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REVIEW

Observing Northern High-Latitude River Systems to Understand Changes in a Warming Arctic

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Abstract

Purpose of Review Streams and rivers are undergoing rapid change as the Arctic warms and thaws. We review recent observations in Arctic stream systems to identify ubiquitous changes and the most useful tools for observing change and exploring the underlying processes.

Recent Findings Recent literature indicates increasingly significant trends in river hydrology and chemistry due to persistent warming in the Arctic and longer observational records for analysis. However, regional differences in the magnitude and direction of these trends persist. We also observe thresholds in ground thaw and surface–groundwater interactions that can impact river hydrology and chemistry.

Summary Warming and thaw are occurring rapidly at high latitudes, resulting in increasing, yet variable responses in stream systems across regions and scales. These differences highlight the need for long-term records and an interdisciplinary approach to explain trends and predict future states. Stream systems respond to multiple landscape changes related to hydrology (changing precipitation and subsurface flow), geology (ground thaw dynamics), and ecology (vegetation change).

Keywords Streams · Rivers · Hydrology · Biogeochemistry · Arctic · Permafrost

Introduction

Stream discharge and chemistry are powerful tools for understanding watershed dynamics and change because they integrate processes occurring throughout the watershed. In Arctic regions, which we broadly define for this review as high-latitude regions and those with permafrost in the Northern Hemisphere, seasonally frozen soils and permafrost (perennially frozen ground) limit water storage and infiltration [1, 2]. As a result, runoff may dominate, and subsurface flow paths are often short and shallow, resulting in streams responding rapidly to hydrologic perturbations such as snowmelt and storms. Stream systems in high- latitude regions are undergoing a rapid change due to climate change [3], which is occurring at a faster rate than the Earth as a whole [4]. Climate change impacts Arctic streams in many ways, including alteration of flow regimes, chemistry and elemental fluxes, and biology. Further, stream hydrology and chemistry can be used to characterize and interpret the magnitude, direction, and rates of change related to warming and permafrost thaw within high-latitude watersheds [2]. As high latitude regions warm, several hydrologic changes have been documented: 1) altered precipitation regimes [3], 2) altered snowmelt timing and duration [5], and 3) thawing of frozen ground [6]. Permafrost thaw is of particular interest given the unique and disparate ways in which it may occur, which has implications for its impact on hydrology [7]. These processes may interact to impact the direction, magnitude, and timing of discharge and stream water quality. Considerable advances have been made over the past five years to expand our understanding of stream hydrologic function and response to climate change across the Arctic. Here, we review these advances, with specific focus on the effects of changing seasonality and permafrost thaw on watershed hydrology and stream chemistry. This review focuses on lotic systems that range from water tracks to large rivers, thereby allowing us to understand trends and inconsistencies that may be scale dependent. We use the term "streams" to refer to smaller, lower-discharge lotic systems

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and "rivers" for larger, high-discharge systems, recognizing that there is overlap in the systems described by these terms.

Common Arctic River Water Sources

In high latitudes, streamflow is generated by a combination of ice melt, snow melt, and rain [8]. In the most extreme high-latitude environments, cold conditions may limit precipitation, resulting in stream hydrographs that are dominated by glacier melt in mid summer [9, 10]. At lower latitudes, snowmelt and rain become more important water sources, with snowmelt typically dominating the annual hydrologic flux in many high-latitude systems [11]. River flows are impacted by freezing conditions and the formation and melt of aufeis. Aufeis are large sheet-like masses of ice that form in the winter as groundwater reaches the surface and freezes [12]. Aufeis melts in the summer, bolstering river baseflow [13].

With warming, greater heat energy in the atmosphere may alter both meteorological inputs and runoff potential. Warming conditions may allow more precipitation to fall [3]. Warmer air temperatures may allow snowmelt to begin earlier in the spring [5]. During the summer months, a warmer atmosphere increases the potential for glacial melt [14], permafrost thaw [6] and convective storms and heavy rains [15, 16]. Warmer conditions are allowing rivers to flow more freely in the winter months [17], and altering aufeis formation and thaw [18, 19]. The impact of these changes on the discharge of high latitude stream systems depends on the interactions of precipitation with the unique features of the land surface and subsurface in the Arctic (Fig. 1).

Impacts of Thawing Ground and Subsurface Connectivity

Arctic rivers and streams are unique due to the presence of permafrost (Fig. 1A) and seasonally frozen ground, which enhance runoff by limiting subsurface water storage and transmission [1]. Frozen ground contributes to distinct Arctic watershed hydrographs characterized by large snow melt pulses, flashy hydrographs, and variability in hydrologic response with thawing of the seasonally frozen active layer. In many low-latitude regions, groundwater is a critical source of water to maintain stream baseflow in the summer months. In the Arctic, groundwater flow is limited by permafrost, though increasing river baseflow suggests that warming may be increasing the storage and transmission of groundwater in the discontinuous permafrost zone [20]. Taliks are unfrozen soil layers adjacent and within permafrost that can transmit groundwater [2]. Taliks have been observed in limited cases through observations [21] and airborne geophysical surveys [22]. The increasing potential for groundwater flow through taliks has been conceptualized and numerically modeled as subsurface flow moving through longer and deeper flow paths as the ground thaws [23, 24].

Shallow soils represent a critical supra-permafrost aquifer that may provide water to streams. In permafrost environments, the thawed active layer above the permafrost may be less than a meter thick, yet serves to deliver water and

