EU-PolarNet

White Paper:

Addressing the challenges of global warming for polar freshwater resources

Who are we?

This White Paper is a product of the project COLDwater, which was funded by EU-PolarNet 2 under its third Call for Service and aims to inform on the challenges to polar freshwater resources. EU-PolarNet 2 "Co-ordinating and co-designing the European Polar Research Area" is an EC-funded Coordination and Support Action which advises the European Commission on polar issues.

The COLDwater consortium is interested in assessing how climate change is challenging polar communities by limiting access to high quality freshwaters for Arctic residents and Antarctic scientists and visitors. Native fauna and flora, for example reindeer/caribou and Arctic char in the north, also have to face this threat, and it can be assumed that any effects spread or cascade throughout polar food webs. Given the unpredictability of catastrophic climatic events, the development of tools to inform decision-making bodies in the context of the needs of the polar regions, their inhabitants, and their biota is essential to guarantee their health, their economies, and future sustainable development. The consortium that has developed this white paper consists of an extensive and experienced group of scientists, educators, representatives of international bodies and Indigenous peoples, NGOs and managers of research stations and logistic operations from different organizations. This international consortium met during a 3-day workshop in November 2023 in Madrid, Spain to develop the present document. Resulting from those discussions, we propose in this white paper the most pressing research needs regarding freshwater quality and quantity in the polar needs through appropriate funding and resources.

Executive Summary

The polar regions are undergoing rapid transformations due to global warming, resulting in temperature increases far surpassing the global average and significantly impacting ecosystems, especially freshwater systems. Understanding the implications of climate change on Arctic and Antarctic freshwater systems is crucial, as vital ecosystem services essential for sustaining human and environmental well-being may be disrupted. Shifts in freshwater availability due to changes in precipitation patterns, ice melt, and permafrost thaw pose significant challenges for local communities, exacerbating their vulnerabilities. Additionally, climate warming can affect water quality, e. g. by releasing pollutants and potential hazardous microorganisms, further jeopardizing human and natural ecosystem health. Arctic communities face multiple challenges in adapting to these changes, including limited resources and infrastructure that may not be resilient to environmental change. Urgent action is needed to mitigate these impacts and safeguard freshwater resources through evidence-based approaches, scientific research, policy involvement, and community engagement to ensure a sustainable future in the polar regions.

In the pursuit of understanding freshwater dynamics in the Arctic and Antarctic, international collaboration across disciplines stands as a cornerstone, essential for addressing the impacts of climate change on polar freshwater resources. Initiatives aiming to understand the dynamics of transboundary water resources underscore the pivotal role of collaboration across institutions and nations, allowing for collective efforts in providing effective solutions to advance the current knowledge of polar ecosystems. Such collaboration not only benefits the polar regions but also carries implications for the global community, aligning with the UN's SDGs. Therefore, funding mechanisms to bridge the knowledge-to-action gap and support international cooperation should be set high in the research agenda.

The scientific and funding roadmap presented here should be implemented urgently, to maximise, in a 10-year term, the benefits to be gained through synergies with the next International Polar Year (2032-33). It will leverage existing transnational initiatives and frameworks, including the Antarctic governance framework, to guide future research initiatives towards sustainable management of freshwater resources. Overall, a comprehensive approach integrating pole-to-pole collaboration, strategic funding, and adherence to governance frameworks is paramount, ensuring collective efforts contribute to the well-being of polar communities and the broader global understanding of climate change implications.

Motivation and background: Local consequences of global climate change

The Arctic region is of key strategic importance for the European Union, in view of climate change, raw materials as well as geostrategic influence and seeks to contribute to a safe, prosperous, and peaceful Arctic region, recognizing its significance for the entire world[1]. The European Green Deal[2] forms the cornerstone of the EU's Arctic engagement, complemented by its new strategy for a sustainable blue economy, underpinned by scientific research, innovation, and regional investment. Key objectives include fostering peaceful dialogue and international cooperation, addressing the ecological, social, and economic impacts of climate change, and supporting comprehensive, inclusive, and sustainable development in Arctic regions, with a focus on Indigenous peoples, women, and youth.

The polar regions are experiencing rapid transformations, primarily due to global warming, leading to temperature increases far exceeding the global average. This trend is significantly altering the delicate balance of these regions' ecosystems and their component human communities and societies. The escalating temperatures are mirrored in water bodies, notably freshwater systems, amplifying the concerns surrounding their stability and quality.

1 A stronger EU engagement for a greener, peaceful and prosperous Arctic

2 European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions

Understanding the implications of climate change on Arctic and Antarctic freshwater systems is vital, as they can disrupt critical ecosystem services crucial for sustaining human and environmental well-being. In this sense, ecosystem services encompassing aesthetics, food and freshwater provision, climate regulation and waste decomposition play a pivotal role in sustaining life in the polar regions[3].

It may seem strange to evoke water scarcity in polar regions that are apparently so filled with water, though mostly in the form of ice. However, alterations in freshwater availability due to shifts in annual precipitation patterns, snow and ice melt, and permafrost thaw pose major challenges for local communities and ecosystems. Fluctuations in water supply, compounded by extreme weather events, threaten the stability of infrastructure and industrial activities, intensifying the vulnerability of Arctic human settlements[4]. Also, Indigenous, and other local populations dependent on reliable freshwater sources for their livelihoods and well-being, face increased risks due to these climate-induced changes.

3 CliC/AMAP/IASC, 2016. The Arctic Freshwater System in a Changing Climate.

4 Povoroznyuk O., et al., 2023. Arctic roads and railways: social and environmental consequences of transport infrastructure in the circumpolar North. Arctic Science. DOI:10.1139/as-2021-0033

Global warming not only alters the quantity but also the quality of freshwater resources in polar regions. Thawing permafrost releases pollutants and potential hazardous microorganisms, compromising water quality, and posing risks to human and ecosystem health. Additionally, changes in hydrological patterns may lead to increased nutrient levels, favouring the growth of potentially harmful cyanobacterial blooms. This deterioration in water quality pose significant challenges for Arctic communities and visitors to the Antarctic.

Arctic communities are confronted with complex challenges in adapting to the changing freshwater landscape. Limited technical and financial resources, coupled with inadequate and sometimes outdated infrastructure, hamper their ability to address emerging water-related issues effectively. Rapid human population growth and their activities further exacerbate these challenges, placing additional pressure on already vulnerable communities. Indigenous people, who have traditionally relied on their thorough knowledge of the environment for survival, are now struggling to cope with unprecedented environmental changes.

The pursuit of a green transition, amidst the imperative to address the challenges posed by global warming, necessitates a nuanced approach that properly considers the impacts on Arctic communities. Initiatives aimed at supporting climate-friendly undertakings, such as rare earth metal mines and large-scale windmill parks, must be approached with caution. While these bids may promise greener, fossil-free energy alternatives, there exists a potential risk to the access of clean drinking water for local Arctic communities over the long term. It is imperative that any economic activities, regardless of their perceived environmental benefits within the current climate agenda, be subject to stringent regulation and thorough assessment before being implemented on a large scale within the delicate Arctic environment.

