et al. 2011). They serve as ice-rafts which physically pick up and drop off sediments as they melt across the river.
- (3) Ice and permafrost can both promote and prevent erosion. Similar to vegetation, inland-permafrost and riverbanks generally strengthen the ground as the ice solidifies sediments together. Thus, reducing its vulnerability to erosion. Similarly, the layer of ice also shields the ground from the elements that would generally break apart sediments (i.e., rainwater and air). On the other hand, the freezing and thawing of meltwater throughout the landscape also introduces loose sediments into the river and watershed through a process known as 'plucking' (Turcotte, B. et al. 2011). Water expands as it becomes ice, the expansion increases the void space between sediment particles, thereby slowly eroding landscapes generating a massive influx of sediments during the thawing cycle. Moreover, the presence of ice floating on the river further adds to erosion as it scrapes and abrades the river wall.

In short, not only does ice add extra water supply into the river, but they also present additional complexity on the river dynamic by effecting sediment transport and erosion. Process that are typically absent in warmer climate rivers. Thus, making these rivers unique in comparison to their temperate and tropical counterparts.

3.3 Climate Change in Cold Regions

Climate change has been a recurring topic in the literature, especially its impact on cold regions. Its most well-known impact is the increase in temperature and its effect on glaciers within high altitudinal (mountains) and latitudinal (polar) regions. In recent studies, for example, Singh, A. et al. (2020) has measured the increase in the rate of glacial retreat of alpine glaciers in Meru, India. They identified the rate of glacial retreat increased from $\sim 0.012\text{km}$ per year to $\sim 1.4\text{km}$ per year as measured from 1976 – 1990 and 2011 – 2019 respectively (Singh, A. et al. 2020). A similar study in the Tibetan Plateau, China also found the accelerated decrease in glacial landcover, whereby 4.5% of glaciers have already disappeared and 80% of the glaciers are starting to retreat (Kang, S. et al. 2010). Furthermore, ice caps within the circumpolar regions have also been reducing in size. Within the outskirts of Antarctica, for example, massive ice glaciers stay afloat on the ocean surface and, consequently, the increase in oceanic temperature results in sea ice melting and glacial shrinkage. Rignot, E. et al. (2002) measured that for every 0.1°C increase in oceanic temperature, ice caps retreat towards the continental land at a rapid rate of 1m per year (Rignot, E. et al. 2002). Likewise, a similar observation can be identified in the opposite polar region, the Arctic. Whereby, in studying multitemporal satellite imagery from 2000 to 2006 of Greenland, Moon T. et al. (2008) observed a decline in ice thickness and increase in sea level rise related to the increase of 1.1°C of summer temperature (Moon T. et al. 2008). Evidently, increases in temperature are being experienced across the globe, particularly within the colder regions. Thereby, reducing the amount of ice present within these regions and its accumulation during the winter months, results in the increase of meltwater and water discharge, and in the rise of sea level.

Continual melting of ice along with a low ground percolation rate has substantially changed the fluvial movement and activity of the arctic region. In fact, sea level rise, longer thawing seasons, and the increase in storm occurrence are observed in an arctic study done by Radosavljevic, B. et al. (2015). Their findings suggested a risk for potential flooding and water surges when they recorded the highest ice recession rate of $-1.3 \pm 0.7 \text{ m}\cdot\text{a}^{-1}$ on the arctic coastal regions from year 2000 to 2011 (Radosavljevic, B. et al 2015). Thence, their study applied their findings by identifying flood hazard regions approximately 20 to 50 years

into the future (Radosavljevic, B. et al 2015). These increases in meltwater pose an obvious change in water discharge in the cold region river. In fact, a study done in the early 2000s by Peterson, B. et al. (2002) has identified an increase in water discharge into the arctic ocean by 7% from 1936 to 1999 (Peterson B. et al. 2002). Likewise, a more recent study in 2019 have concluded with a similar finding, where an approximated increase in temperature of 1°C to 4 °C would result in an increased discharge by 6.8% to 35.0%, respectively in the arctic as founded by Wang, S. (2019). These observations and measurements are empirical evidence that directly links climate change and fluvial movement in the arctic that is primarily based on the increase of temperature. Other drastic movements, geomorphological activity in particular, are also observable in the region in the form of retrogressive thaw slumps.

The increase in temperature of the arctic also results in an increase of erosion rate and sediment flux within the region. In a smaller scale, the increase in meltwater and water discharge promotes the mobilization of sediments across the floodplain. Additionally, land that was previously covered in ice and snow is left vulnerable and exposed for weathering and erosion, thereby increasing the rate of erosion within the landscape. In a much larger scale, on the other hand, the melting of ground permafrost has also resulted into massive landscape movement across the northern region (Rowland, J. et al. 2010; Lacelle, D. et al. 2015; Lewkowicz, A. et al. 2019). As mentioned earlier, thermokarsts and retrogressive thaw slumps (RTS) are collapsed landmass due to the melting of permafrost that aid in keeping the land held together. Their proliferation has undeniably resulted in the increase of loose sediments available in the arctic region. Over the past three decades, Lacelle, D. et al. (2015) has observed that approximately 4,000 RTS events have already started on the Banks, Island, Canada. This will continue to exacerbate as these events are projected to go up to 10,000 in the next half a century (Lacelle, D. et al. 2015). Furthermore, other parts of the country, Peel River in Northwestern, Canada, are also experiencing the same landslide events as captured by Lewkowicz, A. et al. (2019). These are a number of examples of how climate change has directly implicated the geomorphological movement in the arctic. Evidently, these drastic movements would then later result in changes of river movement and migration.

3.4 Studying River Movement using Remote Sensing and Allied Techniques

Based on literature that has studied river movements, there appears to be a lack of standardized method established in measuring lateral migration rates (Lawler, D.M. 1993). Lawler, D.M. (1993) has highlighted seven main techniques used in measuring riverbank erosion: sedimentological evidence, botanical evidence, historical sources, planimetric resurvey, repeated cross-profiling, erosion pin, and terrestrial photogrammetric surveys (Lawler, D.M. 1993). The author described each technique and highlighted their

practicalities and limitations in their review (Lawler, D.M. 1993). Moreover, they were categorized based on which practices are recommended depending on the timescale of the studies (longer vs shorter timescales) (Lawler, D.M. 1993). However, other techniques could also be used depending on other factors, such as the channel's environment and composition (e.g. channel size, materials, and climate), researcher's background, study's logistics, finance, and timeframe, current technologies, and more (Lawler, D.M. 1993; Donovan and Belmont, 2019; Black et al, 2010; Richard et al, 2005). In the past, techniques in measuring lateral migration were concentrated in historical data and land survey (Allen C.R. 1895; Dryer and Davis 1911; Wolman 1959; Lawler, D.M. 1993). More recently, technologies have advanced whereby satellites are becoming more common in measuring river movements (Altena and Kaab, 2021; Wahiduzzaman and Yeasmin, 2022). They have the advantage of viewing the river from an aerial and larger perspective. In remote areas, satellite use is also optimal for logistics, timing, and financial constraints. Hence, more automated tools are being programmed for easier access, processes, and representation of these aerial imageries. Tools such as Google Earth Engine can extract data from Landsat archives, classify landcovers, and map specified time periods within a few lines of code. Furthermore, tools such as Pyris and Rivmap can provide visual representation of river movements across the years and even start to predict its potential movements in the future (Rawee et al, 2020; Williams et al, 2020). Therefore, developments like these have encouraged the use of advanced technologies and practices, remote sensing in particular, to be further used in river movement's observations and measurements.

As much as satellite remote sensing is promising for river studies, it also has several limitations. Given that the imageries are limited to pixels resolution, the features and land covers that it captures are also constrained by their resolution size. This poses an issue with narrow river reaches and the inaccurate classifications of its boundaries. In fact, narrow rivers smaller than the pixel resolution will either be represented as a single pixel or not represented at all (Huang et al, 2018). Therefore, limiting the types of rivers that can be examined using specific satellite outputs. Inaccurate pixel classification due to resolution size also creates uncertainties to a lot of processes that utilize satellites imageries. This is particularly prevalent in accurate pixel identifications between the river and its adjacent land. Furthermore, since satellite is a relatively newly developed technology, historical data is difficult to use and access. The earliest satellite launch only goes all the way back to 1957, Sputnik (National Geographic). Hence, landscapes and objects that predate this period are likely not captured with aerial imagery. Since technology is not as advanced as today, early satellite imageries have coarse resolution, limited coverage, and lacked other spectral imaging, which again limits their usage (Phiri and Morgenroth, 2017). Finally, most satellite outputs are highly dependent on atmospheric conditions. Captured imageries relies on the lack of cloud present at the time when the satellite orbits the area (Marshall et al, 1993). Thus, limiting the viability of

imageries that can be used for studies. These types of issues are only some of the limitations of using satellite images, especially in topics related to capturing historical imageries and/or rivers that vary in width and sizes across a landscape.

CHAPTER 4

STUDY AREA

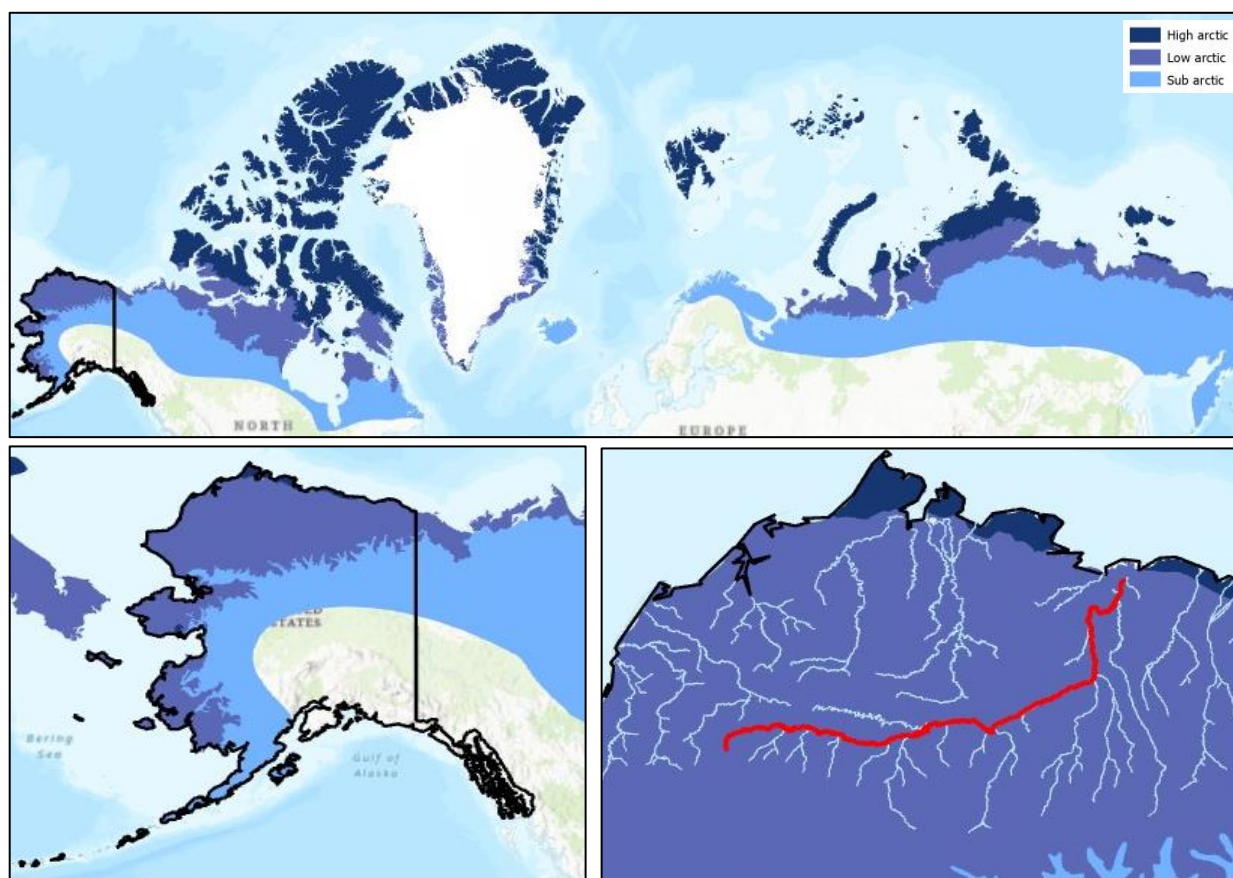


Figure 3: Study Area; (a) presents a world map of spanning the arctic, showing the high arctic (dark blue), low arctic (purple), and sub arctic (light blue) boundaries; (b) highlights the state of Alaska, where the study was conducted; (c) overlays the tributaries across the northern Alaska border – in red is the Colville River, boxed in yellow are Reach A and Reach B, and the orange flag presents the location of the meteorological station.

The arctic landmass is typically subdivided into three zones: high arctic, low arctic, and subarctic, based on the climate and vegetation that prospers within the area (Hislop, L. 2013; Roeggen, A. 2015). The high arctic are primarily composed of polar barrens where the temperature is too frigid for vegetation to grow and prosper. The low arctic is primarily a tundra-like land surface where small vegetation (i.e. shrubs) may grow, but the land remains relatively frozen (Hislop, L. 2013). This area experiences annual freezing and thawing cycles. Separating the low arctic and subarctic region is an isotherm average of +10°C during its warmest month (July) where trees with a minimum height of 2-3 meters could flourish. In fact, tree lines are often drawn in this area, separating the low arctic and subarctic regions (Roeggen, A.). The map in Figure 3a is a layer taken from CAFF – Arctic Biodiversity Data Service ([link](#)), highlighting the subdivided

region of the arctic landmasses. In analyzing the effect of climate change on cold-region rivers, the study was primarily based on an area where ice is present for most of the year. An area that consists of seasonal freezing and thawing cycle to capture river movement during the warmer months. Therefore, the low arctic region was highlighted for the study. Particularly, the North American continent for its vast and freely available data.

The selected river was chosen for its relatively high movement rate and size. A highly mobile river was necessary to identify any drastic and abnormal shifts that can be correlated with climate or temperature changes. Furthermore, its size was also considered to ensure that it is captured by Landsat satellite despite its relatively high-resolution pixel coverage. The river must be at least more than 30 meters wide to remain visible and identifiable in a single pixel. Therefore, Colville River, located in Alaska, USA was selected as it meets most of the desired criteria mentioned.

