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Nordic hydrological frontier in the 21st century

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ABSTRACT

The 21st century has brought new challenges and opportunities and has also increased demands on the Nordic hydrological community. Our hydrological science focus and approaches need rethinking and adaptation to the changing requirements of society in response to climate change and human interventions, in search of more comprehensive and cross-disciplinary solutions. This commentary highlights new possibilities and suggests vital steps forward for the scientific discipline within Nordic hydrological research. By providing a common direction, we hope to increase awareness, accelerate progress in the hydrological community, and emphasize the importance of hydrological knowledge for serving other fields of science and society at large. We hope that our vision and the opportunities we identify will raise awareness of the scientific discipline and assist in the long-term development of the Nordic hydrological frontier in the 21st century.

Key words: education, future, hydrology, possibilities, technology, water

HIGHLIGHTS

- In this commentary, we highlight new possibilities and suggest vital steps forward for the scientific discipline within the Nordic hydrological research.
- By providing a common direction, we hope to increase the awareness, and thus not only accelerate progress in the hydrological community but also emphasize the importance of hydrological knowledge for serving other fields of science and society.

1. WHAT THE 21ST CENTURY BRINGS TO HYDROLOGY FROM THE NORDIC PERSPECTIVE

Water is an essential part of the Nordic landscape and livelihood. It has been of fundamental importance for human survival, historical land use, and cultural traditions (Amorosi *et al.* 1997). Furthermore, natural water systems, such as lakes, rivers, and wetlands, provide key ecosystem services, and their management is essential for sustainable development in the Nordic countries. For centuries, human activities have impacted Nordic water resources due to large-scale land-use conversion to agriculture (Jaramillo *et al.* 2013), hydropower development, and the rapid industrial evolution of our water resources. Urbanization, forest management, and river regulation have also changed our water systems and their inherent aquatic ecosystems (Destouni *et al.* 2013; Ashraf *et al.* 2018). Presently, the Nordic hydrological community is faced with growing challenges caused by the additional pressures from climate change. The need for an improved understanding of the hydrological cycle and the consequences of our past, current, and future actions has never been greater (Marttila *et al.* 2020). To fulfil societal requirements, hydrological science should aim for a better multi-disciplinary understanding of hydrological processes and their relation to complementary scientific fields (Wagener *et al.* 2010).

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Evidently, the awareness of water and environmental issues has spread rapidly over the last few decades, increasing the need to find solutions for pressing water problems, such as flooding, drought, and deteriorating water quality. Digitalization and technological innovations offer new unexplored opportunities to monitor, model, and predict hydrological responses, utilizing high-resolution data on temporal and spatial scales previously not available (Duan *et al.* 2021). We are currently in a situation where (i) past and emerging environmental and societal risks need to be resolved; (ii) novel technologies and methods provide new opportunities; and (iii) the need to educate our society members and the next-generation stakeholders is urgent. In our commentary, we discuss what the 21st century brings to hydrology from the Nordic perspective and form our vision for a new hydrological frontier of the north.

Hydrological science and knowledge have radically developed in the past few decades and moved the field of science from empirical engineering approaches towards a more comprehensive system understanding, integrating across many disciplines (Wagener *et al.* 2010). The 21st century has brought new opportunities for integrating complex human–water relationships using methodologies from sociology, climatology, sustainability science, psychology, and economics (Karjalainen *et al.* 2013; Welling *et al.* 2020). Moreover, the strong focus on a green transition as a method of solving the climate, environmental, and biodiversity crises calls for hydrologists to create comprehensive solutions for the well-being and sustainable use of resources with new knowledge and novel solutions that can also benefit carbon sequestration, nutrient attenuation, and biodiversity in our future landscapes. These actions call for a deeper and more precise understanding of the hydrological cycle, including its temporal and spatial variabilities.

Water surrounds us, and changes in the hydrological cycle are apparent in our landscape and water bodies, changes that feedback to the natural system as well as our societies. The Nordic region (Denmark, Finland, Iceland, Norway, Sweden, and the Baltic States) exhibits a high heterogeneity in terrestrial and hydro-climatological characteristics, and thus shows high diversity in the response to human interventions and climate change. The region covers latitudes of 55°–71 °N and has a pronounced west–east gradient in climate and topography, ranging from high mountains in the west to low topography regions in the south and east, including large boreal forest areas and a diverse range of freshwater ecosystems, including lakes, ponds, river, and wetlands. Additionally, the climate varies from an oceanic to an inland, continental climate and even includes the high Arctic, with its glaciers and permafrost presence. The geology and soils are strongly influenced by recent glaciation and a landscape characterized by numerous lakes, rivers, forests, peatlands, and large areas of exposed bedrock (Bakke *et al.* 2020). The Nordic region thus covers a wide range of landscapes that also characterize other similar high altitude and latitude regions in the northern hemisphere.

