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Opportunities for improved detection of linked hydroclimate-ecosystem dynamics in Arctic catchments

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Climate warming is transforming Arctic landscapes through changes in the cryosphere and water systems that together contribute to alterations in the structure and function of ecosystems. To better understand these interlinked processes and feedbacks, previous research has recommended studies at the catchment scale that explicitly couple hydroclimatic fluxes and their interactions with the environment. However, using such an approach requires coordinated cross-disciplinary monitoring. In this review, we synthesize knowledge on available monitoring of key hydroclimate and ecosystem indicators to identify opportunities to use a catchment-based approach for improved understanding of climate-ecosystem dynamics in the Arctic. There is overall a small spatial overlap between the coverage of hydroclimate and ecosystem monitoring. *In-situ* monitoring of both climate and hydrological variables is sparse with a northward decline in observation density, while most ecosystem monitoring is focused around accessible regions and near Arctic research stations. As a result, our study shows that only two catchments within the pan-Arctic drainage basin include monitoring of both hydroclimate and ecosystem variables. Although this general spatial mismatch results in a limitation in using a catchment-based approach to study hydroclimate-ecosystem interactions across the Arctic, there are opportunities in some data rich regions. We have identified 32 catchments that include monitoring of all hydroclimate variables. These can be used as a starting point for catchment-based approaches to study climate-ecosystem interactions, and continued improvement of observation methods can further help identify regions with the best potential for downscaling climate model output for future projections. But this requires prioritized coordinated ecological and hydroclimatic monitoring efforts in regions most vulnerable to climate change.

KEYWORDS

Arctic, climate change, climate-ecosystem feedbacks, catchment approach, monitoring

1 Introduction

The Arctic, which encompasses a wide range of different ecoregions, has warmed three to four times faster than the planet as a whole during the period 1979–2022 (AMAP, 2024; Rantanen et al., 2022). The recent warming has triggered substantial changes in the terrestrial cryosphere (e.g., permafrost and snow distributions) and water systems that collectively contribute to transformations of landscapes and alterations in structure and function of ecosystems (AMAP, 2024; AMAP, 2021). Examples of cryosphere and water-driven changes in ecosystems include lake-area reductions (Webb et al., 2022; Karlsson et al., 2015), changing river-lake connectivity, vegetation shifts and conversion between terrestrial and aquatic ecosystems (Karlsson et al., 2011). Permafrost thaw can alter local biological activity through altered hydrology and soil nutrient availability (Natali et al., 2012), leading to, for example, vegetation productivity change through shrubification or “terrestrial greening” (Myers-Smith et al., 2011). Concurrent changes in climate variables and ecosystems can further influence rates and magnitudes of nutrient cycling and export (AMAP, 2021; AMAP, 2017; Bring et al., 2016). These observed changes will likely accelerate with further warming of the Arctic (IPCC, 2021).

Given that many Arctic landscape changes are climatically driven and hydrologically mediated, and they in turn affect climate-related fluxes, it is becoming increasingly important to be able to quantify the spatial extent of these complex interactions. As large-scale observations of individual variables may not be able to capture these complexities, we need an approach where multiple variables can be examined simultaneously. A recommended approach for conducting such studies, is the catchment-based approach (as suggested by, e.g., Wrona et al., 2016; Prowse et al., 2015; Karlsson et al., 2011). The hydrological catchment or drainage basin is a natural topographic and geological unit that can couple terrestrial, freshwater, and nearshore ocean environments and their processes. The approach also allows for a direct consideration of heterogeneity at the landscape scale, as hydrological processes and ecosystem variables are controlled by local catchment characteristics, such as geology, geomorphology, the presence of permafrost, and vegetation cover. A catchment-based approach can advance our understanding of these interrelated fluxes and processes and help answer questions related to how ecosystems in catchments are affected by, and in turn, affect climate change, as well as how they are linked to water flows. However, using a catchment-based approach requires coordinated, cross-disciplinary research and monitoring of climate, hydrological and ecological variables. A critical question to address is if (current) monitoring in the Arctic supports such an approach?

In this review, we synthesize knowledge on available monitoring of key hydroclimatic and ecosystem indicators in Arctic catchments that can be used to assess and project ecosystem responses in a changing Arctic, including: i) what and where hydroclimate and ecosystem variables are being monitored, ii) at what scales these variables are being monitored, including regional (e.g., through remote sensing) or local (*in situ* or ground truth data) scales, and iii) whether the current monitoring network represent the many heterogeneous landscapes of the Arctic. Our aim is to identify opportunities for improved detection, interpretation and projection of linked water-cryosphere-ecosystem dynamics using a catchment-based approach.