The Colville River is a remote river on the northern coast of Alaska located in North Slope Borough County within the Umiat community. The river spans about 560 kilometers and drains about 649,270 acres of land (USGS 2000). Its headwater starts at De Long Mountains and exits into the Arctic Ocean. Moving downstream, the river branches into approximately 34 distributaries (Walker, J. and Hadden, L. 1998). Throughout the year, the river generally follows a freeze-thaw cycle whereby being frozen for more than half of the year (September to April) and highly mobile during the thawing season (May to August). Known for its rich source of resources such as fisheries, Colville River is also exploited for its oil and fossil presence. Therefore, scientific research in the area extends to wildlife, land formations, and escarpments. However, few research has focused on the actual river itself and its movement related to the rapid change in temperature occurring in the area. Hence, data is available but studies regarding the river and its migration pattern are limited.

Finally, specific river reaches were pinpointed to acquire the river migration movement. Choosing small reaches allows a more accurate measurement of river activity. As done in numerous studies, only movements of specific riverbanks were measured along the river to quantify migration rate. This is to ensure a specific and static point of reference when measuring lateral river migration overtime, which is quite difficult to achieve when looking at the stream in its entirety. Likewise, a similar approach was done in this study; two smaller sections of the river were selected to represent the rate at which the river migrates. The reach selection process was determined only by selecting reaches that are upstream and downstream from the meteorological station, where ancillary data was collected from, and moderately distanced to capture

the relationship between upstream and downstream movement. Figure 3 is a map that captures the location of the two selected river reaches and the location of the meteorological station in the Colville River.

CHAPTER 5

METHODOLOGY

5.1 Data Collection

5.1.1. Satellite Data Acquisition

In this study, Landsat 7 satellite images were obtained using Google Earth Engine. Beyond Landsat's visual aerial imagery, the Earth Engine Data Catalog provides a pre-classified surface water of Landsat data, called the *Surface Water Occurrence* (Pekel, J. et al. 2016). This product was used as the primary satellite data in identifying yearly river movement for the study. The *Surface Water Occurrence* is a tool that calculates the average monthly water detection and observation. Using this pre-processed layer is advantageous for time efficacy, accuracy, and consistency in landcover classification. Bypassing manual classification of numerous satellite imageries significantly reduces data pre-processing time and potential source for human error. Objectively using such pre-processed satellite imagery could potentially reduce incorrect and inconsistent classifications that are normally associated with manual supervised or unsupervised classification techniques.

The temporal aspect of the collected satellite imagery was also considered. Satellite data from 2002 to 2019 was compiled for the Colville River. This time range was deemed most suitable primarily because of data availability. Although Landsat's water layer imagery has been available since 1984, ancillary data (river discharge, air temperature, and precipitation) were only available in the early 2000s (Pekel, J. et al. 2016). Therefore, the year 2002 was chosen to maintain a consistent initial time range for the satellite imagery and the available ancillary data. Likewise, 2019 was used as the most recent data because the station has not fully processed and published measurements for the year 2020 at the time this study was initially conducted. Leaving only the 2019 data as the most complete and functional dataset available. Furthermore, the significance of the early-2000s on the arctic sea ice formation was also considered. Several research has shown a significant decline of arctic sea ice around this time. As the *National Snow and Ice Data Centre* and *NASA* reported, the arctic's sea ice has not rebounded since the start of the summer of 2002 and continues to decline as the year progresses (Przyborshi, P. and Levy, Robert, n.d.D; Stroeve, et al. 2005). Overall, having approximately 2 decades of data from 2002 to 2019 of satellite data, totaling 432 pre-classified imageries acquired from the monthly data (January to December) of the two reaches, Reach A and Reach B, of the Colville River.

5.1.2. Ancillary Data Acquisition

The ancillary data for this study consisted of temperature, precipitation, and discharge of the Colville River. Like the Satellite imageries, all data range from January of 2002 to December of 2019 but with different acquisition intervals and unit of measure. Temperature was taken at 1-hour intervals totaling to ~157,776 data with degree Celsius as its unit, precipitation was measured as daily sum totaling to ~6,574 records with inches as its unit, and discharge was measured every 15 minutes totaling to ~631,104 records with cubic feet per second as its unit of measure. Both the temperature and discharge were taken from the Umiat meteorological station located at a latitude and longitude of 69.3605, -152.1226944, slightly off the mid-left bank of the Colville River. Data are maintained by United States Geological Survey (USGS) and was acquired from: <https://waterdata.usgs.gov/nwis/uv?15875000>. On the other hand, precipitation was taken from a different, but nearby, meteorological station because precipitation data is unavailable for the Umiat station. This data was taken from Nuiqsut station situated downstream of the Colville River, approximately 100km northeast of Umiat with a latitude and longitude of 70.1652, -150.9197605. This data is maintained by Alaska Climate Research Centre and was acquired from: <https://akclimate.org/data/data-portal/>. Although precipitation may not be captured in the same station as temperature and discharge, it remains situated on the same river, and could still provide a good idea if climate change is prevalent in the area. Precipitation may not be identical but may remain similar enough for determining trends and correlating them with other variables, however this data limitation would certainly produce uncertainties on the results related to precipitation.

5.2 Data Processing

5.2.1 Satellite Data Processing

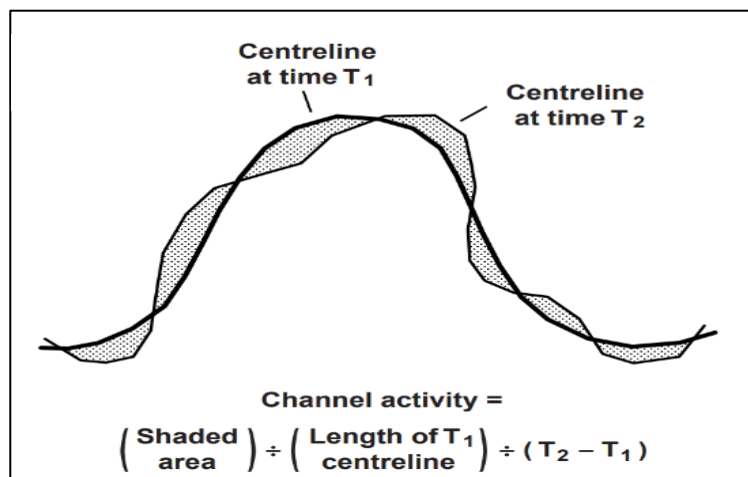


Figure 4: Channel Activity Equation (Shields, F.D. et al. 2000)

Channel activity is defined as, “the mean rate of lateral migration along a river reaches in dimensions of length per unit time”, according to Shields, F.D. *et al.* (2000). Their study tried to identify the mean migration rate of the Missouri River, pre- and post- Peck Dam in Montana using maps and aerial photographs (Shields, F.D. *et al.* 2000). The equation used is shown in Equation 4, where the channel activity is equal to the sum of the area created between two reach centerlines divided by the length of the successive centerline divided by the difference in time between the two centerlines.

$$\text{Channel Activity} = (\text{Shaded Area} / \text{Length of T1 centerline} / (T2 - T1)) \quad (4)$$

An image from the same study was obtained to complement Equation 4 in Figure 4. In fact, their equation was used in more recent studies done by Magdaleno, F. and Fernandez-Yuste, J. 2011 and Esfandiary, F. and Rahimi, Masoud 2019 when also capturing migration rates. Due to the simplicity of the equation and the limited source of data, this study also followed the same approach. In doing so, the time difference between T_2 and T_1 was first established as it is critical in calculating channel activity. Since the Colville River is highly mobile, whereby massive changes take place within a single season, a ‘continuous’ timeframe was deemed appropriate to identify the small-scale changes between one month to another. On the other hand, since the aim of this study is to determine the effect of climate change on river movement, large-scale fluctuations, where the same month is compared from one year to another, are also done to remove the effect of seasonality. Therefore, a ‘continuous’ and ‘yearly’ timeframe was developed to capture both the small-scale and large-scale trends, respectively. Then, variables from the equation were extracted from the processed satellite imageries to calculate the ‘continuous’ and ‘yearly’ channel activities for both Reach A and Reach B.

Most of the satellite processing was accomplished using ArcGIS Pro 3.1.1 software. The downloaded satellite imageries came as a raster GeoTIFF file format (Figure 5b – i.). However, it was deemed more appropriate to work with vector data, rather than raster, when analyzing how riverbanks and centerlines have shifted from one month to another and from one year to another. Hence, the raster format was converted to polygon using *Raster to Polygon* tool (Figure 5b – ii.). The map and each layer were projected to NAD 1983 UTM Zone 5 based on the UTM zone the Colville River is located at. As mentioned, two specific reaches were looked at in greater details to determine the shift of the river by calculating the river-reaches’ activity. Hence, each layer is *clipped* to the specified area as shown in Figure 3 (map). Afterwards, a manual clean-up of each reach for every layer was done. This is to remove any random pixel-converted polygons that are obvious misclassification and/or parts of the reach that have temporarily branched off from the original reach being measured. This is to reduce the ‘noise’ within the data and to only capture the same tributary stretch for every month in every year (Figure 5b – iii.). Note: during the freezing months,

the satellite was unable to differentiate between the river and the land surface, perhaps this is due to the frozen river surface that is covered by snow. Therefore, no data was recorded for these months.

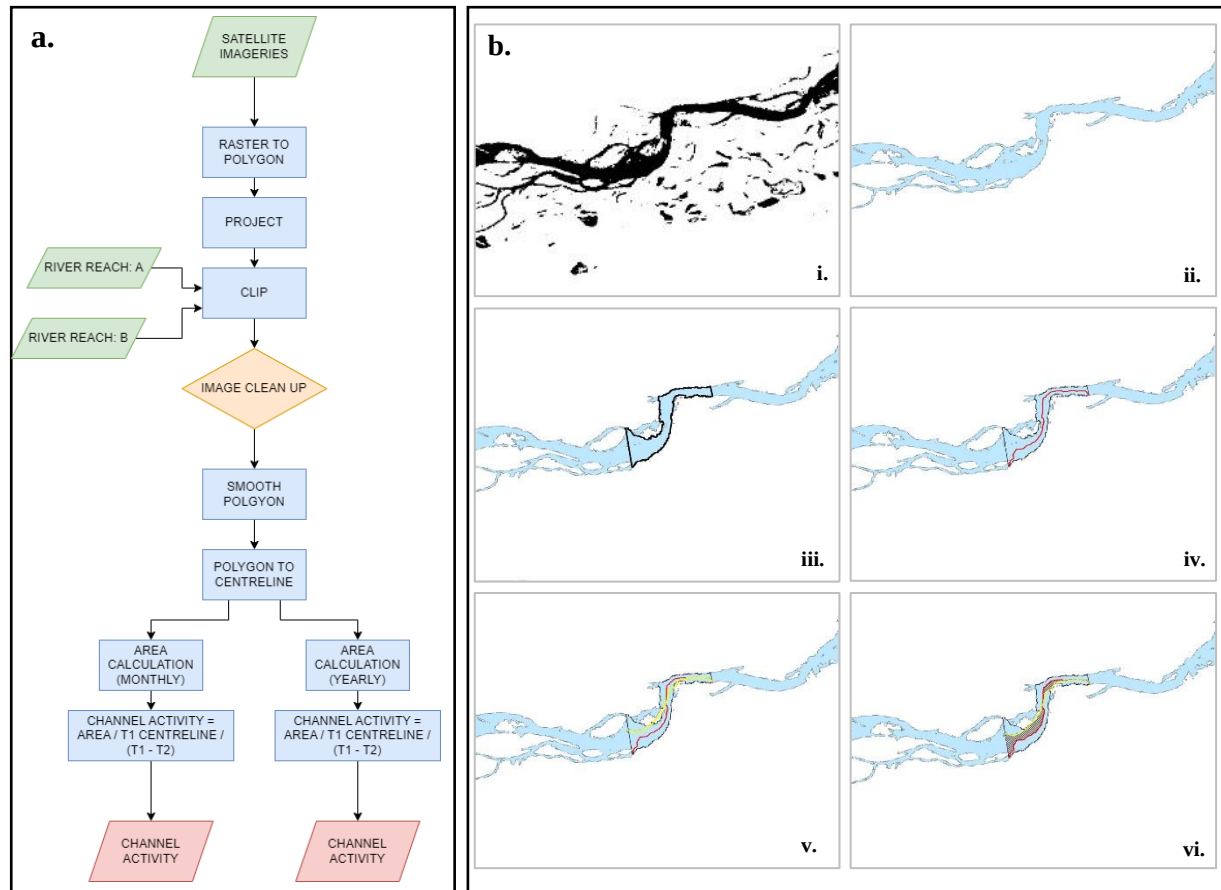


Figure 5: Satellite Imagery Processes. Figure 5(a) and Figure 5(b) presents a visual summary of the methodological process done on each satellite imagery for each river reaches. Figure 5(a) shows the schematic methodology performed on the satellite data. To supplement this, Figure (b) presents what the process looked like in ArcGIS Pro: i. is a sample of the satellite image derived from Google Earth Engine, ii. shows how this is converted from raster to vector data, iii. shows the derived and cleaned polygon clipped to a specific reach; iv. shows the centreline for the clipped area, v. overlays the centreline from the previous year/month that the centreline is being compared to, and vi. presents the calculated area between the two centrelines from different periods that are being compared.

After a manual clean-up of the river reaches, the boundaries were ‘smoothened’. Since the data came from a highly pixelated aerial imagery where riverbanks appeared to be jagged. Hence, to reflect a more natural curvature of river boundaries, similar to the physical world, the layers were smoothened using *Smooth Polygon*. Afterwards, the *Polygon to Centerline* tool was used to generate centerline along the river reaches. A tool optimized specifically for hydrographic network (ESRI 2020) (Figure 5b – iv.). Centerlines were then compared both as a ‘continuous’ and ‘yearly’ timeframe. The ‘continuous’ timeframe compares the centerline of one month to the following month’s centerline when data is available (Figure 5b – v.). For

example, June’s centerline was overlayed with July’s centerline of the same year, with the time difference of one month. In instances where the next available monthly data occurs on the following year, the number of months difference between the two months were then used. For example, if August 2002 is compared to June 2003, then ten months was used as the time difference between the two. This presents a more *continuous* timeframe that compares channel activity from one month to the next. On the other hand, in a ‘yearly’ comparison, the centerline of one year was overlayed with the centerline of the successive year of the same month. For example, June 2002 was overlayed with June 2003 to determine the sum of area of polygons created between the two centerlines, with the time difference of one year (Figure 5b – vi.). Finally, all variables from Equation 4 (Shaded area between two periods, Centerline length of T1, Time difference between T1 and T2) were logged into an excel spreadsheet where channel activity was calculated. Using R-Studio, data was presented in two bar graphs showing the channel activity in both ‘continuous’ and ‘yearly’ timeframe. Since the yearly timeframe compares a month’s value from one year to another, only months where the channel was present in the pre-classified satellite imageries (warmer months) were kept shown in the graph. A continuous and yearly trend were then graphed, identifying their rate of change in a continual timeframe and a yearly timeframe, where its most active months are broken down for further analysis.