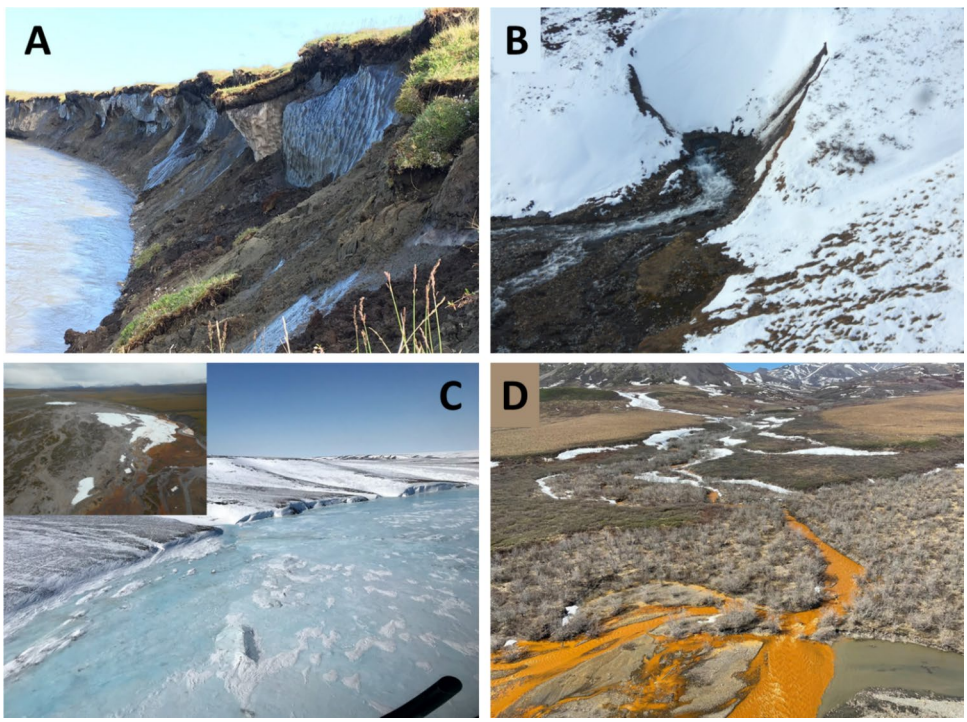


Fig. 1 Examples of unique features in high latitude watersheds. A) Ice-rich permafrost (Joshua Koch, USGS), B) a perennially-flowing Arctic spring (Charlie Couvillion, USGS), C) the Katakturuk aufeis field in April (Charlie Couvillion, USGS) and August (inset; Heather Best, USGS), D) Emergence of orange streams characterized by high metal loads (Joshua Koch, USGS)

solutes to drainage networks [2]. Flow rates may be high near the organic-mineral boundary, where organic soils remain saturated, creating complex flow paths through hummocky or peaty terrain [25, 26]. Deepening flow paths may fundamentally alter stream systems, given the differing chemistry of shallow organic and deeper mineral soils [27, 28].

Thawing ground may also increase surface drainage network development. Polygonal ground, which is found throughout ice-rich terrain in continuous permafrost regions, may become an important conduit of surface flow as permafrost degradation connects individual troughs into a drainage network [29, 30]. Storage and transmission of water through polygonal networks could greatly alter the magnitude and timing of river discharge [29]. The development of surface water drainage networks could also impact riparian evapotranspiration, given widespread vegetation increases in permafrost regions [31].

Common Hydrologic and Chemical Monitoring Metrics

Streams and rivers integrate upstream processes, and can therefore provide information on water sources, runoff, and subsurface flow. Discharge and dissolved solutes are critical tools for determining water sources, observing changes to stream systems, and considering the implications of change, especially when monitoring occurs on a regularly repeating interval. Both the hydrology and water quality of streams provide information, and often it is useful to combine multiple hydrological and chemical metrics to understand watershed processes and change [32]. Because permafrost thaw impacts the storage and transmission of water through the subsurface gradually, studies have focused on long-term Arctic stream records and change in hydrologic metrics through time [33].

The impact of permafrost thaw on subsurface flow is often inferred from stream and river chemistry. For example, the Yukon River in Alaska demonstrates decadal-scale increases in base cations, phosphorus, and sulfate fluxes [34], consistent with expectations of deepening flow paths [20]. Other common tracers include specific conductance, which is an easily measured parameter indicative of the major ion concentration of the water [35]. Dissolved organic carbon (DOC) and dissolved organic matter (DOM) age and composition have also been used as hydrologic tracers, given their high concentrations in water draining permafrost landscapes and shallow organic soils [27, 28, 36, 37] and the ease of monitoring organic matter fluorescence (fDOM) and color (cDOM) continuously with optical sensors. Recent advances in sensor technology allow for continuous monitoring of stream water quality, providing high resolution data for understanding stream hydrology, chemistry, and water sources [38].

Recent Advances in Observing River Systems and Understanding the Impacts of Climate Change on Arctic Surface Water Hydrology and Chemistry

Arctic river observations have been effective in demonstrating the impacts of warming and thaw on stream, river, and catchment hydrology and chemistry. Over the past five years, the Arctic has experienced some of the warmest years on record [3, 4]. Recent research advances during this period of rapid warming have helped to clarify climate impacts to watershed hydrology and expand our understanding of the underlying processes driving change. Here, we summarize these recent advances, with particular focus on changing seasonality, effects of permafrost thaw, and consequences for water quality and biogeochemical cycling.

Increasing Evidence of Changing Water Sources on Broad Scales

As the Arctic warms, scientists have documented changes in both the form of precipitation (i.e. rain vs. snow) and hydrologic flow paths through the drainage network. A broad, space for time approach based on 253 stream and river hydrographs in Alaska suggests that we may expect a transition in hydrographs dominated by ice and snow to dominance of rain [8]. Although this shift in precipitation form has begun across northern high latitudes, the changes that occur to stream hydrographs are complicated by myriad overlapping process of changing inputs and flow paths and the time scales of glacier melt, ground thaw, and vegetation change. Autumn rains are increasing in northern high latitude regions [39–41]. Extreme weather and hydrologic events are also becoming more common as a result of increasing heat and relative humidity in the atmosphere of the Arctic [16, 42].

At the same time, glacier mass loss is accelerating throughout northern high-latitude regions [14, 43]. In the short term, melting glaciers may lead to higher flows in high-latitude rivers [10], but these contributions will decline with advanced melt and glacier loss [44]. Water may also be derived from thawing permafrost, although this tends to be a smaller contribution because in many cases thaw occurs gradually over time, and permafrost water tends to make up only a small fraction of the available water relative to runoff [45]. However, in certain conditions permafrost may thaw rapidly, even in cold, continuous permafrost regions where thermokarst and subsidence suggest the release of substantial amounts of water from thawing ice-rich permafrost [46].

Permafrost thaw water may be a substantial contributor in very dry regions, such as the High Arctic and Mongolia, where other water inputs are minimal [47].

Changing Stream and River Hydrographs

A growing body of evidence across the Arctic indicates increasing discharge during shoulder seasons (spring and autumn) and winter [48–51]. Trends in mean annual discharge vary by region and analysis method [48–52]. Some regions are experiencing an earlier freshet pulse and timing of maximum annual discharge [41, 53]. There is evidence of increasing discharge in permafrost-dominated catchments in North America [49, 50], though an analysis of streamgages of varying size with greater than 60 years of historical records in Alaska found no significant trends in total annual discharge in seven of the nine analyzed basins [48]. In the Lena River basin of Siberia, annual discharge was found to be increasing in the continuous permafrost zone, but decreasing in the discontinuous permafrost zone where enhanced infiltration of precipitation may reduce runoff and discharge [54], a distinction that could also explain the variable findings in North America. Studies have provided new evidence of winter runoff events associated with warming [55, 56], which may impact the spring freshet timing, because the refreezing of winter water in the shallow soils may limit infiltration during snowmelt [56]. Evidence remains split over whether increasing cold season flows will lead to an earlier shift in annual discharge [53], or no change [48]. In some cases, increasing discharge from earlier snowmelt may be balanced by increasing late-summer rains, leading to no change in annual flow timing [39, 41].