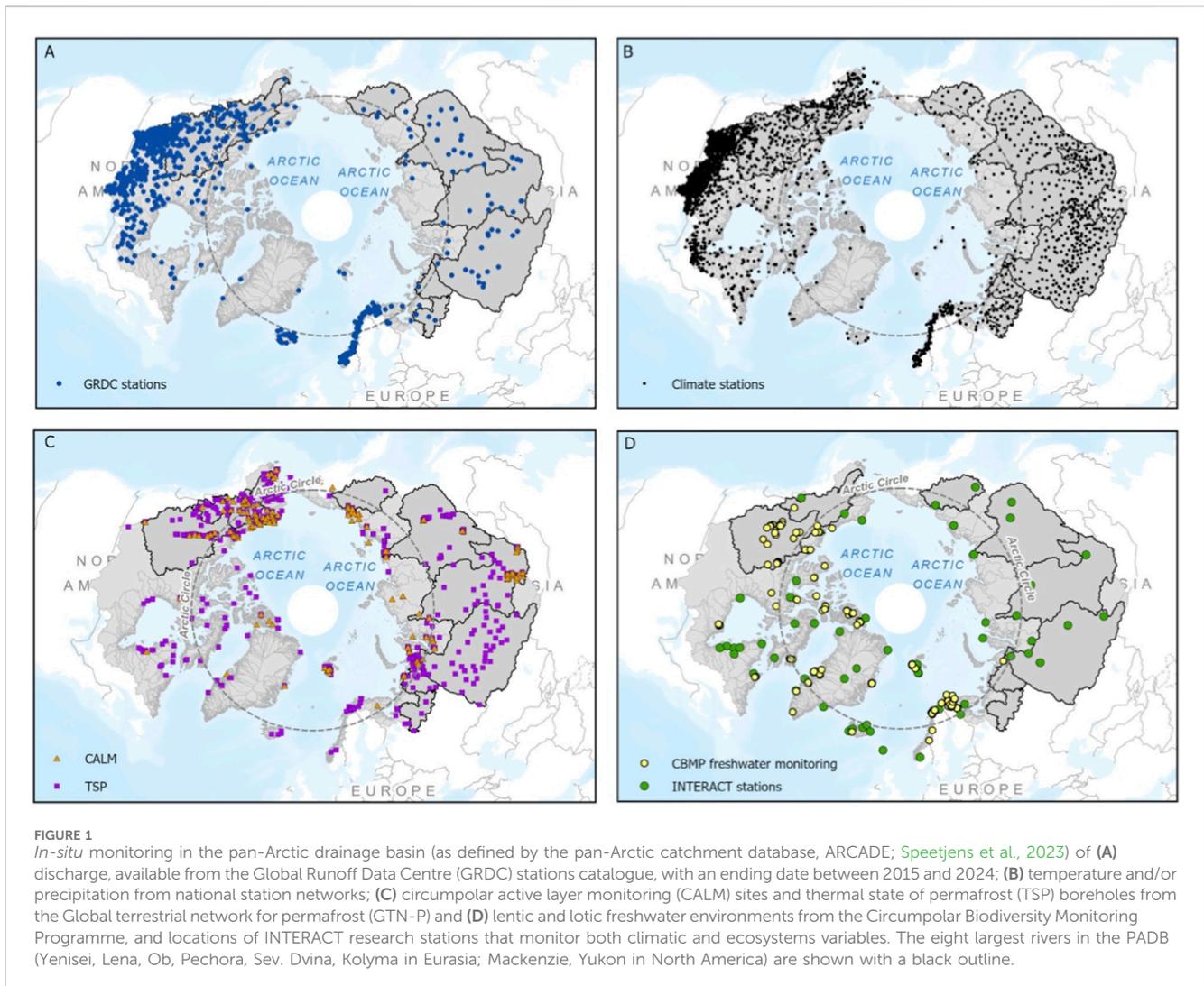
2 Hydroclimatic indicators

2.1 Temperature, precipitation, snow cover

Key climate variables that drive climate change impacts on ecosystems include air temperature, precipitation, snow depth and snow water equivalent. The circumpolar network of *in situ* observations is densest for air temperature measurements. For example, the NASA GISSTEMP archive (Lenssen et al., 2019) contains data from stations with continuous, decadal-scale time series, incorporating measurements from 2652 stations in the pan-Arctic drainage basin (PADB, based on the pan-Arctic catchment database, ARCADE; Speetjens et al., 2023), whereof 512 stations are located north of the Arctic Circle (66.5°N) (Supplementary Figure S1). However, the station network remains sparse over large areas, especially Greenland, northern Canada, and Siberia. This sparse network is particularly concerning in regions experiencing rapid climate warming and large variability in orography and surface types. The rapidly warming regions include Svalbard, the northern half of Greenland, the Canadian Arctic Archipelago, mainland Canada north of Hudson Bay, and much of northern Siberia within approximately 500 km of the coastline (Rantanen et al., 2022). The warming patterns include seasonal differences, with generally strongest warming of the terrestrial Arctic in autumn and spring and weakest in winter, when atmospheric warming has mostly occurred in the marine Arctic and Alaska.

Considering the *in situ* network for precipitation measurements, the spatial distribution of station density closely resembles that of temperature stations (compare Supplementary Figures S1a,b), with the lowest densities occurring in the northernmost and coldest regions. However, the overall number of precipitation stations is substantially smaller, comprising 952 stations within the PADB, of which only 127 are located north of the Arctic Circle (Supplementary Figure S1b). The generally low station numbers in the northern parts of the PADB are largely attributable to logistical constraints in these remote regions, but they may also reflect the difficulties of accurately measuring snowfall accurately, which reduces the cost-effectiveness of gauge-based observations. As a result, recent estimates of Arctic precipitation often rely on a combination of atmospheric reanalysis products and both *in situ* and remote sensing data (Becker et al., 2013; Walsh et al., 2023). The observed changes in precipitation underscore the need for a denser observation network, especially in regions with complex terrain. For instance, the east coast of Greenland, where precipitation increased significantly from 1989 to 2016 (Yu and Zhong, 2021), and Svalbard, where wintertime rain has become more frequent (Peeters et al., 2019), are high-priority areas for enhanced monitoring.