5.2.2 Ancillary Data Processing

Temperature data were wrangled using R-studio. The cleanup processes involved averaging the hourly data into daily, monthly, and yearly temperature data. From this, a boxplot was generated to present the data min, max, median, and variability of each month from 2002 to 2019. For the months where the median is above 0°C, the box plot was highlighted in red, whereas everything below the freezing temperature was colored in blue. Since temperature data highly vary in range (-40°C to 20°C) a z-score normalization was done to standardize and remove the effect of seasonality to allow trends to be more prevalent in the data. Equation 5 presents the equation used for z-score normalization, whereby z is the z-score for the data point, x is the data point value, μ is the mean of the dataset and σ is the standard deviation of the dataset. The dataset is dependent on the timeframe of which trend is being graphed; for the ‘continuous’ timeframe, the dataset are all the data points for that particular year, whereas the dataset for the ‘yearly’ timeframe are all the data points for that particular month being examined.

$$Z = \frac{x - \mu}{\sigma} \quad (5)$$

The ‘continuous’ timeframe was then graphed to determine the overall temperature trend of all data. Additionally, to breakdown each month and identify their trend, the ‘yearly’ timeframe was used. Then, a *decomposition* tool in R-studio that is normally used to identify trends and forecast future data projections was used to validate and verify the temperature trends. This function breaks down trends, seasonality, and residual error within the dataset.

Similarly, the precipitation and discharge data were processed through R-Studio, cleaned-up and were summarized daily, monthly, and yearly using both their sum and average. A bar graph was used to present both data’s monthly mean and monthly sum. For their trends, the sum was used to represent the continuous timeframe, while average was represented in the yearly timeframe. This was done for similar reasons as the channel activity: the sum depicts the small-scale fluctuations within the data better because data variability is better seen using this operation, whereas the average presents the large-scale trends better within the dataset. Finally, Z-score normalization and decomposition tool was not used for these variables because their measurements only hold positive values. Unlike temperature where data is continuous, precipitation and discharge hold many zero values where there is simply little to no discharge and precipitation that occurred for that particular day.

5.3 Result Verification

Finally, Planet Satellite data acquired through www.planet.com was used to verify the results derived from the Landsat Satellite data taken from Google Earth Engine. This satellite was chosen for verification because of its high resolution of 50x50 cm. Thus, providing enough detail to manually identify the riverbank from the actual river. Unfortunately, imagery for the Colville River from Planet Satellite data is only available from August 2016. Therefore, only ~3 years of data was used to verify the result. Nevertheless, this was deemed enough to get a general sense of the reliability of the pre-classified Landsat data. Furthermore, a slightly different approach to acquire the parameters needed in the Shield’s equation was done to ensure that the methodology performed on Landsat data was also reliable. Using the Planet data, riverbanks were manually digitized for each river reach in correspondence to the same time as the Landsat data. In essence, this becomes a more manual and time-consuming approach but provides more accurate and reliable data. Centrelines were then derived using the manually digitized riverbank where parameters for the Shield’s equation are then taken – following the rest of the same method done with the Landsat Data. Figure 6 shows the Planet Satellite data overlayed with Landsat-derived polygon outlining the riverbank. Discrepancies are quite minimal, most of which are due to Landsat’s higher resolution whereby line edges appears to be quite jagged.

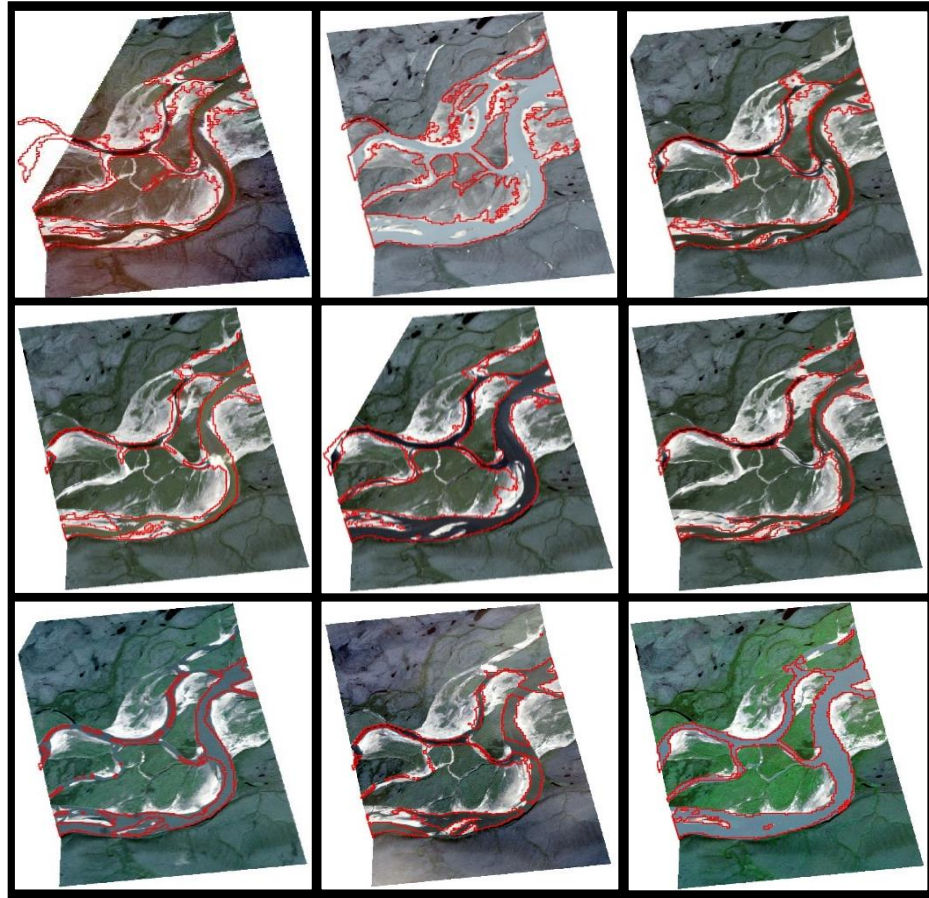


Figure 6: Landsat vs Planet Data. Top to Bottom, left to right, is June 2017, July 2017, August 2017, June 2018, July 2018, August 2018, June 2019, July 2019, and August 2019.

CHAPTER 6

RESULTS

6.1 Channel Activity

6.1.1 Reach A and Reach B Channel Activity

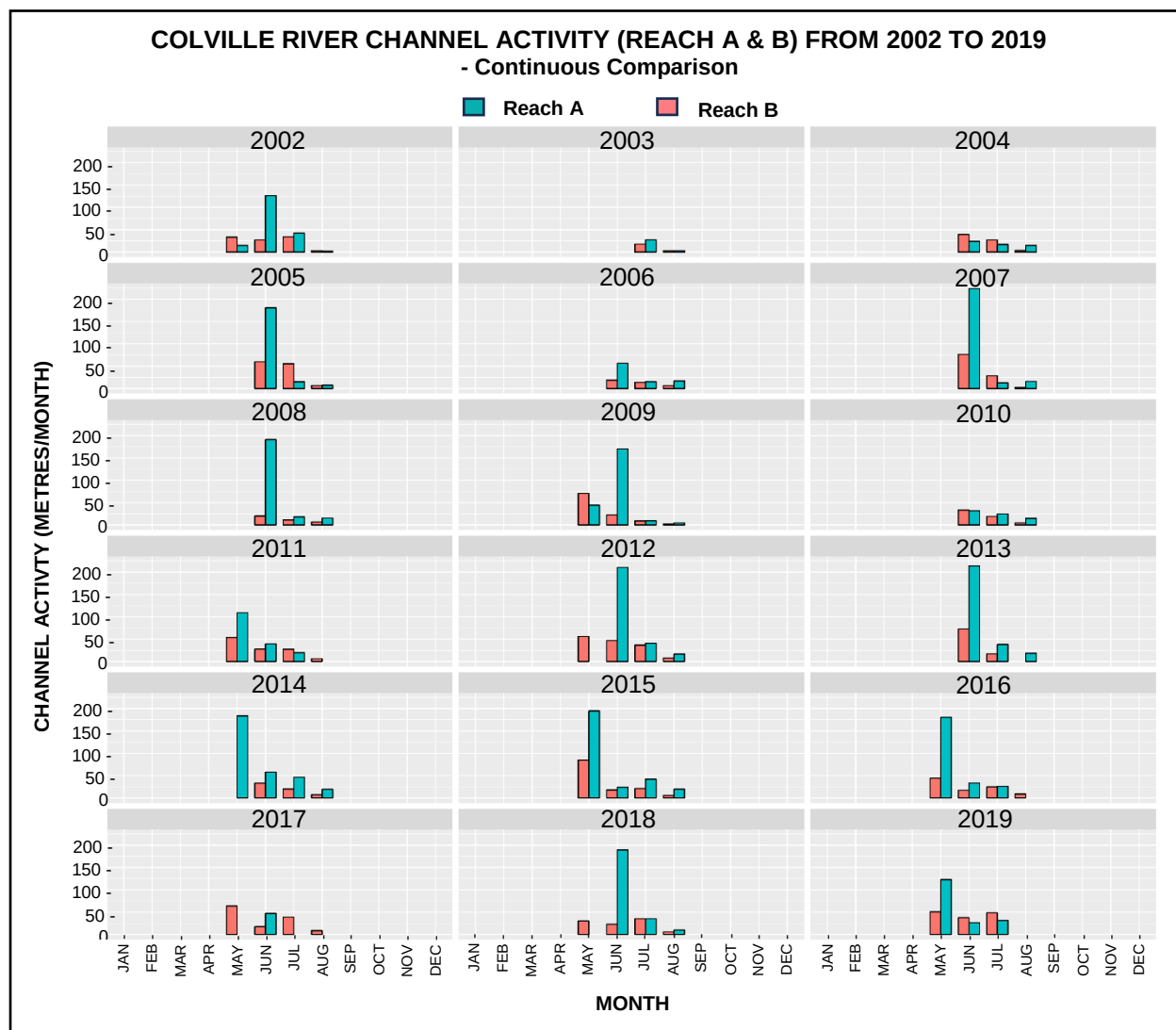


Figure 7a: Channel Activity - Continuous

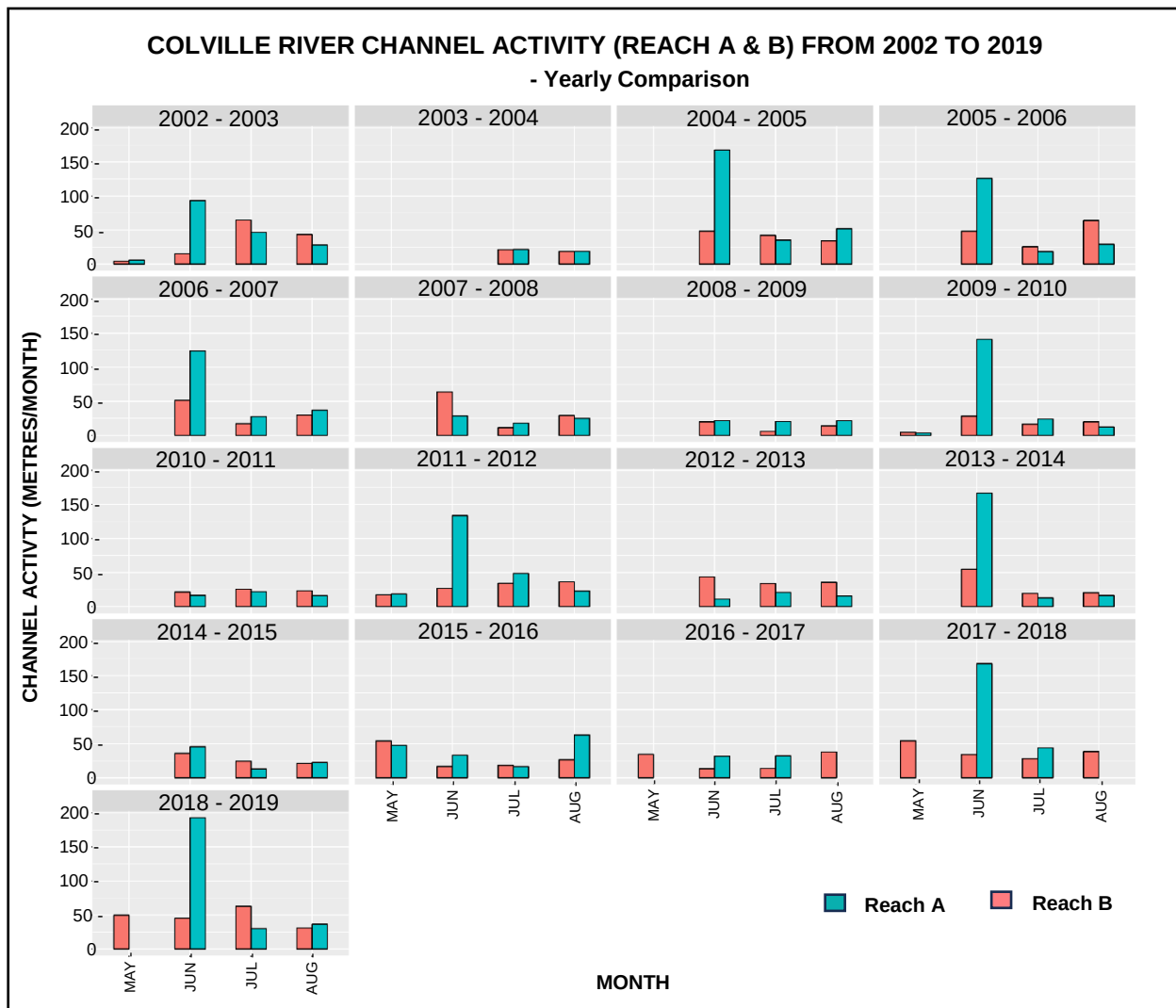


Figure 8b: Channel Activity - Yearly Timescale.

