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Future priorities for Arctic freshwater science from the perspective of early-career researchers[1]

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Abstract: Freshwater systems are a major component of the terrestrial Arctic and are particularly sensitive to climatic and other environmental changes. Recent efforts have focussed on synthesizing and identifying gaps in the current understanding of Arctic freshwater systems. We aimed to identify research priorities for Arctic freshwater science from the perspective of early-career researchers, given their leading role as the next generation of scientists tasked with addressing these research areas. Using a discussion session and an online survey of early-career researchers, we identified five priority topics: (1) establishment of long-term monitoring sites across the Arctic, (2) improved understanding of the implications of permafrost thawing for biogeochemistry of Arctic rivers and lakes, (3) better model predictions of changes in freshwater systems and better integration with the wider modelling community, (4) improved estimates of environmental thresholds and tipping points within Arctic freshwater ecosystems, and (5) the need for community-based monitoring and assessment. These five topics underline the importance of interdisciplinary research and the necessity of developing large-scale environmental monitoring programs and data repositories. Such developments will facilitate long-term understanding of the impact of climate variability upon Arctic freshwater systems and will promote knowledge exchange between local and scientific communities.

Key words: river, lake, permafrost, monitoring, nutrients.

Résumé : Les systèmes d'eau douce constituent un élément important de l'écosystème terrestre arctique et sont particulièrement sensibles aux changements climatiques et aux autres modifications de l'environnement. Les efforts récents étaient centrés sur la synthèse et l'identification des écarts dans la compréhension actuelle des systèmes d'eau douce en Arctique. Nous avons tenté d'identifier les priorités sur le plan de la recherche en science arctique d'eau douce selon les chercheurs en début de carrière, étant donné leur rôle principal en tant que nouvelle génération de scientifiques chargés d'aborder ces domaines de recherche. Au moyen d'une séance de discussion et d'un sondage en direct auprès de chercheurs en début de carrière, nous avons cerné cinq sujets prioritaires, soient : (1) l'établissement de sites de surveillance à long terme à travers l'Arctique, (2) une compréhension améliorée des répercussions du dégel du pergélisol sur la biogéochimie des fleuves et des rivières arctiques, (3) de meilleures prédictions des

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modèles en matière de changements dans les systèmes d'eau douce et une meilleure intégration avec le milieu de la modélisation en général, (4) des estimations améliorées des seuils environnementaux et des points de basculement sur le plan des écosystèmes d'eau douce en Arctique et (5) un besoin de surveillance et d'évaluation à l'échelle communautaire. Ces cinq sujets mettent en lumière l'importance de la recherche interdisciplinaire et la nécessité d'élaborer des programmes de surveillance environnementale à grande échelle et des dépôts de données. De tels programmes faciliteront la compréhension à long terme de l'impact de la variabilité du climat sur les systèmes d'eau douce en Arctique et vont promouvoir l'échange du savoir entre les communautés locales et scientifiques. [Traduit par la Rédaction]

Mots-clés : rivière ou fleuve, lac, pergélisol, surveillance, nutriments.

Introduction

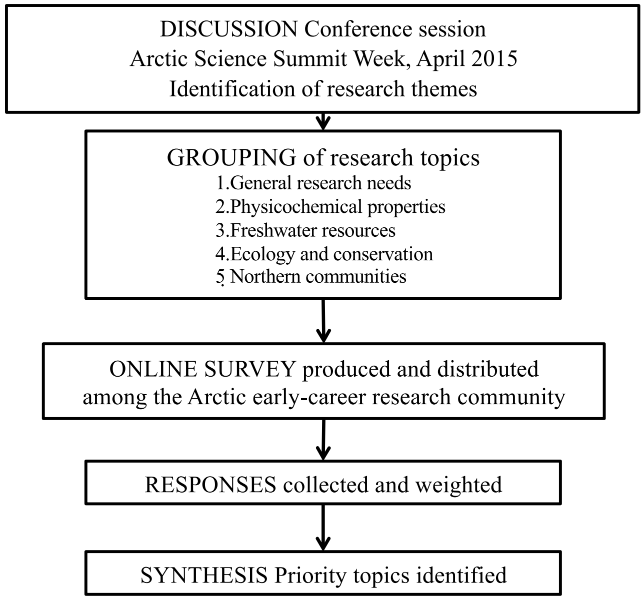
Freshwater systems, comprising perennial or semiperennial liquid water in surface and subsurface terrestrial environments, along with their associated biota, cover almost 1 million km^2 of the terrestrial Arctic and represent >80% of the land area in some regions (Wrona and Reist 2013; Prowse et al. 2015*a*). They are particularly sensitive to environmental change due to their close coupling with atmospheric and cryospheric systems (Prowse et al. 2006). Large-scale changes in climate and hydrology may induce major changes in freshwater systems and in turn affect human communities relying on these systems for hunting, fishing, trapping, and transportation (Prowse et al. 2011*b*). The wide-ranging implications of these changes are reflected in the Iqaluit Declaration of the Arctic Council that recognises freshwater as an important component for both the Arctic biodiversity and the health of northern communities (Arctic Council 2015).

