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Process Synchrony a Key Control of Resilience in a Subarctic Freshwater System

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Key Points:

- Small Taiga Shield streams shifted into a new winter-flow dominated hydrological regime near the turn of the 21st century
- This shift, caused by the synchrony of several non-linear physical processes, results from climate warming
- Current Earth system models do not include process synchrony and cannot predict such regime shifts, likely underestimating tipping points

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Abstract Climate-induced changes in streamflow and biogeochemistry are occurring across the northern circumpolar region but several key unknowns include (a) the mechanisms responsible among landscapes and permafrost conditions, (b) the resilience and precariousness of hydrological and biogeochemical regimes. Even though it is among the largest physio-climatic regions of the northern circumpolar, these knowledge gaps are acute in the Taiga Shield. This research aimed to determine if hydrology and biogeochemistry regimes of the Taiga Shield have been resilient to recent climate warming. We apply a recently developed framework of hydrological resilience that shows the first 20 years of the 21st century were the warmest and wettest of the previous 300 years. These conditions altered the catchment such that >50% of the water year streamflow now occurs during winter, shifting the catchment from a nival to a cold season pluvial hydrological regime. This regime shift has significantly changed the fraction of inorganic nitrogen export, but insufficiently to shift the biogeochemical regime. Sustained multi-year physical process synchronization was the cause of these changes. This behavior is not well simulated by existing Earth system models. The tipping point in local mean annual air temperatures was crossed near the turn of the century well below the warming threshold of the Paris Accord. A one-size-fits-all approach to mitigation targets is not effective at preventing all shifts in Earth systems. This is important to consider as regime changes in small hydrological systems have the potential to trigger cascading effects in the larger catchments to which they contribute.

Plain Language Summary We show that since the turn of the century, most runoff in small northwestern Canadian Shield streams that drain this lake-rich landscape has flowed during the winter rather than after spring snowmelts. This significant departure from the past has not occurred since at least 1700. Recent climate warming means more precipitation in autumn, falling as rain, filling lakes, making runoff more common through winter. The seasonal shift in the streamflow timing has also changed the chemistry of the water. The tipping point coincided with the point in time when global surface temperatures had risen half the 1.5° warming threshold agreed upon in the Paris Accord. These watersheds are not resilient to such an extreme degree of warming because the lake-rich landscape configuration and relatively dry climate make them vulnerable to regime shifts. Therefore, this mitigation goal did not prevent cold freshwater systems in northern Canada from changing regime. Better coupling of atmospheric and hydrological processes in current climate change models is necessary because currently they are unable to predict such regime shifts and are likely underestimating tipping points.

1. Introduction

Streamflow seasonality is changing across the circumpolar north (Peterson et al., 2002) primarily due to precipitation phase changes and alteration of permafrost conditions (Connon et al., 2014; Spence et al., 2011) associated with 20th and 21st century warming. Streamflow is particularly vulnerable to precipitation change where runoff generation is highly threshold mediated. Furthermore, changing streamflow seasonality results from greater surface-subsurface interaction and altered runoff generation processes and pathways where permafrost thaw changes these thresholds. Changes in the seasonality of streamflow have critical implications for surface water biogeochemistry (Tank et al., 2016), through the influence of flushing, dilution, and spatial synchrony of runoff generation, which varies with landscape heterogeneity and hydrological connectivity (Laudon et al., 2011). These changes act synergistically with the effects of warmer and wetter conditions on chemical cycling rates (Lessels et al., 2015). Because hydrological and aquatic chemical system states and trends profoundly influence aquatic ecosystem services, food webs, fisheries, drinking water quality, and chemical fluxes to the Arctic Ocean (Tank et al., 2016), there is a need to improve understanding of how climate-driven effects cascade through hydrological and biogeochemical processes that control system resiliency and regime shifts.

While there are examples of physical process studies that explain trends in northern latitude aquatic chemistry (Kokelj et al., 2013; Zolkos et al., 2022), these are not common and focus on specific landscapes and time scales covered by brief instrumental data. The understanding of runoff pathways' effects on aquatic chemistry emerges primarily from studies in the boreal forest of Alaska (Koch et al., 2013) and Canada's High Arctic (Lafreniere & Lamoureux, 2013), but vast areas with contrasting physiographic, geological, permafrost and hydromorphic conditions are underrepresented in the literature. The consequence is that prediction capability across the diversity of circumpolar landscapes is low. The impacts of warming on streamflow in the circumpolar north have been known for several years (Anisimov et al., 2007; IPCC, 2013), but data scarcity remains an issue in documenting trends in aquatic chemistry or chemical loading from streams across a variety of scales and heterogenous landscapes (Holmes et al., 2013). In some regions, the data to detect change remains absent (Li Yung Lung et al., 2018). The chemical responses of large rivers integrate a diversity of regional signals (Tank et al., 2012), and the hypothesized drivers of change (e.g., permafrost degradation, precipitation increases, vegetation succession) are inferred so causality remains speculative. This uncertainty is due to the myriad possible changes in processes related to warming and associated impacts, such as landscape disturbance and others (O'Donnell et al., 2012) across the diversity of physiographic and hydrologic environments in the circumpolar region. The impacts of environmental change will depend on the driver of the change (temperature or precipitation), the form, intensity and duration of permafrost degradation (Vonk et al., 2015), and the configuration of the landscape. This is partly also dictated by landscape characteristics, including substrate type, permafrost extent, the nature of ground ice, and its distribution, all of which may dampen or amplify the degradation and how it manifests (Kokelj et al., 2017, 2023; Teutschbein et al., 2015). Because of the diversity of these controls on surface runoff, it is unclear how climate warming will impact different watersheds and how impacts will cascade through environmental systems. Nor is it known how resilient (Folke et al., 2004; Holling, 1973; Newton & Spence, 2023), cold regions hydrological and biogeochemical systems are to climate change.

Canada's subarctic Canadian Shield has been subject to late 20th and early 21st century warming (Zhang et al., 2019) with associated changes in land cover and permafrost (Sniderhan et al., 2023). Autumn runoff events are becoming more common as years with ample late summer and fall rain are becoming more frequent. The region's numerous lakes slow this runoff through the stream network into the winter months (Spence et al., 2011). The enhanced winter streamflow has a critical influence on annual geochemical cycling because under-ice processes increase ammonia and nitrate concentrations and affect redox cycling of other elements, such as arsenic (Palmer et al., 2019). Annual nitrogen load, in turn, increases by orders of magnitude (Spence et al., 2015). Resilient systems are those that have not crossed tipping points where system conditions, functions and behaviors are fundamentally altered. The growing body of knowledge from the Canadian Shield enables asking if streams in this landscape are resilient to climate stressors. and if, or at what tipping point, these patterns have led, or will lead, to wholesale changes in hydrological and biogeochemical regimes. The objective of the research was to determine if hydrology and biogeochemistry regimes of the Taiga Shield have been resilient to recent climate warming by investigating time series of streamflow, instrumental climate data and paleoclimate proxy data. These data were used to identify the key processes, thresholds and tipping points that control hydrological and biogeochemical resilience at a representative catchment in the Northwest Territories, Canada.

2. Study Region

The study region is the lake-rich Precambrian Shield landscape in subarctic northwestern Canada. Assessing the response of this landscape to climate change is necessary to understand because it represents a vast area of the circumpolar region (6.5×10^6 km^2) in Canada, Scandinavia and Russia but has been largely neglected in large-scale assessments (Makarieva et al., 2019). The study region is characterized by a mosaic of exposed granitic and metamorphic bedrock, thin unconsolidated till, organic and lacustrine deposits, and numerous lakes (Figure 1). Permafrost in the region is discontinuous. Glaciolacustrine clays, outwash and organic deposits are typically

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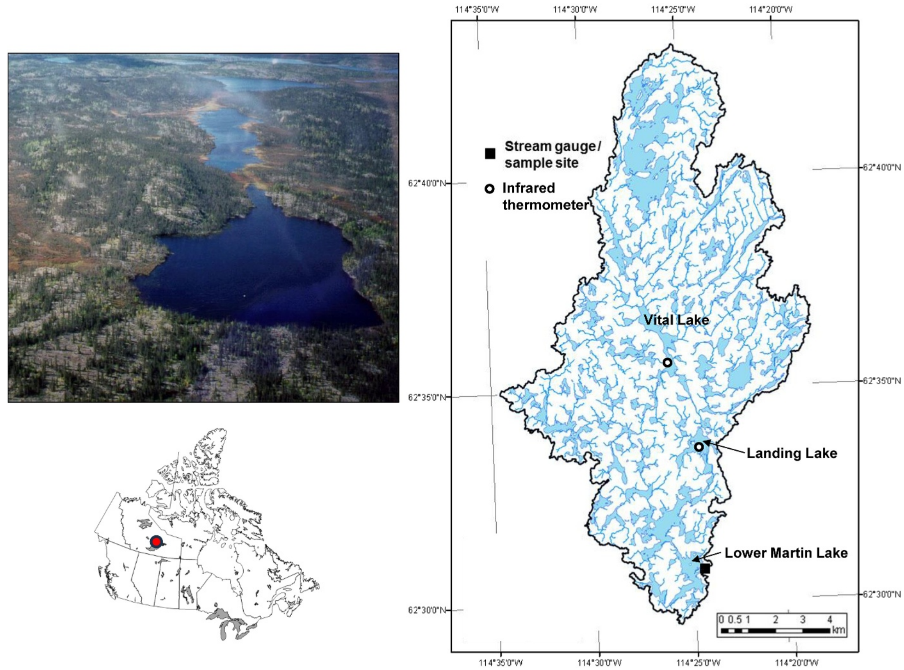