Springs and Aufeis

Springs and aufeis (Fig. 1B and 1 C) continue to be important sources of winter water to rivers, providing evidence of groundwater flow and shifting water sources to streams [52, 57]. Springs in northern Alaska maintained consistent discharge and chemistry over the past 30 years despite warming and thaw, though they also respond to summer rains with increased discharge [58], a trend that has also been observed in springs in permafrost regions of Mongolia [47]. Many springs emanate from mountain fronts, pointing to the importance of fracture flow in transmitting water through the subsurface to springs [52]. However, springs and aufeis also appear far from the mountain front where geologic controls are less evident. Geophysical investigations suggest that glacial impacts including rock fracturing and sedimentation create the necessary aquifer and preferential flow paths to drive upwelling far from the mountain front [59], which has also been demonstrated through numerical modeling [60]. Spring flow paths can vary depending on permafrost continuity. In Svalbard, discontinuous permafrost leads to hydrologic connection of sub- and supra-permafrost aquifers and water ages up to hundreds of years [61]. Springs in the continuous permafrost zone of Alaska, including those emerging from the mountain fronts are generally less than 50 years old, suggesting sources from shallow, near-surface supra-permafrost aquifers [57].

Springs remain important contributors to the development of aufeis, and thus to stream and river baseflow as aufeis melts over the summer months [52]. However, the impact of aufeis may be changing, given that increasing winter river flows and warmer stream temperatures [62] may limit aufeis accumulation, resulting in spring water contributing directly to river baseflow instead [52]. For aufeis that does form, evidence shows that warmer air temperatures may lead to faster seasonal aufeis thaw based on observations [18, 58] and modeling [63]. Although many aufeis fields are shrinking on decadal timescales, some are increasing and all demonstrate interannual variability [57], pointing to interactive controls of watershed size, source water availability, permafrost extent and thaw, and recent climate [52, 55, 57].

Evidence of Continued Ground Thaw Altering Runoff Magnitude and Timing

Recent studies support previous evidence that permafrost thaw may both increase and decrease water budget elements and hence stream discharge, depending on soil type and topography [64]. Permafrost thaw may increase surface runoff and stream discharge, in cases where thermokarst increases drainage network connectivity [29]. Recent evidence indicates accelerating ice wedge degradation [65] and connectivity of the shallow, surface drainage network [66]. By contrast, permafrost thaw associated with increased vegetation growth and subsequent snow interception can lead to increased infiltration and evapotranspiration and drying of small, headwater streams [67–69]. Increasing infiltration and subsequent stream drying has been observed broadly across discontinuous permafrost zones [53]. In addition to altering river hydrology, recent research indicates that permafrost thaw and increasing subsurface flow can also impact stream solutes [69] and temperature [70, 71].

Permafrost thaw has been conceptualized as a gradual thickening of the active layer, before a critical threshold is reached that allows connectivity of shallow and deep aquifers [24], and recent research provides evidence of the occurrence of both processes.

Gradual Active Layer Deepening

Several recent studies have focused on inferring active layer thickening from stream discharge, typically using discharge recession analysis [72–76]. In a watershed on the North

Slope of Alaska, baseflow recession analysis was used to determine that active layer thaw was accelerating based on a 38 year record [72]. Active layer thickening in this region is further supported by increasing major ion concentrations and pH in springs, streams, and rivers between the 1970 s and 2020 s [58]. Slower baseflow recession has also been linked to increases in active layer thickness in Eurasia [73–75], though this trend is not apparent outside of the continuous permafrost zone, which may be attributed to limited permafrost control on subsurface flow where permafrost is less continuous [73]. The stream recession-active layer thickness relationship is also impacted by landscape factors such as soil type and catchment slope, leading to variable responses across regions [75, 76].

Increasing Evidence of Widespread Talik Formation

Over the past five years, a growing body of evidence indicates that we have crossed critical thresholds in thaw and surface–groundwater connectivity based on the widespread emergence and extent of taliks. Deepening of the active layer may allow for regional connectivity or taliks in the subsurface [2]. Taliks have been observed broadly across the discontinuous permafrost zone of Alaska [77] and have been the focus of intensive studies at smaller scales [22, 78]. Cryohydrologic models have been used to conceptualize and describe taliks in discrete locations, occurring as a result of permafrost thaw [79] and disturbances caused by vegetation-snow interactions [80] and fire [81].

Lateral taliks may occur in areas with thick permafrost if a thawed zone forms at the top of the permafrost [81, 82]. A recent study on the North Slope of Alaska found that ages of springs are quite young, and that annual aufeis size was dependent on recent climatology, implying the presence, growth, and regional connectivity of lateral taliks at the top of the permafrost [57]. In this same region of Alaska, near- or sub-river taliks have been demonstrated based on a river water balance [83] and numerical simulations [84].

Taliks have been invoked to explain broad-scale changes in Arctic hydrology and chemistry. A vertical, through-going, or open talik may form on hillsides where vegetation traps snow, providing water and heat to thaw permafrost [80]. Talik formation may explain the emergence of acid seeps on hillslopes in alpine regions of the continuous permafrost zone of Alaska [85]. Questions remain as to the distribution and connectivity of taliks, and to the potential for taliks to refreeze given changes in ground hydrological and thermal properties following talik formation [78].

Effects of Shifting Hydrology on River Water Quality

Monitoring of chemistry in large Arctic rivers provides compelling evidence of change in Arctic watersheds, although trends vary by watershed [86], which is unsurprising given the diversity of observed hydrologic changes across Arctic regions (Table 1). Even within a region, stream chemistry can vary widely, which has been attributed to differences in state factors such as ice content, permafrost extent, parent material [37, 87], and topographical slope [87, 88], as well as to disturbances such as fire [89, 90] and thermokarst [90].