Figure 7 above presents the calculated channel activity for Reach A and Reach B both in a ‘continuous’ and ‘yearly’ timeframe comparison. The continuous timeframe shows the seasonal cycle of the rivers’ activity, whereby movement only takes place during the warmer months between May to August, whereby May and June have most of the activity. On the other hand, yearly comparisons only show the months where satellite data was able to differentiate between the river and land surface, which was again only during the thawing months. In this case, June seems to have the most activity when compared to the year prior.

6.1.2 Reach A and Reach B Continuous and Yearly Trends

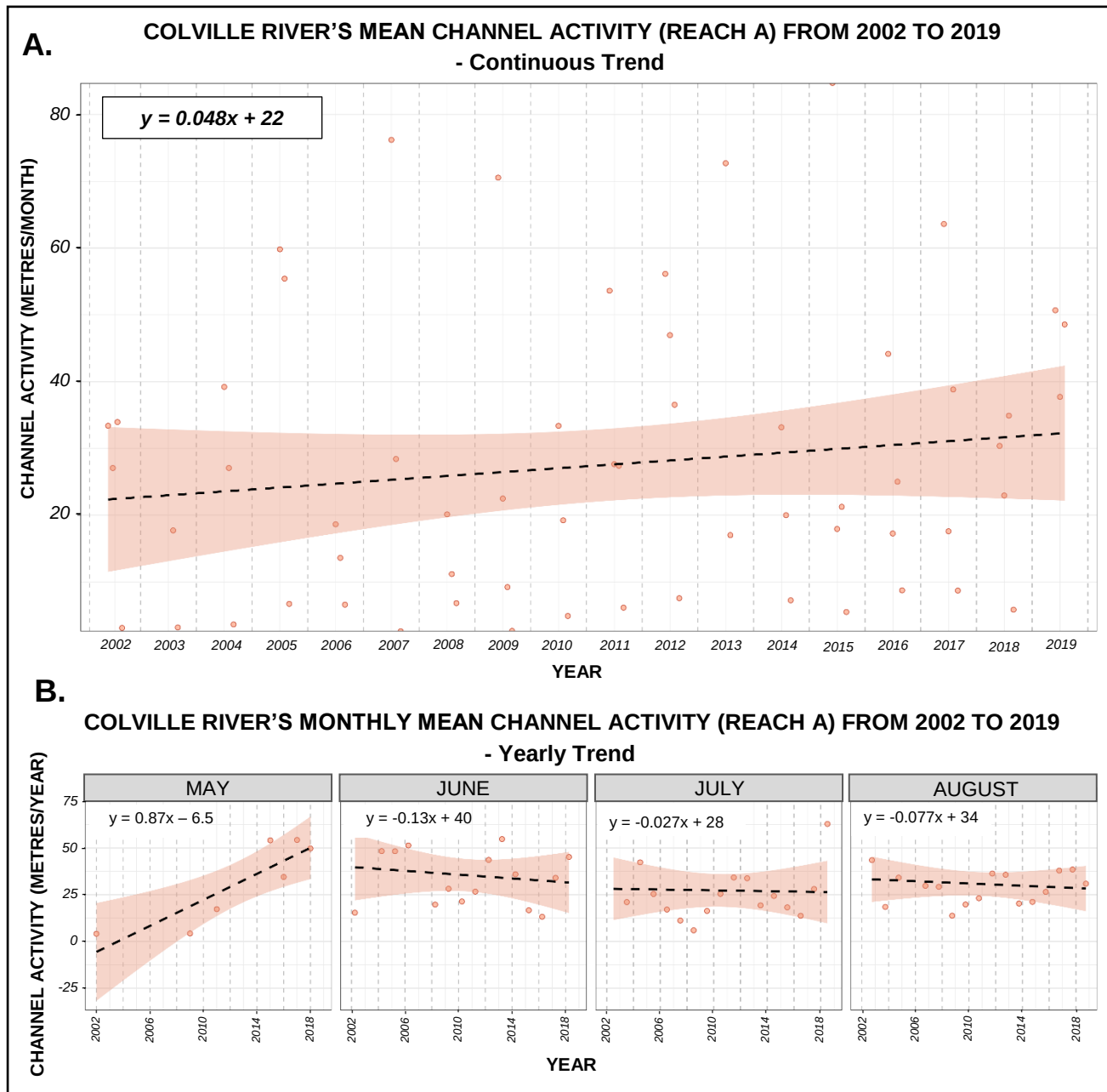


Figure 9a: Channel Activity Trends for Reach A.

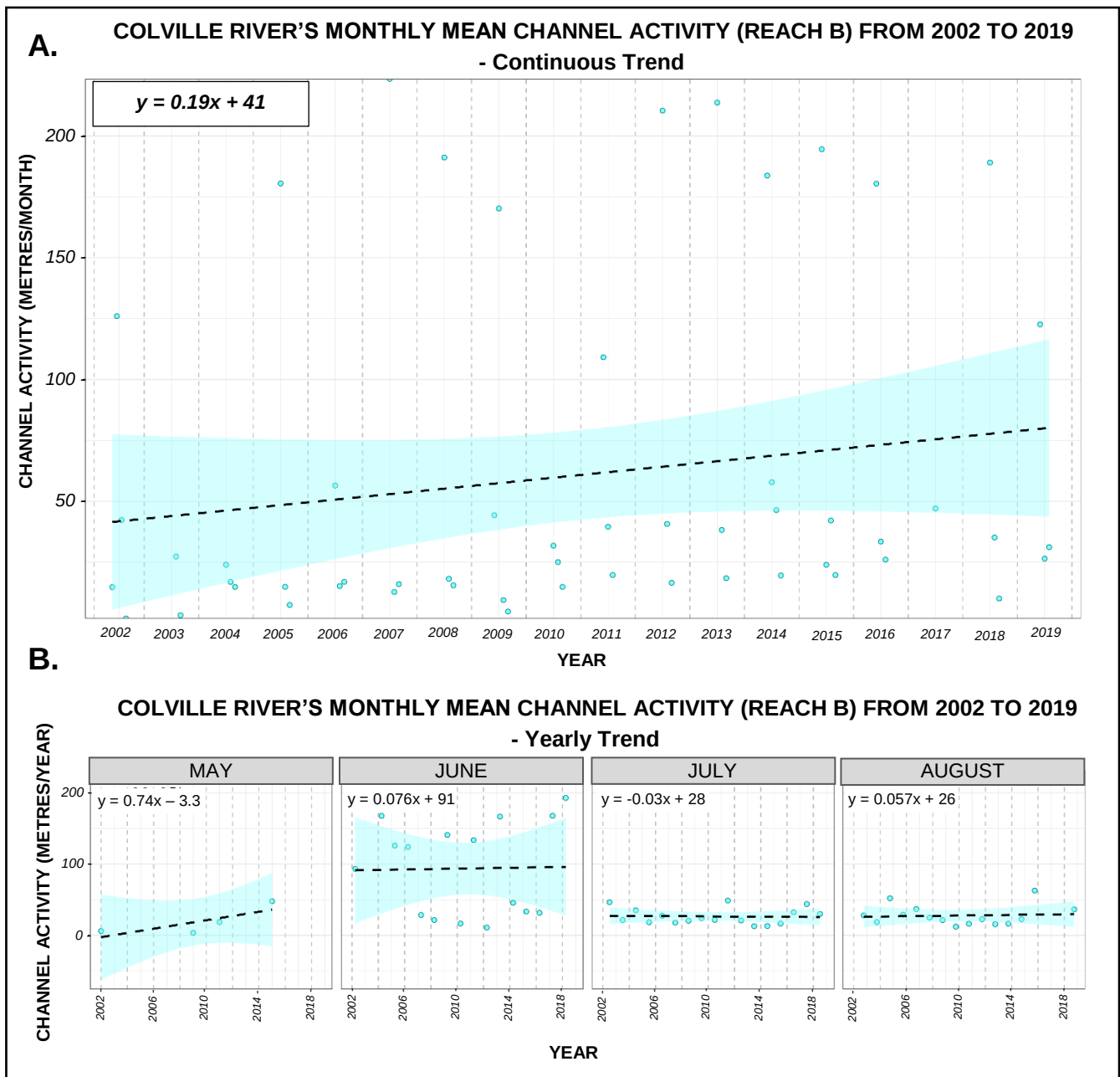


Figure 10b: Channel Activity Trends for Reach B.

Figure 8 above presents the channel activity trend for Reach A and Reach B both in a ‘continuous’ and ‘yearly’ timeframe comparison. Reach A presents an overall increase in channel activity trend from 2002 to 2019 with a slope of 0.048. However, only the month of May seems to have a positive trend of 0.87 when comparing the channel activity from a yearly timeframe. The rest presents a negative trend of 0.13, 0.027, and 0.077 for the months of June, July, and August, respectively. Reach B, on the other hand, also shows an overall increase in channel activity trend from 2002 to 2019 with a slope of 0.19. And looking at the

yearly comparison for each thawing month, May, June, and August consisted of positive trend of 0.74, 0.076, and 0.057 respectively, while July has a negative trend with a slope of -0.03.

6.2 Ancillary Data (Temperature, Precipitation, and Discharge)

6.2.1 Temperature Data

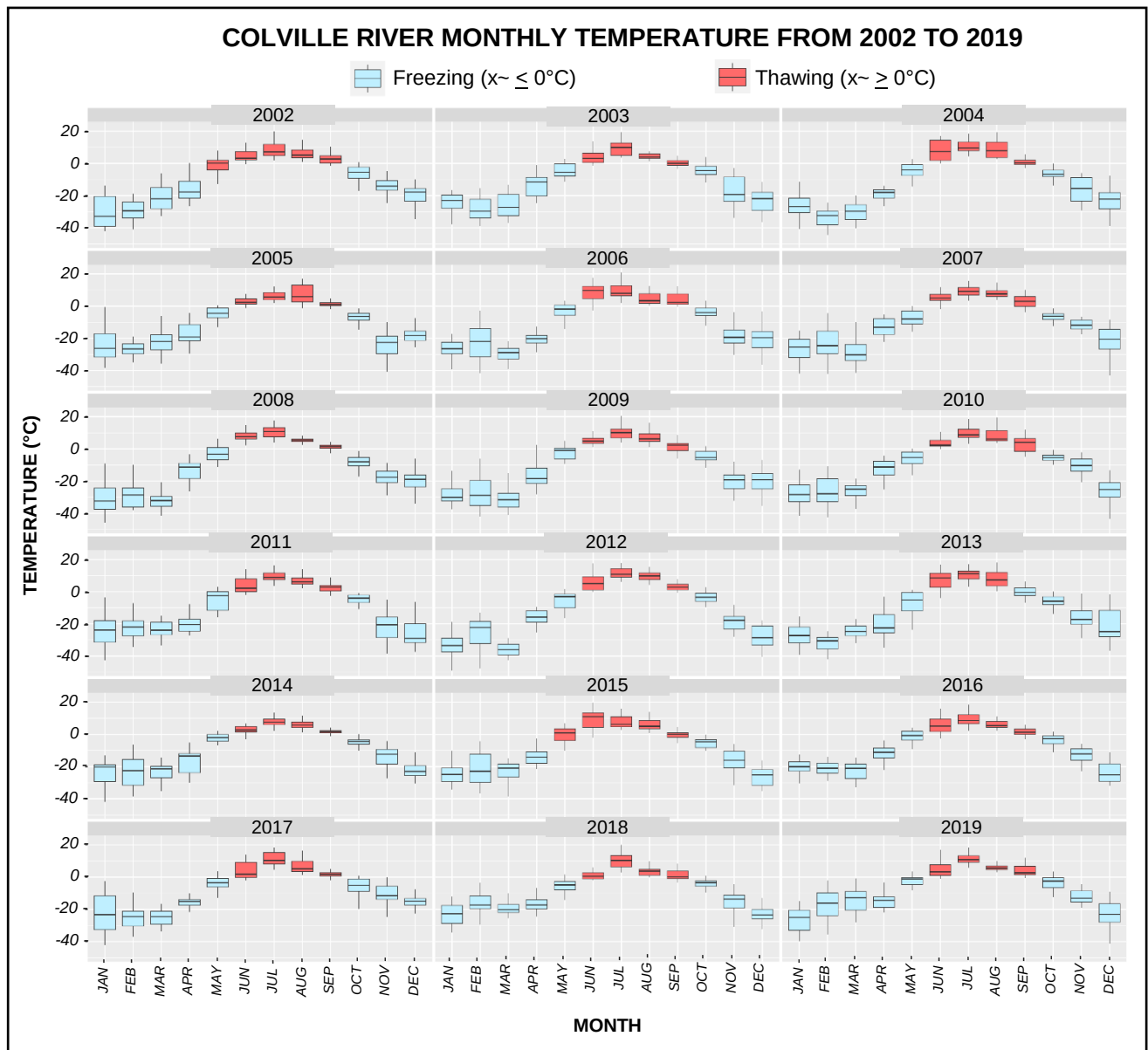


Figure 11: Monthly Temperature Data Boxplot.

Figure 9 above presents the monthly temperature data from January 2002 to December of 2019. Highlighted in red are months where the median is above 0°C , which generally falls during the thawing months (May

to August), and in blue are the months where the median is below 0°C, which fall during the freezing months (September to April). Transitional months between the two seasons take place in the months of May and September, where the median may fall into negative in some years and positive in others. The data clearly presents the data variability of each month and the seasonal cycle of the Colville River in the Umiat station.