Figure 1. Photo of the landscape of the subarctic Canadian Shield illustrating the diversity of land cover types, including upland bedrock outcrops, forested hillslopes, valley bottom wetlands, and lakes. The map shows the Baker Creek Research Catchment and its location within Canada. The red circle denotes the location of Baker Creek. Blue polygons are water bodies.

underlain by permafrost, but bedrock and well-drained glaciofluvial sands are unfrozen (Morse et al., 2016). Overburden thickness can be <1 m, but is rarely >10 m. There is a ubiquitous organic soil layer of ~0.25 m. Vegetation communities are dominated by black spruce (*Picea mariana*), white spruce (*Picea glauca*) jack pine (*Pinus banksiana*), paper birch (*Betula papyrifera*), Labrador tea (*Ledum groenlandicum*), moss (e.g., *Sphagnum* spp.), and lichen (e.g., *Cladonia* spp.). The 1981–2010 regional climate, as represented at the Environment and Climate Change Canada climate station Yellowknife A (https://climate.weather.gc.ca/climate_normals/index_e.html; last date accessed: 15 September 2023), was typified by short cool summers (July mean air temperature ($\overline{T_a}$) of 17°C) and long cold winters (January $\overline{T_a}$ of −25°C). Half of the 289 mm average annual unadjusted precipitation falls as snow. Snow cover is present from October through March. Spring snow melt begins in mid to late April, with the annual peak streamflow typically occurring in May to early June, depending on the size of the watershed.

In this study the focus was on a small watershed, Baker Creek (Figure 1), which drains a 165 km^2 area. At this scale streams are closely linked with their watersheds (Buffam et al., 2007), facilitating the attribution of causality between stream biogeochemistry and catchment processes. A 155 km^2 watershed upstream has been gauged by Water Survey of Canada (WSC) since 1972. Measured at the Meteorological Service of Canada station Yellowknife A, the annual temperature normal during 1971–2000 was −4.6°C which warmed to −3.7°C over 1991–2020 (https://climate.weather.gc.ca/climate_normals/index_e.html; last date accessed: 15 September 2023). Furthermore, similar to many locations in the circumpolar north (Koch et al., 2013; St. Jacques & Sauchyn, 2009) Baker Creek has experienced higher winter streamflow fractions since the turn of the century (Spence et al., 2011). These climate and streamflow changes make Baker Creek an ideal watershed to investigate linkages between climate, hydrology, and aquatic chemistry regimes, in a climate sensitive and under studied region of the circumpolar north.

3. Methodology

There are well-established methods for evaluating sensitivity of hydrological variables to climate stressors and the stationarity in these time series. Resilience is the ability of a system to maintain function while exposed to a

Table 1
Definitions Used Within the Newton-Spence Resilience Framework (Adapted From Newton & Spence, 2023)

Term	Definition	References
Regime	Region in state space where a system flow, flux, or state variable retains the same attributes including states, phases, fluxes (e.g. normal, standard deviation, range), and predominant function and processes such that it is stationary and stable	Coopersmith et al. (2012); Park and Rao (2014); Burn et al. (2016)
Threshold	A point or transition zone where a process changes behavior (e.g., 0°C, infiltration capacity, wilting point, storage capacity) such that predominant phase, state, flows and fluxes change	Phillips (2003); Park and Rao (2014)
Process	A means by which water moves or is stored within the environment (e.g., precipitation, snowmelt, evapotranspiration and runoff)	Dingman (1973)
Process synchrony	A condition when and where one or more processes exhibit high spatial and temporal coherence	Seybold et al. (2022)
Tipping point	A point at which a regime changes function or the system is altered. A state in between regimes that is unstable and acts as a boundary between the two	Peterson et al. (2009); Lenton et al. (2008); Park and Rao (2014)
Function	One of the collection (comprised of processes such as precipitation and snowmelt), storage (comprised of water in the subsurface, snowpack, and surface), and release (comprised of processes such as runoff and evapotranspiration) of water. The predominant hydrologic function at a moment in time and place in space is controlled by phases, states, and fluxes	Black (1997); Wagener et al. (2007); Falkenmark et al. (2019); Gleeson et al. (2020)
Resilience	The ability of a system to maintain function, structure, identity, and/or feedbacks while exposed to a stressor or perturbation, thus remaining within the same regime	Holling (1973); Folke et al. (2004); Walker et al. (2004); Mao et al. (2017); Parsons and Thoms (2018); Gleeson et al. (2020)
Latitude	Distance to a tipping point, delineated by the boundaries of a regime, and representing the maximum amount a system can be changed before losing its ability to recover and beyond which the system moves into a new regime	Walker et al. (2004); Park and Rao (2014); Hodgson et al. (2015)
Resistance	The sensitivity of a process to stressors that control how difficult it is to overcome the latitude. This can include the speed or rate at which a system responds and recovers from a stressor or disturbance and return to its original function	Walker et al. (2004); Park and Rao (2014); Hodgson et al. (2015)
Precariousness	How close the current state of the system is to a limit, where at its absolute minimum precariousness is equal to latitude	Walker et al. (2004); Hodgson et al. (2015)

stressor or perturbation (Table 1), which requires different methodologies than those used to evaluate stationarity, the ability of states and flows to fluctuate within an unchanging envelope of variability. Here, we apply the hydrological resilience framework of Newton and Spence (2023) to measure resilience. The Newton-Spence framework ensures the presence of four key traits necessary for a robust application of the concept of resilience to catchment hydrology. An evaluation of resilience requires (a) the identification and justification of a baseline regime, (b) an evaluation of function, (c) an assessment of both resistance and latitude or precariousness, and (d) an investigation of key processes and how they interact to manifest into thresholds and tipping points. These definitions are summarized in Table 1.

3.1. Baseline Data

Two climatological baseline periods were selected: a 30 years instrumental climate data record (1971–2000) and a 290 years (1700–1990) tree-ring proxy climate data record that together produce a 300 years partially cross-validated record. Daily adjusted and homogenized precipitation and temperature data from the only long-term Meteorological Service of Canada stations in this region (Yellowknife A and Fort Simpson) were extracted from Environment and Climate Change Canada's Adjusted Historical Canadian Climate Data set (AHCCD; https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data.html; last date accessed 2 Nov 2023) for the periods of record. The Yellowknife A record spans from 1942 to 2022 and the Fort Simpson record spans from 1897 to 2022. The records in the AHCCD developed by the Meteorological Service of Canada are corrected for inhomogeneity due to station relocation or improvements in data collection methods and equipment and are the most robust for climate change applications (Mekis & Vincent, 2011). From these data, mean monthly temperature and total monthly precipitation were calculated. The autumn 0°C isotherm day of year was determined and is defined as the first day in autumn at which mean daily temperature dropped below 0°C.