Advances in Monitoring Arctic River Chemistry

The interplay of thaw and transport of major ions, carbon, and nitrogen have been investigated using continuous sensors in various watersheds [91–95], and on broad scales using remote sensing of water quality [85, 96]. Given the novelty of continuous chemistry sensors, new metrics and analytical approaches are still emerging, with most studies focusing on recession slope and the hysteresis index. Recession slopes are often positive for DOM (fluorescent or colored), consistent with transport limitation of the delivery of organic matter to the stream [94, 95]. However, seasonal trends in these two studies differ, with positive trends in time in an Arctic peatland attributed to increasing transport limitation [94], and negative trends in discontinuous permafrost boreal forest attributed to increasing source-limitation [95]. DOM hysteresis has been used to infer the proximity of sources to the stream, and in many cases demonstrates a seasonal shift from near-stream sources during snowmelt to more distal sources as the summer progresses [91, 94]. Differences in solute-discharge trends have been documented between organic and inorganic material [91, 93, 95], which is likely related to their disparate sources in stratified Arctic soils [25, 26, 30]. Nitrate and specific conductance, which are more associated with mineral soils below the organic horizon, tend to relate inversely to discharge, showing diluting trends during storms as a result of source-limitation [91, 95]. Ubiquitous findings are unclear, given that solute-discharge trends are strongly influenced by landscape type [92] and basin size [95]. Although the majority of new studies have leveraged novel sensor technologies for high-frequency chemical monitoring, advances have also been made in synoptic sampling by collecting samples throughout waterways within a single watershed [97, 98]. Such an approach provides important information regarding the most relevant spatial scales for understanding watershed processes [97] and additionally doesn't require leaving equipment in harsh, remote locations. Such approaches have demonstrated that despite large seasonality in Arctic stream discharge and solute loads, trends between subcatchments remain similar throughout the summer [98]. Distributed sampling is vital, given the abundance of small watersheds and their importance to overall riverine solute fluxes [99].

Table 1 Trends and thresholds in stream hydrology and chemistry

Category	Variable	Recent Trend (* = threshold change)	Region
Stream discharge			
	Mean annual	Increasing	North America [50], Pan-Arctic [49]
	Mean annual	No change	Alaska [48]
	Mean annual	Variable	Russia [54]
	Winter discharge	*Increasing	Alaska [48, 51], Canada [52]
	Freshet timing	Earlier	Alaska [48], Canada [53], Eurasia [41, 53]
	Autumn rain	Increasing/earlier	Alaska [39, 48], Eurasia [41]
Stream baseflow			
	recession timescale	Increasing	Alaska [72], Asia [74], Eurasia [73], Europe [75]
		Variable	Pan-Arctic [76]
Stream-groundwater interactions			
	Aufeis melt timing	Earlier	Alaska [58]
	Aufeis size	Variable	Alaska [57]
	Losing stream reaches	Increasing	Alaska [67, 69]
Water Quality			
	Alkalinity	Increasing	Pan-Arctic [86]
	DOC	No change	Pan-Arctic [86]
	Nitrate	Decreasing	Pan-Arctic [86, 87]
	Trace metals	*Increasing	Alaska [85], Canada [108]
	Major ions	Increasing	Alaska [58]
	Temperature	increasing	Alaska [125]

Changing Seasonality

In addition to the impacts of shifting seasonality on watershed hydrology (Table 1), stream chemistry varies across seasons, which must be accounted for in order to quantify fluxes and analyze trends [86]. High-frequency continuous measurements illustrate that shoulder seasons can account for large fractions of the annual flux of DOC and nitrate [92, 95]. As the open-water season lengthens, it is critical to better understand the relationship between flow and solute export, and to understand source- versus transport- limitations [92, 94]. Greater precipitation that is occurring in autumn is altering dissolved organic matter, nutrient and solute export from both glacial [100, 101] and non-glacial permafrost catchments [40]. Increasing precipitation intensity in the Arctic [16, 42] may increase particulate material and carbon fluxes [40, 102]. Further, longer flow seasons are also linked to increased thawing of catchment soils [69] and subsequent effects on subsurface flows and the chemistry of groundwater discharging to streams [87].

Effects of Permafrost Thaw on Water Quality

Because permafrost governs runoff and subsurface hydrology, permafrost presence and thaw influence stream water chemistry and biogeochemical cycling of various elements [103, 104]. There are many factors which dictate stream chemical responses to thaw, including the mode of permafrost thaw (e.g., active layer thickening or talik development vs. thermokarst or thermal erosion), the geological setting, terrestrial-aquatic linkages, and biogeochemical processes occurring within the watershed [105–107]. Further, elements and compounds respond differently to thaw, given differences in chemical sources, mobility, and reactivity within watersheds [79, 107, 108]. In this section, we will discuss recent advances in documenting water quality trends and underlying processes in Arctic streams, with particular focus on carbon, nutrients (nitrogen, phosphorus), metals, and heat.

DOC is a master variable in stream ecosystems, controlling nutrient availability, pH, and metal reactivity. Further, DOC functions as an important component of the Arctic carbon cycle, both in terms of its lateral flux and as a source of greenhouse gas emissions to the atmosphere [107]. At the Pan-Arctic scale, riverine DOC flux has not significantly changed over the past 20 years [86], despite widespread thaw across the Arctic during this period of time. However, at regional to watershed scales, permafrost thaw can impact both DOC concentration, flux, and also the age and chemical composition of dissolved organic matter [90,

109–111]. Recent advances have documented the diversity of DOC pool size across permafrost soil types [112], highlighting differences in the available pool of DOC to streams across organic- vs. mineral-dominated catchments. Changing groundwater-surface water connections with thaw can transport DOC into the stream system [113]. Recent work from the Mackenzie River basin in western Canada indicates that permafrost thaw and supra-permafrost talik development resulted in the abrupt aging of stream DOC [114].

Inorganic nitrogen and phosphorus can both function as limiting nutrients for primary productivity in Arctic stream ecosystems. Recent studies have documented the large pool of nitrogen currently stored in permafrost [115, 116] that is subject to transformation and mobilization upon thaw [117]. Inorganic nitrogen species (i.e., nitrate) are sensitive to shifting hydrologic conditions and storm events, as evidenced by recent work using continuous high-frequency sensors in Arctic streams (92, 93). At the Pan-Arctic scale, nitrate flux has been declining over the past 20 years [86], which may be due to warming effects on nitrogen uptake and immobilization outpacing nitrogen mobilization from enhance mineralization or release of permafrost nitrogen. Increasing delivery of carbon and nutrients in high latitude systems results in an ecosystem response [105, 118], with increased rates of nutrient uptake in water tracks [119], streams [120], and rivers [121].

