

Multi-year and Seasonal Trends in the Water Quality of the Niaqunguk River, Nunavut (2013–2018)

Erika Hille, Melissa Lafrenière & Scott Lamoureux

Department of Geography and Planning, Queens University, Kingston, Ontario, Canada



ABSTRACT

Anthropogenic climate change is modifying the hydrological processes that control fluvial chemistry in Arctic regions. Climatic variability and permafrost thaw have contributed to changes in the timing and intensity of spring snowmelt, the frequency of extreme rainfall events, and lateral flow pathways. Permafrost thaw can increase the connectivity of deeper, subsurface flow pathways with tributary streams and rivers. In combination with increases in snowmelt and rainfall runoff, this can increase the flux of solutes to Arctic rivers.

The Niaqunguk River is located on Baffin Island, NU. With no evidence of physical disturbances to the permafrost, the top-down thawing of permafrost is the primary type of permafrost disturbance influencing river chemistry. For the years 2013 to 2018, water samples were collected from the Niaqunguk River up to three times weekly over the course of the flow period and analyzed for major ions, dissolved organic carbon, and total dissolved nitrogen. Water sampling was co-located with a hydrometric station operated by the Water Survey of Canada. Solute fluxes to the Niaqunguk River were driven by the weathering of carbonate minerals by lateral flow pathways. For most years, solute fluxes peaked during spring snowmelt, when flows were the highest. In 2016, however, solute fluxes were highest in mid-summer, following several consecutive days of rainfall. If rainfall is increasing, as is projected for many regions of the Arctic, our data suggest that this could lead to an increase in solute fluxes to and through the Niaqunguk River. In the absence of recent precipitation data, however, it is challenging to determine whether this is the case.

1 INTRODUCTION

Contemporary climate change and permafrost thaw continue to modify the hydrological processes that control Arctic river runoff. This has profound implications for fluvial chemistry. Specifically, rising surface air and ground temperatures have contributed to the widespread degradation of permafrost across the Canadian Arctic (Smith et al. 2005; Throop et al. 2012). The top-down thawing of permafrost directly affects lateral flow pathways to Arctic rivers by increasing the thickness of the active layer (frost table depth) and in turn, the vertical infiltration of water into the soil profile (Chiasson-Poirier et al. 2020). This can lead to an increase in the connectivity of deeper, subsurface flow pathways with tributary streams and rivers (Chiasson-Poirier et al. 2020; Schwab et al. 2020).

Groundwater flow, particularly through zones of recently thawed permafrost, can be a significant source of solutes to tributary streams and rivers (Kokelj et al. 2003; Lafrenière and Lamoureux 2013). Permafrost, in Arctic and boreal regions, contains large amounts of organic material and mineral sediment (Fouché et al. 2020; Kokelj et al. 2003). As permafrost thaws, this organic material and mineral sediment is exposed to biological and chemical reactions, which can lead to solute enrichment within thaw zones and the mobilization of solutes via lateral flow pathways (Kokelj et al. 2003; Lafrenière and Lamoureux 2013). Consequently, the response of water quality to permafrost thaw is strongly influenced by the nature and magnitude of permafrost thaw and the composition of the contributing landscape (i.e., organic material, surficial geology; Brown et al. 2020; Tank et al. 2020).

The chemistry of Arctic rivers is also driven by temporal variability in precipitation and flow pathways (Quinton et al. 2006; Beel et al. 2021). For most Arctic rivers, the spring

snowmelt period, also referred to as the spring freshet, is the most significant hydrologic event of the year. At the onset of spring snowmelt, the active layer remains frozen, facilitating the rapid delivery of snowmelt water to tributary streams and rivers. Surface flow is the dominant lateral flow pathway at this time of year and is typically a source of particulate matter (Quinton et al. 1999; Quinton et al. 2006).

As the thaw period progresses, the contributing snowpack diminishes and summer rainfall becomes the primary driver of water runoff (Beel et al. 2021). As the thickness of the active layer increases, so does the relative importance of groundwater flow (Quinton et al. 2006). Groundwater flow is slowed by the active layer, which is typically a porous matrix of soil. The slower flow along groundwater flow pathways inhibits the transport of particulate matter, as compared with the rapid-flowing runoff at the ground surface (Frampton and Destouni 2015). Although groundwater flow does not easily transport particulate material, it can be an important source of dissolved material, due to the longer residence time of subsurface flow and enhanced interaction with the active layer (Quinton et al. 2006; Lafrenière and Lamoureux 2013).

Recent climate change is affecting the primary factors controlling the dominant water sources to Arctic rivers. In particular, Arctic freshwater systems are experiencing increasingly intense spring snowmelt periods and a higher frequency of extreme rainfall events (Bintanja 2018; Bush et al. 2019). As mentioned above, spring snowmelt and summer rainfall are the two most significant sources of freshwater, particulate matter, and solutes to Arctic rivers. Therefore, it is likely that these changes in precipitation regimes have and will continue to affect the hydrology and chemistry of Arctic rivers, potentially amplifying the effects of permafrost thaw on water quality.

The vast majority of water quality studies in the Arctic have focused on aquatic systems impacted by physical disturbances to the permafrost (e.g., mass wasting, active layer detachments). Few studies have examined the long-term effects of permafrost thaw on aquatic networks not impacted by physical disturbances to the permafrost. Furthermore, little is known about how the water quality impacts of permafrost thaw are influenced by recent changes in precipitation, lateral runoff pathways, and stream discharge.

The availability of the Niaqunguk River dataset provides us with the opportunity to address this gap in understanding. Over a six-year period (2013–2018), water quality samples were collected from the Niaqunguk River 2–3 times a week over the course of the flow period (June to August). A temporally detailed, multi-year river chemistry dataset, such as this, is unique for this region of the Canadian Arctic.

1.1 Objectives

The overall goal of this study was to examine how the water quality of the Niaqunguk River responds to seasonal and inter-annual variability in climate and how this varied over the period of record. This was achieved via the following key objectives: i. use water quality data to examine seasonal and inter-annual variability in the chemistry of the Niaqunguk River (2013–2018); ii. examine recent meteorological data (precipitation, snowfall, rainfall) and stream discharge data, in order to ascertain how water quality responds to spring snowmelt and summer rainfall events; and iii. examine historical climate (precipitation, snowfall, rainfall) and river discharge data, in order to establish long-term trends in the primary factors controlling solute fluxes.

1.2 Study Site

The Niaqunguk River catchment is located at 63° 44' 09" N, 68° 27' 05" W on Baffin Island, Nunavut (NU), Canada (Figure 1). The Niaqunguk River has a drainage area of 58.5 km² and discharges into Koojesse Inlet (Environment Canada, 2017). Although the catchment is situated within a region of continuous permafrost, it does not contain substantial amounts of massive ice and thus, is not impacted by obvious physical disturbances to the permafrost. Consequently, thermal perturbation of the permafrost and subsequently, increases in maximum active layer thickness is the primary type of permafrost disturbance influencing stream and river chemistry at this site.