6.2.2 Temperature Continuous, Yearly, and Decomposition Trends

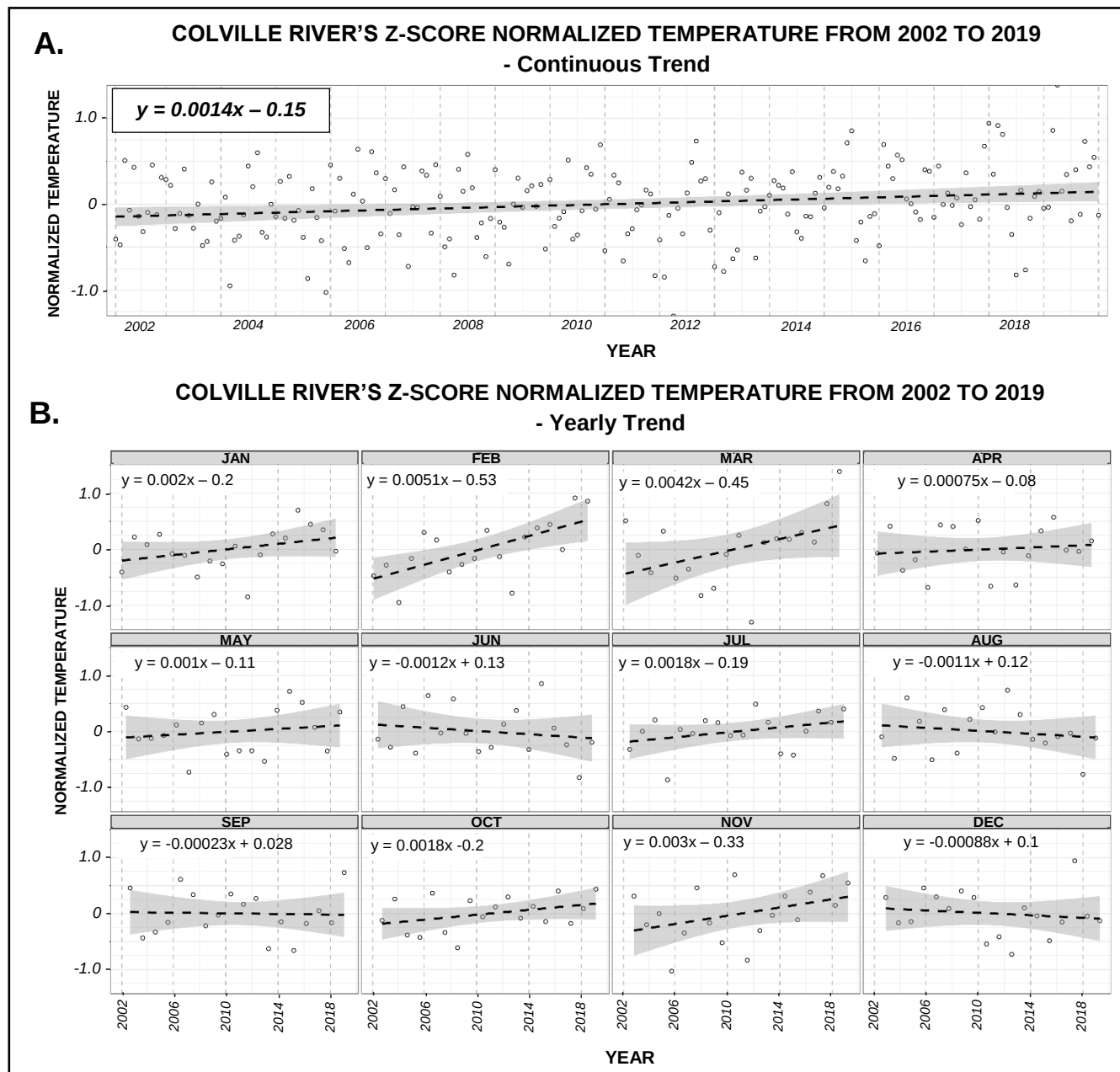


Figure 12: Continuous (top) and Yearly (bottom) Temperature

Figure 10 above presents the Normalize temperature trend both for the continuous and yearly timeframe comparison. The temperature presents an overall positive trend of 0.01 as its slope in the continuous timeframe. Conversely, most months seem to also have a positive trend when looking at the yearly trend for each month. January (slope of 0.002), February (slope of 0.0051), March (slope of 0.0042), April (slope of 0.00075), May (slope of 0.001), July (slope of 0.0018), October (slope of 0.0018), and November (slope of 0.003) are positive, whereas June (slope of -0.0012), August (slope of -0.011), September (slope of -0.00023), and December (slope of -0.00088) are negative trends.

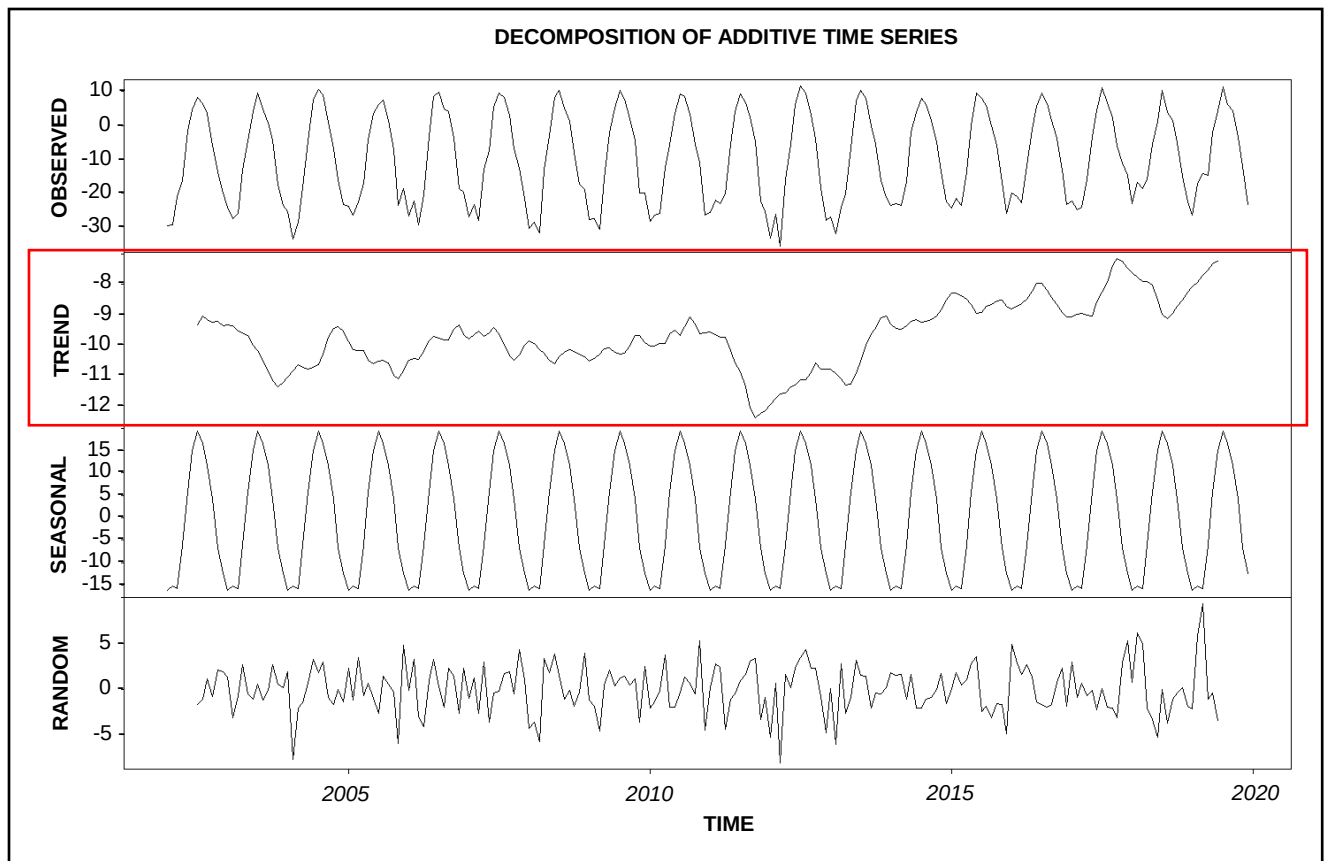


Figure 13: Temperature Trend - Decomposition.

Figure 11 above presents the result for the decomposition tool used in R-Studio to verify the temperature dataset trend. The first row presents the data, second row is the trend, third row is the seasonality, and the fourth row is the residual error. Looking at the second row, it appears to have a relatively positive trend depicted, thereby verifying the overall positive trend presented by the temperature trend.

6.2.3 Precipitation Data

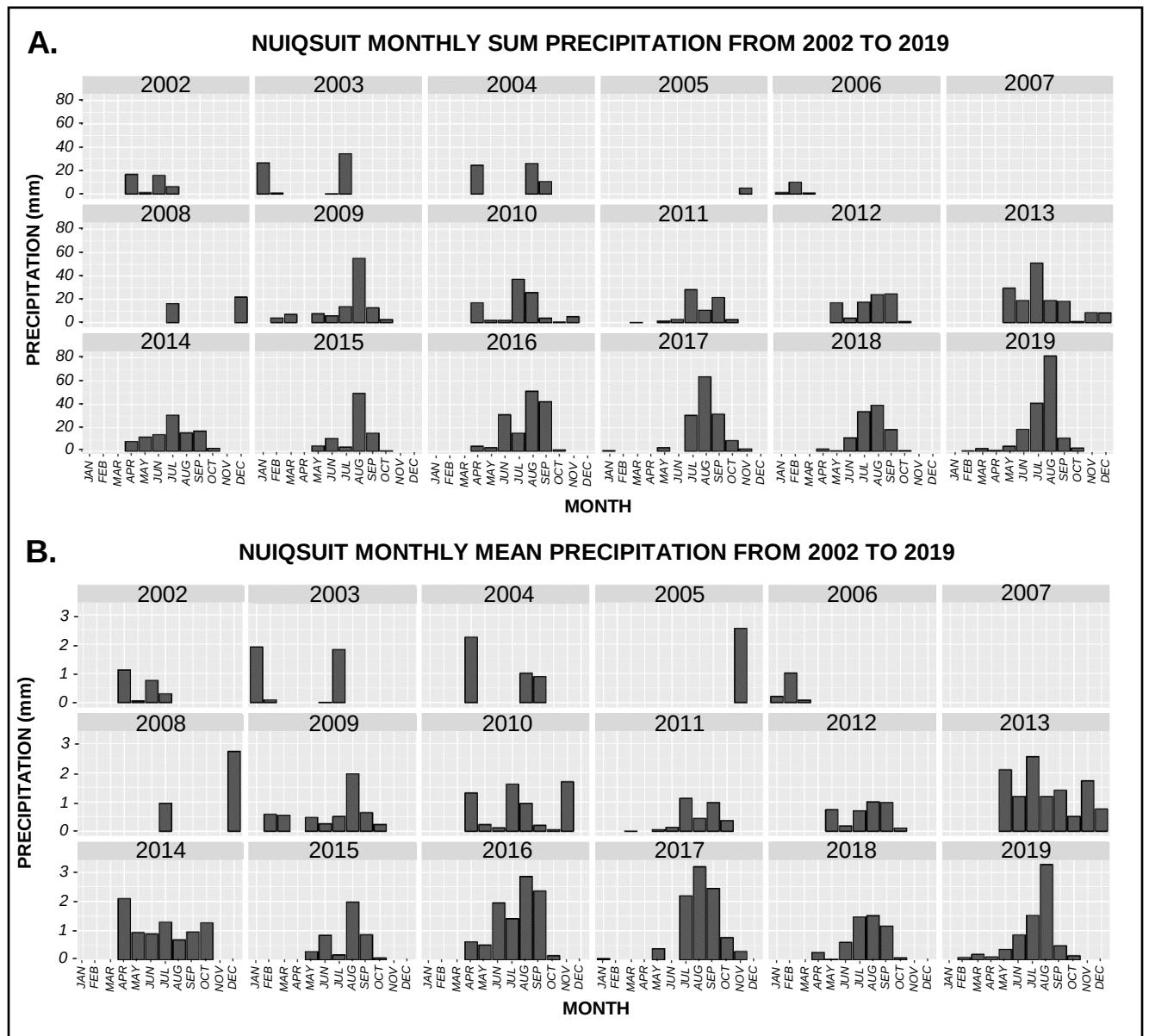


Figure 14: Monthly Sum (top) and Mean (bottom) Precipitation.

Figure 12 above presents the sum (top) and average (bottom) precipitation data taken from the Colville River, Nuiqsuit station. It shows the relative seasonal cycle, whereby most precipitation takes place during the thawing months. As the year progresses, however, precipitation is becoming more prevalent.

6.2.4 Precipitation Continuous and Yearly Trends

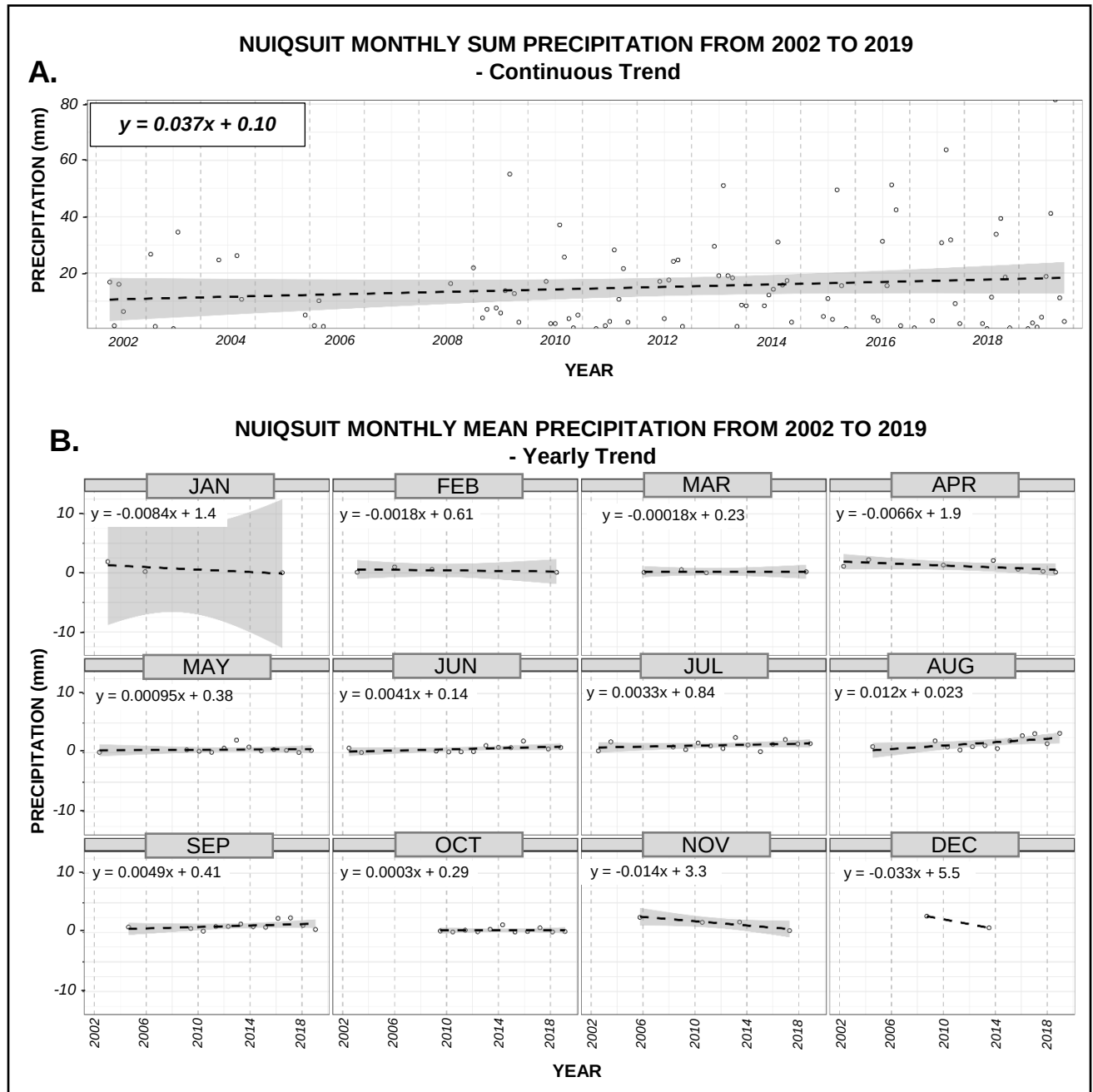


Figure 15: Continuous (top) and Yearly (bottom) Precipitation Trend.

