Randy Brown, fish biologist, prepares to catch, tag, and track Dolly Varden in Arctic National Wildlife Refuge
Photo: Katrina Liebich, USFWS

6. State of Arctic Freshwater Monitoring

6.1. Introduction

In this chapter we describe the current status of freshwater monitoring in the Arctic countries, and address possible ways to improve future monitoring in the Arctic including community engagement. Building on the freshwater biodiversity plan published by CAFF in 2012 (Culp et al. 2012a), this first circumpolar assessment of freshwater biodiversity created and analyzed an expansive, circumpolar data set covering paleo, historic, and contemporary data on Arctic freshwater biodiversity. Biodiversity trends were evaluated at the circumpolar ecoregion level and also within regions defined by areas of similar geography, flora and fauna. The assessment also addresses knowledge gaps that limit our ability to conserve and protect freshwater biodiversity in the circum-Arctic countries, and forwards expert guidance on monitoring network design for Arctic freshwater biodiversity.

The availability and use of data for the SAFBR varied among the Focal Ecosystem Components (Table 61). For example, the Fish FEC had a number of parameters with available data (e.g., numbers, relative abundance, total biomass, presence/absence, age and size structure), but data availability and sampling methods varied for each parameter, and presence/absence offered the best and most consistent spatial and temporal coverage. The macrophyte FEC had the fewest potential parameters (as listed in Culp et al. 2012a), and differences across data sources similarly required the use of presence/absence data. Presence/absence information was available for all of the FECs, because other measured parameters could easily be converted to this parameter. Thus, biodiversity analysis for lakes and rivers were completed using relative abundance information when possible, or with presence/absence when required by inconsistencies in sampling methods or parameter measurements.

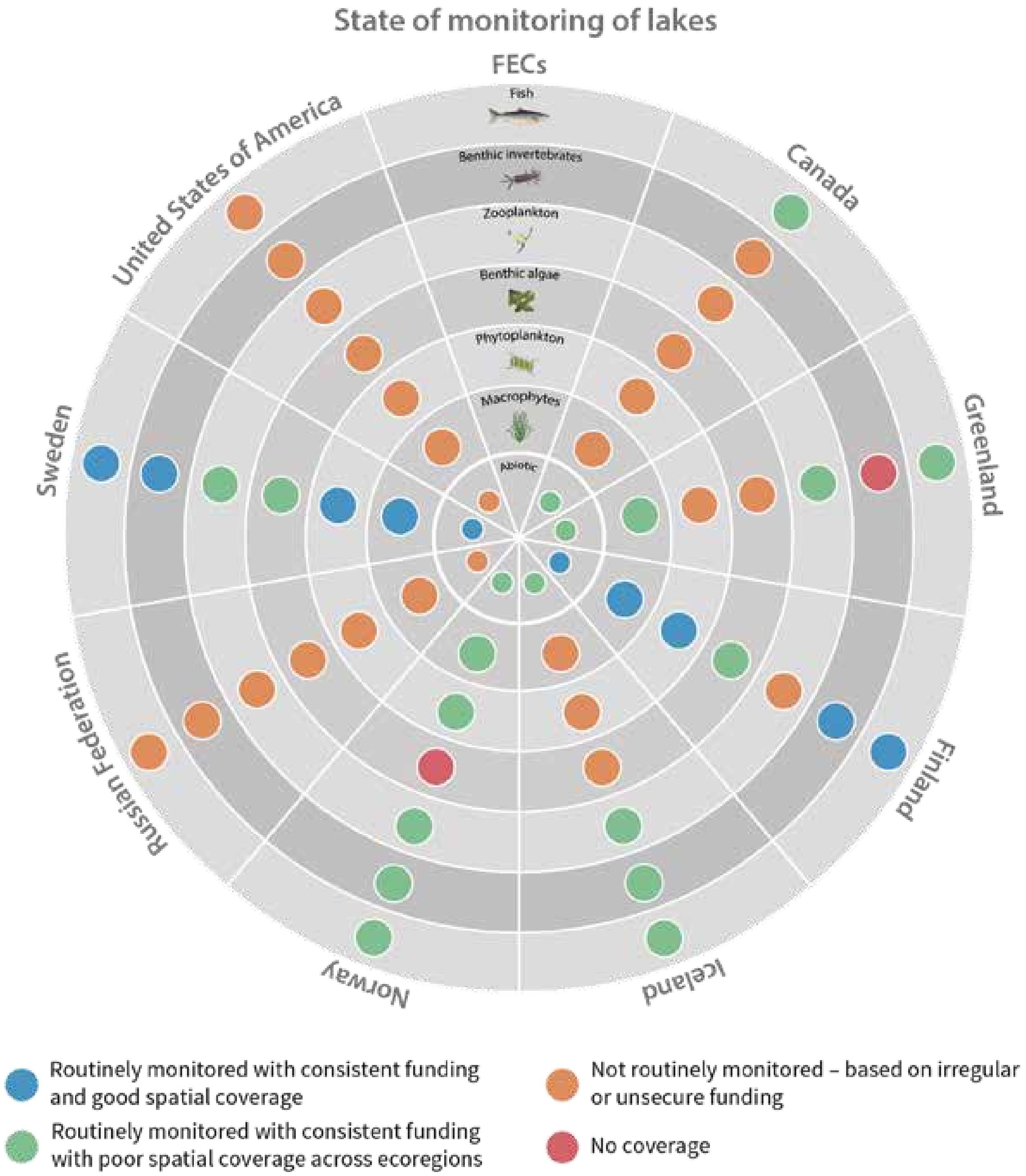

Figure 6-1 Current state of monitoring for lake FECs in each Arctic country.

6.2. Existing Monitoring in Arctic Countries

Although the circumpolar countries endeavor to support monitoring programs that provide good coverage of Arctic and subarctic regions, this ideal is constrained by the high costs associated with repeated sampling of a large set of lakes and rivers in areas that often are very remote. Consequently, freshwater monitoring has sparse, spatial coverage in large parts of the Arctic, with only Fennoscandia and Iceland having extensive monitoring coverage of lakes and streams (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). In many remote areas of the Arctic, monitoring is often associated with planned or ongoing development projects (e.g., hydropower, mining, oil and gas). Such monitoring can be short-term in nature and focused narrowly on point-source and/or regional effects. In contrast, Fennoscandian freshwaters have time-series information dating back to the 1960s for water chemistry, and to the 1980s for several biological variables; Iceland has long monitoring records of fish populations for some rivers. The more extensive data availability in Europe is, in part, the result of requirements by the European Union for regular reporting on the status of their inland waters, including sub-Arctic lakes and rivers within the CAFF-boundary. The availability of such higher-resolution data is critical for the development of predictive models of biodiversity change in other parts of the Arctic.

The following descriptions of monitoring of Lake and River FECs indicate how the current approaches and data coverage vary by country. Table 6-2 and Table 6-3 provide the details of the current monitoring status for lake and river FECs and their parameters within the eight Arctic countries including an assessment of spatial coverage and funding consistency.