In recent years, several syntheses of contemporary knowledge of Arctic freshwater science have highlighted gaps in our current understanding of these systems (Rautio et al. 2011; Haine et al. 2015; Prowse et al. 2015*a*, 2015*b*; Vonk et al. 2015; Wrona et al. 2016). While these syntheses reflect mainly the point of view of experienced researchers, early-career researchers entering the field will also take part in determining the scientific agenda. We conducted a consultation to identify research priorities for Arctic freshwater science over the next 2 decades from the perspective of early-career researchers, given their leading role as the next generation of scientists tasked with addressing these research areas.

Methods

Collaborative consultation initiatives are increasingly recognised as valuable processes to frame future science agendas (Ingram et al. 2013; Adewopo et al. 2014; Seddon et al. 2014; Fritz et al. 2015; Werner et al. 2016). An opportunity to implement such an approach within the Arctic freshwater research field was provided by the Arctic Science Summit Week conference that was held in Toyama, Japan, on 23–30 April 2015. We conducted a discussion session to identify priority research topics for Arctic freshwater science in a session entitled "The Arctic system: changes and effects with emphasis on freshwater ecosystems" that was attended by both experienced and early-career researchers and comprised approximately 50 world experts from a large spectra of fields. This formed part of the "Arctic Freshwater Synthesis", an international project funded by the Climate in the Cryosphere (WCRP-CliC) program, the International Arctic Science Committee (IASC), and the Arctic Monitoring and Assessment Program (AMAP), that placed emphasis on freshwater resources and fluxes in the Arctic Basin (Prowse et al. 2015*b*). Delegates were invited to suggest important research topics, which were refined and grouped into overarching themes (Fig. 1). In total, 37 topics were identified in five major thematic areas, namely general

Fig. 1. Diagram of the consultation process used to define future research priorities for Arctic freshwater science.



research needs (six), physicochemical properties of freshwater environments (eight), freshwater resources (eight), ecology and conservation (nine), and northern communities (six). A complete list of topics is presented in Table S1[2].