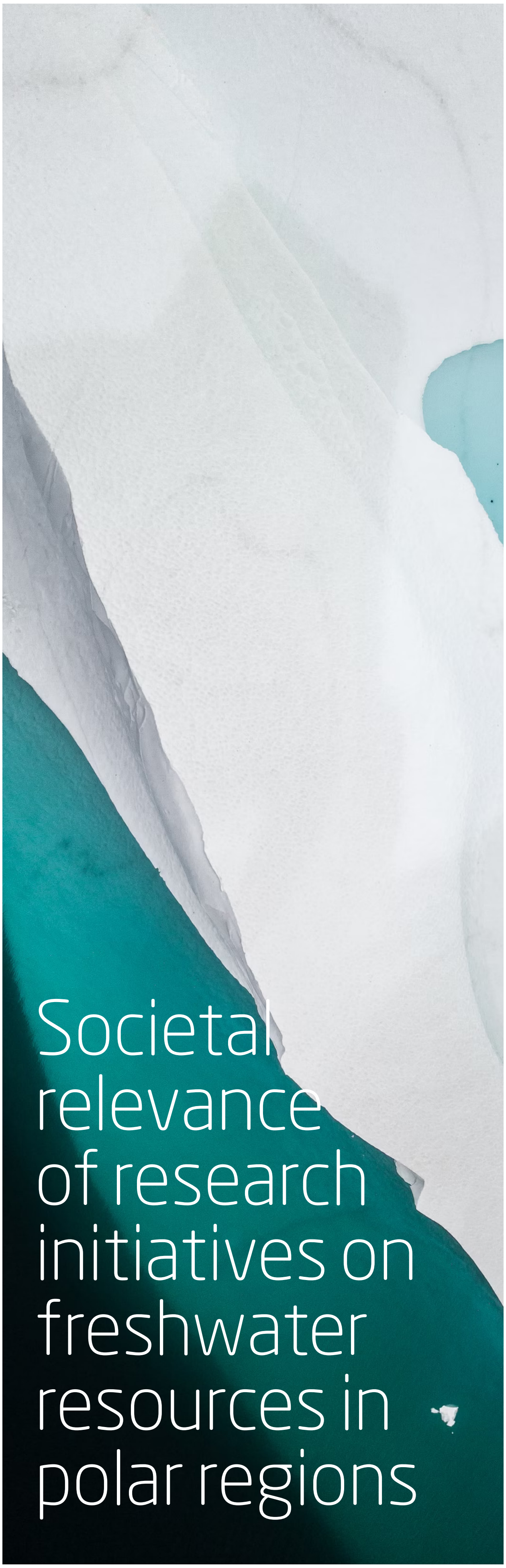
The escalating impacts of climate change on polar freshwater resources are now a critical moment for the Arctic and Antarctic ecosystems. As temperatures continue to rise and permafrost thaws at unprecedented rates, the delicate balance of freshwater systems is at stake. Effective initiatives are required to mitigate the adverse effects on local communities and safeguard the invaluable ecosystem services provided by polar freshwater resources. By adopting a fact-based approach that integrates scientific research, policy involvement, and community engagement, we can aim towards a sustainable future for polar freshwater ecosystems and the communities reliant on them.

Definitions of Polar regions adopted for the purpose of this white paper, including relevant factors demonstrating the aims of this proposal.

The polar realm in this white paper is defined as the parts of both polar regions where human communities and the ecosystems they inhabit are seasonally or fully depending on glacial, ice and snow melt as freshwater sources, and are vulnerable to changes in ecosystem hydrology as a result of permafrost thawing. Although the primary focus is on the polar regions, there are clear parallels in some parts of the proposed research with lower latitude alpine regions, where snow or ice as well as the timing and quantity of seasonal melt are significant socioecological drivers relevant to local economies. Even though the inclusion of lower latitude alpine regions is not precluded in specific contexts, they are not the primary focus of the programme.

In the case of the **Arctic**, the definition for this white paper is not just geographic but also a system of physical, biological, chemical, and climatological features that includes large areas of High-, Low- and Sub-Arctic regions, which extend beyond the area under direct EU 'governance' (i.e., northern Scandinavia and Svalbard). It includes parts of Greenland, Iceland, Canada, Alaska and Russia. Although there is currently no access to Russian Arctic, other than through existing literature and satellite remote sensing, in the foreseeable future. In a later stage, the results of any initiative could eventually be applied in parts of the Russian Arctic.

In the **Antarctic**, both governance and human presence are fundamentally different from the Arctic. Never has any human population existed in the area delimited by the Antarctic Treaty (the area south of latitude 60 degrees), nor in the commonly defined core sub-Antarctic islands. Nevertheless, European, and other nations operate research stations and field activities in regions that rely on both glacial, ice, or snow melt as well as groundwater supplies, and which consequently face analogous potential threats as the Arctic region. Moreover, the cruise tourism industry in the Antarctic has grown rapidly in the last decade, and this trend will likely continue including a diversification towards more on-land activities. Though the impacts of changes in water quantity and quality on human communities are much smaller in the Antarctic than in the Arctic, they may be affected by analogous impacts. The protection of the Antarctic environment is a primary responsibility of the Parties of the Antarctic Treaty, which include several European nations. To also include areas that are concerned by the same problematics of impact of Climate Change and its mitigation or adaptation strategies, we propose the boundary to the southern 'area of interest' for this white paper to include the 'Magellanic sub-Antarctic' region of southern South America and the 'New Zealand shelf or sub-Antarctic islands' extending to the south of South Island. These regions have comparable climates to those already included in the core sub-Antarctic, rely strongly on natural and untreated mountain (e.g., glacial, ice or snow) sourced water and, in the case of the Magellanic region, include the last remnants of Indigenous human populations/lineages.



Societal relevance of research initiatives on freshwater resources in polar regions

Stake- and rightsholders play a crucial, and often legally mandated, role in the management, conservation, and sustainable use of freshwater resources in polar regions. This involvement leads to more impactful, relevant, and ethical outcomes that benefit both society and the economy, while also contributing to the sustainable management of the polar regions. These key stake- and rightsholders include:

- Indigenous and other local Arctic communities: These communities have traditional rights and knowledge related to freshwater resources in their territories. Their rights to access and manage freshwater sources are important to initiatives related to freshwater management in the Arctic regions.

- Arctic governmental authorities: National and regional governmental bodies have legal and regulatory authority over freshwater resources. The fragmentation of responsibilities among institutions in the water sector (e.g., local councils and regional water agencies) is a serious obstacle to the integrated management of water resources. Presently, the already revised Drinking Water Directive for human consumption (Directive 2020/2184/EC) sets the essential standards of quality at EU level, for various microbiological, chemical and other indicator parameters to be monitored and tested regularly.

- Industry related to the green energy transition: As most of the world economies attempt to reduce reliance on fossil fuels, the vast renewable energy potential of the Arctic, including wind and hydroelectric power, has gained significant attention. However, the pursuit of green energy sources also brings challenges, notably in the extraction of rare earth minerals, which are essential for technologies like wind turbines and electric vehicle batteries. The use of those energy resources and mining these minerals will have profound environmental effects, particularly for freshwater systems critical to Arctic ecosystems and Indigenous communities' livelihoods.

- Non-governmental organizations (NGOs): Environmental and conservation organizations may also have an interest in freshwater resources in polar regions. They often advocate for the protection of freshwater sources and are involved in initiatives related to water management and conservation.