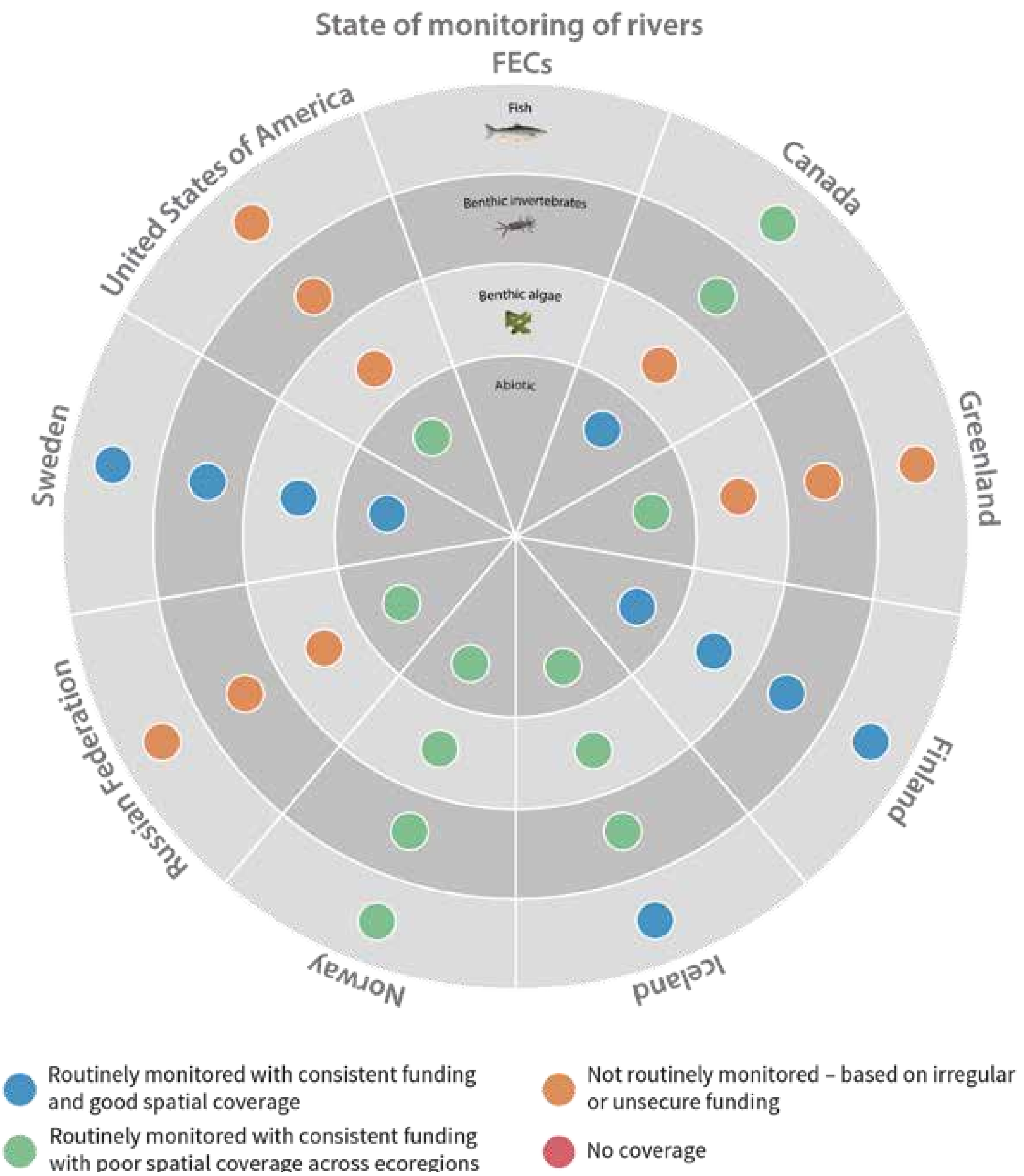

Figure 6-2 Current state of monitoring for river FECs in each Arctic country

Table 6-1 Overview of data availability and use for SAFBR analyses for lakes and rivers, including data from ongoing or past freshwater monitoring programs in the Arctic, as well as data from different sources (academia, industry, NGOs) to increase coverage for some parameters/regions. Values for each parameter indicate that: (1) data were available and were used; (2) some data were available but were not used for the assessment; or (3) there were few or no data available.

FECs and parameters as described in CBMP freshwater monitoring plan**		Data used in SAFBR
Fish	Numbers, relative abundance, total biomass	2
	Presence absence**	1
	Genetic diversity	3
	Size structure	2
	Age structure	2
	Timing of important life history events	3
	Contaminant concentration	3
Benthic invertebrates	Numbers, relative abundance, total biomass	1
	Presence absence**	1
	Size structure	3
	Timing of important life history events	3
	Contaminant concentration	3
Zooplankton	Numbers, relative abundance, total biomass	1
	Presence absence**	1
	Biomass of each taxon	2
	Timing of important life history events	3
Algae from benthic samples	Numbers, relative abundance, total biomass	1
	Presence absence**	1
	Biomass or biovolume of each taxon	2
	Bulk biomass (including chlorophyll a)	2
Phytoplankton	Numbers, relative abundance	2
	Presence absence**	1
	Biomass or biovolume of each taxon	1
	Bulk biomass (including chlorophyll a)	2
Macrophytes	Areal cover, distribution or number of individuals of each taxon	2
	Presence absence**	1

** Aquatic birds were originally included in the Freshwater Monitoring plan, but were taken out and instead included in the CBMP Terrestrial Monitoring Plan*
*** Not explicitly listed in the monitoring plan but necessitated by available data*


Photo: USWFS

6.2.1 USA

Researchers collect fish in the Agashashok River, Alaska
Photo: Michael Records, USGS

Freshwater monitoring in the Arctic region of the USA (i.e., Alaska) is limited in scope (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). Data are available for each of the FECs, yet little overlap in FEC data distribution occurs given the independence of projects and data collection. Monitoring data availability depends on the goals of the agency or group undertaking collection. Data are collected by the National Park Service Inventory and Monitoring network, the U.S. Geological Survey, U.S. Bureau of Land Management, U.S. Fish and Wildlife Service, Alaska state agencies, and academic programs.

Arctic biodiversity monitoring does take place in the country's National Parks located in the low Arctic zone in Alaska. The National Park Service Arctic and Central Alaska Inventory and Monitoring Networks (ARCN) monitor stream and lake communities and ecosystems in the Bering Land Bridge National Preserve, Cape Krusenstern National Monument, Noatak National Preserve, Kobuk Valley National Park, and Gates of the Arctic National Park and Preserve (science.nature.nps.gov/im/units/arcn/index.cfm). Since 2007, the ARCN has monitored water quality (temperature, turbidity, pH, and dissolved oxygen), macrophyte vegetation, and species richness/ abundance of benthic macroinvertebrates of shallow lakes. More recently (< 5 years), National Park Service initiated monitoring of water quality in streams, and in the coming decades they plan to begin monitoring long-term trends on chemical (e.g., pH, dissolved oxygen), physical (e.g., water levels, temperature), and biological (e.g., phytoplankton, zooplankton) characteristics of large lake ecosystems in Gates of the Arctic National Park and Preserve.

Outside of the National Parks, many FECs are not routinely monitored, and efforts to do so are often based on irregular or unsecure funding. Recent collaborative projects (www.fishcreekwatershed.org) between the University of Alaska Fairbanks and federal agencies aim to establish a baseline for fish habitat in streams and lakes, and include monitoring of biotic FECs (fish, benthic macroinvertebrates, zooplankton, and phytoplankton) and abiotic FECs (discharge, temperature, water quality). The Arctic Long-Term Ecological Research Site (LTER) uses long-term monitoring along with surveys and experiments with the goal of predicting Arctic ecosystem response to environmental change (arc-lter.ecosystems.mbl.edu). Numerous FECs have been sampled in the LTER site, including fish, benthic macroinvertebrates, zooplankton, phytoplankton, and physics/chemistry. Additional monitoring may also occur as part of mandated sampling conducted in conjunction with mining or energy extraction, but is localized in specific systems impacted by development.

6.2.2. Canada

Sampling in northern Canada
Photo: Daryl Hallowell

Monitoring of lakes and rivers in the Canadian Arctic is necessarily limited by the enormous spatial expanse of this sub-Arctic to high Arctic region encompassing drainage areas of the Pacific, Arctic, and Atlantic oceans as well as Hudson Bay. Freshwater biodiversity, water quality and water quantity data are collected to meet various federal commitments related to transboundary watersheds crossing international, inter-provincial and territorial borders, or under various other regulatory authorities. Data are collected by territorial governments (Yukon, Northwest Territories, Nunavut), provincial jurisdictions (Quebec, Labrador and Newfoundland) and federal departments (e.g., Fisheries and Oceans Canada, Environment and Climate Change Canada – ECCC, and Parks Canada). Other biodiversity information is collected opportunistically through industrial and academic research programs.