The Niaqunguk River is located near the community of Iqaluit, NU. The mean annual air temperature for Iqaluit is -8.9 °C (1946–2022) and the average total annual precipitation is 524.6 mm (1950–2006). For most months (typically October to May), the dominant form of precipitation is snow. On average, snowfall makes up ~59% of total annual precipitation. This was determined from the third generation Adjusted Surface Air Temperature Data for Canada (Vincent et al. 2020) and the second generation Adjusted Precipitation for Canada (Mekis and Vincent 2011).

The vegetation in the Niaqunguk River catchment is relatively sparse, as compared with other regions of the Canadian Arctic. The landscape is covered by predominantly low-lying tundra vegetation and exposed bedrock (Tremblay 2017). The active layer contains only thin, isolated units of organic material and is primarily comprised of glacial till, a carbonate matrix deposited during the early-Holocene and Wisconsinan period (Tremblay 2017; Hodgson 2003). The glacial sediments present as till (T), till veneer (Tv), till blanket (Tb), and ridged till (Tr). In the region of Tv, ~40% of the area is covered by a < 1 m thick layer of glacial till (Tremblay 2017). The remaining ~60% of the area is rock ledges, knobs, and exposed bedrock (Tremblay 2017). The Tb region contains a continuous cover of predominantly boulder diamicton, which can be up to 10 m thick (Tremblay 2017; Hodgson 2003). Notably, there are also smaller, isolated regions with glaciofluvial and glaciolacustrine deposits, whereby the sediment layer can also be quite thick (up to 40 m; Tremblay 2017; Hodgson 2003).

The bedrock comprises predominantly silicate minerals, including biotite, orthopyroxene, garnet, and K-feldspar (St-Onge et al. 2006). In particular, the bedrock is classified as biotite ± orthopyroxene ± garnet monzogranite, K-feldspar megacrystic monzogranite, and granodiorite (St-Onge et al. 2006).

2 METHODOLOGY

Water quality samples were collected up to 2–3 times weekly over the flow period in the years 2013 to 2018. This was done with support from the Nunavut Research Institute. Sampling increased to three times weekly during snowmelt and rainfall runoff events.

A portion of sample was filtered through a 0.22 µm PVDF membrane filter and stored in the refrigerator for analysis. This filtered sample was analyzed for mineral ions (Ca²⁺, Cl⁻, SO₄²⁻, Na⁺, K⁺, Mg²⁺) by ion chromatography (Thermo-Dionex ICS 3000).

The precision of the analyses was evaluated using the covariance (CV) of sample repeats (Eq. 1; n > 10).

$$CV (\%) = (\overline{SD}_{\text{Repeats}} / \overline{Avg}_{\text{Repeats}}) \times 100 \quad [1]$$

$\overline{SD}_{\text{Repeats}}$ is the mean standard deviation of the sample repeats and $\overline{Avg}_{\text{Repeats}}$ is the mean average of the sample repeats. With the exception of K⁺, CV was less than 1.6% for all of the mineral ions. K⁺ was higher than the other mineral ions (< 5%), due to K⁺ concentrations being much lower (Standard Deviation < 0.017 ppm).

The method detection limit (MDL) of each parameter was determined using Equation 2.

$$MDL = [\text{Blank}] \times (3 \times SD_{\text{Std}}) \quad [2]$$

[Blank] is the concentration measured in Milli-Q water and SD_{Std} is the standard deviation of the concentration measured in the lowest calibration standard.

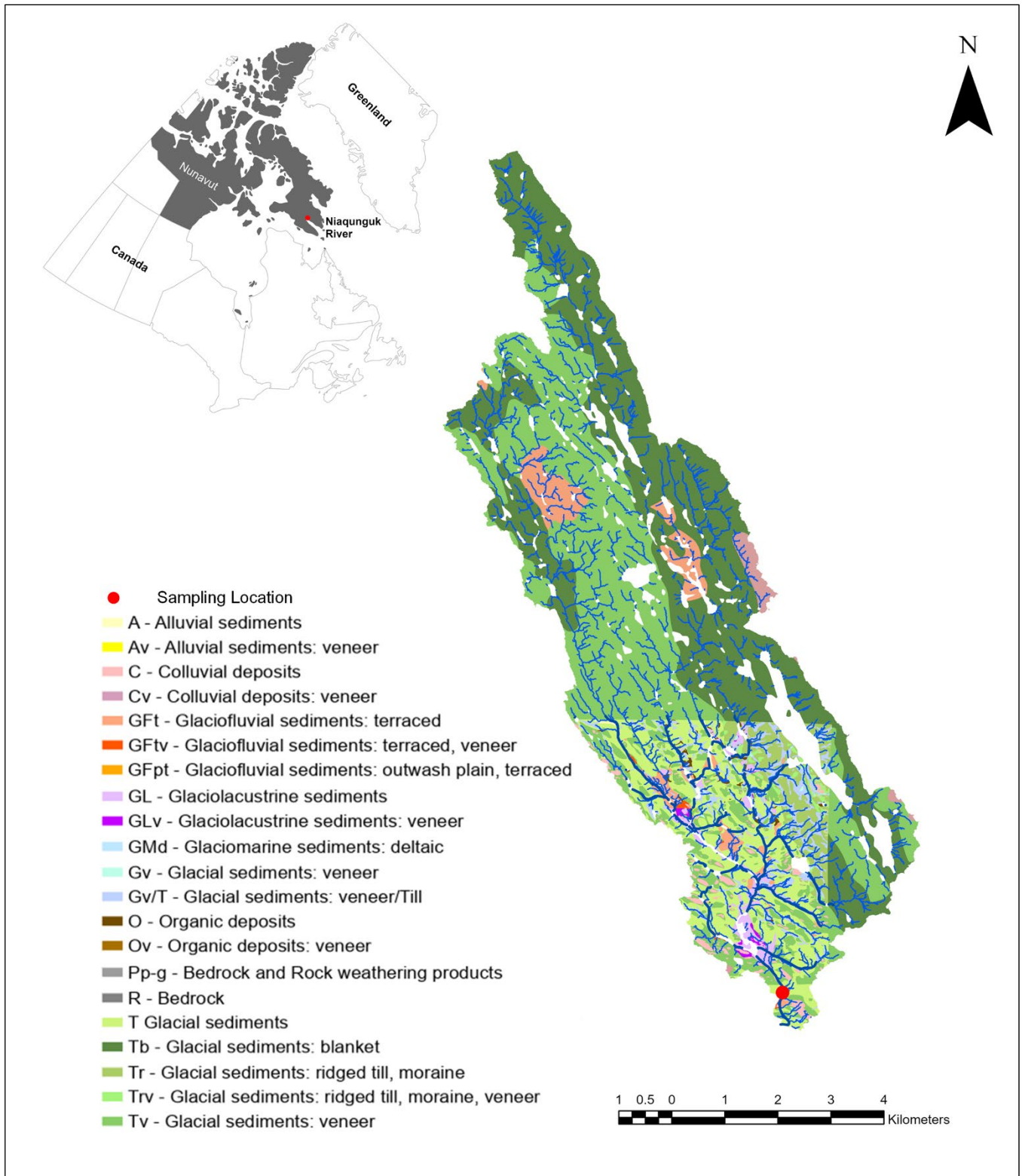


Figure 1. The surficial geology of the Niaqunguk River catchment. This is a compilation of data derived from Hodgson (2003) and Tremblay (2017). The red dot indicates the location of the sampling site and the Water Survey of Canada gauging station. The blue lines represent water flow, which was mapped in ArcGIS using a Digital Elevation Model.