Evidence continues to emerge pointing toward increased chemical weathering following permafrost thaw and subsequent deepening of groundwater flows paths [122, 123]. At the Pan-Arctic scale, alkalinity flux in large Arctic rivers has increased over the past 20 years, reflecting thaw-induced weathering of carbonate lithologies [86]. At regional scales, sulfide oxidation appears to be increasing based on increased sulfate concentrations in stream and river networks [34, 122]. In the Brooks Range of northern Alaska, more than 70 streams recently turned from clear to orange color (Fig. 1D), reflecting increased chemical weathering of sulfide minerals and mobilization of iron and other trace metals into stream water [85]. In this particular case, researchers documented sharp increases in toxic trace metals (e.g., copper, zinc, and others) and declines in stream biodiversity [85]. The chemical consequences of permafrost thaw and chemical weathering increases on streams likely vary across watersheds and geological settings. Further, evidence from the discontinuous permafrost zone indicates that metal and metalloid concentrations are tightly linked to seasonal variations in stream flow [108].

One factor that may impact both aquatic biogeochemical cycling and reaction rates is stream temperature. Stream temperature is controlled by many environmental factors including climate, groundwater contribution, surface water storage, catchment area, and permafrost extent [62, 70, 71, 124]. Permafrost controls various catchment properties including residence time and subsurface water storage and can be particularly important in impacting stream temperature by limiting groundwater flow to shallow, warm soils [70]. Models indicate that lotic water temperatures are increasing throughout Alaska, with some of the warmest temperatures expected in the most northern rivers [125]. Overall, recent research on Arctic water temperature controls and impact are limited, indicating an opportunity and need for future research.

Conclusions

Arctic streams and rivers are changing due to climate change, which is warming the Arctic faster than much of the rest of the planet. These changes are impacting stream and river hydrology, biogeochemistry, and ecosystems, providing an opportunity to understand integrative processes by monitoring Arctic lotic systems. The past five years have witnessed publication of many studies supporting expected changes, demonstrating stronger trends due to both accelerating phenomena and longer records. These changes include changing discharge timing and magnitude, altered stream recession as the subsurface thaws, and increasing impact of talik formation on hydrographs, winter flows, and stream chemistry. Additionally, there is evidence of several threshold changes, such as measurable winter discharge in rivers that were previously fully frozen in the winter, and in stream chemistry upon talik formation and release of solutes to surface waters. New studies have highlighted high variability in trend direction and magnitude, related to heterogeneity in landscapes, permafrost extent and configuration, slope, and the interactive effects of multiple, co-occurring changes and disturbances. Efforts to explain these differences and predict future changes would benefit from interdisciplinary approaches to monitor not only the lotic systems themselves, but also the catchments that they drain.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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References

1. Woo MK, Kane DL, Carey SK, Yang D. Progress in permafrost hydrology in the new millennium. Permafrost Periglac Process. 2008;19:237–54.
2. Walvoord MA, Kurylyk BL. Hydrologic impacts of thawing permafrost—A review. Vadose Zone J. 2016;15:1–20.
3. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B, editors. IPCC, 2021: climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge and New York. 2021;2391 p. https://doi.org/10.1017/9781009157896.
4. Rantanen M, et al. The arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ. 2022;3:168.
5. Musselman KN, Clark MP, Liu C, Ikeda K, Rasmussen R. Slower snowmelt in a warmer world. Nat Clim Chang. 2017;7:214–9.
6. Biskaborn BK, et al. Permafrost is warming at a global scale. Nat Commun. 2019;10:264.
7. Minsley BJ, et al. Rapid and gradual permafrost thaw: a tale of two sites. Geophys Res Lett. 2022;49:e2022GL100285.
8. Curran JH, Biles FE. Identification of seasonal streamflow regimes and streamflow drivers for daily and peak flows in Alaska. Water Resourc Res. 2021;57:e2020WR028425.
9. Gooseff MN, McKnight DM, Doran PT, Fountain A. Long-term stream hydrology and meteorology of a polar desert, the mcmurdo dry valleys. Ant Hydrol Proc. 2022;36:e14623.
10. Van Pelt W, et al. A long-term dataset of climatic mass balance, snow conditions, and runoff in Svalbard (1957–2018). Cryosphere. 2019;13:2259–80.
11. Holmes RM, et al. Seasonal and annual fluxes of nutrients and organic matter from large rivers to the arctic ocean and surrounding seas. Estuaries Coasts. 2012;35:369–82.
12. Ensom T, et al. The distribution and dynamics of aufeis in permafrost regions. Permafr Periglac Process. 2020;31:383–95.
13. Yoshikawa K, Hinzman LD, Kane DL. Spring and aufeis (icing) hydrology in Brooks Range, Alaska. J Geophys Res: Biogeosciences. 2007;112(G4).
14. Dyurgerov MB, Meier MF. Twentieth century climate change: evidence from small glaciers. Proc Natl Acad Sci. 2000;97:1406–11.
15. Poujol B, Prein AF, Newman AJ. Kilometer-scale modeling projects a tripling of Alaskan convective storms in future climate. Clim Dyn. 2020;55:3543–64.
16. Poujol B, Prien AF, Molina MJ, Muller C. Dynamic and thermodynamic impacts of climate change on organized convection in Alaska. Clim Dyn. 2021;56:2569–93.
17. St. Jacques JM, Sauchyn DJ. Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. Geophys Res Lett. 2009;36(1).
18. Pavelsky TM, Zarnetske JP. Rapid decline in river icings detected in Arctic Alaska: implications for a changing hydrologic cycle and river ecosystems. Geophys Res Lett. 2017;44:3228–35.
19. Alekseev V. Long-term variability of the spring taryn-aufeises. Ice and snow. 2016;56:73–92.
20. Walvoord MA, Striegl RG. Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: potential impacts on lateral export of carbon and nitrogen. Geophys Res Lett. 2007;34(12).
21. Jepsen SM, et al. Sensitivity analysis of lake mass balance in discontinuous permafrost: the example of disappearing Twelvemile Lake, Yukon Flats, Alaska (USA). Hydrogeol J. 2013;21:185–200.
22. Minsley BJ, Abraham JD, Smith BD, Cannia JC, Voss CI, Jorgenson MT, Walvoord MA,Wylie BK, Anderson L, Ball LB, Deszcz-Pan M. Airborne electromagnetic imaging of discontinuous permafrost. Geophys Res Lett. 2012;39(2).
23. Walvoord MA, Voss CI, Wellman TP. Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: example from Yukon Flats Basin, Alaska, United States. Water Resourc Res. 2012;48(7).
24. Bense VF, Ferguson G, Kooi H. Evolution of shallow groundwater flow systems in areas of degrading permafrost. Geophys Res Lett. 2009;36(22).
25. Quinton WL, Gray DM, Marsh P. Subsurface drainage from hummock-covered hillslopes in the arctic tundra. J Hydrol. 2000;237:113–25.
26. Koch JC, Toohey RC, Reeves DM. Tracer-based evidence of heterogeneity in subsurface flow and storage within a boreal hillslope. Hydrol Process. 2017;31:2453–63.
27 Maclean R, Oswood MW, Irons JG, McDowell WH. The effect of permafrost on stream biogeochemistry: a case study of two streams in the Alaskan (U.S.A.) taiga. Biogeochemistry. 1999;47:239–67.
28. Koch JC, Kikuchi CP, Wickland KP, Schuster PF. Runoff sources and flow paths in a partially burned, upland boreal catchment underlain by permafrost. Water Resour Res. 2014;50:8141–58.
29. Liljedahl AK, et al. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. Nat Geosci. 2016;9:312–8.
30 Connon R, Quinton W, Craig J, Hanisch J, Sonnentag O. The hydrology of interconnected bog complexes in discontinuous permafrost terrains. Hydrol Process. 2015;29(18):3831–47.
31. Tape K, Sturm M, Racine C. The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. Glob Change Biol. 2006;12:686–702.
32. Beyer M, Jackson B, Daughney C, Morgenstern U, Norton K. Use of hydrochemistry as a standalone and complementary groundwater age tracer. J Hydrol. 2016;543:127–44.
33. Lyon SW, Destouni G. Changes in catchment-scale recession flow properties in response to permafrost thawing in the Yukon River Basin. Int J Climatol. 2010;30:2138–45.
34 Toohey R, Herman-Mercer N, Schuster P, Mutter E, Koch J. Multidecadal increases in the Yukon River Basin of chemical