The observed meteorological baseline is short relative to the periodicities in precipitation known to occur in this region (Newton et al., 2014; Pisaric et al., 2009; Spence & Rausch, 2005). The use of the 30-year instrumental record (1971–2000) is the length typically used for water management purposes but is of inadequate length to assess decadal-to-centennial scale system change known to affect these environments (Dalton et al., 2018; Pisaric et al., 2009). To place the short baseline period into a longer-term centennial-scale context, samples of white spruce taken in 2010 were used to build a second, proxy climatological baseline times series. Ten sites with a minimum of 21 trees were sampled (two cores per tree) within a 50 km radius of Baker Creek at each site for a total of 210 trees and 420 series. Samples were collected from each tree approximately 1.3 m above ground level. At each site, older-looking trees (large trunks and limbs, gnarled shape and structure) were preferentially sampled to maximize the length of the tree-ring record. However, to avoid sub-population biases younger trees were also sampled (Esper et al., 2007). Where dead standing or fallen snags were present, these were sampled to extend the tree-ring series beyond the age of the living trees at a site. In the laboratory, samples were dried, sanded with progressively finer sandpaper, visually cross-dated, and measured using standard dendrochronological techniques (Fritts, 1976; Speer, 2010). Visual cross-dating was checked using the statistical software program COFECHA (Grissino-Mayer, 2001). Ring-widths were measured using a Velmex Unislide sliding bench micrometer with a measurement precision of 0.001 mm and the computer software program Measure J2X (VoorTech Consulting, 2007). Following measuring and cross-dating, a dimensionless standardized site chronology was developed using signal-free regional curve standardization (RCS) methodology (Melvin & Briffa, 2008). This standardized chronology removed biological growth trends and other growth anomalies related to internal and external site factors (Fritts, 1976). A resulting ~300-year signal-free RCS chronology, referred to here as COMP1, was calculated using the program TOMB, which is a beta version of the detrending computer program ARSTAN developed at the Lamont Doherty Tree Ring Laboratory. Relationships among the COMP1 chronology and warm season (June-July-August-September; JJAS) precipitation determined from the AHCCD Yellowknife A site were derived with correlation analysis to determine the value of COMP1 as a proxy for precipitation. This correlation was found to be comparable to those reported in Pisaric et al. (2009). The tree ring reconstruction of the Northern Hemisphere annual air temperature of D'Arrigo et al. (2006) was used as a proxy for air temperature. These precipitation and air temperature proxy records represent the second baseline period, 1700–1990.

Daily streamflow records for the Water Survey of Canada (WSC) hydrometric stations Baker Creek at the outlet of Lower Martin Lake (07SB013) and Baker Creek near Yellowknife (07SB009) from http://www.wateroffice.ec.gc.ca/index_e.html (last date accessed 2 Nov 2023) comprise a 44-year hydrometric data set from 1972 to 2022, where 1972 to 2000 aligns with the observed climate baseline. The record is 97% complete, but there are missing data from 1983, 1984, 1986, 1991, 1996, 1997, and 1998 that prevented the integration of winter and water year streamflow values. Weekly or bi-weekly water samples of Baker Creek downstream of Lower Martin Lake were taken from April 2010 to December 2022. Water samples during this period were analyzed for total inorganic nitrogen (TIN) comprised of ammonia (NH_3-N; mg l^{-1}) nitrate (NO_3-N; mg l^{-1}), and nitrite (NO_2-N; mgl-1). All samples were analyzed at the Taiga Environmental Laboratory in nearby Yellowknife, Northwest Territories. Colorimetric determination was used to measure NH_3-N, NO_3-N and NO_2-N concentrations, to detection limits of 0.01 mg l^{-1}, modified from Standard Methods for the Examination of Water and Wastewater 22nd Ed., Method 4500-NH3 G Automated Phenate Method 2012. The United States Geological Survey LOADEST program (Runkel et al., 2004) was used to identify the best form of a calibration regression between paired streamflow, Q, and constituent concentration, C. This equation ($r^2 = 0.73$, bias $= -2.25\%$, Nash Sutcliffe Index $= 0.3$) was applied to the daily discharge record (1972–2022) to obtain loads of TIN and its component species.

3.2. Evaluation of Function

Black (1997) identified three major hydrological functions; collection, storage and release (Table 1). Collection is how a catchment predominantly receives water (e.g., snowfall vs. rainfall). Storage is how, when, and where water is stored (e.g., snow, surface, subsurface). Release is the removal of water from a catchment, which is comprised of evapotranspiration and streamflow. Because of recent changes in streamflow seasonality across the circumpolar north, the selected focus was on the release function during winter (October to March) as an indicator of the seasonality of the hydrological regime. Winter catchment evapotranspiration (ET_w) is relatively low compared to winter streamflow (Q_w) (Spence & Hedstrom, 2018), so only Q_w needs to be assessed to evaluate

Table 2

Climate and Hydrometric Data Sources, Definitions of Tipping Points Between Regimes, and Methods to Determine Resistance and Regime Shifts (See Also Table 1 for Definitions)

Periods			
	Historic - proxy paleoclimate (1700–1990)	Historic - instrumental record (1971–2000)	Current 21st century (2001–2022)
Climate (precipitation and temperature)	COMP1 and D'Arrigio et al. (2006)	MSC stations Yellowknife A and Fort Simpson	MSC stations Yellowknife A and Fort Simpson
Streamflow		WSC gauges Baker Creek at outlet of Lower Martin Lake (07SB013) and Baker Creek near Yellowknife (07SB009)	WSC gauge Baker Creek at outlet of Lower Martin Lake (07SB013)
Stream chemistry		Bi-weekly samples/LOADEST estimate	Bi-weekly samples/LOADEST estimate
Resistance			
Correlation among P_{JJAS}, PDO, AO, Q_w/Q_{wy}, NH_3-N_{wy}/TIN_{wy}			
Tipping point			
Hydrological release	Winter release function recession versus runoff dominated (<> 0.5)		
Biogeochemical source	Mineralization dominated (<> 0.5)		
Latitude/precariousness/regime shift			
$\Pi = 0.5 - x$			
Kolmogrov-Smirnov test used to confirm a change in Q_w/Q_{wy} probability density function			
Kolmogrov-Smirnov test used to confirm a change in NH_3-N_{wy}/TIN_{wy} probability density function			

Note. P_{JJAS} is summer and fall precipitation (i.e., June, July, August and September). The two teleconnection indices evaluated were the Pacific Decadal Oscillation (PDO) and Arctic Oscillation (AO). The fraction of the water year streamflow that occurs in winter (i.e., October to March) is Q_w/Q_{wy}. The fraction of NH_3-N in total inorganic nitrogen loads in the water year is NH_3-N_{wy}/TIN_{wy}. Precariousness is denoted as Π and x denotes the average of Q_w/Q_{wy} or NH_3-N_{wy}/TIN_{wy} for historic baseline and current periods.

winter release function. The release function of the winter streamflow regime was considered "recession-dominated" if Q_w was less than half water year streamflow (Q_{wy}) (i.e., $Q_w/Q_{wy} < 0.5$) and "runoff-dominated" if it was more than half water year streamflow (Table 2).

Catchments can biogeochemically function as a source, sink, or transport link for constituents (Cole et al., 2007). The annual nitrogen cycle in cold oligotrophic lakes and streams is highly seasonal as effective uptake of inorganic nitrogen in terrestrial and aquatic systems results in very low concentrations during much of the open water season. Allochthonous lake processes dominate the system as the landscape becomes hydrologically disconnected from the stream network during streamflow recession and ice forms on lakes. Mineralization under lake ice cover increases NH_3-N concentrations until late winter after which denitrification by organisms reduce the nitrogen just before spring. Because this seasonality in concentrations can lead to the catchment becoming a source of NH_3-N when cold-season streamflow is high, the catchment's inorganic nitrogen regime was defined as "mineralization-dominated" if water year NH_3-N loads were greater than 50% of total water year inorganic nitrogen loads (i.e., NH_3-$N_{wy}/TIN_{wy} > 0.5$) (Table 2).

3.3. Assessment of Resistance and Latitude

Summer and autumn precipitation (June, July, August, September—P_{JJAS}) data were collated for the 1971–2000 baseline period, as sustained wet conditions through summer and autumn can result in elevated winter streamflow in the subarctic Canadian Shield (Spence et al., 2011, 2014). The Pacific Decadal and Arctic Oscillations (PDO, AO) have been linked to synoptic atmospheric conditions in the southern Northwest Territories that influence late summer and autumn precipitation (Newton et al., 2014; Petrone & Rouse, 2000; Pisaric et al., 2009; Spence & Rausch, 2005). The PDO represents multi-decadal scale fluctuations in sea surface temperature anomalies in the North Pacific Ocean. Positive phases are associated with warmer, drier conditions in north western North

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America, while negative phases are associated with cooler, wetter conditions (Mantua et al., 1997). The AO is a measure of the oscillation between anomalously low pressure (positive phase) and high pressure (negative phase) over the Arctic Ocean, where the latter phase is associated with more frequent cold air outbreaks over North America (Thompson & Wallace, 1998). Monthly values of the National Centers for Environmental Information PDO and AO indices were obtained, which are based on the National Oceanic and Atmospheric Administration's extended reconstruction of sea surface temperatures (Huang et al., 2015; https://www.ncei.noaa.gov/access/monitoring/pdo/; last date accessed 22 February 2024). Resistance of Q_w/Q_{wy} and NH_3-H_w/TIN_{wy} to these three indices, P_{JJAS}, PDO and AO, was measured using the Spearman rank correlation in R (Wilkinson & Rogers, 1973) and the *lm* function in the *stats* package in R (R Core team, 2022) with the correlation coefficient and slope of the best-fit line used as resistance metrics.