Concentrations below the MDL were deemed unreliable. DL was less than 0.051 ppm for all mineral ions, except for K^+ . The MDL for K^+ was less than 0.03 ppm.

HCO_3^- was determined empirically using a charge-balance approach. This approach is justified because the pH of the Niaqunguk River is within the range where HCO_3^- is the dominant contributor to DIC (Drever 1997). Table 1 demonstrates that the pH range of the Niaqunguk River falls between 6.5 and 8.3.

Table 1. The minimum, maximum, and average pH of the Niaqunguk River over each of the study years.

Study Year	pH		
	Average	Minimum	Maximum
2013	7.3	7.1	7.5
2014	7.4	6.5	8.0
2015	7.6	6.9	8.3
2016	7.2	6.8	7.5
2017	7.2	6.8	7.5
2018	7.0	6.7	7.3

Another portion of sample was filtered using a 0.7 μm glass fiber filter. Glass fiber filters were pre-combusted at 500 °C to remove organic carbon. These samples were analyzed for total dissolved nitrogen (TDN) and dissolved organic carbon (DOC) using chemiluminescence and high temperature combustion (Shimadzu TOC -V with TN-M).

Similar to above, the precision of these analyses was evaluated using the covariance (CV) of sample repeats (Eq. 1; $n > 10$). CV was less than 2% for TDN and DOC. The MDL was less than 0.05 ppm for TDN and less than 0.26 ppm for DOC.

All of the above analyses took place at the Facility for Biochemical Research on Environmental Change and the Cryosphere at Queens University.

Mineral ion, TDN, and DOC concentrations were reported in units of $mg.L^{-1}$. This was converted to units of $mg.m^{-3}$, whereby $1 m^3 = 1000 L$. Concentration (in $mg.m^{-3}$) was then converted to flux values by multiplying concentration by mean daily discharge (in $m^3.d^{-1}$). Total daily flux (in $mg.d^{-1}$) was then divided by the catchment area ($5.85 \times 10^7 m^2$), in order to yield flux values in units of $mg.m^{-2}.d^{-1}$.

A time-series plot was used to examine seasonal and inter-annual variability in solute fluxes, relative to discharge (in $mm.d^{-1}$), positive degree days (°C), and unadjusted total daily precipitation (mm).

Mean daily discharge (in $m^3.s^{-1}$) was extracted from the Environment and Climate Change Canada Historical Hydrometric Data site (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html) on July 17, 2023 and July 18, 2023. This was converted to units of $m^3.d^{-1}$, whereby $1 m^3.s^{-1} = 86,400 m^3.d^{-1}$. Total daily discharge (in $m^3.d^{-1}$) was then divided by the catchment area ($5.85 \times 10^7 m^2$), in order to yield units of $m.d^{-1}$. This was then converted to $mm.d^{-1}$.

Positive degree days are the sum total of the mean annual air temperatures that are above 0 °C. This was calculated

for each day between April 20 and January 10 of the six study years using unadjusted mean daily air temperature data. Unadjusted mean daily air temperature and unadjusted total daily precipitation data were extracted from the Environment and Climate Change Canada Historical Climate Data site (https://climate.weather.gc.ca/index_e.html) on July 17, 2023 and July 18, 2023.

The composition of mineral ions was examined using a Piper Plot, which plots the proportions of ion equivalent concentrations.

Long term trends in precipitation, snowfall, rainfall, and discharge were examined using a Mann-Kendall non-parametric test for trend using XLSTAT software. Historical trends in total annual precipitation, snowfall, and rainfall data were developed using adjusted monthly data obtained from the second generation Adjusted Precipitation for Canada (Mekis and Vincent 2011). Missing data were infilled using unadjusted daily data obtained from the Environment and Climate Change Canada Historical Climate Data site (https://climate.weather.gc.ca/index_e.html) on July 17, 2023 and July 18, 2023.

Historical trends in total annual discharge were developed using total annual discharge values (in $mm.y^{-1}$) derived from discharge data extracted from the Environment and Climate Change Canada Historical Hydrometric Data site: (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html) on July 17, 2023 and July 18, 2023.

3 RESULTS

3.1 River Discharge

Flow was initiated when positive degree days increased to above 0 °C. This was the onset of spring snowmelt and was marked by a steep increase in total daily discharge, followed by several defined peaks (Figure 2). The dip in river discharge between peaks is closely associated with positive degree days, which is close to 0 °C at this time of year.

For most years, total daily discharge (in $mm.d^{-1}$) was highest during spring snowmelt, which was initiated in early-June for all of the study years with available data. Over the six-year study period, the highest annual maximum total daily discharge was $17.7 mm.d^{-1}$ and was observed on June 20, 2018. It is worth noting that this value may be higher, as total daily discharge is unavailable for the days preceding this. The lowest annual maximum total daily discharge was $11.87 mm.d^{-1}$ and was observed on June 15, 2017.

Total daily discharge decreased over the summer months, except for temporary increases corresponding to summer rainfall events. Notably, in 2016, the annual maximum total daily discharge did not occur during spring snowmelt. Rather, the annual maximum total daily discharge ($17.53 mm.d^{-1}$) occurred in late-July, following several days of heavy rainfall. Although not as high as during spring snowmelt, several days of heavy rainfall also led to markedly higher flows in September 2013 and September 2017.