Figure 13 above presents the sum precipitation trend in the continuous timeframe, while the average precipitation was used in the yearly timeframe. The continuous timeframe presents an overall positive trend from 2002 to 2019 with a slope of 0.037, with the data variability increasing towards the more recent years. On the other hand, the yearly timeframe trend is split in half where half the year shows positive, and the

other half shows negative trend. Namely, May to October (mostly thawing months) shows positive trends and November to April (mostly freezing months) shows negative trends.

6.2.5 Discharge Data

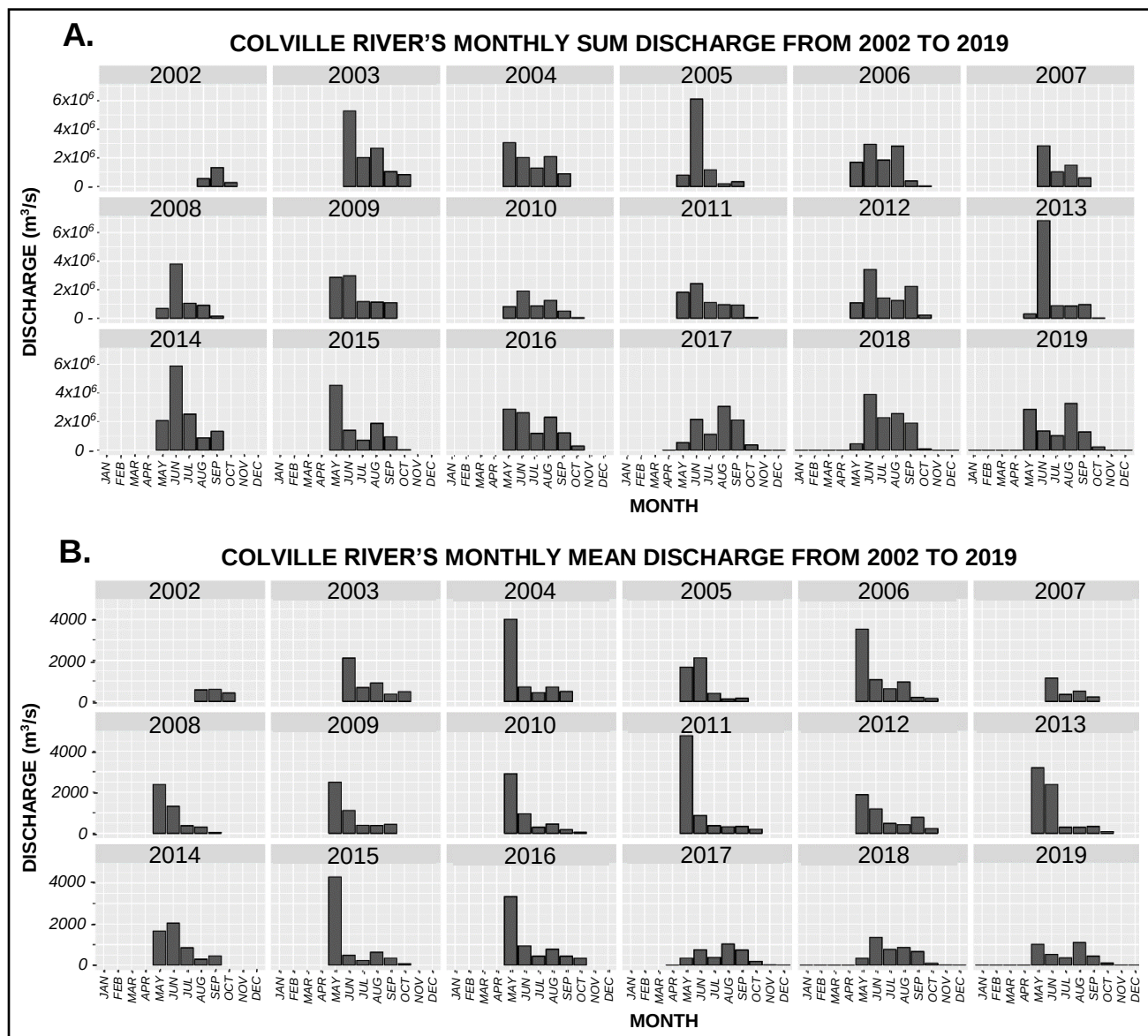


Figure 16: Monthly Sum (top) and Mean (bottom) Discharge.

Figure 14 above presents the sum (top) and average (bottom) discharge data taken from the Colville River, Umiat station. It shows the relative seasonal cycle, whereby discharge primarily takes place during the thawing months. As the year progresses, however, discharge is starting to occur throughout the year (2017 to 2019).

6.2.6 Discharge Continuous and Yearly Trends

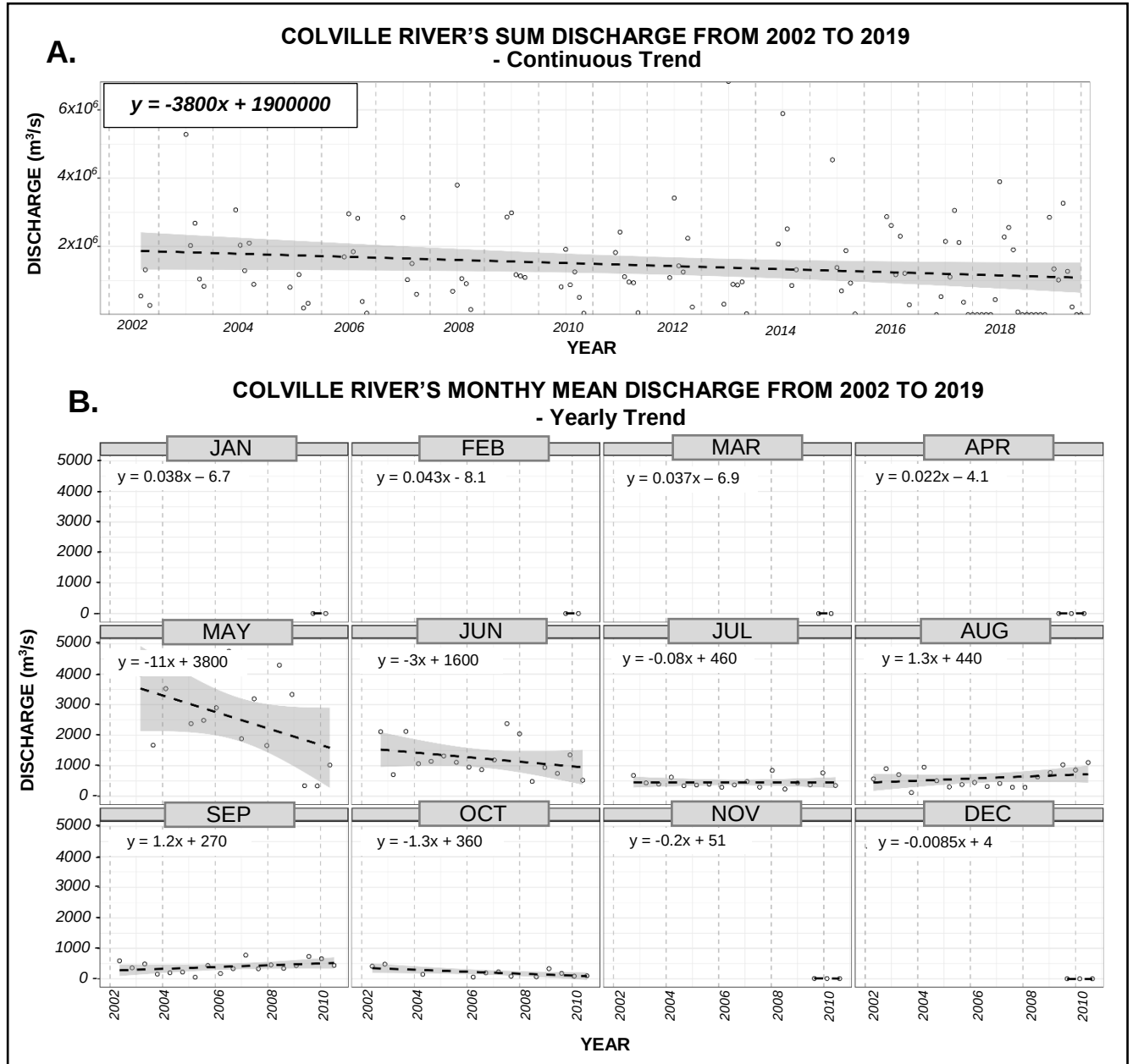


Figure 17: Continuous (top) and Yearly (bottom) Discharge Trend.

Figure 15 above presents the sum discharge trend in the continuous timeframe, while the average discharge was used in the yearly timeframe. The continuous timeframe presents an overall negative trend from 2002 to 2019 with a slope of -0.3800. On the other hand, the yearly timeframe trend is split in half where six months (January, February, March, April, August, and September) presents a positive trend, and the other months (May, June, July, October, November, and December) are in the negative trend.

6.3 Temperature, Precipitation, Discharge, and Channel Activity Correlations

6.3.1 Continuous Timeframe Correlation

Table 1: Continuous Timeframe Correlation

CORRELATION – CONTINUOUS COMPARISON						
		TEMPERATURE	PRECIPITATION (SUM)	DISCHARGE (SUM)	CHANNEL ACTIVITY	
					REACH A	REACH B
TEMPERATURE		1.00				
PRECIPITATION (SUM)		0.48	1.00			
DISCHARGE (SUM)		0.63	0.37	1.00		
CHANNEL ACTIVITY	REACH A	0.48	0.16	0.62	1.00	
	REACH B	0.37	0.07	0.68	0.69	1.00

Table 1 above presents a matrix for the correlation between each variable in the continuous timeframe. All appear to have a positive correlation, whereby Reach A and Reach B have the strongest correlation (0.69) within the dataset, followed closely by Discharge and the two reaches (A: $r = 0.62$, $r^2 = 0.62$, $p\text{-value} = 1.02\text{e-}16$ and B: $r = 0.68$, $r^2 = 0.46$, $p\text{-value} = 2.65\text{e-}19$), and Temperature and Discharge ($r = 0.63$, $r^2 = 0.39$, $p\text{-value} = 4.64\text{e-}17$). The rest are relatively weak, with Precipitation having the least correlation between any other variables.

6.3.2 Yearly Timeframe Correlation

Table 2: Yearly Timeframe Correlation.

CORRELATION – YEARLY COMPARISON						
		TEMPERATURE	PRECIPITATION (MEAN)	DISCHARGE (MEAN)	CHANNEL ACTIVITY	
					REACH A	REACH B
TEMPERATURE		1.00				
PRECIPITATION (MEAN)		0.30	1.00			
DISCHARGE (MEAN)		-0.57	-0.13	1.00		
CHANNEL ACTIVITY	REACH A	0.39	0.01	-0.18	1.00	
	REACH B	0.23	0.11	-0.04	0.43	1.00

Table 2 above presents a matrix for the correlation between each variable in the continuous timeframe. Most appear to have a positive correlation, except for Discharge correlated with any of other variables. The strongest correlation being Temperature and Discharge ($r = -0.57$, $r^2 = 0.32$, $p\text{-value} = 1.88\text{e-}5$).

6.4 Landsat versus Planet Data

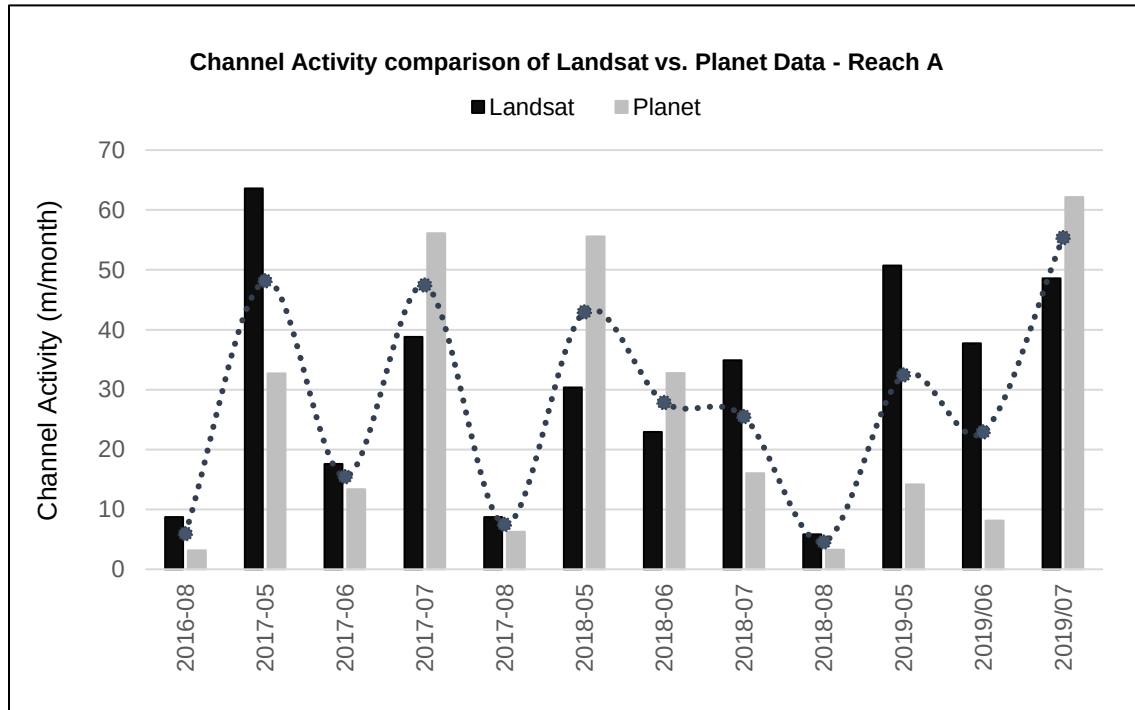


Figure 19: Landsat and Planet Satellite Channel Activity Calculation Comparison for Reach A.