- International agreements and conventions: In the case of Antarctica, Antarctic Treaty System and associated agreements, notably the Protocol on Environmental Protection, play a significant role in governance activities related to freshwater resources and environmental protection. These include environmental codes of conduct and management plans for specific location, including with attention to protection of lakes and streams (e.g. the McMurdo Dry Valleys Antarctic Specially Managed Area (ASMA) and protected areas (ASPAs) as Byers Peninsula). In the Arctic, IASC transnational and bilateral initiatives play a leading role in environmental protection together with additional protections at a local level, for example via National Park management plans.

Co-designing research proposals together with relevant key stake- and rightsholders takes time but makes the research stronger and more focussed on the societal relevance. By integrating the knowledge of local communities, Indigenous Peoples, other stakeholders, and researchers helps to ensure that research activities are conducted in an ethical and responsible manner and that research outcomes are directly relevant to the needs and concerns of society and regional economies. Potentially, the co-creation and shared knowledge will lead to the development of products, services or initiatives that better align with community and environmental priorities. Basic research must bridge knowledge gaps, while applied research must lead to the development of solutions that address current challenges in the water cycle, such as climate change impacts, resource management and community well-being. Such a collaborative approach between concerned stake- and rightsholders will lead to the development of more effective and practical solutions based on diverse perspectives and local knowledge.

Picture: David Velázquez

CyanoHABs: a growing concern in polar freshwaters

Cyanobacterial harmful algal blooms (CyanoHABs) are mass proliferations of cyanobacteria (photosynthetic prokaryotes) that pose a serious threat to humans, animals, and aquatic ecosystems in general. CyanoHABs severely impair freshwater uses (drinking, harvesting, recreational) due to the production of neuro- and hepato-toxins (called cyanotoxins), visual and organoleptic water quality deterioration, and oxygen depletion during biomass decomposition.

Previously associated with warm conditions in tropical and temperate regions, cyanobacterial blooms are increasingly being reported in cold waters (5-15°C) and even in ice-covered waterbodies. These observations coincide with several reports of cyanotoxins at latitudes beyond 60 degrees north or south during the last decade.

Under a scenario of increasing temperatures in polar waterbodies, together with the emergence of more nutrient-rich waters expected from permafrost thaw, CyanoHABs may represent a growing concern to human and wildlife health, which demands careful monitoring and management in polar areas.

Figure 1. CyanoHAB biomass with surface accumulations (scum) as seen from the shoreline of a temperate water reservoir. Source: Claudia Fournier

Main factors influencing the quality and quantity of freshwater resources in polar regions

Small changes in natural processes or economic activities may have big impacts for the need for freshwater. Here we present some relevant examples.

1. Growing concerns on freshwater resources due to the climate crisis.

Change in precipitation patterns

Surprisingly to many, the climate in the polar climate zones is dry in most areas and the moisture content of the air is generally low. Although in some areas close to the coast the climate is maritime, with precipitation between 600 and 1200 mm water equivalent annually[5]. The inner regions of the Arctic have a continental climate with less precipitation, and some areas are even categorised as polar deserts. In Antarctica, the average snow accumulation across the entire continent is estimated to be ~150 mm of water per year.

Current climate models predict both increases and decreases in precipitation in areas of the Arctic[6] and Antarctic[7]. Particularly in the Arctic, but also in the Maritime Antarctic (the Antarctic Peninsula region), a transition from a snowfall to a rainfall regime and a greater frequency of heavy precipitation events are predicted. Improved knowledge about changes in precipitation patterns is important for determining current and predicting future water balance, which is of crucial importance for all aspects of hydrology and limnology in these regions.

Permafrost thaw and temperature changes

Permafrost, defined as ground continuously frozen for at least two years, covers approximately 22.8 million km^2 in the Arctic[8] and ca. 13.9 million km^2 in Antarctica[9]. Near-surface permafrost plays an important role in freshwater systems, as it often keeps lakes, wetlands and peatlands above an impermeable frost layer that limits the water storage capacity of the subsurface. Climate change-induced degradation of the permafrost can result in drainage of lakes and ponds and other drastic changes in local hydrology (e.g., changes in thaw season). Lakes in permafrost regions have already changed rapidly, with some increasing or decreasing in size and number, and others even disappearing. Further, permafrost thaw can result in the release of pollutants stored thereby, as well as the intense production of greenhouse gases.

Altering nutrient concentrations

Climate change may result in both increased and decreased nutrient concentrations in polar freshwaters. On the one hand, changes in catchment hydrology, thawing of permafrost and internal nutrient loading (i.e., the release of nutrients from lake or river sediments) due to temperature-driven water column stratification can lead to higher nutrient concentrations in surface water and promote algal or cyanobacterial blooms. Additionally, earlier melt and loss of lake ice cover that forms during winter may make the access easier for freshwater and marine birds, and marine mammals (especially in coastal lakes in Antarctica). On the other hand, warmer temperatures can lead to an increase in terrestrial vegetation, often referred to as the greening of the polar regions and brownification of Arctic waters. The storage of nutrients in rooted plants in lake catchments can then contribute to a reduction in nutrient loading to lakes and rivers [10].

Harmful microorganisms' developments

Cyanobacteria are microbes very successful at high latitudes in lakes, ponds, wetlands, and rivers, where they can dominate the aquatic primary producer assemblages in terms of biomass and production. They tolerate a broad range of extreme conditions typical of polar regions, including repeated freeze-thaw cycles, variable osmolarity, persistent low temperatures and extremes of irradiance including UV radiation. Cyanobacteria are especially successful in the benthic environment of lakes and seepages

5 National Snow and Ice Data Center.

6 Walsh, J. E., et al. 2022. Precipitation. NOAA Technical Report OAR ARC; 22-04 Arctic Report Card 2022

7 Bozkurt, D., et al. 2021. Temperature and precipitation projections for the Antarctic Peninsula over the next two decades: contrasting global and regional climate model simulations. Climate Dynamics DOI: 10.1007/s00382-021-05667-2

8 Westerveld, L. et al. 2023. Arctic Permafrost Atlas. GRID-Arendal. DOI: 10.61523/KPJI4549

9 Dobiński W, et al., 2023. Area and borders of Antarctic and permafrost—A review and synthesis. Permafrost and Periglac Process. DOI: 10.1002/ppp.2170

10 Huser, B. J., et al. 2022. Spatial and temporal variation in Arctic freshwater chemistry—Reflecting climate-induced landscape alterations and a changing template for biodiversity. Freshwater Biology. DOI: 10.1111/fwb.13645

as part of nutrient-rich microbial mat and biofilm communities that contain taxonomically and functionally diverse microbial components. Cyanobacteria are likely to thrive with ongoing climate change in the polar regions, especially with increasing temperatures and nutrient concentrations. Increased density stratification of the water columns of polar lakes is also likely to favour gas-vacuolate, potentially toxic, bloom-forming species [11].

Also, viruses, bacteria, fungi, and other microorganisms have been trapped for hundreds, thousands or even millions of years in ancient ice and permafrost areas. Increasing temperature in polar areas and the associated thawing of ice and permafrost can release such microorganisms, which may still be viable. This release could potentially include novel microbial taxa, unknown genotypes of pathogens that are different from those already present in the contemporary environment, pathogens that have previously been considered as eradicated, and even known pathogens. The release of such microorganisms into freshwater resources could pose a serious threat to public and animal health, particularly where untreated water is used as drinking water or for domestic purposes [12].