Ongoing freshwater biodiversity monitoring is generally limited to fish populations and benthic macroinvertebrates (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). Fish monitoring is restricted to federal and territorial stock assessments. Monitoring of macroinvertebrates occurs through development of the Canadian Aquatic Biomonitoring Network (CABIN) that has a standardized sampling protocol and assessment approach for assessing aquatic ecosystem condition. Arctic sampling is restricted to northern parts of the Yukon, the Northwest Territories and to locations where industry and academic research programs can provide monitoring synergies. This opportunistic sampling strategy increases spatial coverage of macroinvertebrate sampling but provides limited data for time series trends. Routine monitoring of macroinvertebrates is currently undertaken or under development by Parks Canada and some territorial governments (e.g., Government of Northwest Territories), though existing datasets have limited time series. Some additional monitoring of diatoms in lakes and rivers is currently ongoing in northern Quebec, but this represents an extremely limited geographic area of the Canadian Arctic.

Canada's long-term water quality and water quantify monitoring have contrasting spatial and temporal coverage. The water quality network is administered by ECCC along with territorial partners and Parks Canada, and only includes 46 sites across the North. Parameters regularly measured include temperature, pH, alkalinity, major ions, nutrients and metals. Sampling frequency varies from one to more than 6 times per year as sampling is adjusted according to a risk-based, adaptive management framework. Most sites have been monitored for the last 15 years or longer. In contrast, water quantity monitoring by the Water Survey of Canada is quite extensive with more than 100 sites where water levels are continuously recorded. While most sites are situated in the Subarctic region, several locations in the high Arctic are monitored. In the southern Arctic there are many sites with records exceeding 50 years; however, the relatively few sites in the high Arctic have been monitored for less than 25 years.

6.2.3. Kingdom of Denmark/Greenland/Faroe Islands

Zackenberg light measurement
Photo: Kirsten S. Christoffersen

Monitoring in Greenland focuses on lake ecosystems (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2) as a component of the Greenland Ecosystem Monitoring (GEM) program (http://g-e-m.dk/). GEM is a joint effort of Denmark and Greenland institutions on behalf of the Kingdom of Denmark and includes a sub-program on Arctic biota (BioBasis). The BioBasis program monitors the dynamics of organisms and biological processes in terrestrial and freshwater ecosystems. These efforts have established a coherent and integrated understanding of the functioning of ecosystems in a highly variable climate based upon a comprehensive, long-term interdisciplinary data collection primarily at Kobbefjord (Nuuk) in low Arctic West Greenland and Zackenberg in high Arctic Northeast Greenland. Recently, a field site was added at the southern part of the Disko Island near the high Arctic. Each location has a state-of-the-art field station. The Faroe Islands has no biodiversity monitoring program for freshwaters, but freshwater sources used for drinking water and/or in fish farming are surveyed with respect to contaminants.

The GEM-BioBasis program incorporates monitoring and long-term research on ecosystems to understand climate change effects and related ecosystem feedbacks in the Arctic. Monitoring of freshwater includes biotic and abiotic dynamics, including biodiversity and phenology of phyto- and zooplankton, fish abundance and water chemistry. Sampling is typically performed on 2-6 dates during the ice-free period and occasionally during ice-cover. The longest time series exists for Zackenberg where two lakes have been sampled since 1997. Detailed protocols for the sampling and analysis program can be found on the home pages of the field sites, and data are publicly available through a data portal indexed on the GEM webpage.

6.2.4. Iceland

Sampling of macroinverterbrates in River Jokulsá á Dal, Iceland.
Photo: Guðni Guðbergsson

Freshwater monitoring in Iceland is chiefly based on three categories: (1) short term research projects including industrial or impact assessments, (2) long-term projects on productive and/or species rich areas, and (3) monitoring of rivers and lakes with harvested freshwater fish stocks. Freshwater monitoring is largely conducted by governmental institutions and has produced a good database with many parameters routinely collected (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). Iceland has a systematic monitoring of abiotic factors such as water discharge and glacier coverage. In the near future, Iceland will initiate monitoring of freshwater ecosystems to adopt the requirements set by the Water Framework Directive of the European Union. These new monitoring initiatives will add to existing monitoring and increase the number and geographical coverage of FECs. The monitoring programs in Iceland are almost exclusively dependent on governmental financing. Currently, no national monitoring database exists, but metadata compilation for freshwater research has been established in relation to the work in CBMP.

6.2.5. Norway

Monitoring station for waterflow
Photo: John Brittain

The Norwegian Arctic consists of 1) mainland Norway and the Norwegian portion of the Scandinavian peninsula north of the Polar circle, and (2) the remote islands Svalbard and Bjørnøya in the Barents Sea and Jan Mayen in the Norwegian Sea. Routine monitoring is undertaken but not on a broad spatial scale (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). In mainland Norway, monitoring includes physical, chemical, and biological FECs in both rivers and lakes. The primary purpose is to monitor pollution from industry and physical encroachments, including changes in discharge in connection with hydropower plants. In recent years, a number of reference sites and large lakes have also been monitored as a part of a national monitoring network. On Svalbard the only regular monitoring of freshwater includes two stations for discharge and transport of suspended matter. There are neither hydrochemical nor biological monitoring of freshwater sites in the Svalbard archipelago. However, research programs, specific studies, and student courses have generated some biological data from Svalbard freshwater sites. A few sites have data from multiple years, and these sites will be valuable for designing a future monitoring network on Svalbard. Except for the data collected by the hydrological stations, there are no time series from freshwater in Svalbard. There is also no ongoing monitoring of water chemistry or biota on Bjørnøya, although one lake on Bjørnøya has been studied for elevated levels of organic substances in fish and water birds.

During the last 4 years, monitoring of lakes and rivers has increased substantially in mainland Norway. New monitoring programs have been initiated, following the requirements of the EU Water Framework Directive (WFD). The FECs used in CBMP-Freshwater are similar to the WFD's Biological Quality Elements (phytoplankton, water plants, macroinvertebrates and fish), which are all included in Norwegian freshwater monitoring. The Svalbard archipelago is not a part of the EU-Norway EEA-agreement, but similar monitoring activities as on mainland Norway are also planned for this high-Arctic region. Linnévatnet in western Spitzbergen, Svalbard, was monitored in 2017 as test of traditional monitoring methods in the High Arctic. This lake has been sampled occasionally during the last 40 years, which makes it possible to document effects of climate change. Lake Linnévatnet, a couple of lakes in NY-Ålesund area and river sites in the same area are good candidates for future monitoring sites in the High Arctic. These sites would be good candidates for a circumpolar monitoring network for freshwater based on a hub-and-spoke principle as proposed in section 6.3.3.1.Within the low Arctic, the interior of Finnmark, in northern Norway, harbours an enhanced freshwater biodiversity compared to the coastal areas. This is due to the more continental climate, with a wide range in annual temperature, and dispersal from the east and southeast after the last Ice Age. This high biodiversity needs to be monitored in the light of the rapid environmental changes now taking place in the Arctic. Monitoring data from this region from the last decades make analyses of recent climate change effects possible.

6.2.6. Sweden

CBMP Freshwater co-lead Willem Goedkoop
Photo: Joseph Culp

National monitoring programs of lakes and streams/rivers, covering both biological and abiotic FECs, have been coordinated by the Swedish EPA (until 2011) and by the Swedish Agency for Marine and Water Management (2011–), while regional programs have been coordinated by the various county boards. These nationwide programs also cover the northern boreal forests, birch forests, and sub-Arctic mountainous regions of Sweden that all fall within the CAFF border. Swedish national monitoring has a good spatial and coverage within CAFF border of the Arctic (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). Monitoring of water quality in major rivers and the three largest lakes has been completed since the 1960s. The current national monitoring program started in 1988 and originally had a strong focus on the effects of acidification. The program successively grew to also incorporate streams and more lakes (in 1995). Sweden has also performed a number of synoptic, national surveys to map water quality of lakes across the country, starting in 1972 and repeated with approximately 5-y intervals. The two national surveys of lakes and streams, performed in 1995 and 2000, also included the sampling of benthic macroinvertebrates in some 700 lakes and 700 streams across the nation, among which many are in the Arctic/alpine ecoregion of Sweden.