Due to wind-driven snow transport, snow depth can vary significantly across small distances, limiting the value of isolated point measurements. Manual snow line measurements, while more representative, require substantial labor. Hence, snowpack mapping in the Arctic is increasingly reliant on satellite remote sensing. Radar and lidar altimetry, such as from CryoSat-2 and ICESat-2, can measure snow depth with a spatial resolution of as high as 100–500 m (Wingham et al., 2006; Markus et al., 2017). Passive microwave sensors (e.g., AMSR2, SMOS) provide snow water equivalent (SWE) data with a spatial resolution of 10–50 km



(Kelly, 2009). However, small-scale variations in surface characteristics and snow properties make satellite-based retrievals of snow depth and SWE less reliable over land than over sea ice. Continued surface-based observations are therefore essential to refine remote sensing algorithms for snow depth and SWE, especially in regions with rugged terrain and boreal forest cover. In the future, new tools combining traditional snow lines, drones for near-remote sensing and machine learning techniques could provide further possibilities also in Arctic monitoring to improve snow measurements. Considering *in situ* observations, we see significant potential for stronger collaboration between scientists and Indigenous Peoples and local communities.

2.2 Surface water hydrology

Changes in hydrological conditions, including surface water, both reflect and drive changes in Arctic inland ecosystem functioning by linking abiotic and biotic components. For example, changes in river discharge reflect catchment water balance, including climate, cryosphere and landscape changes of upstream areas, and are in

turn related to key ecosystem characteristics and ecological changes. Rivers further link terrestrial and ocean domains. Sustained river discharge monitoring is therefore an important part of the Arctic observation network.

Efforts to monitor river discharge across the Arctic started in the 1930s, with the number of stations and their spatial distribution changing over time (McClelland et al., 2015) (Supplementary Figure S2). However, current hydrological monitoring is limited by large gauging gaps. The number of hydrological gauging stations and monitored areas has decreased since the 1980s (Shiklomanov and Lammers, 2013; Bring and Destouni, 2009), and about one-third of the PADB is currently ungauged (AMAP, 2024). At present, Russia, Canada, United States and the Nordic countries have 69, 546, 59 and 120 (total 794) active river gauging stations, respectively, within the PADB with an ending date between 2015 and 2024 according to the Global Runoff Data Centre (GRDC, 2024) (Figure 1). Note that some of these stations have not always had continuous operation and may have data gaps. Some gauging stations are also only active during the summer months and may therefore have seasonal data gaps. River discharge is often estimated from water stage using rating curves (relationship between measured stage and

discharge), which require updates to maintain reliable estimates. Inadequate updates on the measured discharge in downstream gauges (i.e., Russian gauging stations Yenisey at Igarka and Lena at Kusr) has resulted in uncertainties in these water stage estimates (McClelland et al., 2015). The discharge stations are maintained by national water authorities, and discharge data availability varies between these. However, much of this data are also openly available in discharge databases (e.g., Arctic Great Rivers Observatory, Global Runoff Data Centre, R-ArcticNET), although the frequency of updates of these databases also varies depending on the data availability from different countries.

Observed changes in annual river discharge from the eight largest rivers in the Arctic (Eurasia: Yenisei, Lena, Ob, Pechora, Sev. Dvina, Kolyma; North America: Mackenzie, Yukon), covering approximately 70% of the PADB area (Figure 1A), indicates a significant increase of 222 km³ in total freshwater influx over 1970–2023 (AMAP, 2024). However, it should be noted that the changes in river flow across the PADB are spatially non-uniform. Despite increasing trends in many Arctic rivers, mainly during the last decades, there are also river basins (e.g., in Siberia, Canada and Alaska) that exhibits decreasing annual flows (e.g., Feng et al., 2021; AMAP, 2024) due to, e.g., decreased precipitation and snow accumulation (e.g., Nesterova et al., 2020). Furthermore, a large majority of the northern catchments in the Arctic (along the land-ocean interface) remains ungauged. These nearshore environments transports hydrochemical fluxes that can have significant ecological implications for coastal, and possibly broader, marine environments (Prowse et al., 2015). Combining remote sensing and hydrological modeling that assimilates discharge across the Arctic can provide spatially and temporally flows at all Arctic rivers (Feng et al., 2021), including small rivers in the high Arctic that are missed by current observation networks, and further extend areas that can be used for coupled water-cryosphere-ecosystem studies using a catchment-based approach.

2.3 Groundwater-related variables

Groundwater resources are crucial for human and ecosystem needs in Arctic regions, and is the largest active reservoir in the global hydrological cycle. Movement of groundwater, from land to water bodies and eventually to the sea represents a major source of freshwater, nutrients and carbon for catchment water budget and biogeochemical processes. Groundwater is also important for sustaining certain groundwater dependent ecosystems. Permafrost constrains water pathways and connections during most of the seasons, but the seasonally thawed active layer provides shallow groundwater sources in summer and fall periods even in the high Arctic (O'Connor et al., 2019). Climate change is also already seen as increases in groundwater discharge during winter months in large Arctic river basins (McKenzie et al., 2021).