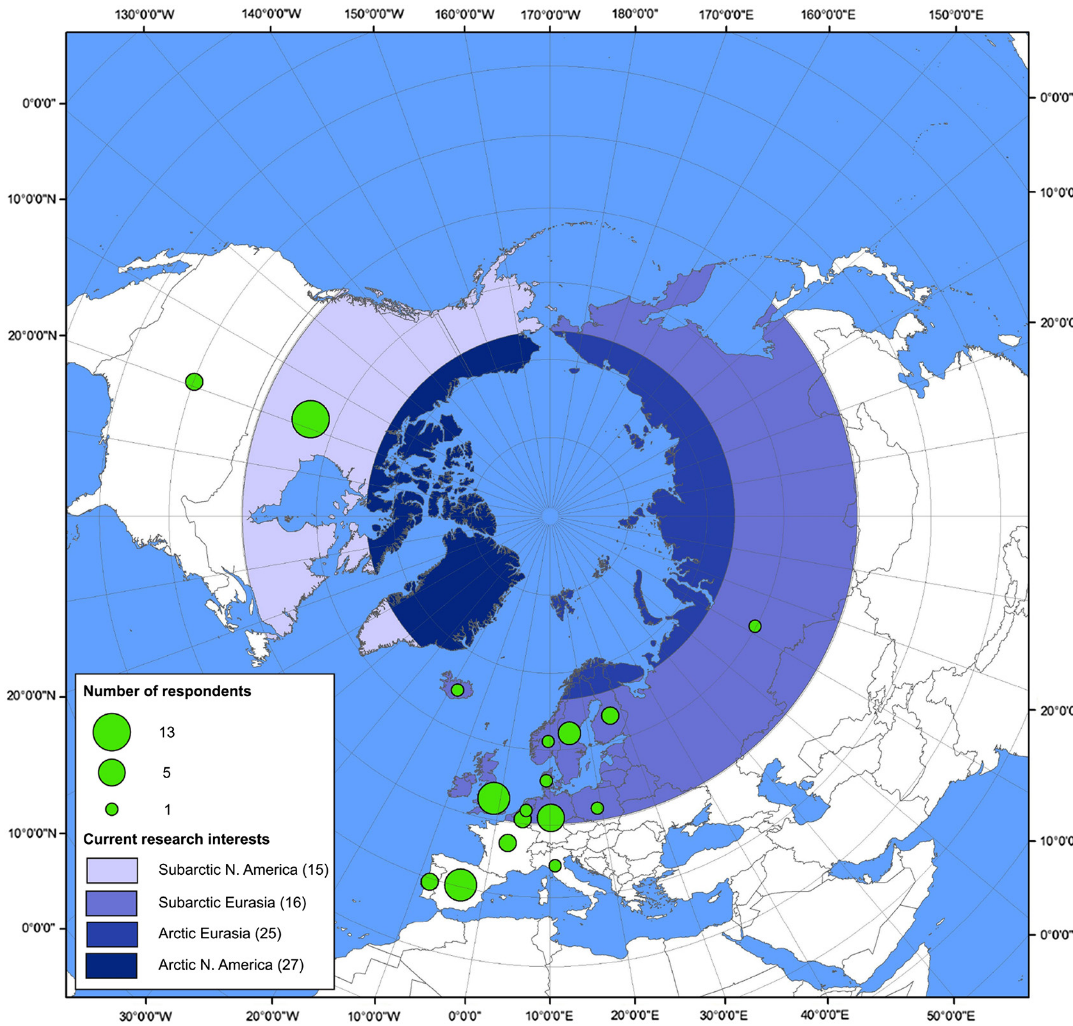
We compiled an online survey that was distributed to early-career researchers with an interest in Arctic freshwater science. For each of the five thematic areas, respondents were asked to select and rank the top three research topics they considered to be priorities for Arctic freshwater science plus any additional topics not listed. The responses were weighted according to rank and summed for each subject area (detailed methods available in the supplementary material[2]).

Results and discussion

In total, 57 individuals from 20 countries provided responses to the online survey (Fig. 2). The majority of respondents were Ph.D.-level graduate students (40%) or postdoctoral researchers (26%) (Fig. 3). A majority of respondents (79%) had more than 2 years of high-latitude research experience (Fig. 4), mostly in the Arctic (Fig. S1[2]). The following priority research topics identified as most important for Arctic freshwater science for each of the five thematic areas are presented based on the views of the 81% of respondents who self-identified as early-career scientists. We note, however, that the exclusion of the remaining 19% of individual responses made no difference in the final ranking of the research topics. The complete list of responses can be found in the supplementary material[2]. No new topics were submitted that differed substantially from those already included in the survey and, as such, are not discussed further here.

[2]Supplementary material is available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/as-2016-0028.

Fig. 2. Map showing number of survey respondents grouped by nationality (dots) and areas of research interest (shaded areas). Not shown are respondents from New Zealand (n = 1) and Brazil (n = 1) and research interests in Antarctica (n = 9) and alpine areas (n = 1). Note that respondents could select more than one area of research interest. Map generated with *ArcGIS* (ESRI, Redlands, California, USA).



1. General research needs

Top-ranked priority: establishment of long-term freshwater monitoring sites across the Arctic

The need for a comprehensive, sustained, and interdisciplinary Arctic observations and data management has been recognised by the Arctic Council and emphasised in reports such as the Arctic Climate Impact Assessment (ACIA 2004) and the Final Report of the International Conference on Arctic Research Planning (ICARP 2016). Climate is a strong driver of change for aquatic systems (Palmer et al. 2009; Isaak et al. 2010), but climate modelling requires long-term high-quality data series to accurately represent land surface dynamics. Given that most observing activities conducted in the Arctic to date have been of relatively short duration, the Arctic Council launched the Sustaining Arctic Observing Networks in 2009 in response to the recognised need to enhance Arctic monitoring (INTERACT 2015). There remains a need for further long-term environmental data sets and

Fig. 3. Number of survey respondents grouped by career level.