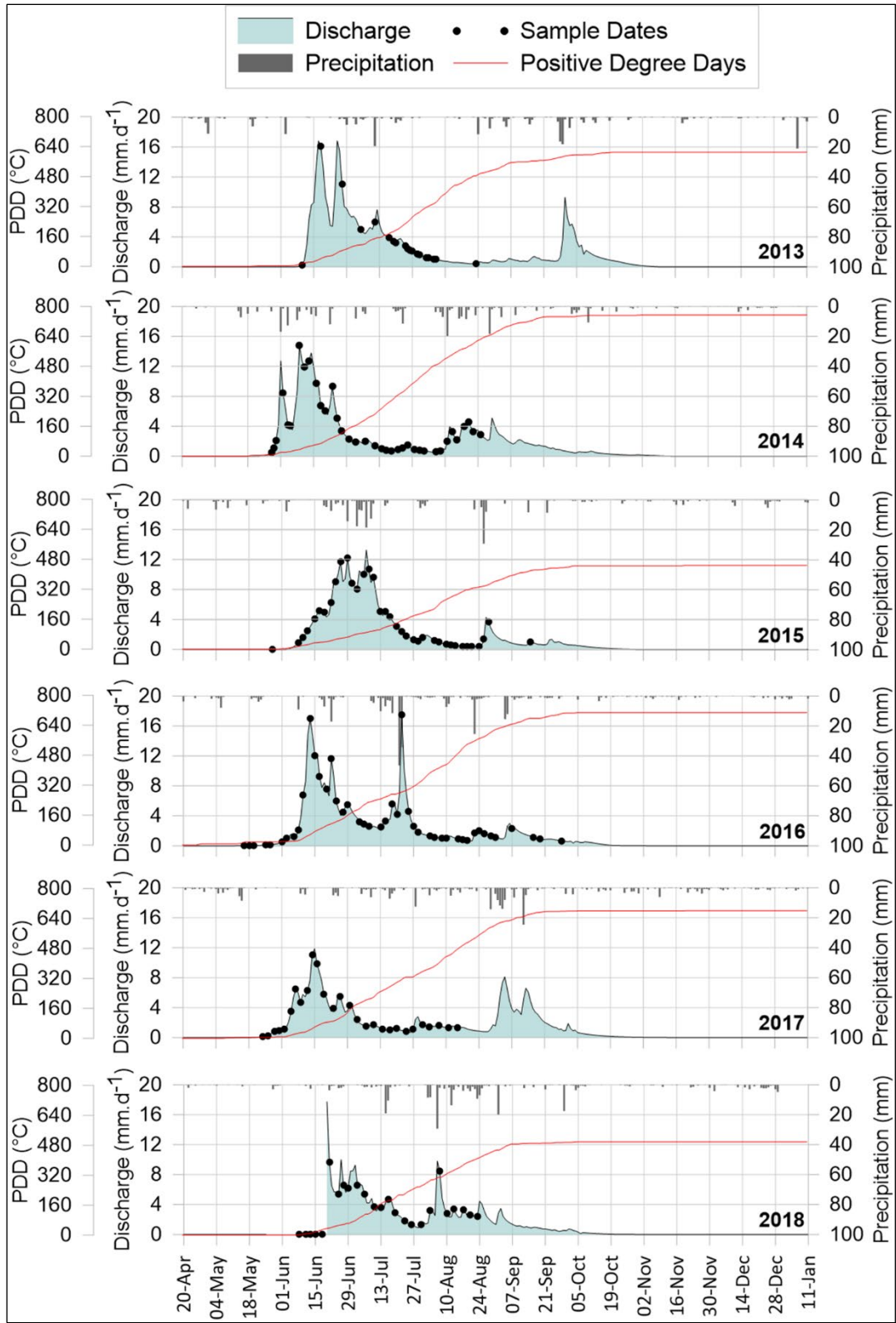


Figure 2. The total daily discharge (in $\text{mm}\cdot\text{d}^{-1}$) measured at the Niaqunguk River for period of April 20 to January 10 is plotted for each study year (2013–2018). Flow is plotted against the positive degree days (in $^{\circ}\text{C}$; PDD) and unadjusted total daily precipitation (in mm) for Iqaluit, NU for the same period. The sampling dates are represented by black dots.

In each study year, the water sampling successfully captured spring snowmelt, including the rising and falling limb of the hydrograph, as well as the summer period. The fall period, however, is less represented. With the exception of 2016, sampling often stopped at the end of August.

3.2 Water Chemistry

3.2.1 Mineral Ions

The flux of Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , and Cl^- (in $\text{mg}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) over the flow period is plotted in Figure 3. Seasonal variability in the fluxes of mineral ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , and Cl^-) through the Niaqunguk River follows a similar seasonal trend as total daily discharge (Figure 3). High fluxes were associated with periods of high flow. Mineral ion fluxes rapidly increased at the onset of the flow period and for most study years, reached a maximum during spring snowmelt. Notably, this was often when the concentration of mineral ions is lowest.

Mineral ion fluxes generally decreased over the summer period, despite the higher concentrations observed at this time. This was, however, with the exception of summer rainfall events. In 2016, solute fluxes peaked on July 22, following a period of heavy rainfall. Notably, this represented the highest Ca^{2+} , Mg^{2+} , and Cl^- fluxes measured over the 6-year study period. The highest SO_4^{2-} , Na^+ , and K^+ fluxes occurred on August 20, 2014, also following a period of heavy rainfall.

Despite strong seasonal variability in fluxes, the composition of mineral ions is consistent across all seasons and all study years (Figure 4). Water samples contained high proportions of Ca^{2+} , Mg^{2+} , and HCO_3^- and low proportions of SO_4^{2-} , Cl^- , Na^+ , and K^+ . This is consistent with carbonate weathering.

3.2.2 Carbon

The flux of Dissolved Organic Carbon (DOC) and Total Dissolved Nitrogen (TDN) over the flow period of each study year (2013–2018) is plotted in Figure 5. DOC and TDN fluxes (in $\text{mg}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) also followed total daily discharge (Figure 5), in that they were typically highest during spring snowmelt and decreased over the summer period. In 2016, however, DOC and TDN fluxes were highest on July 22nd, following a period of heavy rainfall. Preceding this event, DOC was highest on June 22nd and July 18th, also following rainfall periods.

3.3 Multi-Year Trends

3.3.1 Precipitation

Adjusted total monthly snowfall and total monthly rainfall data were available for most years from 1950 to 2006. For months where adjusted data were unavailable, unadjusted total daily snowfall and rainfall data were used. This provided more years with complete data ($n = 55$).

A Mann-Kendall non-parametric test for trend indicated that there was a significant decrease in total annual snowfall over this period (Sen's slope = -0.272 mm per year;

$p < 0.05$; Figure 6). There was a small increasing trend in total annual rainfall over the same time period. However, this was not significant ($p > 0.05$). At the time of these analyses, no complete adjusted or unadjusted snowfall or rainfall data were available after 2006.

Complete total daily precipitation data were available for 1950 to 2006 for most years. Similar to above, unadjusted total daily precipitation data were used to infill months where adjusted data were unavailable. This yielded more years with complete data ($n = 54$). Some data were available for the years between 2007 and 2023. However, it was not complete. For the years 1950–2006, total annual precipitation decreased at a rate of -0.23 mm per year. The percentage of total annual precipitation comprising snowfall also decreased over the period of record, at a rate of 0.223% per year.

3.3.2 Discharge

Complete discharge data were available for the years 1989–1995 and 2007–2017. Although there are some data preceding 1989, there are not enough to calculate total annual fluxes. Additionally, there were no data available between the years 1995 and 2007 or between 2017 and 2023. The total annual discharge (in $\text{mm}\cdot\text{y}^{-1}$) measured in the years 1989–1995 is visibly lower than the discharge measured in the years 2007–2017 (Figure 7). Consequently, there is a positive trend in total annual discharge over the period of record (Sen's slope = 5.404 $\text{mm}\cdot\text{y}^{-1}$; $p < 0.05$). Despite this, it's important to highlight that there may be two separate trends in this figure. Total annual discharge appears to be decreasing over the 1989–2005 period, which is in line with the decrease in total annual snowfall and total annual precipitation discussed above. Conversely, total annual discharge appears to be increasing over the 2007–2017 period.

4 DISCUSSION

Seasonal variability in river discharge was typified by spring snowmelt and summer rainfall. At the onset of spring snowmelt, there is a steep increase in river discharge. Given that the active layer is typically frozen at this stage, this can be attributed to the rapid delivery of snowmelt water via surface runoff (Quinton et al. 2006; Chiasson-Poirier et al. 2020). For most years, river discharge was highest in spring, often peaking several times over the course of the spring snowmelt period. The presence of multiple discharge peaks appears to be associated with variability in surface air temperature and in turn, the rate of snowmelt.