Groundwater monitoring including depth and quality is primarily conducted in large aquifers used for drinking water supply, as part of environmental monitoring of land use impact, e.g., mining and dams or in experimental research sites. Monitoring is mainly done using traditional water depth measurement methods, and requires drilling, and is only at the point scale thereby limiting good representation of larger spatial variation of groundwater resources. Groundwater is still rarely measured in remote areas, and is currently only measured at

research stations and networks, including the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT). In Arctic monitoring programs, only few sites have groundwater monitoring listed, and a review by Lecher (2017) identified only 16 peer-reviewed studies concerning groundwater discharge in the high Arctic. In regions with seasonally frozen soil, namely, sub-arctic and north boreal regions, although a long tradition of groundwater studies exists, the systematic sharing of monitoring data is lacking. A study by Fan et al. (2013) provided a global estimate for groundwater table level including data from government archives and literature also from northern areas. Their study shows that most groundwater monitoring occurs close to municipal areas, and sharing of groundwater data resources is lacking. Groundwater level is also an important variable for Arctic monitoring and predicting damage to infrastructure (housing, industry, etc.), but local monitoring data is difficult to access or restricted due to critical infrastructure reasons.

For better spatial coverage of groundwater level and dynamics, remote sensing offers some possibilities in Arctic areas. Gravity-based measurements with GRACE and GRACE-FO missions are used to track terrestrial water storages (Richey et al., 2015) and are also separated for groundwater storage parts but only with rather coarse resolution. Interferometric Synthetic Aperture Radar (InSar), used for measuring surface deformation or microwave remote sensing of soil moisture, can provide proxies for groundwater dynamics (Adams et al., 2022). Numerical modelling in 1D-3D can provide additional information but are typically applied to case specific sites and large aquifer types, and usually need good calibration data from measurements. This highlights the importance of monitoring groundwater at ground level in Arctic sites where new groundwater formations, especially shallow ones, are formed after permafrost thawing.

Groundwater has an important role in the carbon cycle (Connolly et al., 2020), but dissolved inorganic carbon (DIC, main carbon fraction in groundwater) transport processes are not systematically monitored in a circum-Arctic context. In a recent study, increase in groundwater DIC concentrations was documented in Sweden (Klaus, 2023), indicating potential climate change impacts to groundwater chemistry in the Arctic. Permafrost thaw promotes shallow groundwater flow and water movement in the active layer and strongly impacts carbon transport possibilities (Serikova et al., 2018). We suggest that several lateral carbon transport components of groundwater, namely, shallow groundwater and soil water quality and transport, should be better included in Arctic monitoring since globally lateral C fluxes have been estimated to be similar in size to the terrestrial C-sink (Le Quéré et al., 2016). Groundwater also has a direct link to ecosystem functions, and thus more systematic monitoring of lateral processes in active layer and groundwater in non-permafrost regions would benefit not only carbon, but also understanding of ecosystem processes.

3 Ecosystem indicators

3.1 Terrestrial ecosystems

The exchange of greenhouse gases (GHG) between terrestrial ecosystems and the atmosphere is largely driven by biological

processes of microbial and photosynthesizing nature. These enzymatic processes are constrained by temperature and water availability and interact with other factors (nutrient availability, vegetation composition, topography) and light availability for photosynthesis, which in turn interact with herbivores and other disturbances (Schmidt et al., 2024). Together these are the main controls on the Net Ecosystem Carbon Balance (NECB; López-Blanco et al., 2025) and parameters that can be measured in the field, making NECB an indicator and concept that is particularly well suited for studies at the confined catchment scale. Here it is possible to measure and study all components in the field as well as work with models that can include different levels of the complex ecosystem interactions. The measurements needed within the same catchment for the NECB budgeting include both vertical (atmospheric) and lateral transport of carbon in all its forms (CO₂, CH₄, DOC, DIC) as well as a good handle on the import/export terms relating to herbivory (grazing, insects, etc.). For longer term assessments there is also an important need for a quantitative understanding of the effects of episodic extreme disturbance such as wildfires and extreme insect outbreaks (Virkkala et al., 2025).

Despite limited productivity, substantial amounts of organic material have accumulated in northern terrestrial ecosystems over the postglacial timescale (Hugelius et al., 2023). These ecosystems have globally significant contributions to the NECB, in particular with respect to CO₂ and CH₄ exchanges, which ultimately can amplify the current (and forecasted) warming (Christensen et al., 2019; Fernández-Martínez et al., 2019; IPCC, 2019; Hugelius et al., 2023; Ramage et al., 2024). Individual components and mechanisms that form part of the NECB are being studied at a number of locations in the Arctic and globally, where interannual variability in climate is used to interpret the responses to predicted future climatic development (AMAP, 2021). This coarse scale approach, however, oftentimes falls short as responses are context-dependent and highly influenced by local conditions. At the catchment scale it is possible to work with a higher resolution of driving parameters and the complete and interlinked NECB and greenhouse gas budgets. Such detailed catchment studies can at the same time be compared along gradients from the southern- to the northernmost parts of the Arctic (López-Blanco et al., 2025).