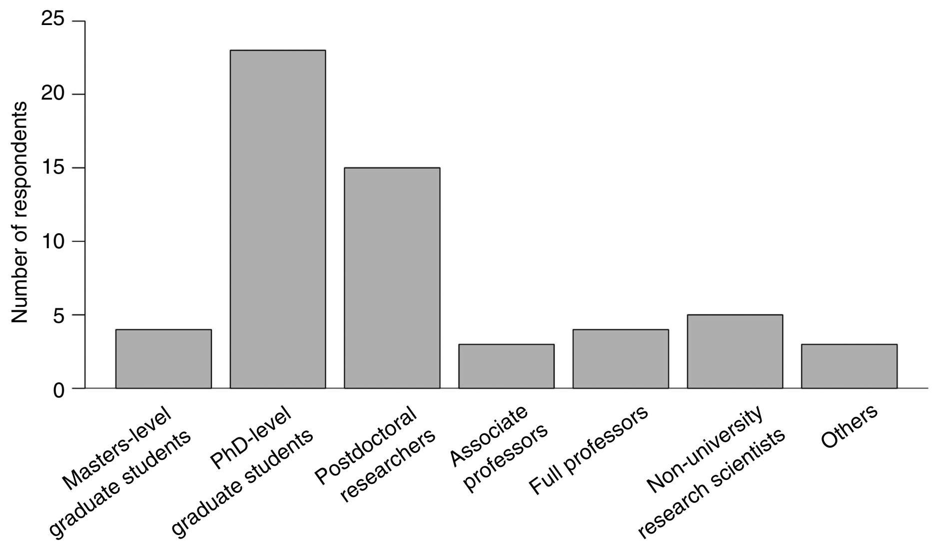
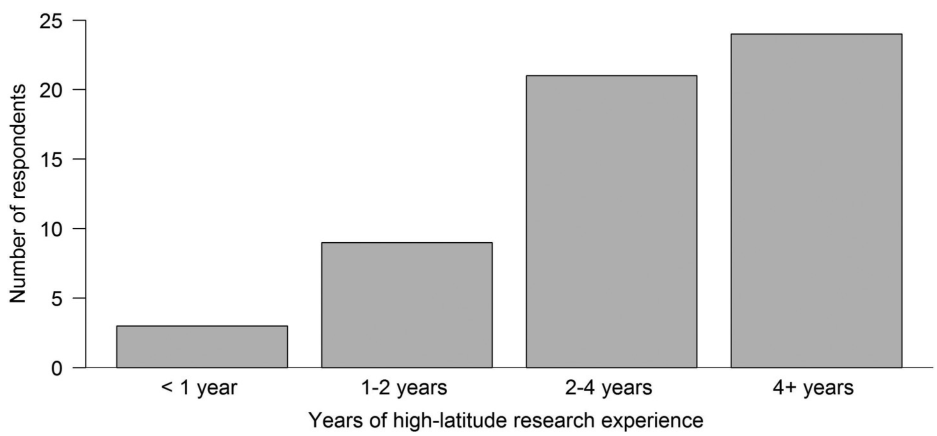


Fig. 4. Number of survey respondents grouped by high-latitude research experience.



associated metadata relating to Arctic freshwater systems, especially on nutrient, sediments, carbon, and water transport (Bring et al. 2016), biodiversity (Culp et al. 2012*a*), contaminant monitoring (Evans et al. 2005), and ice cover regimes (Prowse and Brown 2010; Prowse et al. 2011*b*). In this respect, transnational working groups gathering long-term monitoring data and the use of similar protocols (see Priority 5) (Table S1[2]) may improve our process-based understanding of the interrelationships between different components of Arctic freshwater systems and facilitate the integration of freshwater research with other Arctic research themes. The need for year-round environmental monitoring in order to reduce seasonal data bias was also highlighted (Priority 2), which is coherent with long-term monitoring needs. Substantial efforts have been made in the field of Arctic hydrological monitoring to evaluate current monitoring practices (Mishra and Coulibaly 2010; Mlynowski et al. 2011; Bring and Destouni 2013), identify shifts in hydrological systems

(Karlsson et al. 2011), and identify gaps in monitoring and make recommendations for further monitoring priorities (Azcárate et al. 2013; McClelland et al. 2015; Bring et al. 2017). Developing successful information sharing tools, which could be achieved through open-sourcing (Priority 6), will require successful collaborations between the Arctic scientific community, data managers, and research funders. Existing examples include the Polar Data Catalog and Nordicana D.