11 Reinl, K.L., et al., 2023. Blooms also like it cold. Limnol. Oceanogr. Lett, DOI: 10.1002/lol2.10316

12 Cohen J. 2023. Lurking in the deep freeze?. Science. DOI: 10.1126/science.adl0420

2. Increased pressure in use of freshwater resources by the economic sectors

Persistent organic pollutants and microplastics burdens in the polar ecosystems are silent threatens.

Persistent organic pollutants (POPs) and harmful substances are toxic chemicals that adversely affect human and animal health, as well as our shared environment around the world[13]. They include intentionally produced chemicals such as pesticides, flame retarders, plastic additives among other chemicals derived from petroleum products, and unintentionally produced compounds such as soot or dioxins. Because they can become entrained in long-range transport through the atmosphere and water, they can and do affect humans and wildlife in regions far from where they are produced and released. Pesticides were first found in fat tissues of Arctic polar bears and Antarctic penguins in the late 1960s. They have been detected in the physical environment of remote Arctic and Antarctic regions where they become trapped in ice and snow. Climate change-induced melting of ice and snow leads to the release of these chemicals. Also, microplastics have been described in all polar ecosystem compartments, including the tissues of the animals. As the climate warms, POPs and microplastics deposited in sinks like water and ice are expected to re-volatilize into the atmosphere. Pollutants with lower volatilities are being remobilized into the air in the Arctic due to sea-ice retreat and rising temperatures. POPs and microplastics persist for a long time in the environment and can accumulate throughout the food web.

Matching tourism industry growth with polar conservation.

The tourism industry in the Arctic and Antarctic has flourished in recent decades. The increased pressure of the tourism industry on the use of freshwaters can lead to conflict with the local human population and animal, and jeopardise the sustainability of tourism, in turn further altering the local economies of the places visited. The strong seasonality of tourism can also place a strain on water supply and wastewater disposal systems in these areas. Physical and social structures may not have enough capacity during the peak season or may be underused during the rest of the year[14].

Agriculture possibilities are increasing in the North.

Agriculture in Arctic regions is generally marginal and of low intensity, although greenhouse operations are increasing in the North[15]. There is no equivalent in the wider Antarctic region other than the now largely historical Indigenous communities of Tierra del Fuego and the Cape Horn Archipelago. However, it is expected that with the increased thawing of permafrost, northern agriculture will expand with potential to improve locally sourced food supplies. In addition, the intensified use of fertilizers and pesticides in these areas may impact freshwater resources and increase the risk of harmful algal blooms in lakes and reservoirs as well as the appearance of microbial mats in rivers.

Environmental confronts of mining and extractive industry.

While The Protocol on Environmental Protection to the Antarctic Treaty prohibits all activities not related to scientific research on Antarctic mineral resources, the extractive and mining industry presents notable challenges to Arctic freshwater resources, with primary concerns surrounding the discharge of mine wastewater and tailings. These activities lead to the introduction of heavy metals, toxic chemicals, and pollutants into freshwater systems, posing risks to water quality and aquatic life. Additionally, the construction of mining infrastructure disrupts natural hydrological processes, fragmenting habitats and hindering fish migration. Moreover, the industry's water demand exacerbates competition with Indigenous communities, wildlife, and tourism, potentially leading to water scarcity and ecological imbalance, especially in the face of climate change-induced permafrost melting. Addressing these issues necessitates diplomatic collaboration and sustainable practices to safeguard the integrity of Arctic freshwater ecosystems while meeting socio-economic needs.

Arctic freshwater fishing: a delicate balance between environment, culture and economy.

The freshwater fishing industry in the Arctic faces a complex and evolving situation influenced by environmental changes, regulatory frameworks, and socio-economic factors. Traditionally, freshwater fishing has been an important source of livelihood for Indigenous communities in the Arctic, providing sustenance, cultural significance, and economic opportunities. However, the melting of permafrost, changes in ice cover, and shifting temperatures impact fish habitats, migration patterns, and spawning grounds, pose challenges to traditional fishing practices and the productivity of freshwater ecosystems.

Additionally, regulatory measures aimed at conservation and sustainability play a crucial role in managing freshwater fisheries in the Arctic. International agreements and regional management bodies, such as the Arctic Council and Indigenous co-management organizations, work to establish quotas, fishing seasons, and habitat protection measures to ensure the long-term health of fish populations and ecosystems.

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13 Jurado, E., & Dachs, J. 2008. Seasonality in the "grasshopping" and atmospheric residence times of persistent organic pollutants over the oceans. Geophysical Research Letters. DOI: 10.1029/2008GL034698

14 AWI 2023. Factsheet: Tourism in polar regions.

15 Polar Journal, 2023. In Greenland food self-sufficiency starts with potatoes.

Research needs in the foreseen environmental scenarios.

We define a number of research needs (Table 1) with the aim to trigger relevant research-based proposals that address key scientific questions to protect polar freshwater resources by strengthening EU research interests in the fight against the climate and biodiversity crises (JOIN(2021)). They tackle different aspects, including scientific proficiency, policy coherence, economic engagement, technological innovation, international collaboration, and stake- and rightsholders inclusivity.

Table 1. Identified research needs grouped in capabilities at EU level for freshwater resources in polar regions and the rationale behind their importance.

Research needs		Rationale
International collaboration	Impact of climate change on the diversity and function of microbial communities	Microbial communities play a crucial role in nutrient cycling, water quality, and overall ecosystem functioning. Biogeochemical processes drive the cycling of nutrients like nitrogen and phosphorus, as well as carbon sequestration, in freshwater ecosystems. These processes are critical in polar regions for assessing ecosystem productivity and response to environmental change. Investigating their present and past dynamics in polar freshwater systems is essential for understanding ecosystem health and resilience to climate change induced stressors.
	Resilience to climate change	Polar freshwater ecosystems are particularly vulnerable to climate change impacts such as permafrost thaw and altered precipitation patterns. Assessing ecosystem resilience is vital. Monitoring efforts, paleoenvironmental reconstructions and modelling tools can contribute to the understanding of the response to climate processes and provide insights into ecosystem adaptation strategies and inform conservation efforts.