In recent years, the national monitoring program has been gradually modified and adapted to better fit the requirements of the European Water Framework Directive. It now consists of a Trend Rivers program (67 watercourses evenly distributed across Sweden), and a Trend Lakes

Photo: USFWS

program (106 lakes) in which water chemistry and biotic samples are collected once or multiple times per year, though frequency of fish sampling is lower (29 Trend Rivers sampled annually, 45 Trend Lakes sampled at least every six years). Many of the water bodies in these programs have been sampled since 1988 or the mid 1990's. Sweden has a Rivers Outlet program (47 major rivers) that has monitored water chemistry since the 1960's. The Department of Aquatic Sciences and Assessment at the Swedish University of Agricultural Sciences has a responsibility for national monitoring, is the data host for freshwater data, and works closely with central authorities and many regional county boards. More detailed descriptions of the national programs can be found at the department's home page https://www.slu.se/en/departments/aquatic-sciences-assessment/ under the entry for Environmental Assessment. The history and current status of freshwater monitoring in Sweden has been described in detail by Fölster et al. (2014).

6.2.7. Finland

Benthic invertebrate sampling in Finnish Lapland.
Photo: Petri Liljaniemi

Freshwater monitoring is primarily carried out as part of national programs coordinated by the Ministry of the Environment, regional environmental administration and research institutes (Finnish Environment Institute and Natural Resources Institute) resulting in many parameters collected on a broad spatial scale (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). National programs for rivers and lakes are designed to monitor the long-term trends in different types of regions, including sub-Arctic headwaters. Monitoring programs include a set of biotic and abiotic FECs. Freshwater monitoring is also conducted by the private sector in order to fulfill the monitoring obligations of environmental permits (e.g., sewage treatment plants, industry, and mines). Research institutes and universities also produce data through short-term research projects.

The early biological data come from separate studies. More uniform long-term biological time-series exist from 1980-2000's for several components. Monitored biological components include fish, benthic macroinvertebrates, benthic diatoms, phytoplankton and macrophytes (e.g., species identification and abundance, community structure and some biomass estimates). The longest biological time series are for fish communities and these extend more than 30 years for large sub-Arctic rivers. At present, intensive, yearly fish monitoring includes population estimates and catch statistics for the border rivers Tornio and Teno, and Lake Inarijärvi.

Spatial coverage of especially biological monitoring was significantly expanded to meet the requirements of the EU Water Framework Directive during years 2006-2009. The largest rivers and lakes are monitored at least annually for water quality and biological components. Otherwise monitoring frequency alternates from once in every three to six years. In addition, some research programs collect yearly water quality data from small sub-Arctic rivers and lakes. The results are stored in national databases for water quality and species data. Data registers are designed to meet the needs of the reporting of ecological status for the EU. The Finnish monitoring program has a good coverage for most biological FEC's, and only zooplankton is not routinely monitored (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2).

Water quality indicators include a variety of substances, from basic nutrients to heavy metals and toxins, with the longest time series extending from the 1960s. Additional abiotic monitoring covers hydrological and meteorological variables, such as discharge, water level, precipitation, and snow. Land cover variables including soil/bedrock properties, and human impact (e.g., loading, hydro-morphological alterations) are also available.

6.2.8. Russian Federation

Anadyr River, Eastern Russian Arctic
Photo: Andrei Stepanov/Shutterstock.com

Monitoring of the Arctic regions in the Russian Federation varies across the country, and is often associated with research activities of Russian Academy of Sciences institutions and State Nature Reserves; thus, routine sampling is not widely available (Table 6-2, Table 6-3, Figure 6-1, Figure 6-2). Where long-term monitoring activities exist, they are directed by the research interests of the scientific organizations, with the results published as scientific reports, publications, and less often, in open access sources. In addition, the state of natural aquatic ecosystems is monitored for potential impacts before and after human disturbances such as industrial activities. This impact-driven assessment sometimes includes longer-term monitoring activity. Monitoring of freshwaters includes both chemical and biological components of freshwater ecosystems.

Monitoring of Arctic freshwater ecosystems is directed by water quality standards of the All-Union State Standard (All-Union State Standard, 2018). This standard uses the concept of Maximum Allowable Concentrations (MAC) of chemical elements and their compounds in the environment that can affect human health or cause pathological changes or diseases. MACs have been established for more than 1300 substances, and can be specific for different climate zones. MACs for fishery purposes are intended for quality control of water in reservoirs of fishery (aquaculture) and agriculture (irrigation) purposes.

Table 6-2 Current monitoring status for Lake FECs and their parameters within the eight Arctic countries. The listed values indicate that monitoring of the FEC parameter is: (1: blue) routine with consistent funding and good spatial coverage across ecoregions; (2: green) routine with consistent funding but without good spatial coverage across ecoregions; (3: orange) not routine because funding is sporadic and not secure; (4: grey) unknown; or (5: red) not undertaken.

FECs and Parameters*		US	Canada	Greenland	Iceland	Norway	Sweden	Finland	Russia
Fish	Numbers, relative abundance, total biomass	2	2	2	2	2	1	1	3
	Presence absence**	2	2	2	2	2	1	1	3
	Genetic diversity	3	5	3	3	3	3	3	3
	Size structure	2	2	2	2	2	1	2	3
	Age structure	2	2	2	2	3	1	2	3
	Timing of important life history events	3	5	3	3	3	5	3	3
	Contaminant concentration	3	4	–	2	3	2	2	3
Benthic invertebrates	Numbers, relative abundance, total biomass	3	5	2	2	2	1	1	3
	Presence absence**	3	5	2	2	2	1	1	3
	Size structure	3	5	5	5	3	5	3	4
	Timing of important life history events	4	5	2	5	3	5	3	3
	Contaminant concentration	3	5	5	5	3	5	3	4
Zooplankton	Numbers, relative abundance, total biomass	3	2	2	2	2	2	3	3
	Presence absence**	3	2	2	2	2	2	3	3
	Biomass of each taxon	3	2	4	5	3	5	4	3
Algae from benthic samples	Numbers, relative abundance	3	3	3	5	2	2	1	3
	Presence absence**	3	3	3	5	2	2	1	3
	Biomass or biovolume of each taxon	3	3	5	5	3	3	3	3
	Bulk biomass (incl. chlorophyll a)	2	3	3	5	3	4	3	4
Phytoplankton	Numbers, relative abundance	3	3	3	2	2	1	1	3
	Presence absence**	3	2	3	2	2	1	1	3
	Biomass or biovolume of each taxon	3	2	5	2	2	1	2	3
	Bulk biomass (including chlorophyll a)	3	2	3	2	2	1	1	3
Macrophytes	Areal cover, distribution or number of individuals of each taxon	3	2	3	2	2	1	1	3
	Presence absence**	3	2	3	2	2	1	1	3
Physics and Chemistry	Physics	2	2	2	2	3	2	1	3
	Chemistry	2	2	2	2	2	1	1	3

** as described in CBMP freshwater monitoring plan,*
*** Not explicitly listed in the monitoring plan but necessitated by available data,*
**** Routinely monitored over very small spatial extents as part of mandatory monitoring by industry*

Table 6-3 Current monitoring status for River FECs and their parameters within the eight Arctic countries. The values indicate that monitoring of the FEC parameter is: (1: blue) routine with consistent funding and good spatial coverage across ecoregions; (2: green) routine with consistent funding but without good spatial coverage across ecoregions; (3: orange) not routine because funding is sporadic and not secure; (4: grey) unknown; or (5: red) not undertaken.