2. Physicochemical properties of freshwater environments

Top-ranked priority: implications of permafrost thawing and thickening of active layers for biogeochemistry of Arctic rivers and lakes

Permafrost areas in the Arctic region contain vast quantities of organic matter and are thus of critical importance for the regulation of global climate dynamics and biogeochemical cycling (Tarnocai et al. 2009). Rising borehole temperatures and increases in active layer thaw depths in recent decades (Romanovsky et al. 2010) are projected to continue throughout the 21st century driven by climate warming (Schaefer et al. 2011). The consequences of these changes for Arctic freshwater systems will be to modify hydrological flow pathways through shallow active layer soils, resulting potentially in the mobilisation and decomposition of previously entrained and often highly labile organic matter (Spencer et al. 2015). Mineralisation of permafrost-derived organic carbon by soil microbial communities (Vonk et al. 2015), coupled with further aquatic processing and photodegradation (Cory et al. 2014; Mann et al. 2014), is expected to transfer a large proportion of this ancient carbon pool to the atmosphere and thus drive a positive feedback on climate change (Spencer et al. 2015). This may explain why the need to evaluate the potential for Arctic rivers and lakes to act as a source of greenhouse gas and the impact of climate change on biogeochemical processing rates and nutrient turnover in Arctic freshwater ecosystems was also ranked highly as priority topics in this theme (Priorities 2 and 3, respectively) (Table S1[2]). Key unanswered research questions in this field concern how the composition and lability of dissolved organic carbon in fluvial networks will change under future climate scenarios, the role of microbial communities in processing dissolved organic carbon from both modern and ancient sources (Mann et al. 2014), biogeochemical interactions between dissolved organic carbon and other nutrients (e.g., nitrogen and phosphorus), and major ions potentially liberated by permafrost thaw (Frey and McClelland 2009) and how these processes will combine to alter riverine network gas fluxes (particularly CO_2, N_2O, and CH_4) and the export of nutrients and organic matter to the Arctic ocean (McClelland et al. 2016).

3. Freshwater resources

Top-ranked priority: model predictions of changes in freshwater systems under future climate scenarios and better integration with the wider modelling community

Freshwater fluxes from terrestrial landscapes to the Arctic Ocean are temporally dynamic and spatially uneven and link the whole Arctic freshwater system (Bring et al. 2016). Observation-based assessment of the past and present-day Arctic freshwater changes has been made only at a limited number of long-term monitoring sites, thus adding considerable uncertainty to numerical simulations in this region. Current model projections suggest a wetter Arctic in the future (Jiménez Cisneros et al. 2014) caused by intensification of the hydrological cycle (Vihma et al. 2016). Major future objectives for modelling studies include (*i*) identification and quantitative characterization of climatic and other drivers of hydrological change (of high relevance for water resource managers; see Priority 4), (*ii*) determination of the intensity and mechanisms of biogeochemical reactions of the Arctic freshwater systems in relation to hydrological changes (e.g., induced by permafrost thaw; see Priority 2), and (*iii*) advancement of techniques to improve model evaluation, upscaling, incorporation of process understanding into global and regional models, and coupling of models of different scales and complexity to incorporate linkages and feedbacks between various components of the Arctic freshwater system (Lique et al. 2016). Addressing modelling changes in freshwater systems will involve deepening the knowledge on key drivers (Priorities 2 and 3) and will ultimately provide predictions on freshwater resources availability as an output (Priority 4).

4. Ecology and conservation

Top-ranked priority: environmental thresholds and tipping points within Arctic freshwater communities