Following river discharge, solute fluxes were driven by seasonal changes in snowmelt and rainfall. For most study years, solute fluxes were the highest during spring snowmelt. In surface and near-surface runoff, mineral ions are typically present in low concentrations relative to subsurface flow. This is often attributed to the limited contact surface runoff has with the deeper, mineral layers of the active layer (Quinton et al. 2006; Chiasson-Poirier et al. 2020). Consequently, downstream aquatic systems are normally diluted by snowmelt water (Quinton et al. 2006).

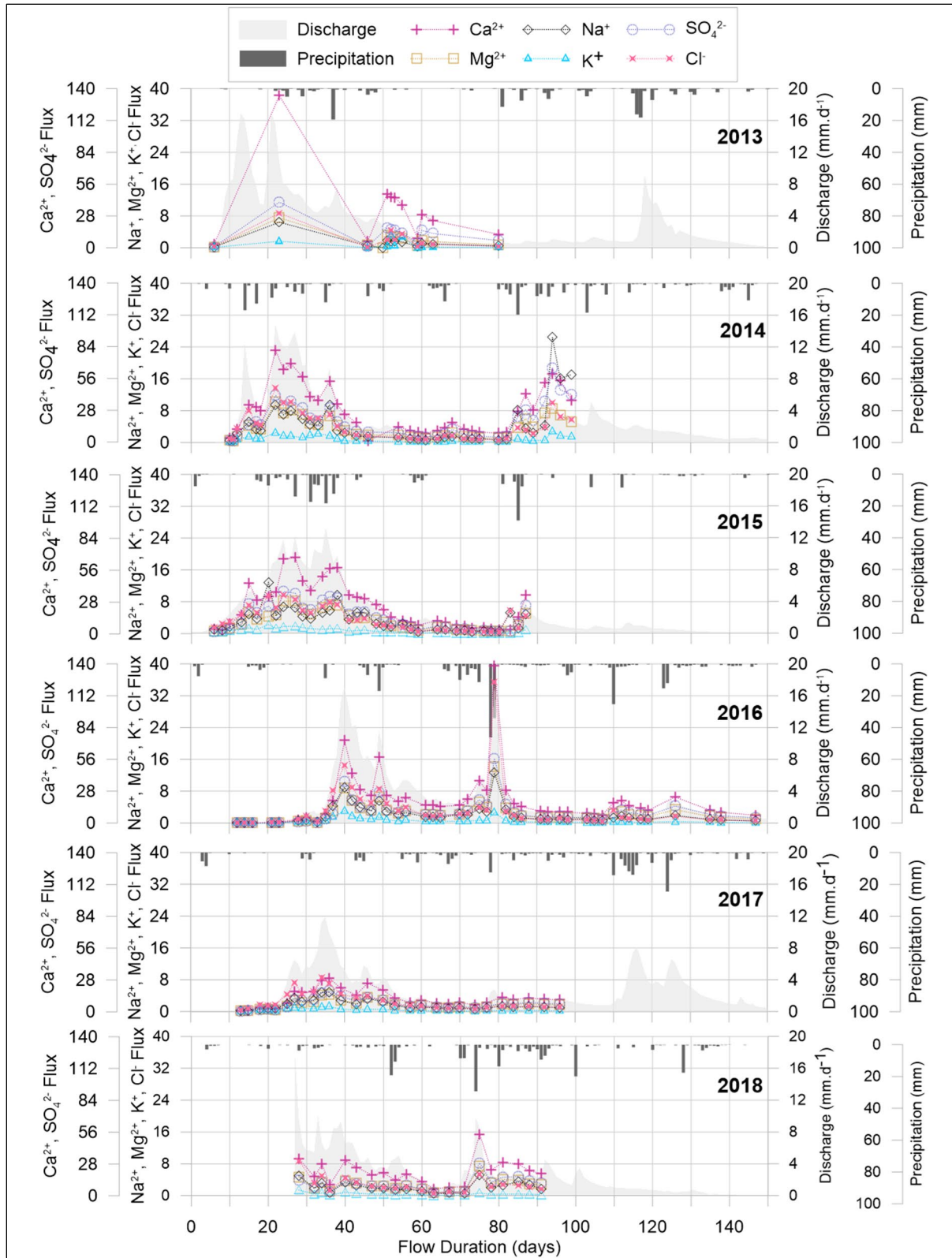


Figure 3. The flux of Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , and Cl^- (in $\text{mg.m}^2.\text{d}^{-1}$) over the flow period is plotted with the total daily discharge (in mm.d^{-1}) for the Niaqunguk River and the unadjusted total daily precipitation (in mm) for Iqaluit.

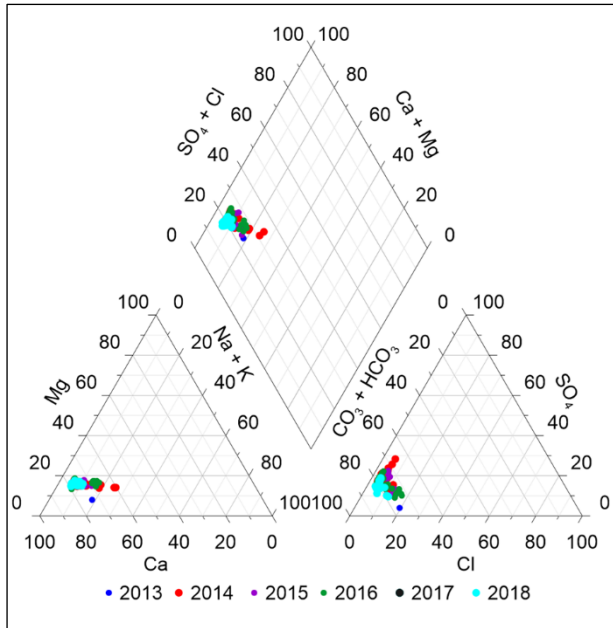


Figure 4. A piper plot of the proportions of ion equivalents of mineral ions in each of the samples across all study years.

In this study, however, mineral solute fluxes were typically highest during spring snowmelt. This indicates that snowmelt is mobilizing solute-rich pore water from near the surface. These solutes could be weathering products derived from surface runoff during spring melt, weathering products that were immobilized during freeze-up of the previous year, or dusts deposited onto the snowpack over the winter and spring.

In contrast with mineral ions, DOC and nutrient concentrations are often elevated in near-surface flow pathways, as organic material is normally the most concentrated close to the surface (Quinton et al. 2006). For the Niaqunguk River, DOC and TDN fluxes were typically the highest during spring snowmelt and decreased over the summer thaw period. This can be attributed to active layer thaw. The thawing of the active layer increases the vertical infiltration of runoff into the soil profile. Consequently, subsurface flow is routed through deeper regions of the active layer that are comprised of predominantly mineral sediment (Quinton et al. 1999, 2006; Chiasson-Porier et al. 2020). Consequently, the concentration of DOC and nutrients typically decreases over the summer (Quinton et al. 2006).