From a greenhouse gas perspective, catchments may be small, yet their large carbon stores suggest that dynamics represent proxies for processes with global implications. The catchment-scale approach allows for characterizing both latitudinal and temporal aspects of carbon dynamics in Arctic ecosystems. Traditionally, differences are considered to be entirely climate-driven, but this is challenged by the fact that local nutrient availability may be a more important factor in determining carbon flux magnitudes between otherwise comparable ecosystems (López-Blanco et al., 2020). In this concept, lateral movement of water, nutrients and ions in the landscape is critical and often not a well-covered component. Additionally, differences in patterns and intensity of herbivory may be another understudied factor (Väisänen et al., 2014; Metcalfe and Olofsson, 2015; Stark and Ylänne, 2015; Min et al., 2021; Post et al., 2021) influencing and changing the overall NECB (via changes in plant composition, energy balance, nutrient availability, etc., see, e.g., Falk et al., 2015; Mosbacher et al., 2019) and how it responds to climate change. It has also been shown that the ongoing long-term warming may see its most

dramatic effects and changes in Arctic ecosystems through local extreme events relating to parameters other than temperature alone such as anomalous precipitation and snow events (Christensen et al., 2021).

Clearly, it is time to challenge existing paradigms using the catchment-scale approach to address questions such as:

1. Local conditions versus large-scale patterns, including herbivory, nutrients, hydrology, snow conditions, and permafrost at the local scale may be the primary controls over NECB and GHG associated ecosystem feedbacks, with underlying large-scale temperature patterns possibly being less important.
2. Extreme events and components, such as heavy rainfall, prolonged drought periods and changes in herbivore (invertebrates as well as vertebrates) activity may exceed the roles of both large-scale temperature patterns and local background conditions in controlling NECB.

Working with such questions in improving our understanding of the NECB as an ecosystem indicator requires a catchment approach.

3.2 Freshwater ecosystems

Lakes and streams are closely linked to their drainage area and reflect changes in runoff patterns and solute concentrations. Freshwater monitoring has normally been designed to associate community samples of different organismic groups (e.g., plankton, benthic invertebrates, fish) to a set of physio-chemical variables that potentially drive ecological change at the local scale. For example, dissolved organic carbon (DOC) is a good indicator of catchment vegetation development (e.g., transition from tundra into boreal forest) and soil processes (e.g., permafrost thaw) in catchments where climate change is the primary driver of change (Huser et al., 2022). Although this historical approach has not normally included climate variables, recent circumpolar assessments of CAFF's (Conservation of Arctic Flora and Fauna; i.e., the biodiversity working group of the Arctic Council) have done this. For example, the Freshwater Circumpolar Biodiversity Monitoring Program (CBMP) analyzed trends in biodiversity variables at the ecozone spatial scale (Culp et al., 2022; Goedkoop et al., 2022). This enabled linkages of freshwater biodiversity and biological processes to climate because terrestrial ecozones are by definition related to catchment and climate attributes (Olson et al., 2001). The temperature regime as well as hydrological connectivity were found to be critical factors that constrain biodiversity and ecological processes in Arctic freshwaters (Laske et al., 2022; Lento et al., 2022; Schartau et al., 2022).

Freshwater monitoring is particularly discontinuous across the Arctic (Lento et al., 2019; Culp et al., 2022) and dependent on accessibility and monitoring traditions in the various countries. For example, the Fennoscandian countries have a long tradition of monitoring the physio-chemical and biological effects of acidification and eutrophication, Iceland and Norway have long monitored fish populations in major rivers, whereas in the vast and remote Arctic regions of Canada, time-series monitoring of baseline

conditions is sporadic and instead built largely on the collection of single samples during surveys (Goedkoop et al., 2022). Arctic Council countries have recognized the need for intensified biological monitoring programs that combine remote sensing with on-site monitoring at regional scales, but this approach has not yet been implemented. Such large-scale monitoring that includes remote sensing and local measurement data could resemble the approach undertaken by ArcticGRO (2025). Since 2003 this program has provided essential data on the biogeochemistry and discharge of the largest Arctic rivers, thus providing an integrated measure of the transport of solutes and materials to the Arctic Ocean (e.g., Behnke et al., 2023). Similar monitoring programs, that also include biological variables, exist for smaller Arctic rivers and lakes on a regional scale, such as in northern Fennoscandia, but are lacking on a circumpolar scale. Such approaches, that include both biological and geochemical variables, have the potential to expand to other Arctic countries and explore synergies with existing research and infrastructure hubs such as the Canadian High Arctic Research Station (CHARS) and Zackenberg on Greenland. The inclusion of high-resolution remote sensing data could further improve the monitoring of large-scale ecological change.