fluxes as indicators of changing flowpaths, groundwater, and permafrost. Geophys Res Lett. 2016;43:12.
35. U.S. Geological Survey. Specific conductance: U.S. Geological Survey Techniques and Methods, book 9, chap. A6.3, 2019;15. https://doi.org/10.3133/tm9A6.3.
36. O'Donnell JA, et al. Using dissolved organic matter age and composition to detect permafrost thaw in boreal watersheds of interior Alaska. J Geophys Res Biogeosci. 2014;119:2155–70.
37. O'Donnell JA, et al. Dissolved organic matter composition of Arctic rivers: Linking permafrost and parent material to riverine carbon. Global Biogeochem Cycles. 2016;30:1811–26.
38. Bieroza M, et al. Advances in catchment science, hydrochemistry, and aquatic ecology enabled by high-frequency water quality measurements. Environ Sci Technol. 2023;57:4701–19.
39 Arp C, Whitman M, Kemnitz R, Stuefer S. Evidence of hydrological intensification and regime change from northern Alaskan watershed runoff. Geophys Res Lett. 2020;47:e2020GL089186.
40. Beel CR, et al. Emerging dominance of summer rainfall driving High Arctic terrestrial-aquatic connectivity. Nat Commun. 2021;12:1448.
41. Osuch M, Wawrzyniak T, Łepkowska E. Changes in the flow regime of High Arctic catchments with different stages of glaciation, SW Spitsbergen. Sci Total Environ. 2022;817:152924.
42. Bieniek PA, Walsh JE, Fresco N, Tauxe C, Redilla K. Anticipated changes in Alaska Extreme Precipitation. J Appl Meteorol Climatol. 2022;61:97–108.
43. O'Neel S, et al. Reanalysis of the US Geological Survey Benchmark Glaciers: long-term insight into climate forcing of glacier mass balance. J Glaciol. 2019;65:850–66.
44. Huss M, Hock R. Global-scale hydrological response to future glacier mass loss. Nat Clim Chang. 2018;8:135–40.
45. Wang L, et al. Quantification of Water Released by Thawing Permafrost in the Source Region of the Yangtze River on the Tibetan Plateau by InSAR Monitoring. Water Resourc Res. 2023;59:e2023WR034451.
46. Farquharson LM, et al. Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian High Arctic. Geophys Res Lett. 2019;46:6681–9.
47. Hiyama T, et al. Groundwater age of spring discharges under changing permafrost conditions: the Khangai Mountains in central Mongolia. Environ Res Lett. 2021;16:015008.
48. Blaskey D, et al. Increasing Alaskan river discharge during the cold season is driven by recent warming. Environ Res Lett. 2023;18:024042.
49. Feng D, et al. Recent changes to Arctic river discharge. Nat Commun. 2021;12:6917.
50. Bennett KE, et al. Recent streamflow trends across permafrost basins of North America. Frontiers in Water. 2023;5:1099660.
51. Rawlins MA, Cai L, Stuefer SL, Nicolsky D. Changing characteristics of runoff and freshwater export from watersheds draining northern Alaska. Cryosphere. 2019;13:3337–52.
52. Crites H, Kokelj SV, Lacelle D. Icings and groundwater conditions in permafrost catchments of northwestern Canada. Sci Rep. 2020;10:3283.
53. Ahmed R, Prowse T, Dibike Y, Bonsal B, O'Neil H. Recent trends in freshwater influx to the arctic ocean from four major arctic-draining rivers. Water. 2020;12:1189.
54. Xue Z, Wang Y, Zhao Y, Li D, Borthwick AG. Impacts of spatially inconsistent permafrost degradation on streamflow in the Lena River Basin. Sci China Technol Sci. 2024;1–12.
55. Alsafi NE, et al. Icings as sentinels and modifiers of water flow through winter landscapes: an exploration of physico-chemical processes on the lake-dominated, discontinuous permafrost Taiga Shield. Hydrol Process. 2024;38:e15251.
56. Mohammed AA, Pavlovskii I, Cey EE, Hayashi M. Effects of preferential flow on snowmelt partitioning and groundwater recharge in frozen soils. Hydrol Earth Syst Sci. 2019;23:5017–31.
57. Koch JC, et al. The dominance and growth of shallow groundwater resources in continuous permafrost environments. Proc Natl Acad Sci. 2024;121:e2317873121.
58. Koch JC, Best H, Baughman C, Couvillion C, Carey MP, Conaway J. A comparison of contemporary and historical hydrology and water quality in the foothills and coastal plain of the Arctic National Wildlife Refuge, Arctic Slope, northern Alaska: US Geological Survey Scientific Investigations Report 2024–5008, 24 p. 2024. https://doi.org/10.3133/sir20245008.
59 Hornum MT, Betlem P, Hodson A. Groundwater Flow Through Continuous Permafrost Along Geological Boundary Revealed by Electrical Resistivity Tomography. Geophys Res Lett. 2021;48:e2021GL092757.
60. Lainis A, Neupauer RM, Koch JC, Gooseff MN. Seasonal and decadal subsurface thaw dynamics of an Aufeis feature investigated through numerical simulations. Hydrol Process. 2024;38:e15106.
61. Rotem D, Weinstein Y, Christiansen HH, Sültenfuß J, Hodson A. Ra isotope perspective on the hydrology and continuity of permafrost in the high Arctic. Sci Total Environ. 2024;950:175412.
62 Blaskey D, et al. A high-resolution, daily hindcast (1990–2021) of Alaskan river discharge and temperature from coupled and optimized physical models. Water Resourc Res. 2024;60:e2023WR036217.
63. Neupauer R, Lainis A, Koch J, Gooseff MN. Effects of climate change on Aufeis Formation in Arctic Regions. Front Hydrol. 2022;2022:233–108.
64. Jorgenson MT, et al. Reorganization of vegetation, hydrology and soil carbon after permafrost degradation across heterogeneous boreal landscapes. Environ Res Lett. 2013;8:035017.
65. Jorgenson MT, et al. Rapid transformation of tundra ecosystems from ice-wedge degradation. Global Planet Change. 2022;216:103921.
66. Liljedahl AK, Witharana C, Manos E. The capillaries of the Arctic tundra. Nat Water. 2024;2:611–4.
67. Liljedahl AK, Timling I, Frost GV, Daanen RP. Arctic riparian shrub expansion indicates a shift from streams gaining water to those that lose flow. Commun Earth Environ. 2020;1:50.
68 Young NL, Lemieux JM, Delottier H, Fortier R, Fortier P. A conceptual model for anticipating the impact of landscape evolution on groundwater recharge in degrading permafrost environments. Geophys Res Lett. 2020;47:e2020GL087695.
69. Koch JC, et al. Sensitivity of headwater streamflow to thawing permafrost and vegetation change in a warming Arctic. Environ Res Lett. 2022;17:044074.
70 Sjöberg Y, et al. Permafrost promotes shallow groundwater flow and warmer headwater streams. Water Resourc Res. 2021;57:e2020WR027463.
71. Szeitz AJ, Carey SK. The influence of permafrost and other environmental factors on stream thermal sensitivity across Yukon, Canada. Hydrol Earth Syst Sci. 2025;29:1083–101.
72 Cooper MG, et al. Detecting permafrost active layer thickness change from nonlinear baseflow recession. Water Resourc Res. 2023;59:e2022WR033154.
73. Evans SG, Yokeley B, Stephens C, Brewer B. Potential mechanistic causes of increased baseflow across northern Eurasia catchments underlain by permafrost. Hydrol Process. 2020;34:2676–90.
74. Feng X, Duan L, Kurylyk BL, Cai T. Impacts of permafrost thaw on streamflow recession in a discontinuous permafrost watershed of northeastern China. Sci Total Environ. 2022;847:157624.