In addition to spring snowmelt, summer rainfall events also led to noticeable peaks in discharge and solute fluxes. In particular, multiple consecutive days of rainfall in 2014 and 2016 led to mineral ion fluxes that were higher than those observed during spring snowmelt. In 2016, the DOC fluxes following periods of heavy rainfall exceeded the fluxes observed during spring snowmelt. This suggests that, potentially, heavy rainfall can lead to the saturation of the active layer, allowing for soluble organic material at the surface to be mobilized.

The data presented here suggest that summer rainfall events lead to enhanced solute fluxes through the Niaqunguk River basin. As the active layer thaws, the potential for the mobilization of solutes via landscape runoff increases, intensifying the water quality response of the river to rainfall. Thus, rainfall events in fall, when the active layer reaches a maximum thickness, are likely an important source of solutes to the Niaqunguk River. Unfortunately, the sampling period did not capture the chemical composition of these runoff events.

Arctic rivers are more challenging to sample in the fall and winter, largely due to inclement weather and ice conditions. This can make it difficult to travel safely to and across field sites. Additionally, the fall and winter months overlap with the two main academic terms, which often restricts university-based researchers' ability to travel to remote field locations. Consequently, the shoulder seasons are not represented in many research programs (Shogren et al. 2020). In contrast with university-based researchers, northern-based research institutions and Indigenous organizations are less constricted by the academic schedule and have greater capacity to sample during the colder months. The meaningful engagement of community-based monitors and researchers could help address this gap in understanding.

Recent climate change has contributed to more intense spring snowmelt periods and a higher frequency of extreme rainfall events for many Arctic regions (Bintanja 2017; Bush et al. 2019). The data presented here, however, indicate that there was overall, statistically significant decrease in total annual precipitation over the period of record (1950–2006; $p < 0.05$). This is likely driven by declining total annual snowfall, which showed a significant decrease over the same period ($p < 0.05$). Although there was not a significant trend in total annual rainfall, the decrease in total annual snowfall has contributed to an increase in the proportion of precipitation that falls as rain. Consequently, the relative importance of rainfall in driving discharge and solute fluxes is increasing.

There was an overall increase in total annual discharge over the period of record (1989–2017). It's important to note, however, that there may be two separate trends. Total annual discharge appears to decrease from 1989–2005. This period directly overlaps with our precipitation record, which suggests that the observed decrease in total annual discharge could be driven by declining total annual precipitation. By contrast, flow appears to have increased over the more recent period with data (2007–2017). Since there are no precipitation data for this period, the reason for this is unclear. It's possible that long term trends in precipitation have changed since 2006, which would have significant implications for solute fluxes.

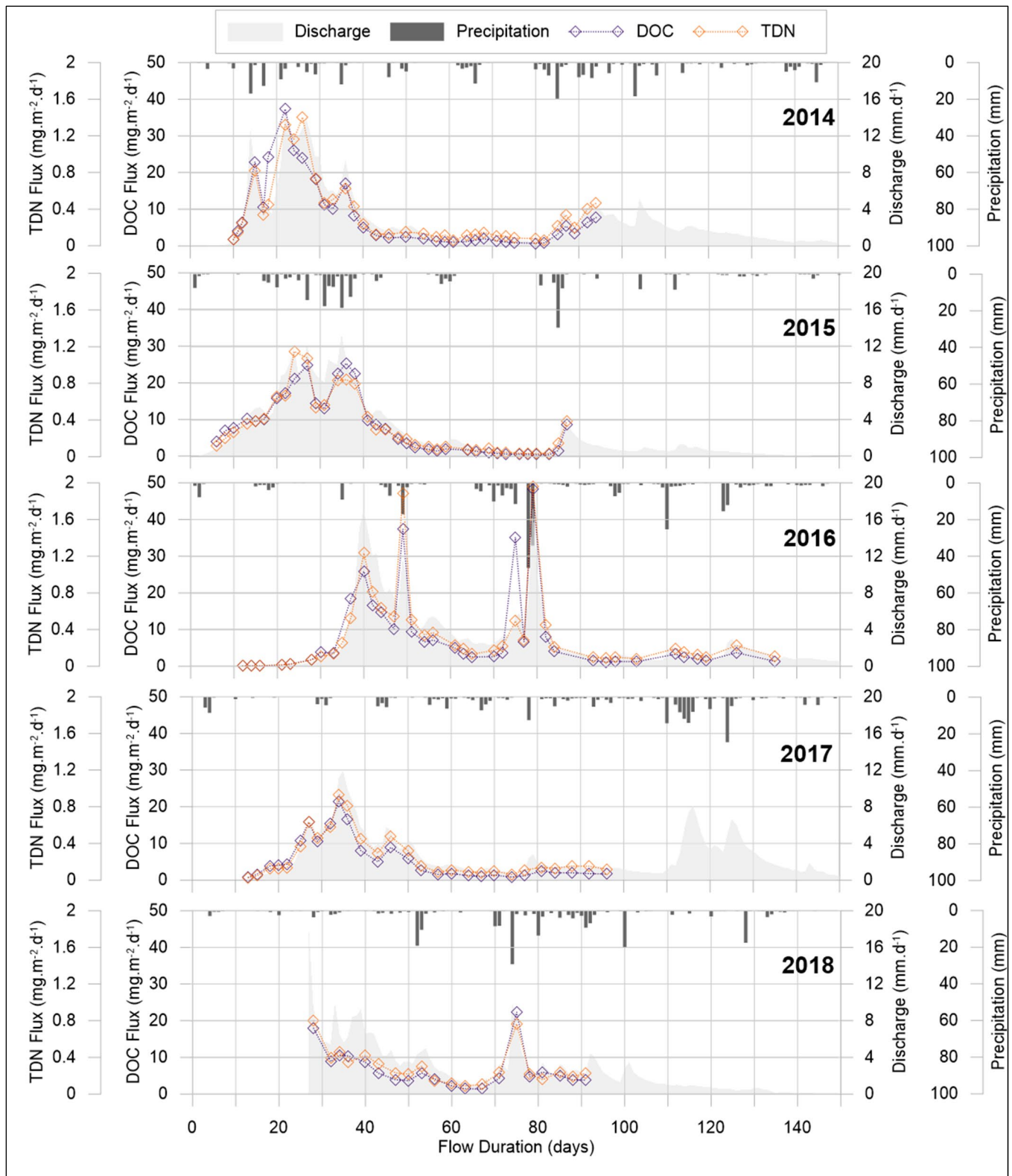


Figure 5. The flux of Dissolved Organic Carbon (DOC) and Total Dissolved Nitrogen (TDN) in units of $\text{mg.m}^{-2}.\text{d}^{-1}$ over the flow period of each study year (2013–2018). This is plotted with the total daily discharge (in mm.d^{-1}) for the Niaqunguk River and the unadjusted total daily precipitation (mm) for Iqaluit.