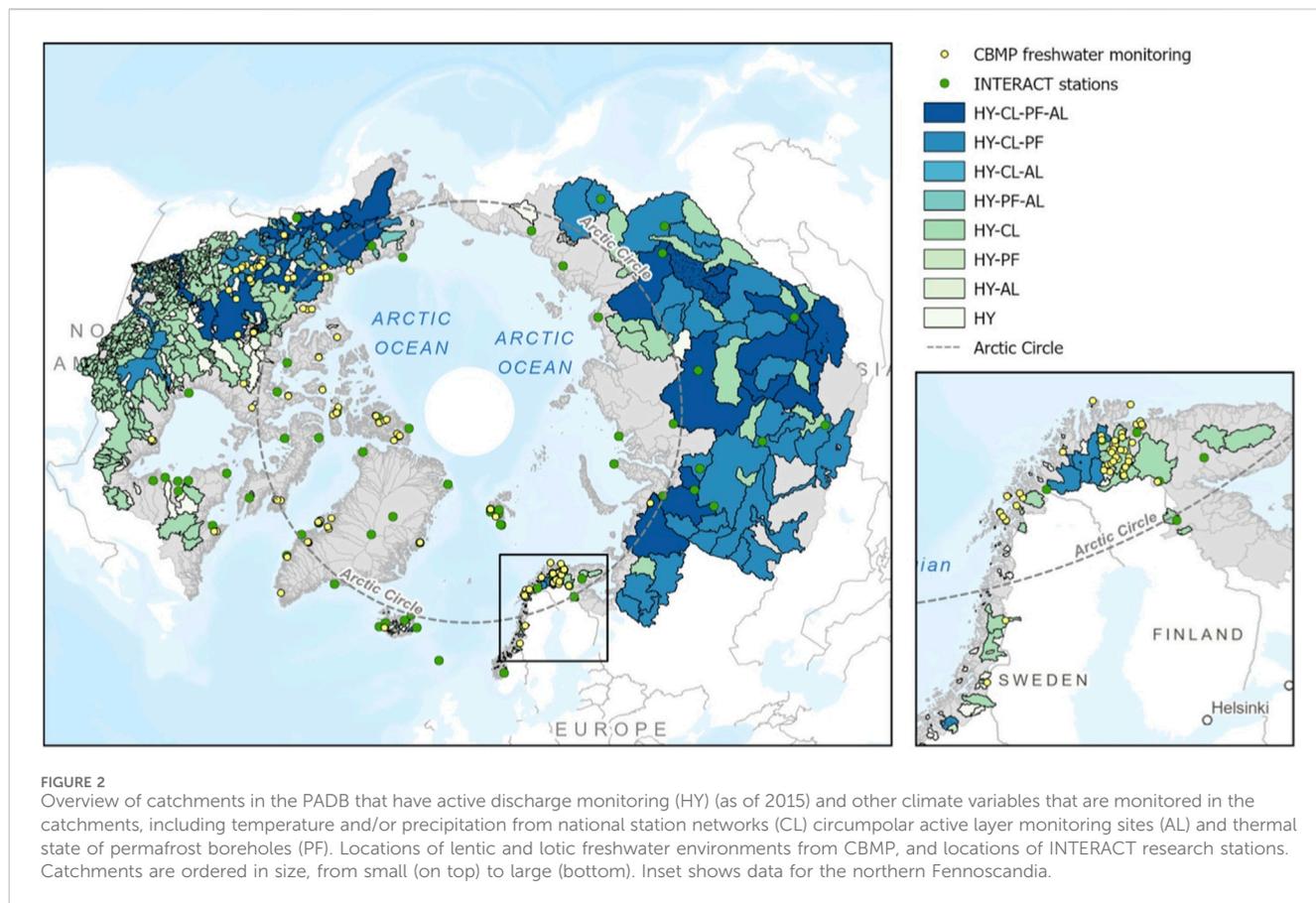
Rapid vegetation changes in the Arctic and subarctic, as well as permafrost thawing, can directly impact nutrient inputs delivered from terrestrial to freshwater ecosystems (Wrona et al., 2013). For example, permafrost thaw can cause enrichment with nutrients including nitrogen, phosphorus, and dissolved organic matter (Kokelj et al., 2013; Chin et al., 2016). In contrast, terrestrial vegetation development can lead to increased sequestering of nutrients in soils, thereby leading to oligotrophication of northern freshwater ecosystems (Arvola et al., 2011; Eimers et al., 2009; Huser et al., 2018). Goedkoop et al. (2025) recently demonstrated that long-term sequestration of nitrogen and phosphorus nutrients within terrestrial environments in northern Sweden have led to the oligotrophication of Arctic/alpine lakes. This conclusion was rendered by linking long-term monitoring of subarctic lakes to the greening of landscapes. Similar processes are likely ongoing in other parts of the Arctic, but remain undetected due to the lack of long-term monitoring data. To better define and understand these changes to ecological processes in Arctic freshwaters, intensified monitoring programs that link remote sensing information with regional monitoring are required (Goedkoop et al., 2022).

Culp et al. (2022) and associated papers in this special issue reporting on CAFF-CBMP work demonstrated that existing freshwater monitoring data could be accumulated within terrestrial ecoregions. These regions were described by Olson et al. (2001) and are defined by unique biogeographical features, and can be used to aid broad assessments of hydroclimatic change on freshwater biodiversity at the circumpolar scale (Culp et al., 2022; Lento et al., 2022). Moreover, this approach forms a natural unit for the summarization of geospatial variables associated with global hydrological basin layers (i.e., hydrobasins) that were delineated by Lehner and Grill (2013). The use of ecoregion scale assessment is therefore a promising approach to improve the association of climate variables to freshwater ecological processes, that will also provide improved context for catchment scale observations. Recent work of the Arctic Council's Freshwater CBMP provides proof of

this concept as broad latitudinal and circumpolar trends in freshwater diversity across ecoregions could be related to the climate (e.g., Kahlert et al., 2022; Lento et al., 2022). It is imperative that existing databases are utilized to build these broad trends in freshwater biodiversity, with particular emphasis on including long-term monitoring sites such as those at relatively accessible locations (e.g., in northern Fennoscandia) or at isolated sites where necessary infrastructure is in place including Zackenberg in Greenland, CHARS in Canada, and other sites within INTERACT.