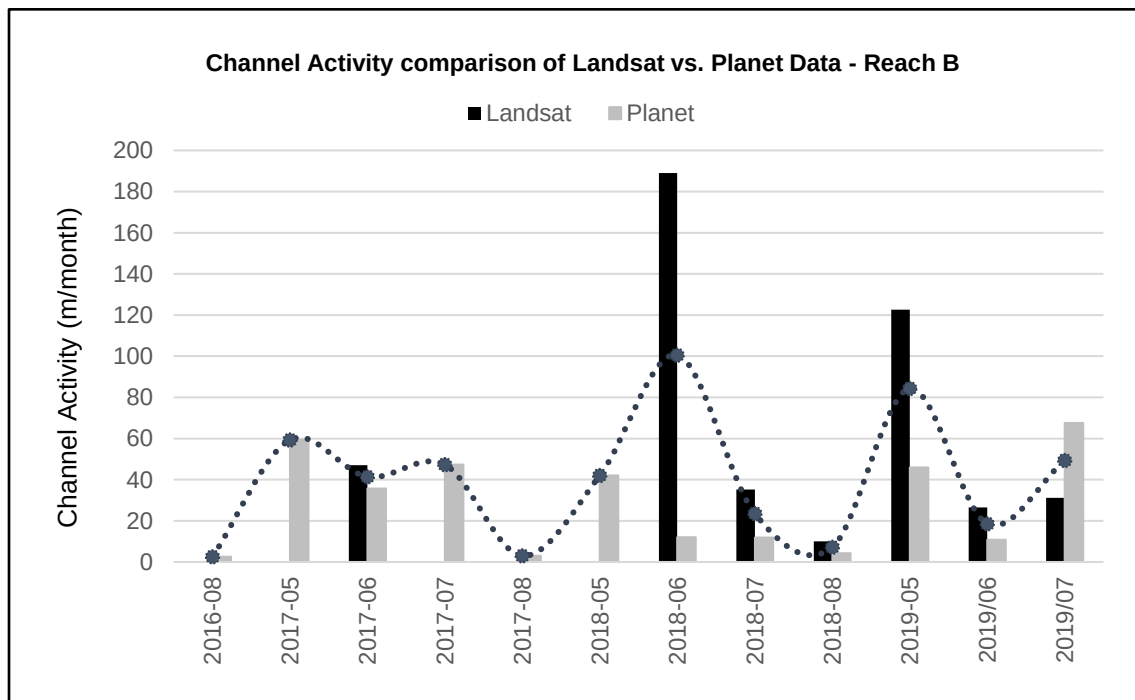


Figure 18: Landsat and Planet Satellite Channel Activity Calculation Comparison for Reach B.

Figure 16 and Figure 17 compare the continuous channel activity calculations derived from Landsat Satellite data (black) and Planet Satellite data (grey) for reach A and reach B, respectively. Overlaid on each graph is a line graph of the average/median between the two calculations, which also presents the general trend/fluctuations of the data. For Reach A, there is a minimum difference of 2.44 meters/month, average difference of 5.40 meters/month, and maximum difference of 30.90 meters/month. For Reach B, there is a minimum difference of 5.81 meters/month, average difference of 39.08 meters/month, and maximum difference of 177.09 meters/month. However, when the June 2018 Landsat-data-anomaly is removed, the average difference B becomes 16.08 meters/month and a maximum of 76.67 meters/month.

Note – Yearly channel activity calculations were exempted from the report as it only compares two datasets for June, July, and August since Planet data was only available for August 2016 and onwards. Additionally, the purpose of the Planet data was to primarily verify the discrepancy between the two satellites; the same Planet datasets are used but the calculations are just slightly different. Thence, the continuous calculation is sufficient for this purpose.

CHAPTER 7

DISCUSSION

7.1 Result Discussion

In reviewing the research question of this study: *How does climate change affect cold region rivers' discharge and activity, particularly the Colville River's?* The following objectives includes: (1) determine the prevalence of Climate Change in the Area by examining Temperature, Precipitation, and Discharge, (2) analyze Channel Activity of specific reached within the river, and (3) identify the relationships between each variable examined in the prior objectives. Therefore, the Result Discussion shall outline and respond to each listed objective to answer the research question.

7.1.1 Prevalence and Effect of Climate Change in the Colville River

Perhaps the earliest and most common sign of climate change is the warming temperature. Examining collected temperature data more closely in Figure 8, the winter temperature of the Colville River has generally increased. During the early-2000s to early-2010s, the lower quartile during the coldest months is generally closer to -40°C , where the minimum temperature would often be colder. However, in more recent years the coldest temperature has gone up relatively. This is better seen in the Z-score normalization trends in Figure 9. When looking at the yearly comparison trends (Figure 9B), most of the winter months showed a positive trend, which means that the temperature during these months is increasing over time. In fact, the overall trend shown in the continuous timeframe (Figure 9A) also presents the same general positive trend of 0.0014. This is further verified by the decomposition tool in R-Studio where the trend is extracted from the dataset, also showing a relatively positive progression rate (Figure 10). Therefore, based on these observations and trends derived from various tools, temperature is undeniably increasing in the area. In fact, this aligns with a number of literatures mentioned earlier whereby an overall increase in temperature is observed in many cold-region areas around the world (Marcot et al, 2015; Overland et al, 2019; Cook et al, 2019).

Another sign of climate change's impact are the unpredictable and extreme weather patterns in areas across the globe, and this region is not exempt from this phenomenon. The Precipitation data taken from the Nuiqsuit station presents unusual patterns that are likely caused by the changing climate. Noticeably, precipitation is less frequent in the early 2000s and became more regular starting the year 2009, and by 2019, precipitation is taking place almost every month (Figure 11). Furthermore, the trend not only shows the increase of rain events but also their intensity. The continuous timeframe presents an overall increase

in precipitation with a slope of 0.037 (Figure 12A), meaning that as the years progress monthly measured rainfall is also increasing. A similar trend is seen for the yearly comparison timeframe (Figure 12B), where most of the warmer months' precipitation presents a positive trend. In other words, not only does the frequency of precipitation rise, but also the intensity of rainfall increases. This finding aligns with various academic literatures presenting an overall increase in precipitation frequency and intensity causing an increase in water level (Palash, W. et al., 2023; Gain, A. K. et al, 2011).

Finally, stream flow changes are an indirect impact of climate change on many rivers around the world especially in cold-region rivers where the primal source of water comes from melted ice and precipitation (Wang et al, 2021; Laidler and Ikummaq, 2008). Discharge in the Colville River has also experienced some similar changes. In reviewing Figure 13, discharge fluctuations have certainly changed from 2002 to 2019. In the early 2000s, discharge primarily only takes place during the thawing months. However, it appears that discharge is starting to occur even during the freezing months in more recent years. Additionally, not only is it occurring throughout but it is gradually decreasing in volume during months when peak discharge normally occurs. Examining the continuous timeframe trend in Figure 14A certainly presents a decreasing discharge trend with a slope of -3,800, where most of the thawing months, May in particular, are experiencing drastic volume decline (Figure 14B). This is an interesting observation as discharge was expected to increase with response to the increase in temperature and precipitation frequency that should increase meltwater and rainwater moving into the channel. However, a different observation is seen based on the data retrieved and trend calculated and graphed. A plausible explanation for this is because of the lack of ice volume that is typically present during the thawing months. Since temperature has generally gone up for both freezing and thawing seasons, discharge is starting to occur throughout the year. Then, when the thawing season starts, the majority of the ice has already melted, thereby lowering the total volume of discharge that is normally experienced during this period. Thus, presenting an overall negative trend experienced monthly, especially during the thawing months.

7.1.2 Channel Activity in the Colville River

As explored in the literature review, channel movement is impacted by countless number of external variables that impacts their internal forces, thus the channel's dynamic. Therefore, as these variables continually change in the Colville area, the river is bound to respond accordingly. Figure 6 clearly depicts the seasonal cycle of peak activity occurring at the beginning of the thawing season (May/June) and gradually decreasing towards the end of the season (August). The peak movement happening at the beginning of the thawing period is likely due to two following reasons: (1) discharge is at its peak from snowmelt during this time; hence the river becomes more active in response to the increase in water

velocity, and (2) this is the accumulated (or ‘backlogged’) channel activity that must be occurring underneath the frozen river surface but is simply not captured by the satellite due to snow-covered exterior. In fact, this corresponds well with the pattern observed with discharge. As the discharge starts to take place even during the winter months, when the river is hidden from the satellite, an increase in the calculated channel activity at the beginning of when the channel becomes visible again (May/June) is expected. This is because more movement is occurring under the frozen water surface, that is only drastically revealed when the river is once again visible. This relationship is better presented in Figure 7Bs, whereby a strong positive trend for both reaches occurs in the month of May, but negative (or relatively flat) trend is observed for June, July, and August. This is because as the years progress, discharge is starting to take place throughout the winter months, where the activity occurring from September to April is only captured in the month of May. Hence, generating this positive trend at the start of the thawing months, but an overall negative trend for the rest of the remaining thawing months, which corresponds to the overall decrease in discharge monthly volume. In fact, this argument is further supported when the correlation between channel activity and discharge is discussed in Section 7.1.3.1.

7.1.3 Correlations between Variables

7.1.3.1 Continuous Timeframe Correlation

Temperature x Precipitation Correlation (Table 1: Col 2, Row 2) presents a relatively weak positive correlation between the two variables ($r = 0.48$, $r^2 = 0.23$, $p\text{-value} = 2.24e-11$). In fact, one variable is likely not directly caused by the other, nor does it pose a strong impact on each other. Both, however, are impacted by climate change. Thus, showing that both variables are changing congruently as the time progresses, whereby temperature is generally increasing at the same rate that precipitation frequency and volume is also increasing.

Temperature x Discharge Correlation (Table 1: Col 2, Row 3) presents a relatively strong positive correlation between the two variables ($r = 0.63$, $r^2 = 0.39$, $p\text{-value} = 4.64e-17$); As temperature increases, discharge increases in response and the same pattern occurs when temperature decreases. This is likely because temperature has a strong influence in the ice melt, which is the main source of water flowing on the Colville River. Since this is a continuous timescale, this strong relationship represents the seasonal cycle of the area. As mentioned, this aligns with existing literature. Perhaps if the two variables have more of a direct relationship, a stronger correlation might be observed.

Precipitation Correlations (Table 1: Col 3) generally has relatively low correlation with all variables, whereby discharge has the most correlation of 0.37 ($r^2 = 0.14$, $p\text{-value} = 2.01e07$). This is probably because

the precipitation data was taken from a different station, downstream of the Colville River, hence, its lack of correlation between discharge and, especially, the channel activity in the two upstream reaches. The slightly higher correlation with discharge may be attributed to the relatively similar weather pattern between the two areas (Umiat and Nuiqsut Stations). Nevertheless, since Nuiqsut is situated close to the ocean, its weather dynamic would still be quite different from the more inland Umiat station. On the other hand, weather pattern occurring downstream would surely have little to no impact on reach activity occurring upstream, as reflected accordingly.

Discharge x Channel Activity (Table 1: Col 4, Row 4 & 5), as expected, poses a strong positive correlation (A: $r = 0.62$, $r^2 = 0.62$, $p\text{-value} = 1.02\text{e-}16$ and B: $r = 0.68$, $r^2 = 0.46$, $p\text{-value} = 2.65\text{e-}19$); as discharge increases, channel activity increases and the same pattern occurs when discharge decreases. This is because discharge is highly indicative of channel activity as this is one of the primary internal forces that encourages or discourages channel movements. The imperfect correlation may be explained because of the other internal variables that also dictate river movement (i.e., erosion and sediment transport). Likewise, this is also supported by existing literature that studies the relationship between discharge and channel movement/activity (Chant, 2002; Earle, S. 2015).

Reach A and Reach B have one of the strongest correlations in Table 1 (Col 5, Row 6) of $r = 0.69$ ($r^2 = 0.47$, $p\text{-value} = 1.30\text{e-}19$). Although not perfect, upstream movement certainly affects downstream movement. This is due to the change in configuration of the upstream channel that affects water velocity, which then affects erosion and sediment transport downstream, thereby reforming its riverbanks in accordance with the shift in stream flow. Again, the imperfect correlation may be attributed to another factor affecting the difference in fluctuation between Reach A and Reach B.

Overall, the variables that are expected to affect each other exhibit their correlations accordingly. Namely, Temperature x Discharge, Discharge x Channel Activity, and Reach A x Reach B, consisted of strong positive correlations. Interestingly, this is only seen in the continuous, small-scale, timeframe correlation. The yearly, large-scale, timeframe reveals intriguing results.