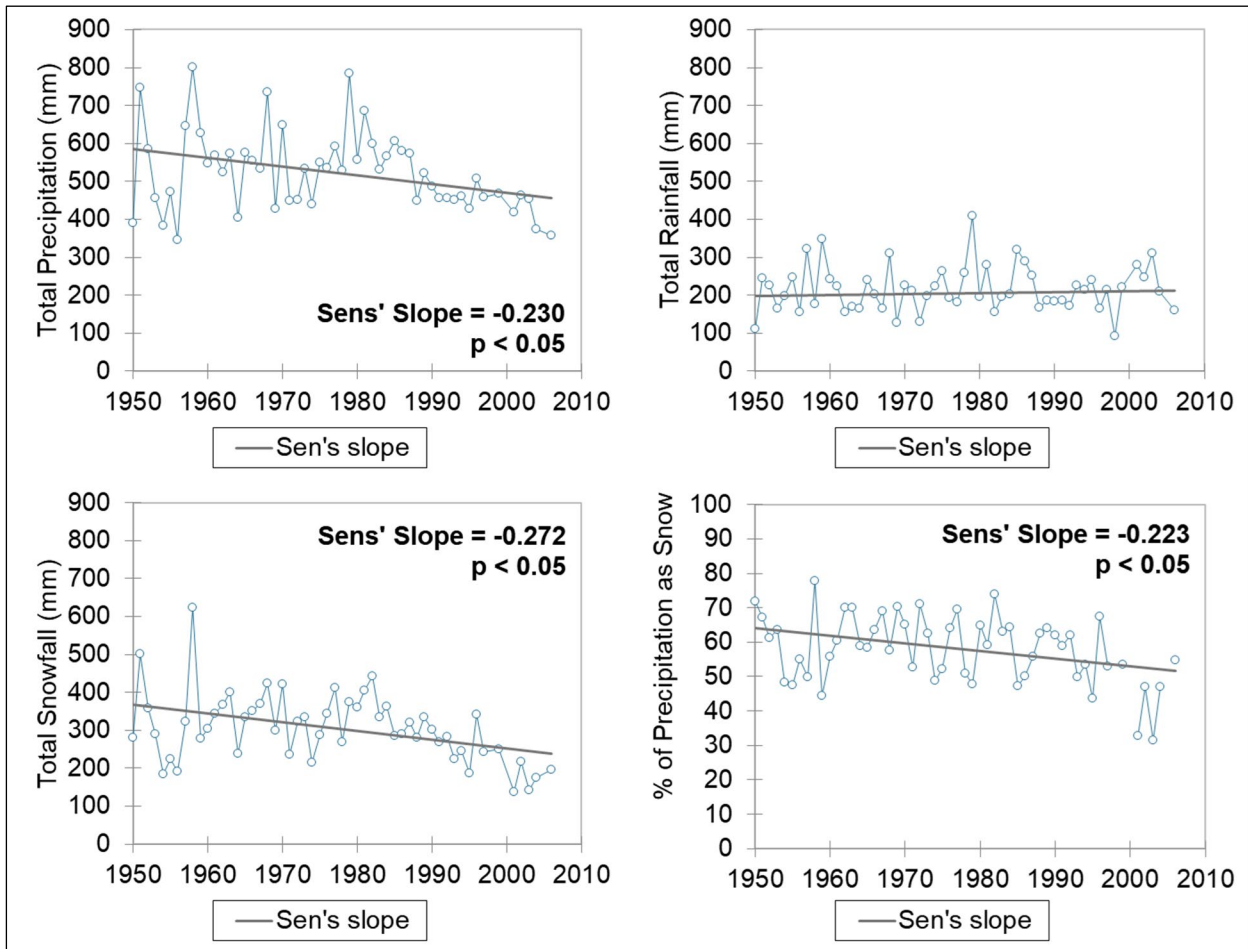


Figure 6. Mann-Kendall Trend and Sen's Slope for the Total Annual Precipitation, Total Annual Snowfall and Total Annual Rainfall in Iqaluit over the period of record.

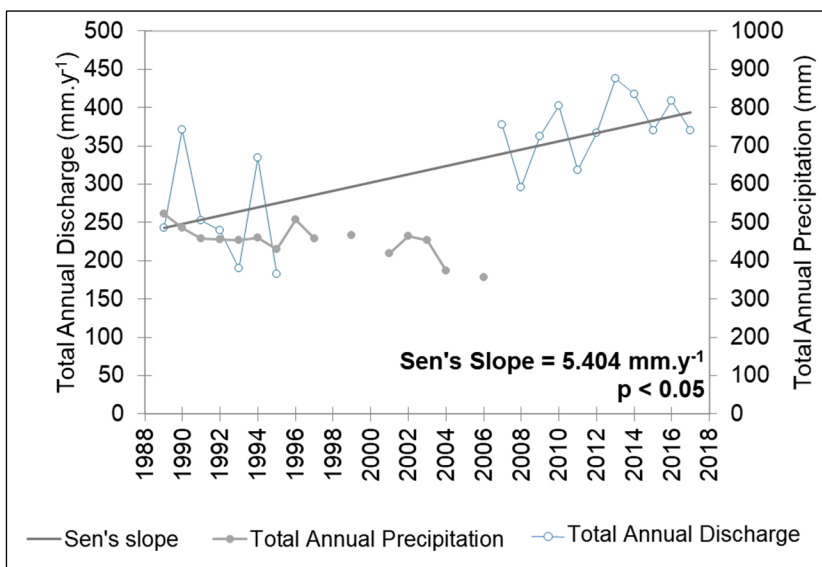


Figure 7. Mann Kendall Trend and Sen's Slope for the Total Annual Discharge of the Niaqunguk River over the period of record.

The contributing landscape has limited organic deposits and as a result, DOC and total dissolved nitrogen are only present in low concentrations. The chemical composition of the Niaqunguk River indicates that water chemistry is mainly driven by the weathering of organic material and carbonate minerals, likely by carbonic acid (H₂CO₃) and organic acids. This is associated with subsurface flow through the organic material and glacial till that makes up the active layer. Note that the glacial till is rich in carbonate minerals (Tremblay 2017).

In addition to glacial till, there is extensive bedrock. However, bedrock does not weather appreciably in this environment and likely, does not contribute substantially to solute loads. If subsurface runoff was contained to the glacial till, it's reasonable to expect that increases in total annual precipitation and discharge would lead to increases in the mineral ions associated with carbonate weathering. In regions where the glacial till is thick, this would be amplified by permafrost thaw. For example, the glacial till can be up to 20 m thick in regions occupied by till blanket.

For many Arctic regions, permafrost thaw has contributed to thicker active layers and in turn, the potentiality for deeper flow pathways. If the subsurface flow pathways extended to below the carbonate-rich glacial till, we would likely see a change in water chemistry. For example, bedrock is present near the surface (less than 1 m) in many areas of the Niaqunguk River catchment. Deeper flow pathways could lead to longer rock-water contact times, which could lead to enhanced chemical weathering. In this case, we might see the emergence of solutes associated with silicate minerals, such as aluminum and iron. In future research, it would be interesting to explore techniques for deciphering the relative contribution of glacial till vs. bedrock weathering products to river chemistry.

5 CONCLUSIONS

The water chemistry of the Niaqunguk River is predominantly driven by the weathering of organic material and carbonate-rich glacial till. This is facilitated by landscape runoff during spring snowmelt and following summer rainfall events. Although spring snowmelt often leads to the highest solute fluxes, rainfall is an important factor in the mobilization of solutes from the contributing catchment. Therefore, projected increases in summer rainfall have important implications for water chemistry. Increases in summer rainfall, particularly in combination with permafrost thaw, could lead to enhanced interaction between lateral flow pathways and organic deposits, carbonate-rich glacial till, and bedrock.