Arctic freshwater systems have undergone drastic changes in their physical, chemical, and biological variables over the past few decades (Vincent et al. 2013). While there has been a great interest in freshwater biodiversity and community structure (Culp et al. 2012*a*, 2012*b*), thresholds (points at which a slight change of a variable engenders a relatively large response) and tipping points (permanent and drastic changes of state) were identified as a priority by survey participants. Examples of tipping points include reductions in the duration and thickness of ice cover (Prowse et al. 2011*a*; Paquette et al. 2015), which can induce shifts in lake stratification (Mueller et al. 2009), primary producers in the water column and the benthos (Vadeboncoeur et al. 2003; Culp et al. 2012*b*), and exposure to UV radiation (Williamson et al. 2009). Environmental thresholds related to climate change can lead to the emergence of new freshwater ecosystems associated with thermokarst processes (Payette et al. 2004) and glacial recession (Milner et al. 2009) or their loss by drainage of basins (Mueller et al. 2003) or by permafrost degradation (Smith et al. 2005). Shifts in microbial communities could be driven by organic carbon input from the watershed (Roiha et al. 2015) and from the degradation of permafrost (Crevecoeur et al. 2015). Hence, the following priorities in the ranking, addressing the effect of future environmental change on Arctic freshwater communities and the effect of climate-induced shifts in species distribution and dispersal mechanisms (Table S1[2]), are coherent. Inputs of allochthonous CDOM (addressed in Priority 9) can absorb UV radiation, reducing the harmful effects on the organisms (Gareis et al. 2010). Invasive species may be favoured by climate change and economic development (Vincent et al. 2013) and tip aquatic ecosystems to a new food web configuration and water quality regime. More information about the interactions in freshwater ecosystems is needed. To do so, a long-term coordinated monitoring effort is critical but constitutes a challenge due to the immensity of the Arctic and the heterogeneity of its habitats (Wrona et al. 2006; Culp et al. 2012*b*). Satellite remote sensing (e.g., Watanabe et al. 2011; Boike et al. 2016) along with automated monitoring sensors may help meet this challenge.

5. Northern communities

Top-ranked priority: Community-based monitoring and assessment of Arctic freshwater systems

As the Arctic undergoes pronounced changes in its hydroclimatic regime, there is an increasing need for comprehensive monitoring of environmental variables on global and local scales (Alexander et al. 2011). Northern communities, whose livelihoods often depend on freshwater resources, are particularly adept at accurately observing changes and trends in their environment (Alessa et al. 2008, 2016). Their body of knowledge on past and present environmental conditions often extends beyond the knowledge acquired by western science and hence represents a valuable source of information (Pearce et al. 2009; Alessa et al. 2016). Integration of this traditional knowledge with scientific approaches (Priority 3) may lead to benefits for both indigenous communities and scientific studies (Tremblay et al. 2008; Alexander et al. 2011; Alessa et al. 2016). Involvement of local communities in environmental research strengthens monitoring of the Arctic by providing year-round, accurate, and detailed observations of the areas with scarce instrumental records due to limited access (Alexander et al. 2011). International science, in turn, provides up-to-date information that can help local communities to adapt to the changing environment, such as safe routes to travel during the winter season, safe drinking water supplies, and sustainable subsistence fisheries, and can contribute to the management of community resources (Tremblay et al. 2008; Alexander et al. 2011; Alessa et al. 2016). Although there have been few studies addressing specifically freshwater environments that used a collaborative approach with local communities in the Arctic, a notable example is provided by Tremblay et al. (2008) who showed how traditional community knowledge can be used to enhance river ice-monitoring activities in northern Canada. However, we note that such approaches will be more viable for some subject areas (e.g., ice cover, fish movements) than for others (e.g., zooplankton dynamics). Nonetheless, the establishment of new community-based monitoring and observing networks, the expansion of the coverage of existing ones, the improvement of the ways in which relations with communities are established and maintained, and the dissemination of the results (e.g., easily interpretable water resource indicators) to local and national organizations to assist with policy-making are important avenues for Arctic freshwater research.

Conclusions

This consultation exercise was designed to help identify research priorities for Arctic freshwater science from the perspective of early-career researchers. Given their potential future contributions to this knowledge area, we aimed to provide the next generation of researchers with an opportunity to frame the scientific agenda for Arctic freshwater systems over the following decade, although as with most surveys, our results inevitably represent only a subset of potential respondents. In coherence with recent reviews and syntheses (Culp et al. 2012*a*, 2012*b*; ICARP 2016; Wrona et al. 2016), the research priorities identified through this exercise highlight the need for increased interdisciplinary efforts between multiple scientific subjects as well as stakeholders within the wider Arctic community. In particular, the importance of large-scale monitoring programs using similar protocols and repositories that draw data together from sites across the Arctic is critical to understand the long-term impacts of climate variability upon freshwater systems in this region. While there have been some welcome advances in this area, such as the Toolik LTER program in Alaska, regional data archiving (NEIGE 2016), and INTERACT initiatives at a circumpolar level (INTERACT 2015), further efforts are needed to broaden the scope of these environmental databases and secure funding for their continued existence over longer timescales. Furthermore, developing localised monitoring and assessment networks has the potential to promote knowledge exchange between local and scientific communities and thus provide benefits to both groups.

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