FECs and Parameters*		US	Canada	Greenland	Iceland	Norway	Sweden	Finland	Russia
Fish	Numbers, relative abundance, total biomass	3	2	3	1	1	1	3	2
	Presence absence**	3	2	3	1	1	1	3	2
	Genetic diversity	3	3	3	3	3	3	3	2
	Size structure	3	2	3	1	1	2	3	1
	Age structure	3	2	3	1	1	2	3	1
	Timing of important life history events	3	3	5	4	3	3	3	3
	Contaminant concentration	4	3	2	4	4	2	3	2
Benthic invertebrates	Numbers, relative abundance, (total biomass)	3	2	3	2	1	1	3	2
	Presence absence**	3	2	3	2	1	1	3	2
	Size structure	3	3	3	5	5	3	3	5
	Timing of important life history events	3	4	5	3	5	3	3	3
	Contaminant concentration	4	3	5	5	5	3	4	5
Algae from benthic samples	Numbers, relative abundance	3	3	3	2	2	1	3	2
	Presence absence**	3	3	3	2	2	1	3	2
	Biomass or biovolume of each taxon	3	3	3	3	4	3	3	5
	Bulk biomass (incl. chlorophyll a)	3	2	3	2	5	3	4	4
Physics and Chemistry	Physics	2	2	2	1	2	1	2	1
	Chemistry	3	1	2	2	1	1	3	2

** as described in CBMP freshwater monitoring plan,*
*** Not explicitly listed in the monitoring plan but necessitated by available data,*
**** Routinely monitored over very small spatial extents as part of mandatory monitoring by industry*

6.3. Advice for Future Monitoring of Arctic Freshwater Biodiversity

This assessment has made substantial progress towards the development of a harmonized program for monitoring the state of Arctic freshwater biodiversity. However, future assessments will be improved through the adoption of the advice detailed below that identifies potential improvements in monitoring design, sampling methods and assessment approaches. Monitoring of Arctic freshwater biodiversity will benefit from such improvements and the use of an adaptive monitoring strategy.

6.3.1. Emerging Approaches

6.3.1.1. Incorporation of Traditional Knowledge

The incorporation of Traditional Knowledge (TK) and the engagement of Indigenous Peoples through observational networks and monitoring efforts can make an important contribution to freshwater biodiversity monitoring in the Arctic. A systematic literature review of TK indicated the prevalence of themes related to fish abundance, health, and quality, water quality, and changes to lake and river ice (Figure 63). Observations related to these themes, many of which are from the historical period prior to 1950 for which monitoring records are scarce, have the potential to fill gaps in our knowledge of biodiversity changes. Indigenous Peoples have a unique and holistic perspective on the landscape that spans multiple generations. The increased contribution of TK has enormous potential for future monitoring of biodiversity and the detection of ecological change in Arctic lakes and rivers. **We recommend the inclusion of Traditional Knowledge as an integral part of future circumpolar monitoring assessments and networks**.

6.3.1.2. Increased Use of Citizen Science

Citizen Science and the engagement of northern residents through observational networks and monitoring efforts has the potential to increase our capacity to monitor ongoing changes in Arctic freshwaters. Many of the barriers to monitoring in Arctic systems relate to logistical difficulties associated with travelling to the Arctic to conduct sampling. Engagement of local communities has the potential to reduce the financial burden associated with repeated visits to northern locations, Furthermore, this approach would provide opportunities to monitor the local/regional effects of human settlements and activities in the landscape (e.g., exploration, roads). For example, Finland uses educational programs involving children ranging from 7 to 17 years of age to collect various observations on freshwater ecosystems, and Canada is expanding the Canadian Aquatic Biomonitoring Network (CABIN) to include northern communities. Increased engagement of northern residents in Citizen Science has strong potential to support future monitoring activities and the detection of ecological change in Arctic lakes and rivers. Therefore, **we recommend the engagement of local communities in monitoring efforts through Citizen Science efforts as an integral part of future circumpolar monitoring networks**. These efforts could include adoption of existing platforms (e.g., iNaturalist) and programs (e.g., Globe program for schools) to quickly implement citizen science programs in northern regions.

6.3.1.3. Use of Remote Sensing Approaches

We also **recommend that this monitoring network includes an increased focus and use of remote sensing approaches (e.g., satellite imagery) and automated measuring devices (e.g. in situ data sensors)** for better coverage of chemical and physical supporting variables, and for estimating biodiversity in freshwaters, as allowed by future technological advances. Satellite images and aerial photography are efficient approaches to monitor indicators of landscape change and habitat variables (e.g., ice cover duration, snow cover, lake connectivity, turbidity of large lakes, terrestrial vegetation changes) across large spatial scales. In coming years, we expect an increased use of remote sensing in monitoring of freshwater, especially for lakes. This will

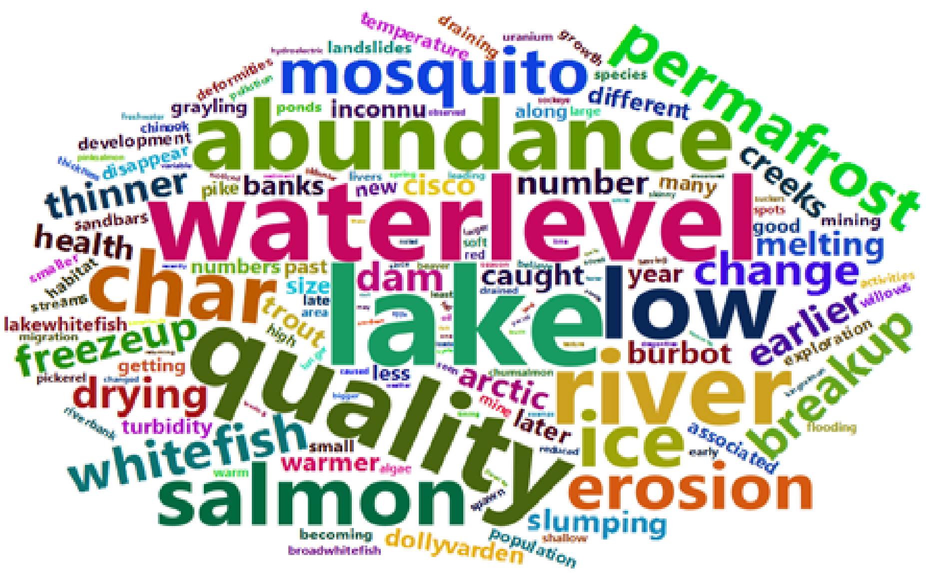

Figure 6-3 Word cloud of the common themes found in a systematic literature search of TK from Permanent Participants in Canada and Alaska, with word size indicating frequency of occurrence.

increase the collection of key parameters such as chlorophyll concentrations, water color, surface temperature and ice conditions, thereby improving environmental monitoring and the ability to estimate ecological status in remote areas of the Arctic.

6.3.1.4. Application of eDNA approaches

The Focal Ecosystem Components used in this report were necessarily restricted to those most likely to be commonly represented in existing databases for the circumpolar Arctic (Table 6-1). Indeed, important FECs such as microbial assemblages could not be assessed due to a lack of data. This deficiency may be corrected if future monitoring efforts **make use of recent advances in environmental DNA (eDNA) methods**, as these methods are particularly well advanced for microbial assemblages (Thomsen and Willerslev 2015). Furthermore, they provide a non-destructive way of monitoring presence/absence of fish. Thus, future monitoring activities should aim to build eDNA database information on freshwater assemblages, including microbial assemblages (i.e., bacteria, Archaea, fungi) as this FEC is pivotal to biogeochemistry processes and water quality, and likely will account for more alpha diversity than the other biotic groups combined. Furthermore, eDNA techniques can be applied to other FECs, such as macroinvertebrates, benthic algae and phytoplankton, to improve estimates of species richness. Clearly, the application of eDNA methods will require combination and calibration with traditional taxonomic and sampling methods to preserve the quality and continuity of long-term data series. Furthermore, it must be considered that while these techniques provide information about the presence/absence of taxa, they provide no information about lifestage or biomass/abundance.