Legend: **Arctic** **Both polar regions**

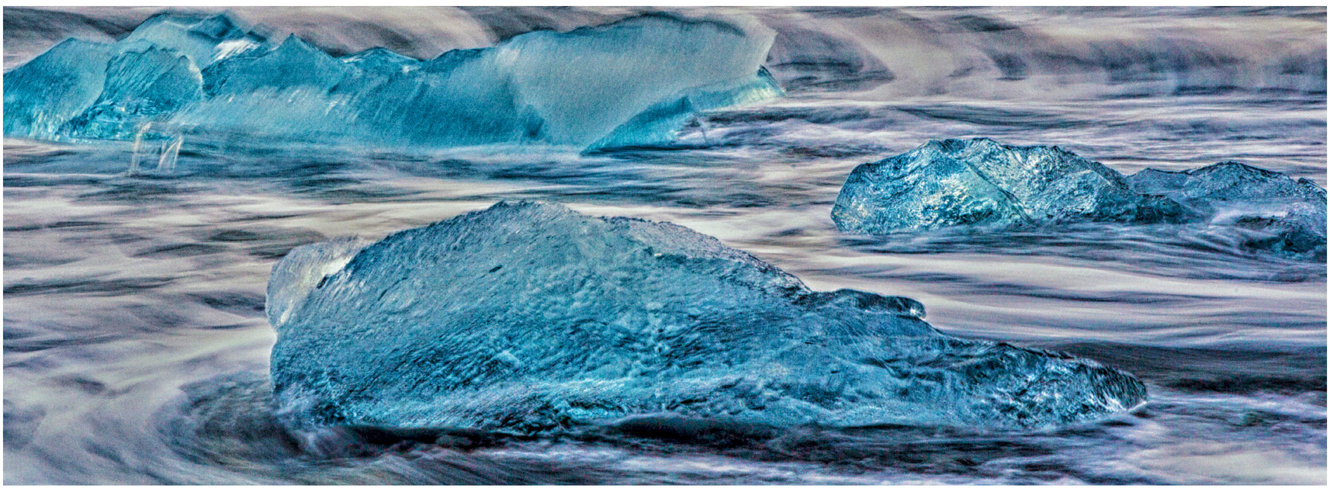
Research needs		Rationale
Policy alignment	Effectiveness of conservation and management strategies in preserving biodiversity and ecosystem services.	Effective conservation and management strategies are essential for preserving biodiversity and ecosystem services in polar freshwater habitats. Assessing their effectiveness helps to identify best practices for sustainable ecosystem management.
	Freshwater resource exploitation and its implications for ecosystem integrity and human well-being.	The potential exploitation of freshwater resources in polar regions raises concerns about ecosystem integrity and human well-being. Investigating the environmental impacts of resource extraction helps inform sustainable development policies.
	Integrated water resource management	Adopting an integrated water resource management approach that considers the interconnectedness of surface water, groundwater and ice melt processes is essential for promoting sustainable freshwater and wastewater management in polar regions, particularly in the face of increasing anthropogenic pressures and environmental change.
	Risk assessment and resilience planning towards future freshwater needs	Conducting risk assessments and developing plans to build resilience for polar freshwater systems can help identify potential threats, such as pollution incidents, introduction of invasive species, or extreme weather events, sensitivity of key species for ecosystem health and services (e.g. Arctic char or reindeer/caribou) and implement proactive measures to mitigate their impacts and enhance ecosystem resilience.
	Policy and governance mechanisms	Research into effective policy and governance mechanisms for freshwater management in polar regions, including stakeholder engagement processes, legal frameworks, and transboundary cooperation agreements to balance the challenges brought by tourism industry and agriculture. Also, the involvement of Arctic municipalities is crucial for promoting sustainable development and safeguarding freshwater resources for future generations.
Socio-economic engagement	Distribution and fate of pollutants in polar freshwater environments, including their bioaccumulation in aquatic organisms.	Freshwater ecosystems in polar regions are interconnected with surrounding terrestrial and marine environments. Pollutants introduced into polar freshwater systems can have significant ecological and human health implications. Studying their distribution, transport mechanisms, and fate in these environments is critical for effective pollution management and conservation efforts. These interactions help to understand the broader ecosystem dynamics and responses to environmental changes.
	The role of freshwater ecosystems in supporting Indigenous communities' livelihoods and cultural practices.	Polar freshwater ecosystems often support Indigenous communities' livelihoods and cultural practices. Understanding their role in supporting Indigenous well-being as well as better understanding future threats is crucial for safeguarding sustainable development and community resilience.

Legend: Arctic (beige) — Both polar regions (light blue)

Research needs		Rationale
Technological innovation	Impacts of invasive species and zoonotic diseases on polar freshwater ecosystems and native species diversity.	Invasive species and diseases can disrupt polar freshwater ecosystems and threaten native species diversity. Studying their impacts helps to develop strategies for invasive species management and infective disease prevention.
	Connectivity and hydrological dynamics of polar freshwater systems, including the role of glacier and ice melt in regulating freshwater availability and quality.	Understanding the connectivity and hydrological dynamics of polar freshwater systems is essential for predicting future changes in freshwater availability and quality. This knowledge is critical for water resource management and climate change adaptation planning. Research into the specific impacts of climate change on hydrological processes in polar regions, including changes in precipitation patterns, snowmelt timing, permafrost thaw, and glacier dynamics, becomes vital for the prediction of future freshwater availability and quality.
	Long-term monitoring and data sharing	Long-term monitoring programs which promote data sharing initiatives can enhance our understanding of temporal trends and spatial variability in polar freshwater systems, facilitating evidence-based decision-making and adaptive management strategies. Identifying specific targets for monitoring, such as microbial products and environmental pollutants as well as biogeochemical changes, ensures a comprehensive understanding of the complex polar ecosystems. They also pave the way to identifying funding schemes for advanced research infrastructures.
Stakeholder engagement	Community-based monitoring and Indigenous knowledge	The integration of community-based monitoring approaches and Indigenous knowledge systems into freshwater research initiatives can provide valuable insights into local hydrological dynamics, water quality concerns, increased transmission of diseases, and adaptation strategies in the polar regions.
	Ecosystem services of freshwater systems	The ecosystem services provided by polar freshwater systems, such as water purification, habitat provision, and cultural significance, are critical for understanding their value to both local communities and the broader environment.

Legend: **Arctic** **Both polar regions**

Each research need aligns with one or more of the EU's world-leading capabilities, demonstrating the multitalented approach required to effectively address the challenges and opportunities associated with polar freshwater resources through leveraging these essentials, the EU is ready to assume a pivotal role in advancing the filling of knowledge gaps by fostering sustainable development and addressing global priorities regarding polar freshwater resources.



Permafrost thaw: Exploring One Health implications for polar freshwater resources.

Permafrost thaw in polar regions has significant impacts on Artic residents and Antarctic visitors from the One Health perspective, which recognises the interconnectedness and balance of the health of people, animals, and ecosystems (Figure 2).