4 Opportunities and limitations to track climate-ecosystems interactions using a catchment-based approach

The pan-Arctic drainage basin (PADB) contains around 47,000 river basins and covers an area of more than 20 million km² (based on the pan-Arctic catchment database, ARCADE; Speetjens et al., 2023) (Figure 1). To further assess which key hydroclimate and ecosystem variables are being monitored and where in the PADB and to identify opportunities for using a catchment-based approach, we collected georeferenced information of key variables from existing national and international monitoring networks, and (global) databases that include data from monitoring networks (number in parentheses represent number of stations included for each variable). Inclusion of monitoring networks and databases was guided by the FAIR data principles (Findable, Accessible, Interoperable, Reusable) (Wilkinson et al., 2016), and we only included sites and stations that are within the PADB (based on ARCADE). For hydroclimate variables, we collected locations of temperature and precipitation stations (2652 and 952, respectively, 3,604 in total) from national and international networks (Lenssen et al., 2019; Government of Canada, 2025; Razuvaev et al., 1993; USGS, 2025; Norwegian Meteorological Institute, 2025; Finnish Meteorological Institute, 2025), and locations of discharge stations (794) from the GRDC (2024), with an ending date between 2015 and 2024. The reason for choosing 2015 as a lower boundary for the year with latest data available for discharge is that there is at times a delay in reporting from national water authorities to the GRDC. For example, when choosing 2020 as a lower boundary, a majority of the Russian and Norwegian catchments are excluded and some of the northernmost catchments in North America. As permafrost may be the primary control of NECB and an important component in other cryosphere-water-ecosystem interactions, we also included locations of circumpolar active layer monitoring (CALM) sites (191) (GTN-P, 2025a) and thermal state of permafrost (TSP) boreholes (870) (GTN-P, 2025b). For ecosystem variables, we use the freshwater ecosystem (lotic and lentic) monitoring locations (157) from the Conservation of Arctic Flora and Fauna - Circumpolar Biodiversity Monitoring Programme (CBMP freshwater monitoring; Metadata for the CBMP freshwater data is available at the CAFF website <https://abds.is/>). We also use the locations of the research stations (39) included in the INTERACT network, which have served as platforms for the majority of field-based ecosystem studies in the Arctic (Metcalfe et al., 2018). In total, we included 5,655 hydroclimate and ecosystem monitoring stations (Figure 1).



Note that not all stations may be active today (e.g., some of the GRDC and CBMP freshwater locations) (Figure 1; Supplementary Figure S3), but are included here as they provide (long-term) data that can be used for studying (past) climate change impacts, and guidance where monitoring could potentially be reestablished for comparative studies.

Only a small number of the monitored catchments (539 or 1% of the catchments in the PADB) contain at least one station monitoring climate, permafrost or ecosystem variables, with a median station density of roughly one station per 250 km². Although the eight largest catchments include more stations, their densities are much lower, with approximately one station per 1,000–10,000 km². The spatial distribution of hydrological, climate and ecosystem observations reviewed here reveals only limited overlap among these monitoring networks. There are only two catchments (Mackenzie and Yukon, the two largest Arctic rivers in North America) that have monitoring of all hydroclimate and ecosystem variables in consideration. This is mainly due to the sparse network of the INTERACT stations, as well as the limited number of CBMP freshwater locations in the Russian part of the PADB. Moreover, although downstream stations in the Mackenzie, Yukon, and the six largest Russian Arctic rivers capture about 70% of PADB discharge, their very large basin sizes (300,000–3,000,000 km²) and strong spatial heterogeneity limit catchment-based analyses. Smaller catchments and sub-catchments, therefore, provide a more appropriate scale for linking hydroclimatic fluxes with ecosystem processes and local

environmental dynamics. In summary, the spatial coverage of hydroclimate, permafrost or ecosystem variables varies across the PADB (Figure 1). For example, as previously noted a large majority of the northern catchments in the Arctic (along the land-ocean interface) remains ungauged (Figure 1A), and other monitored areas have decreased over time (Supplementary Figure S2). The density of temperature and/or precipitation stations from national networks appears to be decreasing with latitude, apart from the Nordic countries (Figure 1B). The network of active layer monitoring is less dense compared to the network of permafrost boreholes, and much of the monitoring of both variables is centered in Alaska (Figure 1C). Regarding the spatial distribution of the CBMP freshwater locations, they are mainly found in North American and Nordic regions, while the INTERACT stations, although few in number, are spread across the Arctic (Figure 1D).