75. Hinzman AM, Sjöberg Y, Lyon SW, Ploum SW, van der Velde Y. Increasing non-linearity of the storage-discharge relationship in sub-Arctic catchments. Hydrol Process. 2020;34:3894–909.
76. Sergeant F, Therrien R, Oudin L, Jost A, Anctil F. Evolution of Arctic rivers recession flow: global assessment and data-based attribution analysis. J Hydrol. 2021;601:126577.
77. Farquharson LM, Romanovsky VE, Kholodov A, Nicolsky D. Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. Nat Geosci. 2022;15:475–81.
78 Fortier P, Young NL, Lemieux JM, Walvoord MA, Fortier R. Long-term, high-resolution permafrost monitoring reveals coupled energy balance and hydrogeologic controls on talik dynamics near Umiujaq (Nunavik, Québec, Canada). Water Resourc Res. 2023;59:e2022WR032456.
79. Mohammed AA, et al. Mobilization of subsurface carbon pools driven by permafrost thaw and reactivation of groundwater flow: a virtual experiment. Environ Res Lett. 2022;17:124036.
80. Jafarov EE, et al. Modeling the role of preferential snow accumulation in through talik development and hillslope groundwater flow in a transitional permafrost landscape. Environ Res Lett. 2018;13:105006.
81. Walvoord MA, Voss CI, Ebel BA, Minsley BJ. Development of perennial thaw zones in boreal hillslopes enhances potential mobilization of permafrost carbon. Environ Res Lett. 2019;14:015003.
82. Connon R, Devoie É, Hayashi M, Veness T, Quinton W. The influence of shallow taliks on permafrost thaw and active layer dynamics in subarctic Canada. J Geophys Res Earth Surf. 2018;123:281–97.
83. King TV, Neilson BT, Overbeck LD, Kane DL. A distributed analysis of lateral inflows in an Alaskan Arctic watershed underlain by continuous permafrost. Hydrol Process. 2020;34:633–48.
84. Zheng L, Overeem I, Wang K, Clow GD. Changing Arctic river dynamics cause localized permafrost thaw. J Geophys Res Earth Surf. 2019;124:2324–44.
85. O'Donnell JA, et al. Metal mobilization from thawing permafrost to aquatic ecosystems is driving rusting of Arctic streams. Commun Earth Environ. 2024;5:268.
86. Tank SE, et al. Recent trends in the chemistry of major northern rivers signal widespread Arctic change. Nat Geosci. 2023;16:789–96.
87. Tank SE, et al. Landscape matters: Predicting the biogeochemical effects of permafrost thaw on aquatic networks with a state factor approach. Permafrost Periglac Process. 2020;31:358–70.
88. Connolly CT, et al. Watershed slope as a predictor of fluvial dissolved organic matter and nitrate concentrations across geographical space and catchment size in the Arctic. Environ Res Lett. 2018;13:104015.
89. Rodríguez-Cardona BM, et al. Wildfires lead to decreased carbon and increased nitrogen concentrations in upland arctic streams. Sci Rep. 2020;10:8722.
90. Koch JC, et al. Heterogeneous patterns of aged organic carbon export driven by hydrologic flow paths, soil texture, fire, and thaw in discontinuous permafrost headwaters. Global Biogeochem Cycles. 2022;36:e2021GB007242.
91. Shatilla NJ, Tang W, Carey SK. Multi-year high-frequency sampling provides new runoff and biogeochemical insights in a discontinuous permafrost watershed. Hydrol Process. 2023;37:e14898.
92. Shogren AJ, et al. Arctic concentration–discharge relationships for dissolved organic carbon and nitrate vary with landscape and season. Limnol Oceanogr. 2021;66:S197–215.
93. Shogren AJ, et al. Hydrology controls dissolved organic carbon and nitrogen export and post-storm recovery in two arctic headwaters. J Geophys Res Biogeosci. 2024;129:7583.
94. Croghan D, et al. Seasonal and interannual dissolved organic carbon transport process dynamics in a subarctic headwater catchment revealed by high-resolution measurements. Hydrol Earth Syst Sci. 2024;28:1055–70.
95 Koch JC, Dornblaser MM, Striegl RG. Storm-scale and seasonal dynamics of carbon export from a nested subarctic watershed underlain by permafrost. J Geophys Res Biogeosci. 2021;126:e2021JG006268.
96. Griffin C, McClelland J, Frey K, Fiske G, Holmes R. Quantifying CDOM and DOC in major arctic rivers during ice-free conditions using landsat TM and ETM+ data. Remote Sens Environ. 2018;209:395–409.
97. Shogren AJ, et al. Revealing biogeochemical signatures of Arctic landscapes with river chemistry. Sci Rep. 2019;9:1–11.
98. Grewal A, Carey SK. Synoptic sampling reveals spatial stability in flow and chemistry patterns despite large seasonal variability in a subarctic mountain catchment. Hydrol Process. 2024;38:e15080.
99. Vonk JE, Speetjens NJ, Poste AE. Small watersheds may play a disproportionate role in arctic land-ocean fluxes. Nat Commun. 2023;14:3442.
100. Fouché J, et al. Rainfall impacts dissolved organic matter and cation export from permafrost catchments and a glacial river during late summer in Northeast Greenland. Permafrost Periglacial Process. 2025;36(1):3–2.
101. Bergstrom A, Koch JC, O'Neel S, Baker E. Seasonality of solute flux and water source chemistry in a coastal glacierized watershed undergoing rapid change: Wolverine Glacier watershed, Alaska. Water Resourc Res. 2021;57:e2020WR028725.
102. Repasch M, Arcuri J, Overeem I, Anderson SP, Anderson RS, Koch JC. Impacts of convective storms on runoff, erosion, and carbon export in a continuous permafrost landscape. In: ICOP 2024 12th International Conference on Permafrost. 2024. https://doi.org/10.52381/ICOP2024.104.1.
103. Frey KE, McClelland JW. Impacts of permafrost degradation on arctic river biogeochemistry. Hydrol Process. 2009;23:169–82.
104. Vonk JE, et al. Reviews and syntheses: effects of permafrost thaw on Arctic aquatic ecosystems. Biogeosciences. 2015;12:7129–67.
105. O'Donnell JA, et al. Permafrost hydrology drives the assimilation of old carbon by stream food webs in the Arctic. Ecosystems. 2020;23:435–53.
106 Zolkos S, et al. Permafrost landscape history shapes fluvial chemistry, ecosystem carbon balance, and potential trajectories of future change. Global Biogeochem Cycles. 2022;36:e2022GB007403.
107 Hirst C, et al. Seasonal changes in hydrology and permafrost degradation control mineral element-bound DOC transport from permafrost soils to streams. Global Biogeochem Cycles. 2022;36:e2021GB007105.
108. Skierszkan EK, et al. Seasonal controls on stream metal(loid) signatures in mountainous discontinuous permafrost. Sci Total Environ. 2024;908:167999.
109 Estop-Aragonés C, et al. Assessing the potential for mobilization of old soil carbon after permafrost thaw: a synthesis of 14C measurements from the northern permafrost region. Global Biogeochem Cycles. 2020;34:e2020GB006672.
110. MacDonald EN, Tank SE, Kokelj SV, Froese DG, Hutchins RH. Permafrost-derived dissolved organic matter composition varies across permafrost end-members in the western Canadian Arctic. Environ Res Lett. 2021;16:024036.
111. Bröder L, et al. Preferential export of permafrost-derived organic matter as retrogressive thaw slumping intensifies. Environ Res Lett. 2021;16:054059.
112. Heffernan L, Kothawala DN, Tranvik LJ. Review article: terrestrial dissolved organic carbon in Northern permafrost. Cryosphere. 2024;18:1443–65.