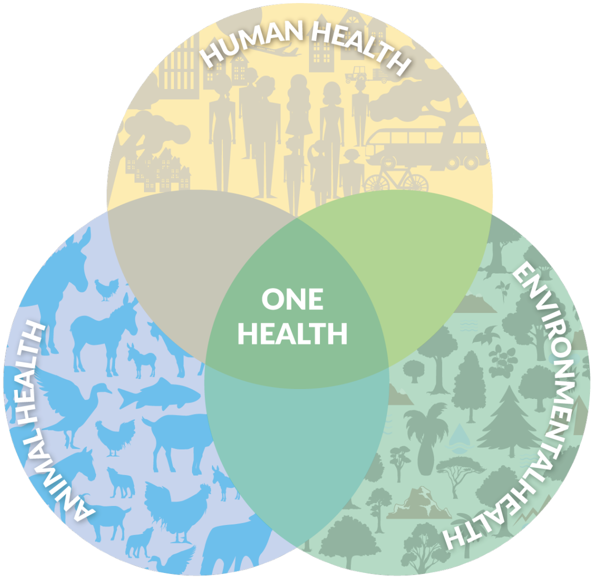
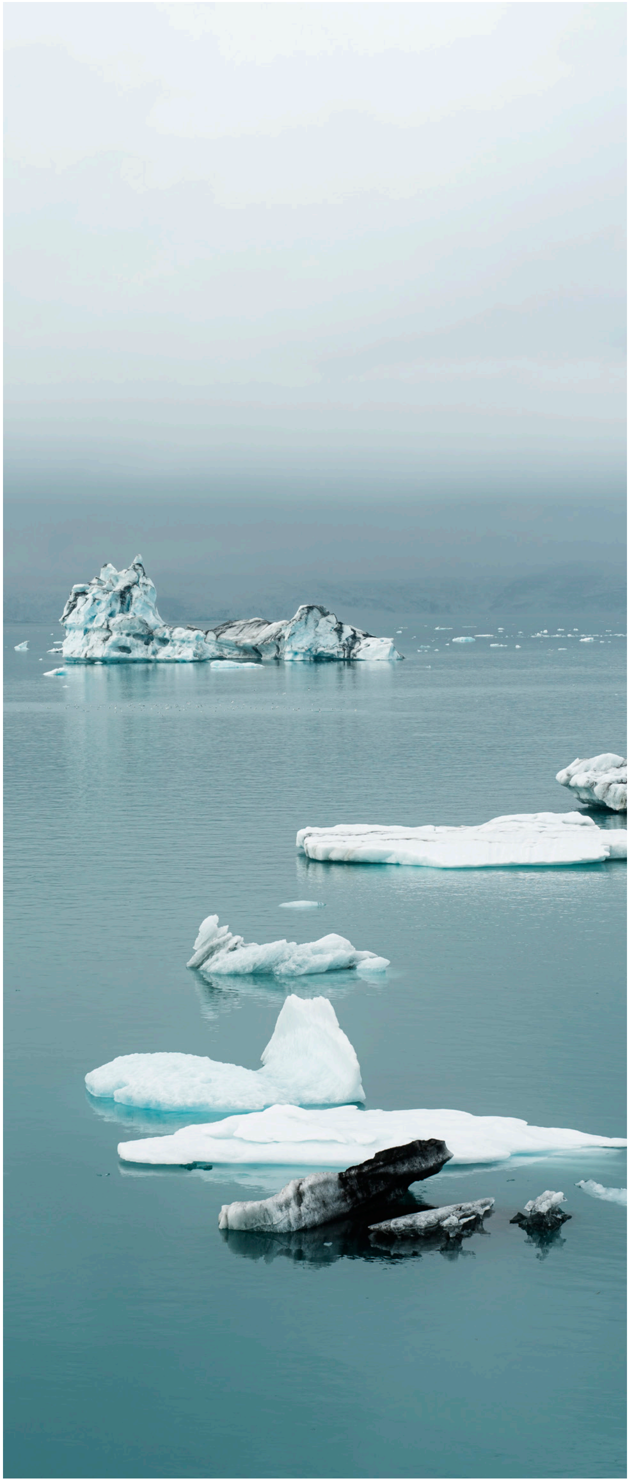


Figure 2. One Health approach based on the concept developed by the Center of One Health Research (University of Alaska Fairbanks)

An indirect effect of climate change on water resources linked to permafrost thawing is the increase in greenhouse gases (GHG) emissions in the tundra. Permafrost thawing increases the degradation rates of the organic matter accumulated in the temporarily melted soils and, consequently, trigger the rates of GHG emissions in these areas with respect to those occurring when soils were permanently frozen. However, permafrost thawing relates to polar freshwater resources by different means:

- Pathogen resurgence: permafrost thaw can release ancient microbiological agents including viruses and bacteria, that have been preserved in the frozen soil. This poses a potential risk of disease emergence, as dormant pathogens could be reintroduced into the environment, affecting the health of people, animals, and aquatic organisms in freshwater ecosystems.
- Antibiotic resistance: bacteria which carry antibiotic-resistance thrive everywhere, and permafrost thaw may lead to the emergence of new antibiotic-resistant strains. The release of microbiological fragments and agents into freshwater ecosystems and wildlife could contribute to the spread of antibiotic resistance among aquatic ecosystem, thus affecting both people and animal health.
- Environmental contamination: permafrost thaw may release hazardous compounds and pollutants into freshwater ecosystems, impacting the health of aquatic organisms, wild-life and human populations relying on these water resources. Contaminants transported through aquatic systems can have far-reaching effects on the health of both animals and people.
- Community vulnerability: communities living in the Arctic, where permafrost degradation is occurring, are particularly vulnerable to the impacts of thawing permafrost on freshwater resources. Infrastructure damage, exposure to emergent constituents, and increased health risks due to lack of clean drinking water and are some challenges faced by these communities.



Capacity-building and resource requirements

Picture: David Velázquez

It is unknown how key ecosystem services related to the terrestrial water cycle will be affected under climate change. Water scarcity in the Arctic is not yet evident, but climate change threatens to reduce freshwater availability, with associated consequences affecting water quality, requiring water managers to incorporate climate change into their planning and investment decisions. To address the risk of future water constraints in populated polar regions, a user-friendly technical and resilient to future change infrastructure needs to be developed creating a strong alliance by scientists and stake- and rightsholders.

Enabling capacities on environmental awareness and education are crucial for the ongoing development of knowledge, underpinning a deeper understanding of water constraints in the populated polar regions and the formulation of effective mitigation and adaptation strategies. Preparedness to increase awareness becomes essential by establishing a robust network that encompasses not only the natural and social sciences, but also stake- and rightsholders. The involvement of the young generations is crucial, and educators should play a key role in shaping the structure and activities of this network. The goal is to foster a shared and considered approach grounded in genuine basic needs, local characteristics, and potentials. Given the varying water resources and risks at the local level, geographically specific management plans will be required.

Infrastructure and observations

Given the challenging access to some polar areas and the inevitable cost considerations, remote-operable technologies need to be integrated with more traditional ground surveys and observations to appropriately answer research questions. The application of ongoing developments in hyperspectral technology, remote sensing, and the operation of drones and piloted aircraft missions provide opportunities to contribute to the study of freshwater bodies, as well as certain aspects of quality assessment. Examples of initiatives that could support the implementation of such monitoring include the ESA Polar Science Cluster in accordance with the EU Polar Cluster or the new Copernicus Hyperspectral Imaging Mission for the Environment (CHIME). Under such funding schemes, ground trained scientists may find support through citizen science for in-field monitoring of water-related issues (e.g. cyanobacterial blooms, permafrost thaw, pathogens' impacts), which, in turn, promotes collaborative efforts between scientists, local residents, and municipalities. Involving local communities in monitoring efforts not only provides access to valuable Indigenous and local knowledge but can also be a practical way to contribute to regional economies. Furthermore, increasing engagement of existing scientific institutions and established research groups with activity in European research stations, both in the Antarctic and the Arctic, represents a valuable potential source of knowledge relating to freshwater quality status. Examples include initiatives like the Arctic Monitoring and Assessment Programme (AMAP), coordinating bodies such as the Scientific Committee on Antarctic Research (SCAR) and its component umbrella programmes, and other national and international initiatives.

Addressing climate change impacts on freshwater resources in polar regions demands a multi-scale approach towards environmental assessment and monitoring. By prioritizing the integration of appropriate remote sensing technologies and local community involvement with the expertise of the existing research community, and developing a robust and effective coordination system, Europe will make a major contribution to environmental sustainability and scientific knowledge of polar freshwater ecosystems and their deep functional association with regional societies.