7.1.3.2 Yearly Timeframe Correlation

In the Yearly Timeframe correlation matrix (Table 2), weak correlations are seen across all variables, except for Temperature x Discharge ($r = -0.57$, $r^2 = 0.32$, $p\text{-value} = 1.88\text{e-}5$). Similar to the Continuous Timeframe Correlation, these two variables are correlated as temperature impacts ice melt, which then affects discharge. However, the negatively strong correlation indicates that the increase in Temperature trend from

May to August throughout 2002 to 2019, parallels a decrease in Discharge trend from the same timeframe. One strong plausible explanation for this is because there is little to no more ice to melt during the thawing months. Over the years, discharge during the thawing period has slowly declined because there is less ice regained during the freezing months and a consistent and higher volume of discharge taking place throughout the year. Thence, exhibiting the negative trend, whereby the continual, long-term, increase in temperature has resulted in an overall decrease in discharge during the thawing season. On the other hand, the weak correlations with other variables are likely because of the relatively longer time gap between each record, whereby yearly trends in temperature and precipitation for the thawing months (May to August) exhibits little to no impact on channel activity, especially because of their indirect relationship. Moreover, since the Colville River is a highly mobile braided river, the long-term trend of Reach A may not necessarily reflect the same long-term trend of Reach B activity. This is because other strong variables also affect Reach B movement outside of upstream fluctuations, as observed in Table 1. Finally, the weak and negative correlation between Discharge and Channel Activity trend may be attributed to two plausible explanations: (1) the channel movement that has accumulated during the winter months (September to April) is only accounted for in May, which skews the Channel Activity data, or (2) the channel activity is responding with the decrease in discharge that has taken place and the transitional lag time is captured. Nevertheless, since a decrease in discharge trend is only starting to occur, future observation is required to come up with a more definitive answer on how the channel activity shall response.

7.1.4 Data Verification – Landsat and Planet Data

Comparing the two satellite data both visually and quantitatively presents a generally reliable result. By overlaying the Landsat data on the Planet satellite data, the two datasets were compared visually (Figure 6). Discrepancies were mainly noticeable on a few point bars, nevertheless most lines follow the riverbanks quite accurately. Furthermore, examining the difference quantitatively suggests the same findings. When June 2018 Landsat data anomaly is removed for Reach B – Channel Activity calculation, the difference only ranges between 2.44 (min) to 76.67 (max) meters per month. Given that Landsat data has a 30x30 meter resolution, this suggests that it would only be off by 0 to 2 pixels misclassification. Therefore, this verification exercise suggests that the presented results above are somewhat reliable.

7.2 Implications

Evidently, timescale differentiation is important when examining the results produced. There are some trends and correlations that are revealed in the continuous, short-term, timescales, while others may be more obvious in the yearly, long-term, timeframe. For instance, Reach A and Reach B pose a relatively strong

correlation amongst each other for the shorter time scale, but not over the longer timeframe. This is likely because the Colville River is a braided river; movement is volatile and more mobile compared to other river types like a meandering river. Hence, showing a stronger relationship between the upstream and downstream in the shorter timescale, than it would for a longer time comparison. Moreover, temperature and discharge exhibit a positive relationship for the continuous timeframe, but a negative correlation for the yearly timescale. This reveals the seasonal versus climatic relationship between the two variables. The continuous timeframe presents the seasonal relationship between temperature and discharge, in which as the temperature increases, discharge increases in response. However, the yearly timeframe exhibits the long-term climatic potential for discharge, whereby as the temperature continues to increase, discharge will gradually decrease from its norm due to the lack of meltwater supplied during the thawing months. Clearly, recognizing the timeframe to use when identifying trends and correlations is imperative depending on the purpose of the study. For braided rivers, small-scale timeframe is optimal as it captures the external and internal variables affecting the channel concurrent on the actual changes imposed upon it. Likewise, the short-term, continuous, timescale should be used for seasonal variations because it presents the continuity from one season to another. Climatic variations (i.e. the effect of climate change), on the other hand, are better presented for the long-term, yearly, timescale comparison because they expose the prolonged trend from one period to the other reducing the effect of seasonality and weather anomalies.

With the rising temperature, unpredictable precipitation patterns, and prolonged river discharge, climate change has evidently impacted the external and internal forces of the Colville River's activity. The increase in temperature throughout the year has extended the thawing season of the area. Thus, extending the discharge period from 3 or 4 months during the thawing season to an all-year-round dynamic. Furthermore, the rise in precipitation events will not only introduce more water into the stream but also increase erosion and sediment transport. Splash erosion both onto the land surface and snow cover introduces more sediments to the watershed carried down towards the river. And the increase in sediment supply encourages further formations of sediment bars and deltas across the stream. Finally, the prolonged discharge will follow the same trend for the channel activity and movement. As the discharge begins to take place during the winter months, the channel movement will also respond accordingly. The river will begin showing a relatively different morphology once the river is, again, exposed during the thawing season because of the increased movement underneath the frozen surface during freezing months. Likewise, the continuous decrease in discharge from June to August will also be reflected in the river movement: decreasing the channel activity during the same period. Overall, presenting a more balanced and leveled dynamic between the freezing and thawing months for both discharge and channel movements as the years progresses.

Given the projection of the overall climatic trend and the corresponding river movement, the results suggests that the area is starting to transition to a more temperate-like environment. A global portion that consists of a more prolonged changeover between the freezing months (winter months) and thawing months (summer months) by having autumn and spring seasons to mark such transitional period. Likewise, the river will likely follow the same variation by having a less distinct sharp activity pattern between one season to another. River mobilization was initially dependent on temperature or annual seasons as meltwater is the primal source of water discharge flowing in the channel. As this trend continues, however, the Colville River will potentially start to act similar to other braided rivers in temperate climate that is more governed by weather patterns (i.e., precipitation) as well as temperature: where movement shall also take place soon after water becomes available from precipitation events, rather than being primarily reliant on meltwater coming from the snow accumulated during the winter. Evidently, such changes in climatic patterns and river flow will have repercussions on the environment and other elements dependent on the Colville River's pattern and behavior.

7.3 Limitations

The satellite-driven river classification for the Colville River is not always reliable throughout the year, particularly when the river's surface is frozen solid and covered in snow, which is generally during the freezing period. This is because satellite imagery captures the Earth's surface from above; its visible spectrum does not show what lies beneath the snow. Since channel activity is captured only when the satellite can identify the river's outline, there is generally no data available from September to April as snow covers the river and the Earth. Therefore, the data shows a significant increase in channel movement for the month of May as the data for these months also includes the accumulated river activity that was not captured in the previous season. However, river movement would have likely taken place during these months, underneath the frozen surface. As such, the data for channel activity for the freezing months and the month of May is not accurately represented. Accurate data collection and representation for these months would have likely shown a stronger trend and correlation between the temperature and discharge variables, which would have supported the findings and implications of this research and offered further insight into the freezing months' channel activity.

Although the channel activity equation (Equation 4) used is intuitive and well-recognized within the academic community, it does not capture the actual channel migration pattern. The result does not explain whether the channel has moved laterally across the floodplain, nor does it capture which bank has accreted or eroded over this timespan. This equation only quantifies the general activity that took place in a specified

reach from one time to another by comparing how much the centerlines has shifted between the two periods. Therefore, using another method or equation to identify channel activity could attain more elaborate and explicit information on how or what movement took place in the timespan. Unfortunately, the Landsat satellite data acquired may not be suitable for taking this measurement because of its high resolution. Since the river is captured as only a few pixels wide, identifying one- or two-pixel accretion/erosion may not be strong evidence of an actual river migration. The acquired Planet satellite data, on the other hand, would be able to identify these small changes, but a longer time range is necessary to approximate an actual trend. Furthermore, since the river transitions from being covered and uncovered from season to season that is evident for both Landsat and Planet data, tracing the classified riverbank would not be accurate during the freezing months as this may not be the actual shoreline. It may still be a snow-covered frozen surface attached to the shoreline that the satellite captures as land surface from an aerial view though it is still part of the river underneath. Errors like these tend to only be resolved by obtaining in-situ data to verify the result or acquiring a much higher resolution imagery of the study area. Otherwise, it remains as another drawback of this study because of the data limitations and in-situ measurement being improbable for the scope of the study.

Data availability is another issue that has limited the analysis and the direction of this research study. For instance, the Umiat station did not have available precipitation data, so this data was taken from a different station located in a different area of the river (~100km from the Umiat station). This inconsistent data acquisition has resulted in skewed results pertaining to precipitation data as it relates to other data variables such as discharge and channel activity. Although the data presented observable climatic shifts, its accuracy pertaining specifically to the study area is still questionable, given that it is observed from a different meteorological station situated relatively far from the where the rest of the data is taken. Moreover, as this study focused on specific internal factors, it did not account for other external factors (as discussed in *Chapter 3*) that affect the internal movement of the river. Evidently, other variables like soil composition, vegetation, animal movement, thaw slumps, are external variables that would impact the river movement. Not incorporating these in the study has certainly limited the direction and extent of the study. For example, if the soil composition of the area around the river is determined, the correlation between channel movement and soil type can further be explored. Furthermore, if thaw slump occurrences within the watershed are gathered, the link between channel movement and climate-change-caused events may be identified. These are a number of possibilities that could be looked into if data availability is not a limiting factor. These ideas shall be explored further in the following section, under *Section 7.4 Future Work*.

7.4 Future Work

Collecting additional data directly relevant to phenomenon caused by climate change may pose stronger correlations between the impact of climate change and channel movements. As mentioned in the background, the proliferation of retrogressive thaw slumps across the arctic and subarctic regions has certainly contributed to the morphological shifts across of the area. Pinpointing these locations, either via in-situ data collection or satellite imageries, would pose additional evidence on the effect of climate change in the influx of sediments within the watershed, which consequently impacting channel movement. By identifying a closed proximity reach from these events and comparing this section to an upstream portion of the same river may present strong evidence that these phenomena does, in fact, affect river movement and pattern. Hence, their increase in occurrences would certainly result in accelerated river movement and migration. Rivers are controlled primarily by three internal forces: river discharge, sediment transport, and erosion. This study has identified a strong correlation between discharge and channel activity. By incorporating variables that impact the two other internal forces (i.e., sediment transport and erosion) like RTSs, scientists can better understand, model, and predict channel movement and migration pattern.

In expanding the number of rivers being examined across the semi-arctic region, the study could have a stronger and more conclusive argument on the effect of climate change not just on the Colville River, but in all cold-region rivers. The Colville River is one of many streams across the semi-arctic region. Although it spans over a great area, the two reaches within this study are significantly small sample size to conclusively identify the effect of climate change on channel activity of the river, let alone all the rivers in the semi-arctic region. Therefore, more research needs to be conducted on rivers across the semi-arctic region; varying in latitudes, river types, proximity to urban areas, and other variables that would affect their movement. In doing so, a more definitive conclusion may be made on the overall effect of climate change on channel migration and movements. This study provides only a small, preliminary, step in identifying plausible methods in studying river movements of cold region rivers and better understanding the relationship between climate and river. Future work is undoubtedly needed to support these findings.

7.5 Relevant Study

The effect of climate change, particularly atmospheric warming, has led to meltwater increase and ground destabilization caused by permafrost melt. Hence, this study initially hypothesized a corresponding increase in river movement overtime. Looking at the trend from 2002 to 2019, however, suggests a long-term decrease in channel movement rate when comparing yearly channel activity. We hypothesize that this was the result of the shifting discharge pattern that is overall decreasing over time and is starting to occur

throughout the year. In fact, a study that was published last year supports a similar claim, but with different rationales. A study done by Ielpi, A. et al. (2023), examined a half-century timelapse of channel migration of rivers across North America that is also supplemented with Temperature, Precipitation, and Discharge during this period. Their finding presents an overall decrease of ~20% in channels' lateral migration from 1970 to 2020, with a mean rate of 3.7% per year. However, their paper hypothesized that the decrease in channel movement is a result of bank shrubification, decrease in overland flow, and the land's meltwater absorption due to the absence of permafrost by examining the Normalized Difference Vegetation Index (NDVI) of Landsat satellite imageries during this period (Ielpi A. et al. 2023). This paper, on the other hand, hypothesized that the decrease in movement is a result of reduced discharge caused by the lack of ice melt due to the increase in recession rate of ice cap overtime, as literature suggests. Regardless, the study done by Ielpi, A. et al. (2023) that has a larger timescale and spatial scope corroborates the finding of this paper, which further validates that idea that river movements are rapidly changing in the arctic that corresponds to the climate change. Scientists, river managers, and other stakeholders best be prepared on the implications this change shall have on other environmental systems within the arctic and sub-arctic region that are reliant on river activity, dynamic, and migration.

CHAPTER 8

CONCLUSION

In conclusion, it is evident that the channel activity of Colville River is influenced by temperature, precipitation, and discharge. In the continuous, short-term timescale period, temperature, discharge, and channel movement show a positive correlation amongst each other. As the temperature increases, discharge and channel movement would tend to increase, and vice versa when temperature decreases. This pattern reflects the seasonal variability of each variable in their overall annual dynamic within the study area. However, climate change has impacted the internal and external variables of the Colville River (temperature, discharge, and precipitation): temperature is rising, discharge is prolonged throughout the year and precipitation is becoming more frequent and intense. Thus, the channel activity is also affected accordingly. For the yearly, long-term timeframe, the month of May showed a steep increase in channel movement, but June, July, and August have presented a relatively flat and mostly negative trend in channel activity. This suggests that there is an increase in channel activity during the freezing months occurring underneath the river's frozen surface but is only captured when the river is finally exposed at the beginning of the thawing season (May). However, for the remainder of the season, the data presents a negative trend as the channel movement is not as mobile as it was in the past during this period. This reflects the same pattern as discharge, whereby movement is also starting to take place all year round but is overall reducing in mobility at times when activities would typically be at their peak. This is potentially the result of the overall temperature increase, which would cause ice to melt at a rate more than it is being replenished during the freezing season. Therefore, discharge responds by having a negative correlation with temperature for the long-term, yearly, comparison, whereby as temperature increases, discharge decreases because of the lack of ice available for meltwater to make its way down towards the channel, which is then reflected in the channel activity. Overall, the long-term, yearly, timeframe has likely captured the effect of climate change and has identified how each variable is affected by these climatic shifts. Should these changes continue to happen, the semi-arctic river may start to exhibit behavior similar to temperate river. In which the transitional period between the freezing season (winter) and thawing season (summer) will be prolonged, creating a period like autumn and spring that normally occurs in temperate environments. Likewise, braided rivers in the low-arctic area, like the Colville River, will act correspondingly to these changes, where movements will not be predominantly dictated by seasonal variations when meltwater is available (freezing and thawing season), but would also be dependent in weather patterns (i.e., rain) when rainwater is supplied into the watershed. Identifying these shifts is crucial in further understanding the Colville River's movement and channel activity which in turn could affect other factors that rely on the

river. This study provides the initial findings on how the climate affects the Colville River and potentially other braided and non-braided rivers within the area.

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