To supplement these statistical analyses of the observational climate time series, spectral analysis was used to identify if there were statistically significant cycles in climate indices to which the catchment function was non-resistant. Instrumental climate time series (1942–2000), the PDO values (June-July-August; JJA; 1854–2000), and an overlapping portion of the COMP1 tree-ring data set (1854–2000) were analyzed. All data were detrended by linear regression before time series analyses. Redfit analysis (Schulz & Mudelsee, 2002) was used once a runs test was applied to test the appropriateness of this model. A rectangular window and a 95% false alarm level were used to determine statistically significant periodicities in the data. Wavelet analysis of the tree ring chronology and PDO (JJA) data sets and cross-wavelets of PDO (JJA)—tree ring chronology were carried out. The Morlet mother wavelet was used in all cases and the lag for determining the 95% significance levels was calculated using an ARMA model (AR = 0; MA = 1) The *biwavelet* package (Gouhier et al., 2016; Hammer et al., 2001) in R v. 3.2.4 were used for time series analysis.

To determine if tipping points in the Baker Creek hydrological release and biogeochemical source functions have been reached and to determine if Baker Creek, as representative of the western subarctic Canadian Shield region, has been resilient to current warming a third record, the current 21st century (2001–2022), was evaluated. Latitude, Λ, is the range within which a function is predominant between tipping points (Peterson et al., 2009; Walker et al., 2004) (Table 1). For example, the regime of the hydrological release function is defined as "recession-dominated" if Q_w was less than half water year streamflow (Q_{wy}) (i.e., $Q_w/Q_{wy} < 0.5$) and the recession dominated regime Λ is $0 < Q_w/Q_{wy} < 0.5$. Precariousness, Π, the proximity to a tipping point, was calculated as the difference between 0.5 and Q_w/Q_{wy} or NH_3-N_{wy}/TIN_{wy} for each water year. Finally, if there were significantly different statistical distributions between historic and current metrics identified using the two-sample Kolmogorov–Smirnov (KS) tests (R stats package 3.5.1, R Core Team, 2022), this was taken as evidence of a regime shift. The KS test was selected as it is widely used to test the hypothesis that two data series are the same continuous distribution (e.g., Gleeson & Paszkowski, 2014; Newton et al., 2014).

3.4. Hydrological and Biogeochemical Processes

We selected data from two exemplar water years to identify important physical processes that control hydrological and biogeochemical functioning. Each water year exhibited predominant processes during which winter streamflow was either (a) predominantly a recession of the spring freshet (2012–2013); or, (b) enhanced by runoff due to high summer and autumn precipitation (2011–2012). Data from June 1 to April 30 for each of the periods were collated. These include daily precipitation and air temperature data from Yellowknife A. These data were used to determine the first arrival date of the autumn 0°C isotherm, which is aligned with the cessation of rainfall that can generate winter streamflow. They were also used to identify if cumulative P_{JJAS} exhibited a threshold typically required to generate streamflow. Streamflow data from the Baker Creek WSC gauge (07SB013) were also collated. Water chemistry data for those two periods were extracted from the time series calculated with LOADEST, described above. The date of the onset of lake ice cover is important as lake ice is a catalyst for an increase in mineralization. These dates were identified from surface temperature data collected using Campbell Scientific SI-111 infrared thermometers pointing at Landing Lake and Vital Lake in the Baker Creek watershed (Figure 1).

4. Results

4.1. Baseline Conditions

Within a series of wet and dry cycles, Yellowknife experienced a consistent increase in P_{JJAS} from 1971 to 2000 (Figure 2a). Average P_{JJAS} from 1971–2000 was 150 mm. The longer (~300 years) reconstructed baseline

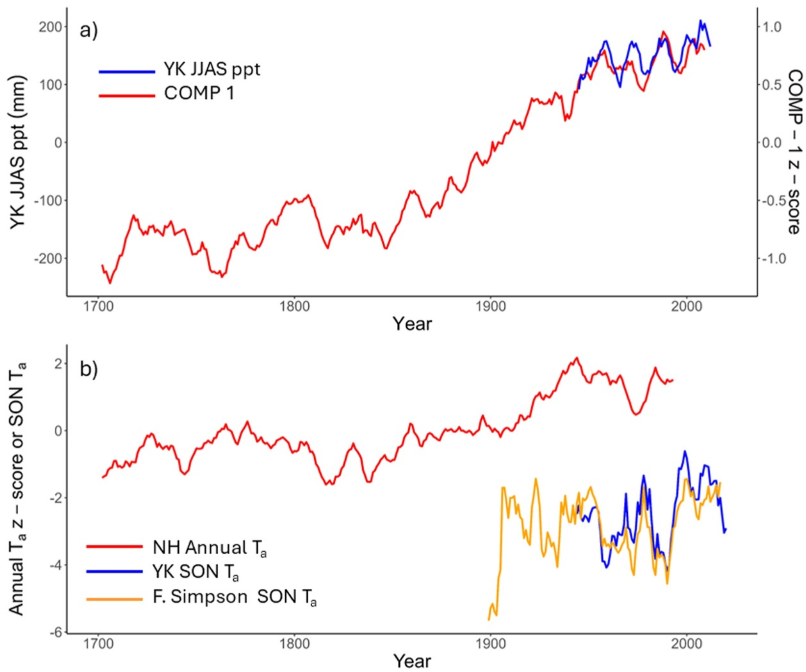

Figure 2. (a) Time series of 5-year running means of P_{JJAS} at Yellowknife A and COMP-1 z-scores and (b) September, October, and November (SON Ta) air temperatures at Yellowknife A (YK) and Fort Simpson and reconstructed Northern Hemisphere (NH) annual temperatures (D'Arrigio et al., 2006).

indicates that at no other time in the previous 270 years was the summer and autumn climate at Yellowknife as wet as during the last thirty years of the twentieth century. Figure 2b illustrates autumn (SON) air temperatures from 1971 to 2000 were −2.6°C at Yellowknife and −3.2°C at Fort Simpson, 370 km to the SW. The reconstructed air temperature record of D'Arrigio et al. (2006) indicates the Northern Hemisphere during the previous 270 years was always cooler than the last part of the 20th century, and Yellowknife autumn air temperatures would have been approximately −5°C.

Median water year streamflow for Baker Creek (Q_{wy}) from 1972 to 2000 was 0.13 m^3/s (Table 3). During this baseline period, the winter streamflow (Q_w) median was 0.003 m^3/s; in many winters, streamflow was absent, producing a baseline median Q_w/Q_{wy} of 0.02. Median water year TIN and NH_3-N loads were 379 and 71 kg, respectively, yielding a NH_3-N/TIN fraction of 0.2 for the 1972–2000 period (Table 3). Water years with winter runoff events occurred four times and experienced median Q_{wy} values of 0.26 m^3/s, twice that of water years with recession-dominated winters (Figure 3). Median values of Q_w between the two conditions (recession- and winter runoff-dominated) were 0.001 and 0.15 m^3/s. When winters were dominated by recession, Q_w/Q_{wy} median values

Table 3
Median Values for Baseline and Current Periods, Positive and Negative Phases of the PDO, as Well as All Years in Which Winter Runoff was Dominated by Recession Processes or Runoff Generating Processes

	1972–2000	2001–2022	Recession years	Runoff years	+PDO	−PDO
Q_{wy} (m^3/s)	0.13	0.26	0.1	0.33	0.09	0.21
Q_w (m^3/s)	0.003	0.13	0.001	0.15	0.0006	0.09
Q_w/Q_{wy}	0.02	0.53	0.01	0.57	0.008	0.38
TIN_{wy} (kg)	379	650	265	840	193	512
NH_3-N_{wy} (kg)	71	215	46	221	37	181
NH_3-N_{wy}/TIN_{wy}	0.2	0.3	0.19	0.29	0.19	0.23

Note. Streamflow is denoted by Q, ammonia by NH_3-N and total inorganic nitrogen by TIN. Subscripts are w for winter and wy for water year.