Capacity building

Europe holds considerable potential for capacity building in the study of freshwater resources in populated polar regions, since numerous European countries boast long-established, highly productive, and world-leading polar research programs. With the aim of increasing awareness, the development of training activities by polar associations of early career researchers (ECR), not least the well-established Association of Polar Early Career Scientists (APECS), has great potential and the added benefit of being pole-to-pole. Many ECRs already contribute to their national polar programs, so that creating specific freshwater working groups in associations such as APECS could help catalyse the development and integration of this European and a wider international research community. It is crucial to integrate the local population into capacity building initiatives, thus generating common spaces to share knowledge between scientists and local populations, thereby increasing the knowledge of both about the status, uses and constraints of freshwater resources.

Implementation

The challenges faced by polar freshwaters under current global warming scenarios require implementation of actions on realistic timescales and using feasible strategies. A practical roadmap for actions could include four main stages: data gathering, data synthesis, pilot testing and upscaling. Throughout this roadmap (Figure 3), several cross-cutting aspects require consideration, such as the availability of resources enabling capacity building via national and international funding and cooperation, as well as the involvement of stakeholders and local communities at all levels.

- **Data gathering** should be focused on covering the uncertainties faced regarding the type and classification of water bodies affected by different challenges. This stage would lead to the construction of an inventory and classification of freshwater resources. Data sources would primarily include available databases from already established monitoring networks complemented and including citizen science from local communities, such as the Circumpolar Local Environment Observer (CLEO) Initiative. It is crucial to identify networks already existing in polar programs that may provide automated provision of diverse data sources such as remote-sensing, meteorological observations, and water presence (such as the Global Water Observation systems). Other important sources of information include historical records and educational networks available through pan-polar bodies such as the Arctic Council or AMAP.

- **Data interoperability and synthesis**: results from data gathering require synthesis. The FAIR principles require the data to be easily findable, accessible, interoperable, and reusable, so issues such as metadata storage and data formats are relevant. Then, the synthesis phase will lead to the identification of knowledge gaps, the determination of key indicators to monitor trends in ecological pressures, and the design of solutions to solve the specific ecological and socioeconomic concerns. The conceptual models used to forecast future pressures on freshwater resources (e. g., increase of tourism, melting of permafrost, etc.) should address long-term scenarios. This same long-term vision should also lay at the foundation of any adaptation, prevention and mitigation solutions proposed.

- **Pilot testing**: a series of representative pilot sites should be defined within the polar regions, acting as flagship locations for two main purposes: Validation of models via high resolution monitoring as well as paleoenvironmental reconstructions, and experimental testing of prevention or mitigation solutions proposed. This last stage will also be intimately connected with data gathering and data synthesis via feeding of the predictive models. It is crucial that local communities surrounding pilot areas are engaged and feel an essential part of the actions proposed.

- **Upscaling**: prevention and mitigation solutions successfully identified at pilot scale may be progressively implemented in larger polar areas, recognizing local resources and national regulatory frameworks in each specific region and where appropriate.

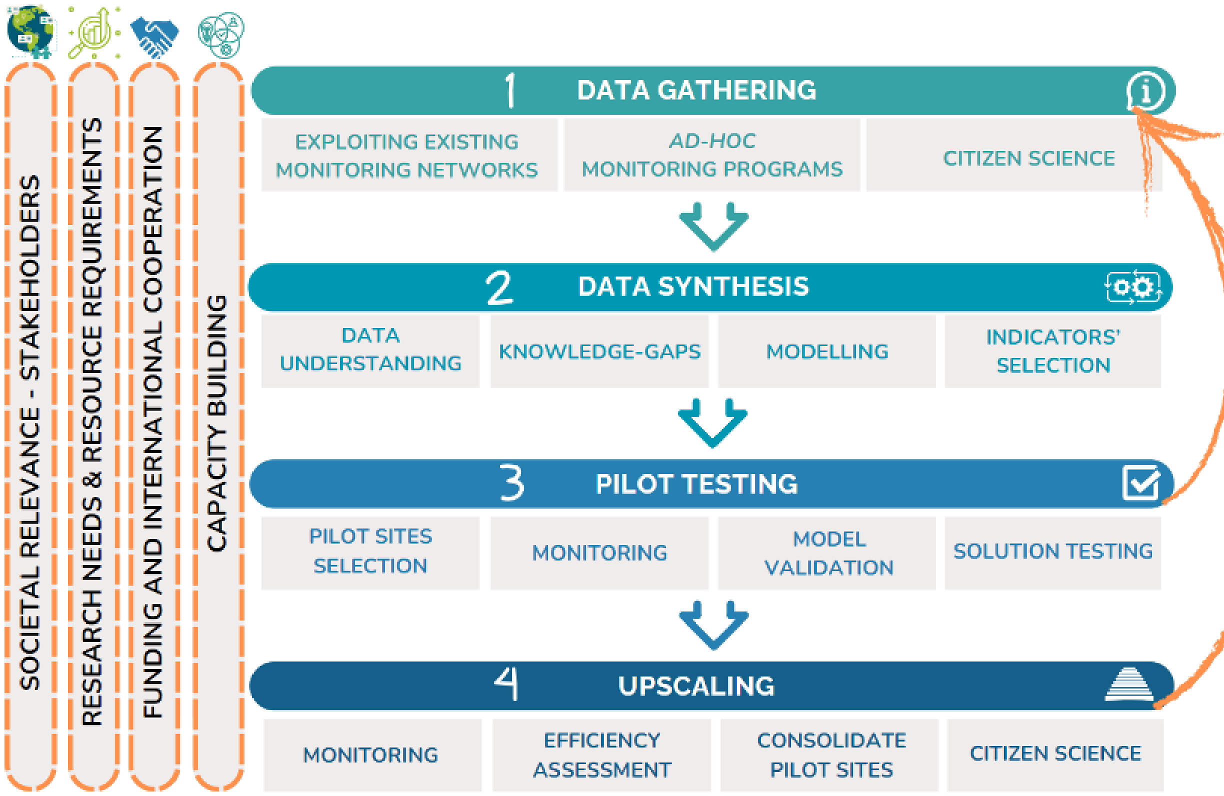


Figure 3. Roadmap for the implementation of actions addressing climate-driven challenges in polar freshwaters.

Identifying funding for advanced research infrastructure aligns with current global emphasis on leveraging technology for sustainable development beyond the polar regions. Digital twins and artificial intelligence approaches align with the global commitment to data-driven decision-making for solutions in the real world, avoiding just another redundant model of it. Both will serve as powerful tools for authorities and stakeholders to understand the potential consequences of climate change. This understanding is essential for making informed decisions that contribute to the long-term sustainability of polar regions.

Funding and international cooperation

In the ongoing pursuit of deepening our understanding of freshwater resources and dynamics in the Arctic and Antarctic regions, a global collaborative approach must form a cornerstone. This section explores the imperative of international collaboration and the pivotal role funding plays in propelling initiatives related to the study and mitigation of climate change impacts to polar freshwater resources.