6.3.2. Future Monitoring Methods

6.3.2.1. Sampling method harmonization

An important factor in the development of circumpolar monitoring is the consideration of using harmonized and intercalibrated monitoring approaches that are based upon intercalibrated international quality standards. In our analysis, differences in sample collection and processing methods were evident across the circumpolar region, reflecting the variety of sources from which data were obtained. For the purpose of the report, subsets of stations were selected to ensure comparability of data, controlling for differences in sampling methods, equipment, sampled habitats, and processing methods. However, **future sampling of Arctic freshwaters will require increased attention to harmonization of sampling approaches** (e.g., Culp et al. 2012a) to ensure broad-scale assessments can be completed. Such efforts ideally begins with harmonization of the suite of FECs that is sampled, to ensure that (1) multiple FECs are collected at each monitoring station (rather than only a single FEC, as was common in many areas) and (2) the full assemblage is sampled (e.g., species-specific sampling, which was common for fish in some areas, does not provide information about biodiversity) or a comparable portion of the assemblage is consistently sampled (e.g., if both diatoms and non-diatoms cannot be processed from benthic samples, ensure that diatoms are always processed so data are comparable with other countries). However, it will also be necessary to consider the different conditions that exist throughout the Arctic. For example, conditions in the high Arctic can be so different from low Arctic sites that specific or adapted methods are necessary. This can include specially-adapted field equipment, sampling effort, location of sampling sites (for example, sampling in the littoral or sub-littoral zones due to ice cover) and sampling time and frequency. Some adaptation may be required in these situations, though effort should be made to maintain as much continuity with harmonized methods as possible.

The selection of appropriate sampling methods and equipment must strike a balance between maintaining consistency and comparability with historical data and aligning with common methods used across the circumpolar region. Sampling approaches and sample processing are standardized to reduce observation variability and increase the ability to detect ecological changes (i.e., provide greater statistical power of assessments). The use of new methods will require calibration of the old and the new methods to preserve and guarantee the quality of long-term data series. Method comparison studies are available for several FECs including macroinvertebrates (Friberg et al. 2006, Buss et al. 2015, Poikane et al. 2016) and fish (Appelberg et al. 1995), and EU-countries have completed intercalibration assessments of ecological status using standardized methods for key FECs that are applicable to Arctic freshwaters. These studies can be used to inform the selection of harmonized sampling protocols, as outlined in Culp et al. (2012a). But additional effort is required to ensure sample processing is also broadly consistent across the circumpolar region. For example, large differences in magnification for algal sample processing could affect the accuracy of identification of small cells, and differences in methods used to estimate phytoplankton biovolume could affect comparability of data. Where sample collection and processing methods are not consistent across large spatial or temporal scales, analysis of data will be limited to qualitative or semi-quantitative assessments which, though informative, may not be sufficient to detect minor shifts in biodiversity.

Freshwater biomonitoring has traditionally focused on the assessment of ecosystem health rather than biodiversity, per se. Using a standardized sampling effort, this type of monitoring can provide a good estimate of the biodiversity of certain organism groups. However, these methods are not designed to measure biodiversity of a site because they underestimate the presence of rare species. Standardized biological samples of lakes and rivers can be modified to improve estimates of taxon richness and biodiversity. For example, Johnson and Goedkoop (2002) found that an additional 2-minute sample collection could increase taxa richness while not affecting the assessment of ecosystem health. Furthermore, the use of emerging technologies such as eDNA could provide additional information to better support the assessment of biodiversity patterns. We recognize that currently used, standardized monitoring efforts aim at assessing the ecological quality/integrity of freshwater and are not optimized to quantify biodiversity. Hence, we recommend that freshwater monitoring networks in the Arctic countries develop supplementary monitoring methods that provide better standardized estimates of biodiversity.

6.3.2.2. Sample distribution and replication

Analysis and comparison of diversity measures for each FEC was done using a regionalization approach based on ecologically-similar geographic regions. Such a regionalization approach reduces variability among data and increases statistical power as analyses compare areas that have similar climate and vegetation, and thus have similar climatic drivers. Furthermore, this approach supports the development and testing of impact hypotheses, particularly those related to changes in climate and vegetation. **We recommend that future monitoring uses such an ecoregion approach to guide the spatial distribution of sample stations.** The selection of ecoregions in a monitoring program could be driven partly by environmental conditions and predictions for expected change within ecoregions, and partly by the baseline diversity information presented in this report, including a selection of ecoregions with low and high alpha diversity, and with dominance of either nestedness or turnover components of beta diversity. Selection of ecoregions for monitoring should also recognize the distribution of existing or historic sampling stations for each FEC, to **ensure spatial coverage of sampled ecoregions is sufficient to address the overarching monitoring questions of the CBMP across the circumpolar region, maintain time series in key locations, and fill gaps where monitoring data are sparse.** For example, many FECs (including plankton and algae from benthic samples) had patchy distributions across the circumpolar region, which did not allow for a full assessment of spatial patterns in biodiversity.

Selection of stations for monitoring should also consider the spatial distribution within hydrobasins. Hydrobasins are standardly-derived geographic areas that relate directly to freshwater flow and sub-catchments, providing a smaller-scale geographic grouping of stations that can be used in combination with ecoregions. Within the SAFBR, stations were grouped by size level 5 or level 7 hydrobasins (see section 4.1.1), depending on sample replication. However, for many FECs, the stations in an ecoregion were found within a single hydrobasin, which indicated that there was inadequate spatial coverage of stations across the ecoregion. Estimates of alpha diversity and biodiversity in these cases were focused on individual sub-catchments within an ecoregion, and thus, may not provide an accurate picture of diversity patterns across the entire ecoregion. Future monitoring should ensure that multiple mid-level hydrobasins (size level 5 or level 7) are sampled within an ecoregion to improve the spatial distribution of stations.

In addition to sampling an adequate number of ecoregions and hydrobasins, it is necessary that **the number of monitoring stations should provide sufficient replication within chosen ecoregions**. In the SAFBR, alpha diversity was assessed across ecoregions by using rarefied taxonomic richness values to estimate the number of taxa found at a set number of stations. Where large numbers of stations were sampled within an ecoregion (e.g., 100 or more), rarefied alpha diversity estimates were more accurate, species accumulation curves reached or approached a plateau (e.g., Figure 6-4), and confidence intervals allowed for sound assessments of similarity among ecoregions with low variability. Even where sampling was more limited (e.g., 30-50 stations per ecoregion), alpha diversity could be compared among ecoregions with moderate confidence, though it was harder to distinguish differences among some ecoregions. However, comparison of alpha diversity at the rarefied level of only 10 stations per ecoregion, though necessary, was clearly inadequate, resulting in wide confidence intervals for poorly-sampled ecoregions (< 10 stations) and masking some differences among highly-sampled ecoregions that were evident when more stations were considered. For example, when three highly-sampled river BMI ecoregions were compared at approximately 40 stations or more,