The water quality of Arctic rivers is intrinsically linked to seasonal and inter-annual patterns in rainfall, snowfall, and discharge. However, the availability of these data in Arctic regions is limited. In the absence of climatic and hydrologic data, it's challenging to predict how climate change will influence Arctic freshwater systems. This is a critical gap to address, as the sustainability and health of Arctic communities is invariably linked to freshwater systems.

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7 REFERENCES

- Beel, C.R., Heslop, J.K., Orwin, J.F., Pope, M.A., Shevers, A.J., Hung, J.K.Y., Lafrenière, M.J., and Lamoureux, S.F. 2021. 'Emerging dominance of summer rainfall driving High Arctic terrestrial-aquatic connectivity', *Nature communications* 12 (1), pp. 1448–1449. doi:10.1038/s41467-021-21759-3.
- Bintanja, R. and Olivier, A. 2017. 'Towards a rain-dominated Arctic', *Nature climate change* 7 (4), pp. 263–267. doi:10.1038/nclimate3240.
- Brown, K.A., Williams, W.J., Carmack, E.C., Fiske, G., François, R., McLennan, D., and Peucker-Ehrenbrink, B. 2020. 'Geochemistry of Small Canadian Arctic Rivers with Diverse Geological and Hydrological Settings', *Journal of Geophysical Research: Biogeosciences* 125(1), e2019JG005414. doi:10.1029/2019JG005414.
- Bush, E. and Lemmen, D.S. (eds.) 2019. *Canada's Changing Climate Report*. Ottawa, Ontario, Canada: Government of Canada, 444 p.
- Chiasson-Poirier, G., Franssen, J., Lafrenière, M.J., Fortier, D., and Lamoureux, S.F. 2020. 'Seasonal evolution of active layer thaw depth and hillslope-stream connectivity in a permafrost watershed', *Water Resources Research* 56, e2019WR025828. doi:10.1029/2019WR025828
- Drever, J.I. 1997. *The Geochemistry of Natural Waters: Surface and Groundwater Environments*. Third edition. Upper Saddle River, New Jersey, United States: Prentice Hall, 436 p.
- Fouche, J., Christiansen, C.T., Lafrenière, M.J., Grogan, P., and Lamoureux, S.F. 2020. 'Canadian permafrost stores large pools of ammonium and optically distinct dissolved organic matter', *Nature Communications* 11, pp. 4500–4500. doi:10.1038/s41467-020-18331-w.
- Frampton, A. and Destouni, G. 2015. 'Impact of degrading permafrost on subsurface solute transport pathways and travel times', *Water Resources Research* 51, pp. 7680–7701. doi:10.1002/2014WR016689.
- Hodgson, D.A. 2003. 'Surficial geology, Frobisher Bay, Baffin Island, Nunavut', *Geological Survey of Canada Map 2042A*, scale 1:100 000.

- Kokelj, S.V. and Burn, C.R. 2003. 'Ground ice and soluble cations in near-surface permafrost, Inuvik, Northwest Territories, Canada', *Permafrost and Periglacial Processes* 14(3), pp. 275–289. doi:10.1002/ppp.458.
- Lafrenière, M.J. and Lamoureux, S.F. 2013. 'Thermal perturbation and rainfall runoff have greater impact on solute loads than physical disturbance of the active layer', *Permafrost and Periglacial Processes* 24, pp. 241–251. doi:10.1002/ppp.1784.
- Mekis, É. and Vincent, L.A. 2011. 'An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada', *Atmosphere-Ocean* 49(2), pp. 163–177. doi:10.1080/07055900.2011.583910.
- Quinton, W.L., Marsh, P., Anderson, M.G., Peters, N.E., and Walling, D. 1999. 'A conceptual framework for runoff generation in a permafrost environment', *Hydrological Processes* 13(16), pp. 2563–2581. doi:10.1002/(SICI)1099-1085(199911)13:16<2563::AID-HYP942>3.0.CO;2-D.
- Quinton W. and Pomeroy J. 2006. 'Transformations of runoff chemistry in the Arctic tundra, Northwest Territories, Canada', *Hydrological Processes* 20, pp. 2901–2919. doi:10.1002/hyp.6083.
- Schwab, M.S., Hilton, R.G., Raymond, P.A., Haghipour, N., Amos, E., Tank, S.E., Holmes, R.M., Tipper, E. T., and Eglinton, T.I. 2020. 'An Abrupt Aging of Dissolved Organic Carbon in Large Arctic Rivers', *Geophysical Research Letters* 47(23), e2020GL088823–n/a. Available at: <https://doi.org/10.1029/2020GL088823>.
- Shogren, A.J., Zarnetske, J.P., Abbott, B.W., Iannucci, F. and Bowden, W.B. 2020. 'We cannot shrug off the shoulder seasons: Addressing knowledge and data gaps in an Arctic Headwater', *Environmental Research Letters* 15(10), 104027. doi:10.1088/1748-9326/ab9d3c.
- Smith, S.L., Burgess, M., Riseborough, D., and Nixon, F.M. 2005. 'Recent trends from Canadian Permafrost Thermal Monitoring Network Sites', *Permafrost and periglacial processes* 16, pp.19–30. doi:10.1002/ppp.511.
- St-Onge, M.R., Ford, A., and Henderson, I. 2006. 'Geology, Baffin Island (south of 70°N and east of 80°W), Nunavut', *Geological Survey of Canada Open File* 4931, scale 1:500,000. Available at: http://www5-ott-h000947/projects/of5116/digital_release/data/bedrock_geology/bas4931_1_arc.shp.
- Tank, S.E., Vonk, J. E., Walvoord, M.A, McClelland, J.W., Laurion, I., and Abbott, B.W. 2020. 'Landscape matters: Predicting the biogeochemical effects of permafrost thaw on aquatic networks with a state factor approach', *Permafrost and Periglacial Processes* 2020, pp. 1–13. doi:10.1002/ppp.2057.
- Throop, J., Lewkowicz, A.G., and Smith, S.L. 2012. 'Climate and ground temperature relations at sites across the continuous and discontinuous permafrost zones, northern Canada', *Canadian Journal of Earth Sciences* 49(8), pp. 865–876. doi:10.1139/e11-075.
- Tremblay, T. 2017 'Surficial Geology, Beekman Peninsula, Baffin Island, Nunavut, NTS 25P and NTS 15M (part)', *Canada-Nunavut Geoscience Office Open File Map* 2017-03, scale 1:125,000.
- Vincent, L.A., Hartwell, M.M., and Wang, X.L. 2020. 'A third generation of homogenized temperature for trend analysis and monitoring changes in Canada's climate', *Atmosphere-Ocean* 58(3), pp. 173–191. doi:10.1080/07055900.2020.1765728.
- Zolkos, S., Tank, S.E., Kokelj, S.V., Striegl, R.G., Shakil, S., Voigt, C., et al. 2022. 'Permafrost Landscape History Shapes Fluvial Chemistry, Ecosystem Carbon Balance, and Potential Trajectories of Future Change', *Global biogeochemical cycles* 36, e2022GB007403. doi:10.1029/2022GB007403.