Initiatives to comprehend transboundary and trans-regional water resources in the context of climate change usually point towards Arctic communities and Antarctic research stations and gateway cities as central beneficiaries, but the significance of international collaboration cannot be overstated. The collaboration across institutions and nations allows for a collective effort in providing solutions that effectively address the diverse effects of climate change on freshwater resources across wide geographic scales. This collaboration is not only crucial for the benefit of the polar regions themselves, but it also carries important implications for the global community at large. Initiatives must align with the UN's SDGs, ensuring relevance for the polar regions and all stakeholders involved. A global perspective on water issues in the polar regions aligns with the UN 2030 Agenda, necessitating international collaboration that transcends geographical boundaries.

The research agenda must be meticulously crafted, considering the EU's emphasis on sustainability and global initiatives for sustainable development in polar regions. Tailoring responses to different typologies and scenarios, incorporating a One Health perspective and fostering collaboration internationally remain critical for the effective development of adaptation and mitigation solutions in polar regions.

Understanding the water cycle demands transboundary approaches. Addressing water-related issues requires substantial investments in prospective works and continuous monitoring, aligning with The Paris Agreement on Climate Change Targets and the EU Green Deal's commitment to research and innovation. Robust funding mechanisms, in collaboration with other EU tools and third countries, are required to bridge knowledge gaps and support international cooperation for the benefit of the polar regions.

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Collaborative initiatives allow for pooling knowledge and resources, aligning with major international scientific assessments, including IPCC, Arctic Council and SCAR reports. Collaboration facilitates mutual learning, drawing on diverse experiences to develop effective guidelines and solutions. Funding strategies must align with global goals, prioritizing precise knowledge acquisition and technological advancements. Potential non-EU funding in general schemes, from countries like New Zealand, Canada, Chile and others should be included, developing the spirit of global cooperation and shared responsibility. The existence and accessibility of appropriate funding schemes is a fundamental prerequisite to strengthening and guaranteeing the financial resources available for these initiatives.

International collaboration is crucial in advancing modelling efforts, supporting with the UN 2030 Agenda and major international scientific assessments. Modelling should extend beyond physical parameters to include ecological, biological, social, and cultural realities influenced by climate change, consistent with global goals for comprehensive research.

Extending monitoring efforts allows for the enhancement of ongoing models, the characterization of their strengths and weaknesses, and a more nuanced understanding of ecosystem functions, which side with global frameworks like the Sendai Framework for Disaster Risk Reduction. The multiscale outcomes derived from combining different granularities in modelling initiatives serve as tools for forecasting new vulnerabilities. Forecasting is essential for communities to develop appropriate strategies to adapt to and mitigate the social, economic, and environmental impacts of climate change, making them more resilient in the face of a changing climate. Effective monitoring requires collaboration with all relevant actors, including Indigenous and other local communities (where appropriate), local authorities, and the international community in the Arctic and Antarctic. Identifying specific targets for monitoring, such as microbial and biogeochemical products and pollutants, ensures a comprehensive understanding of the complex polar ecosystems.

Leveraging opportunities and services from existing transnational initiatives like INTERACT and POLARIN for installing and operating equipment is a strategic move to ensure efficient monitoring. Utilising existing national and bilateral funding mechanisms facilitates access to specific regions and promotes international standardisation of operational procedures. Integrating existing data across disciplines through collaborations facilitated by organisations like IASC, SCAR, and the Arctic Council working groups, including AMAP as well as Sustainable Development Working Group (SDWG) will enhance the overall understanding of Polar Regions.

In expanding our global perspective, the Antarctic governance framework, notably the Antarctic Treaty and its Protocol for Environmental Protection, becomes crucial. This framework underlines the importance of collaborative efforts in preserving the unique Antarctic environment. The principles of the Antarctic Treaty, emphasizing scientific cooperation and environmental protection, provide a blueprint for sustainable practices in both polar regions.

The practical aspects become pivotal as initiatives progress to the next phase. Proposals for calls must be comprehensive and include all relevant methods and cost calculations. Networking and standardising protocols, as the example of Synoptic Arctic Survey, are crucial aspects that need to be prioritised to ensure seamless collaboration and information exchange among stakeholders. However, this has rarely been achieved in international, or even national, contexts as groups work with the equipment and funding available to them.

A thorough understanding of current knowledge and areas where information is lacking is instrumental in guiding future research initiatives and their funding schemes. The involvement of Indigenous communities in the Arctic in the definition of the research needs and project implementation needs to be well described and documented throughout the projects. The provision of a final roadmap for this white paper (Figure 4) provides a structured approach for synthesising and disseminating the gathered knowledge. This document will serve as a valuable resource for policymakers, researchers, and stakeholders invested in the sustainable development of polar regions.

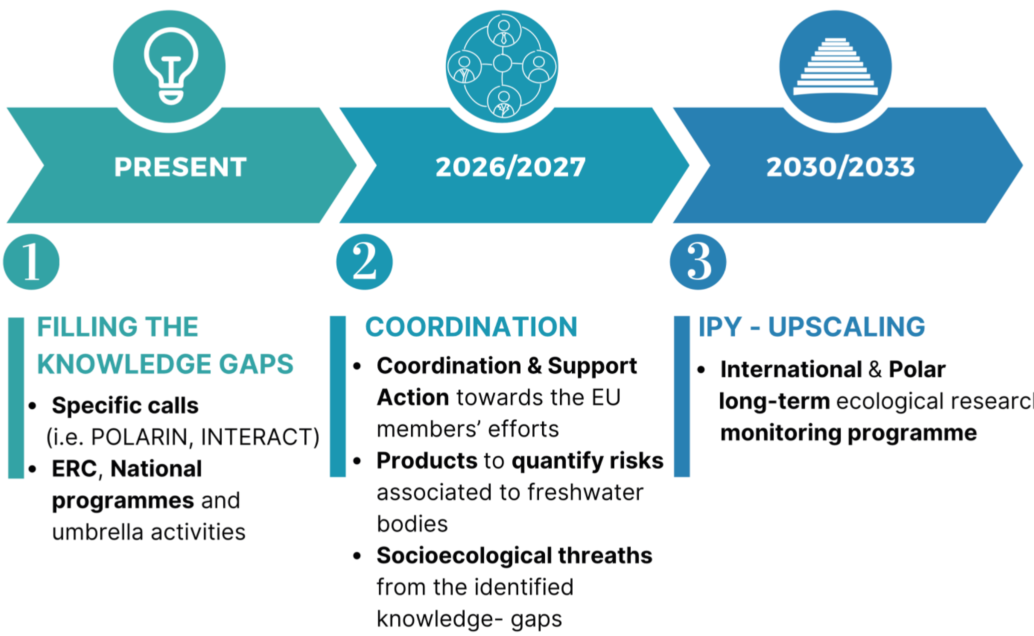

Figure 4. Roadmap for funding the advancement of freshwater resources investigation. IPY refers to the International Polar Year, which will be held in 2032/33.

In conclusion, a comprehensive approach that integrates a global perspective, international collaboration, strategic funding, and adherence to Arctic and Antarctic governance frameworks, and their peculiarities, is paramount. As we embark on this journey, collaboration and funding must be seen as integral components, ensuring that the collective effort contributes not only to the well-being of polar communities but also to the broader global understanding of climate change and its implications for polar regions and their inhabitants. The inclusion of environmental stewardship principles reinforces our commitment to preserving the unique and fragile ecosystems of both polar regions.

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