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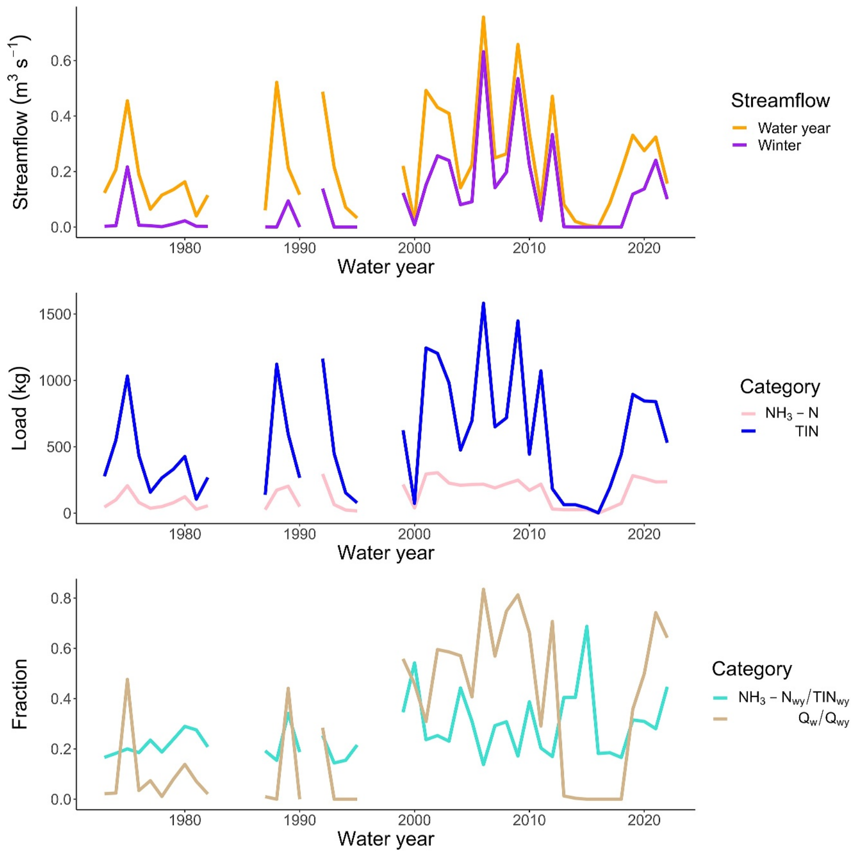

Figure 3. Time series of water year and winter streamflow at Baker Creek at the outlet of Lower Martin Lake, NH_3-N and TIN water year loads and the fractions of winter streamflow and NH_3-N loads relative to water year streamflow and TIN loads.

were 0.01, but when winter runoff events occurred, they dominated the water year hydrograph (median Q_w/Q_{wy} value of 0.57) (Table 3; Figure 3).

4.2. Resistance, Precariousness and Regime Shifts

Significant correlation between the PDO and summer/autumn precipitation (P_{JJAS}) indicates the strong influence of the Pacific atmospheric teleconnections on precipitation quantity and patterns in the Northwest Territories (Table 4). A negative anomaly of the PDO is associated with wetter conditions in this region (Figure 4a; Table 4). Streamflow the following winter, $Q_w + 1$, exhibited threshold-mediated behavior with ~120 mm of precipitation from June through September (P_{JJAS}) required to generate streamflow in all but one instance (Figure 4b). Winter streamflow can remain low and near zero with rainfall as high as 200 mm, depending on intensity, duration and timing of the rainfall during the preceding year's summer and autumn period. Every case of P_{JJAS} above 200 mm resulted in a winter runoff event in the Baker Creek watershed. This pattern suggests Q_w is resistant to P_{JJAS} below 200 mm because of storage demands in the landscape and lakes, after which it becomes non-resistant. Similarly, NH_3-N water year loads remain low without winter runoff (Figure 4c). When Q_w averaged <0.05 m^{3}s^{-1}, NH_3-N_{wy} averaged 63 ± 52 kg. Above a Q_w of 0.05 m^{3}s^{-1}, average NH_3-N_{wy} was an order of magnitude higher at 235 ± 38 kg.

The period 2000–2022 continued the trend toward wetter conditions as average P_{JJAS} increased to 172 mm. Warming continued as SON T_a averaged −1.8°C at Yellowknife and −2°C at Fort Simpson (Figure 2), up roughly 1°C from the preceding period. The combination of wet and warm autumn conditions experienced during the 21st century was unprecedented in the last 300 years. Since 2000, Baker Creek water year flows have increased by 42%, and winter flows have increased 433% such that the median fraction of winter flow is now 0.53. These changes have been driven by more frequent winter runoff events generated by summer and autumn rains (Figure 4) that have exceeded landscape and lake storage capacities.

Table 4
Resistance Metrics (i.e., Best Fit Line Slopes and Spearman Correlation Coefficients) of Precipitation, Winter Streamflow and Water Year NH_3-N Load Response to Atmospheric Circulation, Warm Season Precipitation and Winter Streamflow, Respectively

	P_{JJAS}	$Q_w + 1$	$NH_3\text{-}N_{wy} + 1$
Slope of line of best fit			
PDO	−20	−0.07	−38
AO	13	0.009	−23
P_{JJAS}		0.002	1.4
$Q_w + 1$			449
Correlation coefficient			
PDO	**0.36**	**0.4**	**0.34**
AO	0.11	0.02	0.09
P_{JJAS}		**0.71**	**0.71**
$Q_w + 1$			**0.65**

Note. Bolded values are significant with 95% confidence. The three relationships that represent1) the control of large scale atmospheric conditions (i.e., the Pacific Decadal Oscillation, PDO) on seasonal precipitation (P_{JJAS}), 2) the influence of seasonal precipitation on streamflow the following winter ($Q_w + 1$), and 3) the correlation between winter streamflow and the following water year NH_3-N load ($NH_3\text{-}N_{wy} + 1$) are illustratedin Figure 4.

Kolmogrov-Smirnov test results (Table 5) examining the distribution of winter streamflow fraction reveal a statistically significant shift in 2000 (Figures 5a–5c). Median Q_w/Q_{wy} values above 0.5 indicate the release function has shifted to a new winter runoff-dominated regime. With Π equal to 0.03 it remains precarious in the new regime. Kolmogrov-Smirnov test results indicate there too was a significant shift in $NH_3\text{-}N_{wy}$ loads (Figures 5d–5f and Table 5), but these were insufficient to change the nitrogen regime. Median values of $NH_3\text{-}N_{wy}/TIN_{wy}$ that approach 0.5 suggest that there has only been an increase in precariousness (Tables 3 and 5). The synchronization of atmospheric and hydrological processes has occurred often enough since 2000 to shift the hydrological regime, but the synchronization did not have a frequency and magnitude necessary to cascade and affect biogeochemical functioning.

4.3. Processes

Figure 6 illustrates three non-linear processes; precipitation, runoff, and mineralization that become synchronized during winter runoff generation. Comparison of the dry 2012–2013 and wet 2011–2012 winters show that warm autumn air temperatures delay the onset of the 0°C air temperature isotherm (Figure 6a). This causes a phase shift in precipitation to rainfall rather than snowfall in autumn. Runoff response from watersheds in cold landscapes is a threshold-driven phenomenon (Mielko & Woo, 2006, Figure 4). A longer rainfall season increases the probability that late summer and autumn precipitation will address summer storage deficits in the soil and water bodies that develop in this continental, lake-rich region (Spence & Rouse, 2002) (Figures 6b and 6c). A longer rainfall season also provides more water at a time of reduced evaporative demand. With the onset of ice cover, biological activity slows in lakes, which comprise a significant component of stream networks in a shield-dominated landscape. Slower biological activity under ice decreases in-lake uptake processes and mineralization becomes relatively more important, resulting in the rapid increases of aqueous NH_3-N concentrations (Figure 6d). When rainfall, runoff, and mineralization synchronize NH_3-N loads increase by orders of magnitude (Figures 4 and 6e).

Spectral analysis identified significant periodicities of 38, 6, 5 and 2.1–3 years in the PDO that influences precipitation and streamflow in this region (Figure 7). The shorter cycles (Haynes, 1998) may be attributable to the Quasi-Biennial Oscillation (QBO), which impacts stratospheric circulation during northern Hemisphere winters (Baldwin et al., 2001). Eastward QBO meridional circulation leads to weakened subpolar and polar stratospheric winds, and a downward propagation of high latitude cold temperature anomalies into the lower atmosphere (Garfinkel et al., 2012). The 38-year periodicity is temporally consistent with the 35-year and 30-year

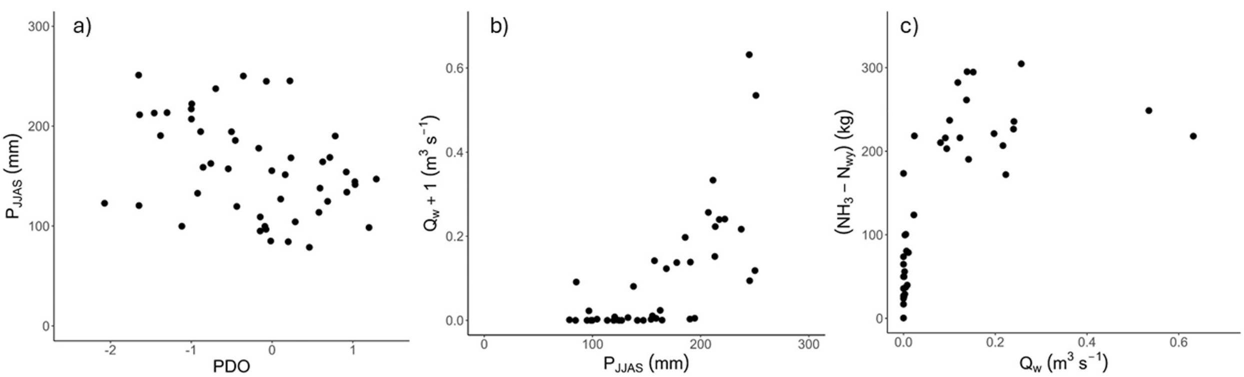

Figure 4. Scatterplots illustrating significant relationships listed in Table 4 including those between atmospheric conditions as represented by the Pacfic Decadal Ossicilation and local seasonal precipitation (a) PDO and $P_{JJAS)}$; local seasonal precipitation and streamflow the following winter (b) P_{JJAS} and $Q_w + 1$); and winter streamflow and NH_3-N water year load (c) $Q_w + 1$ and $NH_3\text{-}N_{wy}$).