However, some monitoring opportunities exist at catchment or sub-catchment scale that can be used to improve our understanding of linked hydroclimate-cryosphere-ecosystem dynamics. Figure 2 shows catchments (including sub-catchments) with active discharge monitoring (HY; as of 2015) within the PADB together with other active monitoring of climate variables, including temperature and/or precipitation data (CL), permafrost borehole data (PF), and active layer monitoring (AL), as well as the location of CBMP freshwater locations and INTERACT stations. Of the 794 catchments (including sub-catchments) shown in Figure 2, 32 have monitoring of all hydroclimate variables (catchment size ranging

from 3,900 Km² to 2.95 M km²) (Supplementary Figure S3). A total of 73 catchments include the combination HY-CL-PF (72) or HY-CL-AL (1) (catchment size ranging from 1980 km² to 2.69 M km²), and 394 catchments include the combination HY-PF-AL (4), HY-CL (381), HY-PF (8), or HY-AL (1) (catchment size ranging from 31 to 293,000 km²). The remaining catchments (295) only have hydrological (HY) monitoring (catchment size ranging from 1.8 to 93,900 km²). The spread of catchment sizes appears to be decreasing with decreasing number of monitored hydroclimate variables. Many of the catchments that include three or more hydroclimate variables are, however, located at the lower latitudes, are not near ecosystem monitoring sites, or have areas exceeding 100,000 km² and thus unsuitable to study hydroclimate-ecosystem dynamics at landscape scale. Yet some catchments exist, where monitoring of hydroclimate variables overlap with regions of ecosystem variables that can be used to improve detection, interpretation and projection of linked water-cryosphere-ecosystem dynamics using a catchment-based approach. These catchments are located in northern Fennoscandia, Zackenberg in northeastern Greenland, Alaska (US), Yukon, Northwest Territories, British Columbia, Alberta in Canada, and some larger catchments in Russia (Yamalo-Nenets, Altai, Novosibirsk, Sakha, Magadan) (Figure 2).

5 Discussion

In this review, we synthesized knowledge on available monitoring of key hydroclimatic and ecosystem indicators to identify opportunities for improved detection, interpretation and projection of linked water-cryosphere-ecosystem dynamics using a catchment-based approach. In summary, *in situ* monitoring of climate variables (temperature, precipitation and snow cover) remains sparse over large areas (e.g., towards higher latitudes). A similar latitudinal pattern can be seen for surface water (discharge) monitoring, as a majority of northern catchments (along the land-ocean interface) remains ungauged. Groundwater monitoring is even more sparse, with most of its monitoring occurring at research stations and networks. The northward decline in observation density presents a major challenge for two key reasons. First, the rate of climate warming in the terrestrial Arctic intensifies toward the north. Second, the surface topography in the northern coastal and archipelago regions is highly heterogeneous, reducing the spatial representativeness of individual observation stations. To compensate for the limited spatial monitoring of hydroclimate variables, more recent estimates are increasingly reliant on remote sensing data. Current freshwater and terrestrial ecosystem monitoring has poor representation in large parts of the Arctic, and areas with better coverage are often found around relatively accessible locations or near research stations where necessary infrastructure is in place. To improve our understanding of hydroclimate and ecosystem interactions in a continued warming Arctic, we need to prioritize coordinated ecological and hydroclimatic monitoring in regions most vulnerable to climate change.

Overall, there is currently a large spatial mismatch between the coverage of hydroclimate and ecosystem monitoring. This

mismatch results in limitations in using a catchment-based approach to study hydroclimate-ecosystem interactions across the PADB, as, i.e., only two catchments have monitoring of all hydroclimate and ecosystem variables considered in this review. However, there are opportunities in some data-rich regions where smaller catchments or sub-catchments have available monitoring of hydroclimate variables, and overlap with regions of ecosystem monitoring. Although these regions do not represent all Arctic heterogeneous landscapes (e.g., due to monitoring biases; López-Blanco et al. 2024), they can be used as a starting point for catchment-based approaches to study climate-ecosystem interactions. Continued improvements in observation methods, including drone mapping of heterogeneous landscapes, advances in satellite remote sensing, and better atmospheric reanalyses with higher horizontal and vertical resolution, including layers in the snow, ground, and lakes, can complement *in situ* measurements and help fill spatial gaps between observation networks. These advances can also identify regions with the best potential for downscaling climate model outputs to project future linked climate-ecosystem dynamics. Moreover, incorporating multiple knowledge systems, including Indigenous and local knowledge through participatory research and community-based monitoring, can, in addition to scientific information from *in situ* and satellite data, substantially enhance the spatial coverage of observation networks (see, for example, Johnson et al., 2016, and the Atlas of Community-Based Monitoring – <https://www.arcticcbm.org>).

Author contributions

JM: Writing – original draft, Visualization, Formal Analysis, Conceptualization, Project administration, Investigation, Writing – review and editing. TC: Investigation, Writing – original draft, Writing – review and editing, Conceptualization. JC: Investigation, Writing – original draft, Writing – review and editing. WG: Investigation, Writing – original draft, Writing – review and editing. HM: Investigation, Writing – original draft, Writing – review and editing. NS: Investigation, Writing – original draft, Writing – review and editing. TV: Investigation, Writing – original draft, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2025.1598722/full#supplementary-material>

SUPPLEMENTARY FIGURE S1

In-situ monitoring of temperature (a) and precipitation (b) from national station networks. The eight largest rivers in the PADB (Yenisei, Lena, Ob, Pechora, Sev. Dvina, Kolyma in Eurasia; Mackenzie, Yukon in North America) are shown with a black outline.

SUPPLEMENTARY FIGURE S2

In-situ monitoring of discharge, available from the Global Runoff Data Centre (GRDC) stations catalogue, including latest data available.

SUPPLEMENTARY FIGURE S3

Catchments in the PADB that have monitoring of all hydroclimate variables, including discharge, climate (temperature and/or precipitation), active layer and permafrost.

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