113. Neilson BT, et al. Groundwater flow and exchange across the land surface explain carbon export patterns in continuous permafrost watersheds. Geophys Res Lett. 2018;45:7596–605.
114 Schwab MS, et al. An abrupt aging of dissolved organic carbon in large arctic rivers. Geophys Res Lett. 2020;47:e2020GL088823.
115. Hugelius G, et al. Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. Proc Natl Acad Sci. 2020;117:20438–46.
116. Strauss J, et al. A globally relevant stock of soil nitrogen in the Yedoma permafrost domain. Nat Commun. 2022;13:6074.
117. Strauss J, et al. Potential nitrogen mobilisation from the Yedoma permafrost domain. Environ Res Lett. 2024;19:043002.
118. Gan Y, Su Y, Ma J. Effects of microbial-converted ancient permafrost organic carbon on the growth and reproduction of Daphnia magna. Oecologia. 2023;203:335–48.
119. Harms TK, Cook CL, Wlostowski AN, Gooseff MN, Godsey SE. Spiraling down hillslopes: nutrient uptake from water tracks in a warming arctic. Ecosystems. 2019;22:1546–60.
120. Covino TP, Wlostowski AN, Gooseff MN, Wollheim WM, Bowden WB. The seasonality of in-stream nutrient concentrations and uptake in arctic headwater streams in the Northern Foothills of Alaska's Brooks range. J Geophys Res Biogeosci. 2021;126:e2020JG005949.
121. Francis A, et al. Permafrost degradation and nitrogen cycling in Arctic rivers: insights from stable nitrogen isotope studies. Biogeosciences. 2023;20:365–82.
122 Walsh EV, Hilton RG, Tank SE, Amos E. Temperature sensitivity of the mineral permafrost feedback at the continental scale. Sci Adv. 2024;10:eadq4893.
123. Zolkos S, Tank SE, Kokelj SV. Mineral weathering and the permafrost carbon-climate feedback. Geophys Res Lett. 2018;45:9623–32.
124. Yang D, Park H, Peterson A, Liu B. Arctic river water temperatures and thermal regimes. In: Yang D, Kane DL (eds) Arctic Hydrology, Permafrost and Ecosystems. Springer, Cham. 2021. https://doi.org/10.1007/978-3-030-50930-9_10.
125. Blaskey D, Cheng Y, Newman AJ, Koch JC, Gooseff MN, Musselman KN. Alaskan hydrology in transition: changing precipitation and evapotranspiration patterns are projected to reshape seasonal streamflow and water temperature by mid-century (2035–2064). J Hydrometeorol. 2025;26(6). https://doi.org/10.1175/JHM-D-24-0121.1.

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