Table 5
Kolmogrov-Smirnov Test Results Determining Regime Shifts and Precariousness

	KS	Π (1972–2000)	Π (2001–2022)
Q_{wy} (m^3/s)	**D = 0.4 p = 0.04**	-	-
Q_w (m^3/s)	**D = 0.53 p = 0.002**	-	-
Q_w/Q_{wy}	**D = 0.53 p = 0.002**	0.48	*0.03*
TIN_{wy} (kg)	$D = 0.35$ $p = 0.09$	-	-
NH_3-N_{wy} (kg)	**D = 0.5 p = 0.004**	-	-
NH_3-N_{wy}/TIN_{wy}	$D = 0.35$ $p = 0.08$	0.3	0.2

Note. Precariousness (Π) values of the release and nitrogen regimes. Bolded text implies statistically significance ($p < 0.05$). Italicized values denote precariousness of the new release regime.

periodicities in the proxy precipitation record COMP1 indicating that the PDO is an important mechanism influencing water availability in the Northwest Territories (Pisaric et al., 2009). Cross-wavelet analysis (Figure 7) identifies significant ∼30–40 years and ∼2–5 years signals in tree-ring width proxies of precipitation that are respectively coherent with periodicities in the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO).

5. Discussion

5.1. Drivers of Change

The resilience of hydrological regimes and drivers of change will vary with climate and landscape configuration across the diverse range of northern circumpolar landscapes. Understanding these drivers is important as attribution of shifts could be misplaced without proper diagnosis. The focus may then turn to incorrect theories. This risks the viability of prediction systems if resources are spent incorporating flawed physical mechanisms. Adaptation efforts may also be poorly designed if water managers are focused on the wrong drivers of change. Several of the original studies that identified increasing trends in circumpolar winter streamflow attributed them to permafrost loss (St. Jacques & Sauchyn, 2009; Streletskiy et al., 2015; Toohey et al., 2016) even though there would have had to have been a variety of mechanisms among the diversity of climates and permafrost conditions. As Walvoord et al. (2012) and Evans et al. (2020) point out, these were inferences. While difficult to disentangle the interacting and compounding environmental changes responsible for the enhanced winter streamflow (Hinzman et al., 2020),

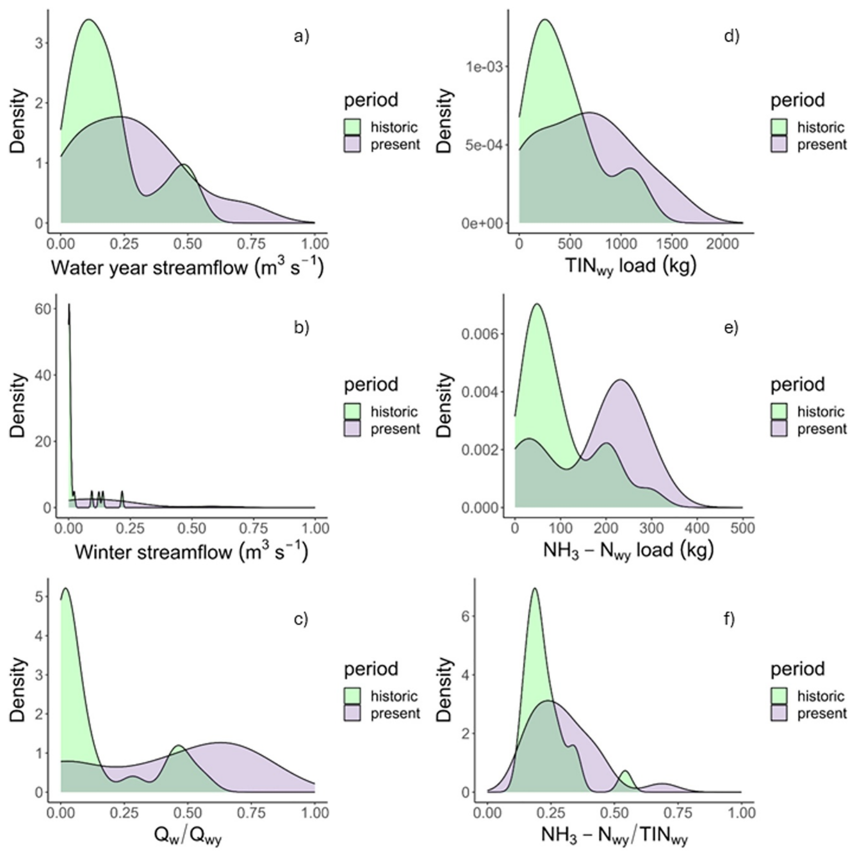

Figure 5. Probability distributions for the short historic baseline (1971–2000) and present (2001–2022) records of (a) water year and (b) winter streamflow, that illustrate the precariousness of fractions of winter to water year streamflow (c), as well as probability distributions of water year (d) TIN and (e) NH_3-N loads and the (f) NH_3-N_{wy}/TIN_{wy} fractions as metrics of the resilience of Baker Creek biogeochemical regimes.

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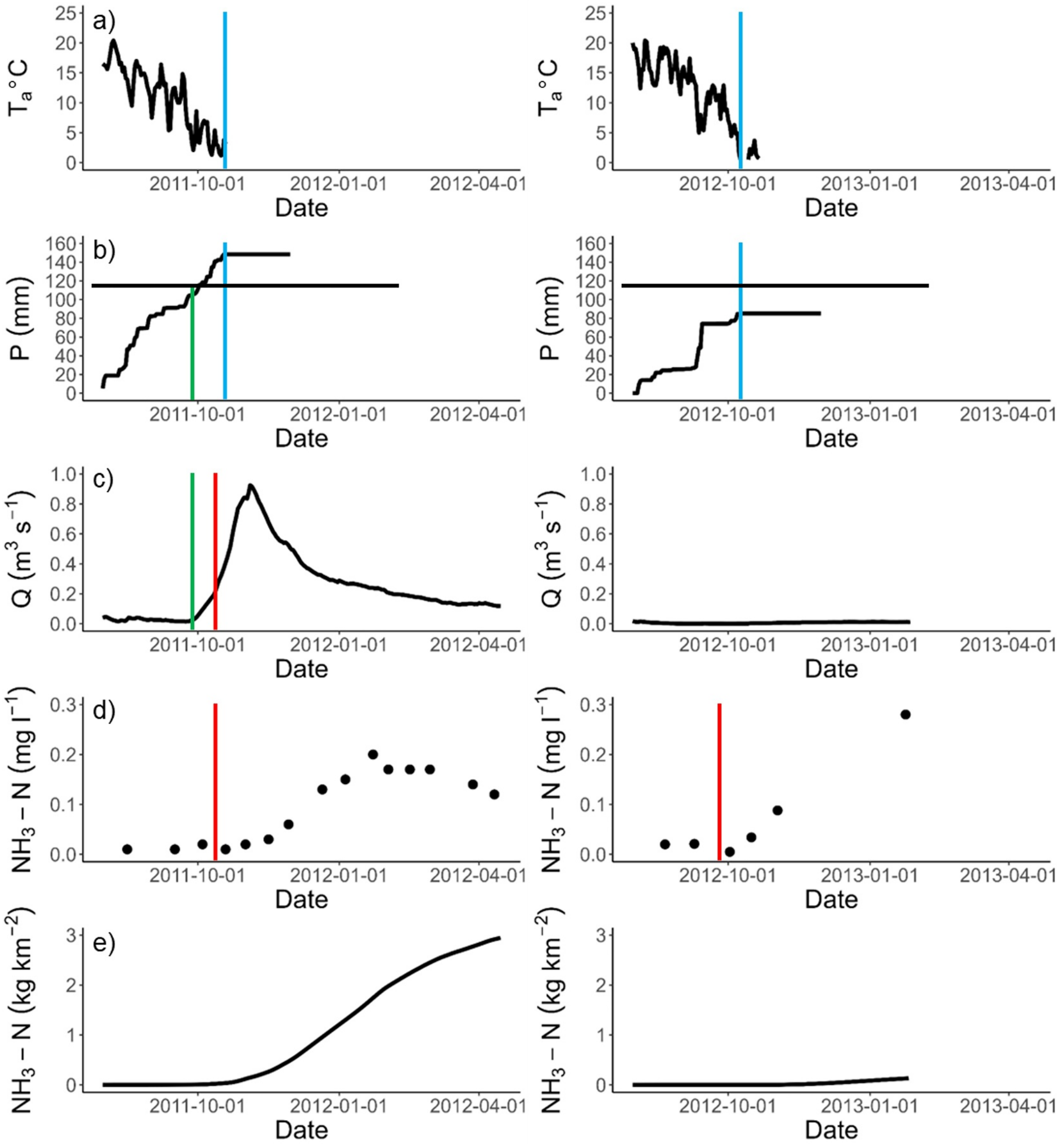