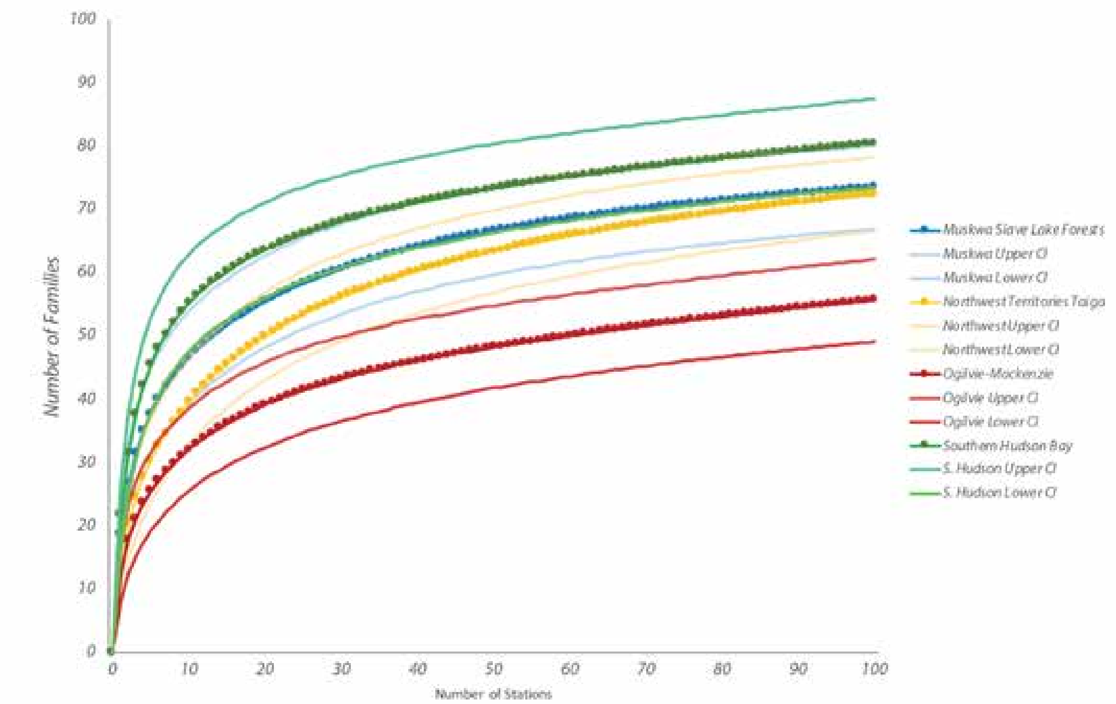

Figure 6-4 Rarefaction curves for river BMI in three ecoregions (Northwest Territories Taiga, Ogilvie-Mackenzie Alpine Tundra, and Southern Hudson Bay Taiga), showing the estimated number of families for each number of stations (up to 100 stations; thick lines with points) and 95% confidence intervals for diversity estimates (thin lines).

rarefaction curves indicated that alpha diversity was not significantly different between the Northwest Territories Taiga and the Southern Hudson Bay Taiga (confidence intervals overlapped), but that alpha diversity was significantly lower in the Ogilvie-Mackenzie Alpine Tundra than in either of the other two ecoregions (confidence intervals did not overlap; Figure 6-4). In contrast, when alpha diversity was compared at 10 stations on these rarefaction curves, the Southern Hudson Bay Taiga appeared to have significantly higher diversity than the other two ecoregions, and there was no difference between the Northwest Territories Taiga and Ogilvie-Mackenzie Alpine Tundra (Figure 6-4). Future monitoring should therefore increase replication within ecoregions to at least 30-40 stations to ensure more accurate assessments of alpha biodiversity patterns. As more targeted sampling designs are developed to address specific impact hypotheses, it may be possible to use estimates of variation from the CBMP database to inform sampling effort beyond the ecoregion-level recommendations.

6.3.3. Future Monitoring Design and Assessment

6.3.3.1. Integrated Experimental Design of Hub-and-Spoke Monitoring Networks

To provide better knowledge of the status and trends in Arctic freshwater biodiversity and the physico-chemical habitats supporting biodiversity, **we envision that Arctic countries develop joint efforts to establish a circumpolar monitoring network based on a hub-and-spoke principle in remote areas.** The hubs could provide the infrastructure platform required to monitor the effects of climate change and diffusive pollution on freshwaters in more remote Arctic areas and would include intensive sampling over time. Monitoring at secondary sites associated with the hub (i.e., spokes moving away from the central hub) would provide additional, more extensive baseline measures that would help generalize observations across larger spatial expanses. Good candidates for such platforms are existing Arctic monitoring and research stations such as the Canadian High Arctic Research Station (CHARS), Disko, Zackenberg, Longyearbyen/Ny Ålesund and Abisko. These locations could be linked to form a circumpolar network of hubs from which harmonized monitoring of lake and river biodiversity are undertaken. Such biological monitoring would be enhanced by incorporating remotely sensed data to improve the spatial applicability of models for environmental prediction across ecoregions. Several of the research locations listed above already have ongoing freshwater monitoring programs, while others are developing such programs.

The experimental design for the hub-and-spoke network should focus on addressing the Impact Hypotheses developed in the CBMP freshwater plan (Culp et al. 2012a), although regional and country-specific questions may also be considered. Many of the impact hypotheses require targeted study designs for detection of impacts and/or assessment of time series data. A future monitoring plan design will benefit from the use of large spatial analyses across gradients of expected change including those related to a warming climate (e.g., permafrost thaw, nutrient release, sediment loading). These gradients need to extend from reference (i.e., least impacted) areas to regions of high impact. An important consideration will be to examine the potential for climate change and development to impact areas of particular vulnerability (e.g., areas with low functional redundancy, important conservation areas). In addition, future monitoring should consider re-sampling previously visited sites to increase the potential to detect biodiversity changes over time and address the overarching CBMP monitoring questions that relate to changes in biodiversity and boundaries of Arctic zones (Culp et al. 2012a). Such a broad, integrated program will benefit from the use of harmonized monitoring protocols that can facilitate environmental and regulatory assessments, such as measuring the potential impact of industrial developments including mining and petroleum extraction. Moreover, a monitoring program that integrates biological variables with the drivers of biotic assemblage structure and function better identifies the primary drivers of biodiversity and contributes to our understanding of multiple stressors in this process (e.g., nutrient-contaminant interactions as impacted by warming).

We recommend that the Freshwater Steering Group of the CBMP continue to serve as the focal point for the development and implementation of pan-Arctic freshwater biodiversity monitoring. The CBMP steering group, which includes representatives of all Arctic countries with diverse expertise in science and decision making, should incorporate input from other key Arctic scientists to adjust and harmonize existing programs so that future freshwater biodiversity monitoring achieves the aims of the original CBMP freshwater plan (Culp et al. 2012a). A main objective of this steering group would be to optimize the circumpolar monitoring program to integrate the data flowing from the hub-and-spoke network of the Arctic countries. Finally, consideration needs to be given to how the Arctic freshwater biodiversity monitoring efforts can be linked to, contribute to and draw from the global Freshwater BON of GEO BON.

6.3.3.2. Maintaining and Building the Arctic Freshwater Biodiversity Database

A very important and unique output of this assessment is the creation of a pan-Arctic database of the Focal Ecosystem Components and supporting variables that were used to evaluate the status and trends in Arctic freshwater biodiversity. This database establishes a set of baseline data for future assessments of temporal and spatial change in biodiversity. It also represents an opportunity to derive a number of value-added outputs. For example, these baseline data can be used to produce indicators for monitoring and reporting on trends to support policy development in the Arctic. Furthermore, indicators can be aligned with those used in other programs (e.g., through development of Essential Biodiversity Variables, as used by GEO BON; Pereira et al. 2013) to support international efforts to monitor biodiversity. The database can also support future monitoring and research efforts by providing information about spatial and temporal variability within and among regions that can inform sampling design and monitoring extent.