Figure 6. Data from the high rainfall 2011–2012 season (left column) and low rainfall 2012–2013 season (right column) that illustrate the impact of non-linear processes on inorganic nitrogen flux at Baker Creek. The blue lines in the air temperature row (a) denote the first arrival date of the 0°C isotherm, which is aligned with the cessation of rainfall in cumulative precipitation row (b). In 2011, cumulative rainfall before the 0° isotherm arrived exceeded the precipitation threshold for generating runoff (the black line in row b), which coincided with runoff initiation (green line down to row c). The completion of lake freeze-up in late October (red line in rows c and d) results in increasing mineralization, which when coincident with enhanced streamflow, increases NH_3-N load by orders of magnitude (row e).

advances have been made. Numerical model exercises provide growing evidence about how permafrost loss enhances baseflow during winter. Large basin scale model simulations reveal that the change in groundwater flux with permafrost thaw depends on the relative hydraulic conductivity between the antecedent frozen and subsequent thawed states of the geologic materials (Walvoord et al., 2012). Steeper hydrograph recession slopes imply that thicker active layers and longer periods of active layer freezeback are responsible for enhanced baseflow in continuous permafrost zones, but limited empirical evidence means the mechanism responsible in discontinuous permafrost zones remains elusive (Evans et al., 2020). In the Taiga Plains ecozone of the southern Northwest Territories, Connon et al. (2014) and Chasmer and Hopkinson (2017) measured enhanced hydrological connectivity in the drainage network with the loss of permafrost hosting peat plateaus. These changes enhanced annual runoff ratios but it is unclear if winter streamflow has been enhanced through this process. Large scale

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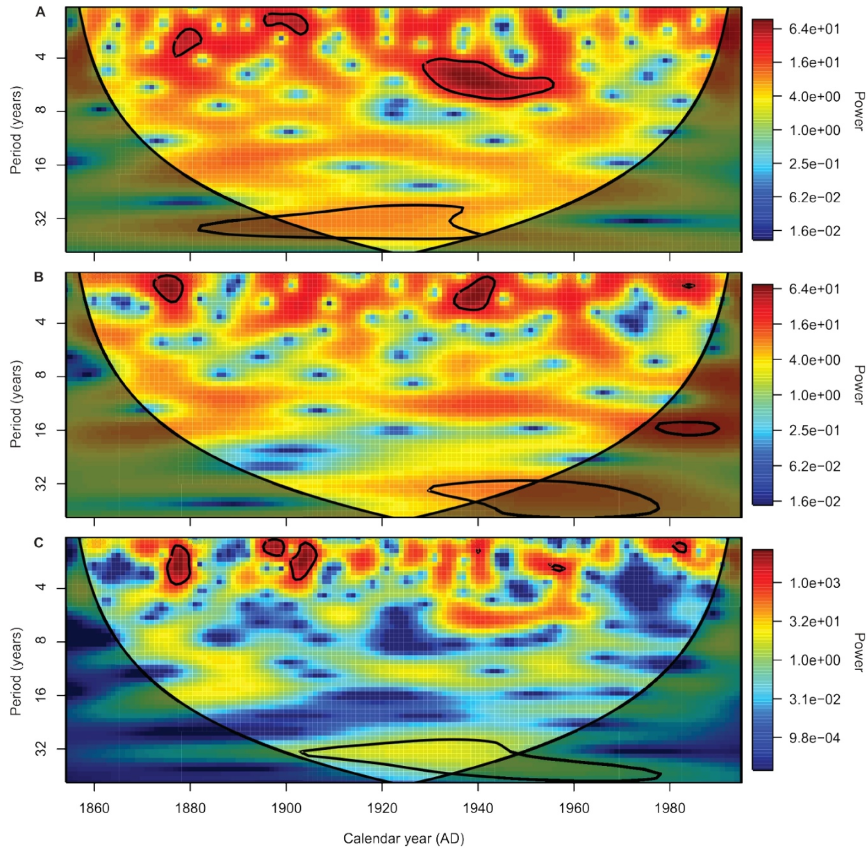

Figure 7. Wavelet analysis of Pacific Decadal Oscillation June-July-August (a); COMP1 tree ring proxy of P_{JJAS} (b); Cross-wavelet analysis of PDO JJA versus COMP1 (c). 95% significance levels shown by the black outline indicate significant periodicites approximately every 4 and 32 years.

cryohydrogeological models applied in the discontinuous permafrost zone under warming climate conditions suggest this could be the case as previously long flow paths get truncated, enhancing vertical connectivity of intrapermafrost groundwater and the proportion of runoff emanating from subsurface pathways (Rawlins & Karmalkar, 2024). Baker Creek is in the discontinuous permafrost zone, but the watershed is mostly non permafrost hosting exposed bedrock and lakes. Permafrost is present in the wetland conduits between lakes (Morse et al., 2016) and these may evolve into hot spots of subsurface hydrological connectivity, but the results presented here show that meteoric water needs to be available. Bennett et al. (2023) found that trends in streamflow time series in the discontinuous permafrost zone were more highly correlated with climate variables (e.g., rainfall) than with permafrost characteristics, suggesting winter streamflow response is more directly influenced by climate than permafrost loss. Similarly, higher autumn and early winter flows documented in Finland (Lintunen et al., 2024) and Russia (Makarieva et al., 2019) have been attributed to more frequent late autumn rain and increasing rain:snow ratios.

5.2. Regime Change

Much of the research investigating enhanced winter streamflow has focused on identifying trends and/or shifts in streamflow time series (Bennett et al., 2023; Smith et al., 2007). However, there has been no clear identification of a change in hydrological regime until this study. There is a statistically significant change in winter streamflow that suggests there has been a change in regime, and this can be attributed specifically to changes in precipitation phase because of recent warming. The Baker Creek watershed arguably partitions water differently since the turn of the century and no longer exhibits a nival streamflow regime because of the rise in frequency of late autumn rains in a warmer atmosphere. This more frequent fall rain allowed for more frequent exceedances of a runoff generation threshold of ~120 mm rainfall, enhancing streamflow and raising lake levels over winter. Spence

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et al. (2014) suggests the source of winter runoff is recent meteoric water, so we suggest Baker Creek and comparable watersheds in the region are now in a newly documented "cold season pluvial" regime.

This study focused on inorganic nitrogen as an example of how biogeochemical systems could respond to climate warming induced changes in hydrological systems. Documented mechanisms responsible for changes in aquatic biogeochemical regimes in response to climate warming include altered runoff pathways (Frey et al., 2007) and terrestrial chemical cycling (Maclean et al., 1999), but this study presents a mechanism by which other constituents could be altered by hydrological regime change. Winter streamflow influences within-lake biogeochemical processing of nutrients, metal (loid)s, and carbon by mediating the delivery of organic matter and oxygen. For example, Palmer et al. (2021) identified how winter streamflow conditions influence arsenic cycling in these lake-dominated drainage networks. The volume of water entering a lake controls the position of redox boundaries within the water column with higher flows supressing the rising of the iron and sulfate reduction fronts, which reduces dissolved arsenic concentrations. Winters with low streamflow experience arsenic concentrations double to triple those of winters with high streamflow, suggesting that a change from a nival to a cold season pluvial regime will affect the mobility and fate of redox-sensitive elements.

While the cascading impacts of climate warming and permafrost loss on biogeochemistry are dependent on terrestrial changes (e.g., altered subsurface pathways), there are also important processes in the aquatic environment. Since lakes occupy upwards of 40% of some permafrost landscapes (Downing et al., 2006) and exhibit distinct processes important for biogeochemical fluxes, these processes (e.g., mineralization in this study) must be considered when assessing biogeochemical resilience. The loss of ice cover and associated changes in lake temperatures, stratification, and dissolved oxygen is one example (Woolway et al., 2022) among several (Saros et al., 2023) beyond changes in hydrological regimes (Smol & Douglas, 2007) and streamflow seasonality that should be considered in future research.

Similarly, the focus of this study was on the direct role of climate, specifically precipitation and temperature, on the resilience of hydrological and biogeochemical regimes in the Canadian subarctic. There are other indirect stressors, such as wildfire, that have the capacity to alter catchment hydrology and chemistry (Burke et al., 2005; Emmerton et al., 2020). The literature suggests fire would accelerate the trend toward enhanced baseflow documented here by promoting permafrost loss that expands subsurface pathways (Holloway et al., 2020; Nossov et al., 2013). It should be recognized that the degree to which this happens depends on antecedent land cover distribution; Spence et al. (2020) demonstrated that Taiga Shield catchments with more exposed bedrock and lakes are more hydrologically resilient to fire. However, this depends also on climate conditions as wet conditions following fire reduce hydrological resilience.

The Paris Agreement under the United Nations Framework Convention on Climate Change aims to keep global average surface temperatures from increasing well below 2°C from the post-industrial baseline (1850–1990) (i.e., <1.5°C) to prevent tipping points in Earth systems. The evidence presented here suggests that because northern latitudes warm faster than the global rate (i.e., Arctic amplification) (England et al., 2021; Serreze & Barry, 2011) hydrological regimes can lose resilience and regime shifts will occur, and have occurred, well below the +1.5°C global scale mean surface temperature value. From 1850 to 1900 to 1995–2014, global mean surface temperatures increased 0.85 ± 0.12°C (Gulev, 2021). Near the turn of the 21st century, the mean annual air temperatures at Yellowknife surpassed −4.5°C (Table 6), which was a regional air temperature tipping point for the new hydrological regime. This coincides with a global scale tipping point of 0.6°C–0.95°C above post-industrial baseline global mean surface temperature (Gulev, 2021; IPCC, 2001) that was all that was required to shift the hydrological regime in small scale watersheds in the Taiga Shield of northwestern Canada. This regime shift may be limited to smaller catchments, but there is ample evidence that larger catchments are exhibiting trends that could manifest into these types of regime shifts as the climate continues to warm (Bennett et al., 2023).

5.3. Process Synchrony

Signals such as those observed in the hydrological and biogeochemical responses of Baker Creek to atmospheric conditions have been likened to cycles of different temporal scales (Brown et al., 2023). The wavelet analysis (Figure 7) identifies the presence of climate periodicities in regional precipitation indices. The hydrological and biogeochemical processes documented here show how responses to these cycles can be amplified; particularly once tipping points have been crossed. Upon crossing the air temperature tipping point of −4.5°C, once the PDO entered a wet cycle, the frequency in the streamflow cycle increased, which permitted synchronization with the

Table 6
Normal Mean Annual Air Temperatures Observed at Yellowknife a (T_a) for Four Sequential 30-Year Periods From 1961—2020, as Well as the Change From the 1961–1990 Baseline (ΔT_a)

Period	Yellowknife T_a (°C)	Yellowknife ΔT_a (°C)	GMST (°C)	ΔGMST (°C)
1961–1990	−5.2	-	0.36	-
1971–2000	−4.6	-	-	-
1981–2010	−4.3	+0.9	0.79	+0.43
1991–2020	−4.0	+1.2	0.99	+0.63

Note. Change in global mean surface temperatures from the pre-industrial baseline (GMST) are provided for context (Gulev, 2021), as well the change from the 1961–1990 baseline (ΔGMST). Because of different reporting protocols the period 1971–2000 is not available from the IPCC.

annual mineralization cycle, and amplified nutrient loading. A single instance of this occurring as documented by Spence et al. (2015) would not shift hydrological and biogeochemical regimes. The cause of the hydrological regime shift and the higher precariousness in the biogeochemical regime was the sustained synchronization of cycles (i.e., high degree of synchrony; Seybold et al., 2022) associated with precipitation phase formation, runoff generation and mineralization within lakes over several years. To create the regime shift, the processes dominant in each of these cycles needed to synchronize often enough over a large enough area to cause a change in the distribution of water year streamflow and the fraction of winter streamflow.

Society should be aware of the possibility of process synchrony occurring in other environmental systems. Understanding future change is contingent on an accurate description of the type of (a)synchrony processes exhibit that could lead to complex, divergent and surprising environmental change (Seybold et al., 2022). It's importance for snowmelt-generated streamflow in previous studies, for example (Gordon et al., 2022; Musselman et al., 2017), was a counter intuitive finding. Instances where processes become newly (a)synchronous may not be entirely obvious because they have not ever been documented. For instance, the shift documented here was not possible from 1700 to 2000 because the larger scale temperature trend had not crossed the climatological tipping point that allowed for the possibility of precipitation, hydrological and biogeochemical cycles synchronizing. However, the long-term perspective herein used, and illustrated by the wavelet results, show that the next wet cycle capable of promoting the hydrological-biogeochemical process synchrony that enhances nutrient loading that could eventually shift the biogeochemical regime could begin as early as 2029.

6. Concluding Remarks

This research aimed to determine if the hydrology and biogeochemistry regimes of a representative Taiga Shield catchment have been resilient to recent climate warming. At Baker Creek, in Canada's Northwest Territories, summer and autumn precipitation increased to 172 mm from the baseline of 150 mm, and autumn temperatures warmed to −1.8°C from −2.6°C. This allowed for more frequent exceedances of a runoff generation threshold of ∼120 mm rainfall. Subsequently, winter streamflow fraction increased orders of magnitude to 0.57 from 0.01. The higher winter streamflow synchronized with the higher mineralization rates under ice in this lake-dominated environment. The NH_3-N fraction in annual inorganic nitrogen loads rose 30% above the late 20th-century baseline. These changes were responsible for statistically significant changes in the distribution of NH_3-N/TIN, and a more precarious nitrogen regime, but not a regime shift. However, the hydrological regime of Baker Creek has changed from a nival to a cold-season pluvial regime. The nature by which the Baker Creek watershed releases water has fundamentally changed. Paleoclimate records indicate the combination of warm and wet conditions responsible for the regime shift are unprecedented in 300 years. The regime change observed for Baker Creek was due to more frequent process synchrony, a product of sustained warm and wet conditions associated with climate warming.

Process synchrony is a powerful means by which the effects of climate change can cascade through environmental systems and become amplified. There is the potential for process synchrony to occur in other systems, and other system changes may happen. The literature suggests that other chemical constituents could be vulnerable to process synchrony and change, as observed with inorganic nitrogen, arsenic, and other redox-sensitive elements.

An analysis comparable to this one with constituents beyond inorganic nitrogen is an opportunity for future research.

Knowledge gaps make it difficult to recognize and adapt to complex or non-linear responses in a warming circumpolar Arctic. Identifying process synchrony in freshwater systems and its role in system shifts highlights the need for inter- and trans-disciplinary research. It is strategically important to identify and quantify vulnerabilities and stability of systems to inform policy. A tipping point in mean annual air temperatures at −4.5°C was crossed upon which small Taiga Shield catchments in northwestern Canada lost hydrological resiliency. This tipping point occurred when global mean surface temperatures had only risen 0.6–0.8°C, well below the 1.5°C warming agreed to in Paris meant to prevent exceeding tipping points in earth systems. This study highlights the importance of appreciating the complexity of non-linear process synchrony when developing climate policy and mitigation strategies. The current suite of Earth system models used by the Intergovernmental Panel on Climate Change do not represent the hydrological and aquatic biogeochemical processes that we observed to synchronize in this study in a sensitive northern high latitude region. Failure to couple processes into land surface schemes will amplify uncertainty in predictions of future freshwater regimes and fluxes from catchment to continental scales. This field study highlights the importance of observation and focused investigations for understanding complex responses across diversity of northern landscapes to validate/inform models, and provide regionally relevant knowledge to inform climate adaptation. The response to this challenge has world-wide consequences as the Arctic Ocean and the northern circumpolar watersheds that feed it are a key component of the global climate system.

Data Availability Statement

Environment and Climate Change Canada station Yellowknife A meteorological data used within the study are available from https://open.canada.ca/data/en/dataset/9c4ebc00-3ea4-4fe0-8bf2-66cfe1cddd1d (Environment and Climate Change Canada, 2024a). Water Survey of Canada data are available from https://wateroffice.ec.gc.ca/index_e.html (Environment and Climate Change Canada, 2024b). Water chemistry data used in this study were collected as part of the Government of the Northwest Territories environmental monitoring networks and can be obtained by visiting https://www.nwtwaterstewardship.ca/en/lodestar (Government of the Northwest Territories, 2024).

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