T**o fully realize the benefits of this database, future resources must be provided to maintain and continue to build the database for future assessments**. Building of the database must include not only the incorporation of future data from the proposed integrated, hub-and-spoke monitoring programs and from ongoing national monitoring activities, but also the incorporation of existing data from scientific studies that are complementary to monitoring efforts. Improved documentation of research data, and at a minimum appropriate metadata, needs to be catalogued in an appropriate database according to the "open data" strategies recently adopted by national funding agencies in many of the Arctic countries. Though extensive, the integration of research data into the CBMP database was not exhaustive as such data catalogues are not fully established in most countries. For example, there are a number of existing data sources that could improve spatial and temporal coverage of FECs, such as European research-based paleolimnological databases that could contribute to a more extensive assessment of temporal trends using top/bottom and downcore data. Another important data source is available in the "catch" information recorded for commercial, sustenance, and recreational fisheries. These catch statistics are usually coordinated by official authorities for regulatory purposes and often provide a unique, long-term record of the status and trend of species valued by humans. **We recommend that Arctic countries make efforts to document and preserve data from short-term research projects, research expeditions, industrial, university and government programs** because this broad range of activities can provide valuable information on Arctic freshwater biodiversity and the physico-chemical habitats supporting this biodiversity. Although many sites may have been visited only once, this suite of sites could provide a framework by which re-sampling visits could be planned based on an optimal sampling approach that allows for multiple environmental gradients to be covered (e.g., latitudinal transects) and the establishment of long-time series (albeit with low sampling frequency).

6.3.3.3. Assessment Methods

Rarefaction curves provide an effective way and a sound approach to estimate alpha diversity where irregular sampling has occurred, because these curves control for variation in sampling effort by comparing taxa richness at a set number of stations. Where many stations have been sampled in an ecoregion, the result is an estimate of richness based on repeatedly randomly selecting a subset for analysis, thus simulating the number of taxa that might have been collected with less sampling effort (in line with less-sampled ecoregions). The extraction of a full rarefaction curve for each station provides the opportunity to assess alpha diversity at different levels of sampling effort, as in this report, providing more accurate assessments of taxa richness in highly-sampled ecoregions. Rarefaction approaches also allow for the extrapolation of richness estimates to a higher number of stations than was sampled, to bring less-sampled ecoregions in line with those that had more sampling; however, large extrapolation or extrapolation from a very small number of stations (e.g., < 5) should be used with caution, as they result in large confidence intervals that make it difficult to compare alpha diversity estimates among ecoregions. Given the spatially patchy nature of existing data and of ongoing monitoring efforts, **future assessments will require the continued use of rarefaction curves to estimate alpha diversity for comparison across ecoregions.**

Spatial and temporal patterns in diversity across the circumpolar region should be assessed and compared among FECs to contribute to a whole-ecosystem understanding of the potential for change, but further application of this approach will require improvements to sample coverage. Each FEC responds to a different suite of environmental drivers, and assessment of multiple FECs provides the greatest potential to detect biotic shifts in response to stressors. However, limited sampling of multiple FECs at a station or even within an ecoregion (particularly in North America, where sampling efforts were more strongly research-based, focusing on specific questions related to a single FEC) often precluded such assessments, or masked some patterns in diversity. For example, the highest diversity for several FECs (e.g., macrophytes, plankton, lake BMI) was found in Fennoscandian ecoregions, which suggested that these were hot spots for diversity across multiple FECs. However, this was likely a reflection of the low or patchy availability of lake data for Canada, which led to overall lower diversity than in Fennoscandia. For example, when data with extensive spatial coverage in North America (e.g., river BMI) and Fennoscandia were compared, there was evidence of southern Canadian ecoregions that had higher alpha diversity than was found in Fennoscandia. Furthermore, areas of the Arctic that are known to have low diversity for a particular FEC (for example, low diversity of macroinvertebrates on Svalbard; Blaen et al. 2014, Chertoprud et al. 2017)may not have had a sufficient number of stations to draw broad conclusions across FECs and in comparison with other ecoregions. With increased sample coverage focused on filling gaps and improving replication within ecoregions, such assessments will be of high priority to inform management and policy.

An increased focus on assessing biotic-abiotic relationships in Arctic freshwater systems is necessary in order to effectively test impact hypotheses and address the overarching monitoring questions of the CBMP. This report begins to address these questions by relating biotic patterns to abiotic drivers, but more direct testing of these relationships is necessary to understand biodiversity change in the Arctic. Supporting abiotic data are not consistently recorded with biotic sampling data, nor are they always available or in a useable/comparable format. Thus, data on water chemistry, hydrology, water temperature, and site-level habitat structure were not available for a large share of monitoring stations, thus limiting the extent to which these relationships could be examined. Where possible, we have used geospatial variables (e.g., long-term air temperature and precipitation, ground ice content, thermokarst) by calculating summaries of parameters for the hydrobasin in which each station was found. The use of remote sensing and geospatial data allows for broad-scale assessments using abiotic variables that are inherently harmonized when they come from a single circumpolar data source. However, it was not always possible to access geospatial data that covered the entire area of interest (particularly where data were limited to above the Arctic Circle, e.g., Walker et al. 2005, Harrison et al. 2011). Despite these limitations, the use of geospatial data will continue to be necessary to provide standardized circumpolar measures of abiotic variables, particularly where in-stream measurements have not been collected or when variability within those measurements is too great.

6.3.4. Recommendations/Summary

The rapid change occurring in Arctic ecosystems highlights the need for the CAFF-CBMP initiative to establish baselines against which future biodiversity change can be assessed and promote the requirement of harmonizing monitoring efforts among Arctic countries. This report on Arctic freshwater biodiversity further emphasizes that status assessments of Arctic lakes and rivers must explore the association of biodiversity with spatial patterns of physico-chemical quality of aquatic habitats that can drive biological systems. Key recommendations for consideration in future biodiversity monitoring of freshwater ecosystems in the Arctic include the following:

Emerging Approaches

- Include Traditional Knowledge as an integral part of future circumpolar monitoring assessments and networks.
- Engage local communities in monitoring efforts through Citizen Science efforts as an integral part of future circumpolar monitoring networks.
- Include an increased focus and use of remote sensing approaches (e.g., satellite imagery, deployment of in situ data sensors).
- Make use of recent advances in environmental DNA (eDNA) methods

Future Monitoring Methods

- Employ a combination of traditional and novel approaches to improve monitoring efficiency, and further efforts focused on sampling approach harmonization among countries.
- Select appropriate sampling methods and equipment to balance between maintaining consistency and comparability with historical data and alignment with common methods used across the circumpolar region.
- Develop supplementary monitoring methods that provide better standardized estimates of biodiversity to maximize the likelihood of detecting new and/or invasive species.
- Use a regionalization approach based on ecoregions (Terrestrial Ecoregions of the World; TEOW) to guide the spatial distribution of sample stations and, ultimately, to provide better assessments.
- Ensure that spatial coverage of sampled ecoregions is sufficient to address the overarching monitoring questions of the CBMP across the circumpolar region, maintain time series in key locations, and fill gaps where monitoring data are sparse.
- Ensure that multiple mid-level hydrobasins (size level 5 or level 7) are sampled within an ecoregion to improve the spatial distribution of stations.
- Ensure the number of monitoring stations provides sufficient replication within chosen ecoregions.

Future Monitoring Design and Assessment

- Arctic countries should establish a circumpolar monitoring network based on a hub-and-spoke (intensive-extensive) principle in remote areas.
- Experimental design for the hub-and-spoke network should largely focus on addressing the Impact Hypotheses developed in the CBMP freshwater plan.
- An increased focus on assessing biotic-abiotic relationships in Arctic freshwater systems is necessary in order to effectively test impact hypotheses.
- The Freshwater Steering Group of the CBMP should continue to serve as the focal point for the development and implementation of pan-Arctic, freshwater biodiversity monitoring.
- Resources must be provided to maintain and build the freshwater database for future assessments in order to maximize the benefits of this database
- Arctic countries should make efforts to document and preserve data from short-term research projects, research expeditions, industrial, university and government programs.
- Due to the patchy nature of sampling, future assessments require the continued use of rarefaction curves for scientifically-sound comparisons of alpha diversity across ecoregions.
- Spatial and temporal diversity patterns across the circumpolar region should be assessed and compared among FECs to contribute to a whole-ecosystem understanding of the potential for change.