In the Nordic region, scientific observations have shown alarming air and water temperature changes, about three times greater than the average global temperature change, especially in higher latitudes (Tietäväinen *et al.* 2010; Jyväsjärvi *et al.* 2015; Carvalho & Wang 2020), affecting all components of the hydrological cycle. There have been changes in precipitation seasonality and form (rain and snow) (Silander *et al.* 2006; Irannezhad *et al.* 2017; Bailey *et al.* 2021), enhanced evapotranspiration (ET) (Ge *et al.* 2013), milder winters (Minville *et al.* 2008), more unstable ice conditions in winter (Gebre *et al.* 2014; Latkovska *et al.* 2016), the shorter duration of snow cover (Brown & Robinson 2011; Kozii *et al.* 2017), and increased snowfall in some high-altitude regions (Rizzi *et al.* 2018). Climate extremes have led to more frequent floods and landslides and enhanced drought conditions in summer (Lopez *et al.* 2021). This has altered soil moisture patterns, runoff processes (Stonevicius *et al.* 2017), and nutrient and dissolved organic carbon (DOC) export (Øygarden *et al.* 2014; Meriö *et al.* 2019; de Wit *et al.* 2020; Fork *et al.* 2020; Wenng *et al.* 2021a, 2021b). High-latitude environments are particularly vulnerable to the impacts of global warming as these regions are experiencing the most evident and rapid warming when compared to other regions of the world. This is a region influenced by a distinct seasonal snow regime, and a general reduction in snow cover will result in positive feedbacks to the atmosphere (enhancing warming through reduced albedo and changing the snow–vegetation interaction), as well as leading to changes in the hydrological regime. There is a need to better understand how changes in climate (precipitation, air temperature) will affect key water balance components (ET, runoff, and snowmelt) across different regimes, information that is essential for robust water management in the future.

An assessment of observed and predicted changes in hydrological variables due to global warming is critical and will strongly impact the research direction of the hydrological community and how it will respond to current and emerging challenges. At the same time, human interventions are radically shaping water storage and movement across the landscape. For example, Nordic societies have a long tradition of draining the soils to maintain sufficient soil moisture conditions for agriculture, forestry, and urban needs (Norstedt *et al.* 2021). Forestry management influences water and nutrient balance (Kuglerová *et al.* 2021), hydropower production has shaped our river flows and lake water levels (Ashraf *et al.* 2018), and

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groundwater resources are more frequently used to support municipal water demands (Gunnarsdottir *et al.* 2020). Continuing urbanization and population movement is creating a challenge for water management, and new innovations are needed to improve sustainability in densely built-up environments (Lähde *et al.* 2019). We advocate for the Nordic hydrologic community to take a more prominent role in ensuring sustainable water availability and resolving the effects of these and other yet unknown drivers on water resources.

2. HYDROLOGICAL UNDERSTANDING IS CRITICAL FOR NORDIC SOCIETIES

Although Nordic society has a long tradition of managing water resources, we need to rethink our approaches and better control and protect our water resources and enhance their resilience to climate change and human interventions. This should include climate change assessment in all parts of our water management, including a nexus approach that considers different sectors of society and sustainable development goals. A way forward is to restore the lost resilience of our landscapes through the implementation of nature-based solutions, such as restoring rivers, wetlands, etc. (Hoffmann *et al.* 2020). We argue that the role of hydrology should be more comprehensively assessed and integrated at all levels of decision-making and highlighted at all levels of society. A key challenge is to transmit our knowledge of the sustainable use of water resources to municipalities, companies, and consumers, allowing this knowledge to be used in decision-making, planning, and budgeting (Figure 1). This requires a focus on hydrological research, education, and interdisciplinary communication. This would improve living conditions for humans and ecosystems, strengthen Nordic identity, and create sustainable business and educational opportunities that could be shared globally. The challenges that must be faced will also compel the hydrological education structures to rethink and harmonize the hydrological curriculum and tailor it to address the societal and ecosystem needs of tomorrow.

Like other natural science fields, high-quality empirical data of adequate spatial and temporal resolution is of fundamental importance for understanding underlying mechanisms and processes, deciphering trends, and creating robust model predictions for the future. Hydrological processes are inherently complex and often scale-dependent (temporal and spatial), making reliable predictions of future conditions difficult. Despite the importance of field observations and experiments, a steady shift towards model-only approaches has become apparent in hydrology (Burt & McDonnell 2015). This trend is especially noticeable at northern latitudes, where the number of long-term research sites in permafrost regions has declined over the last few decades, leaving only a few locations that generate sufficient empirical data to answer the most pertinent questions about the

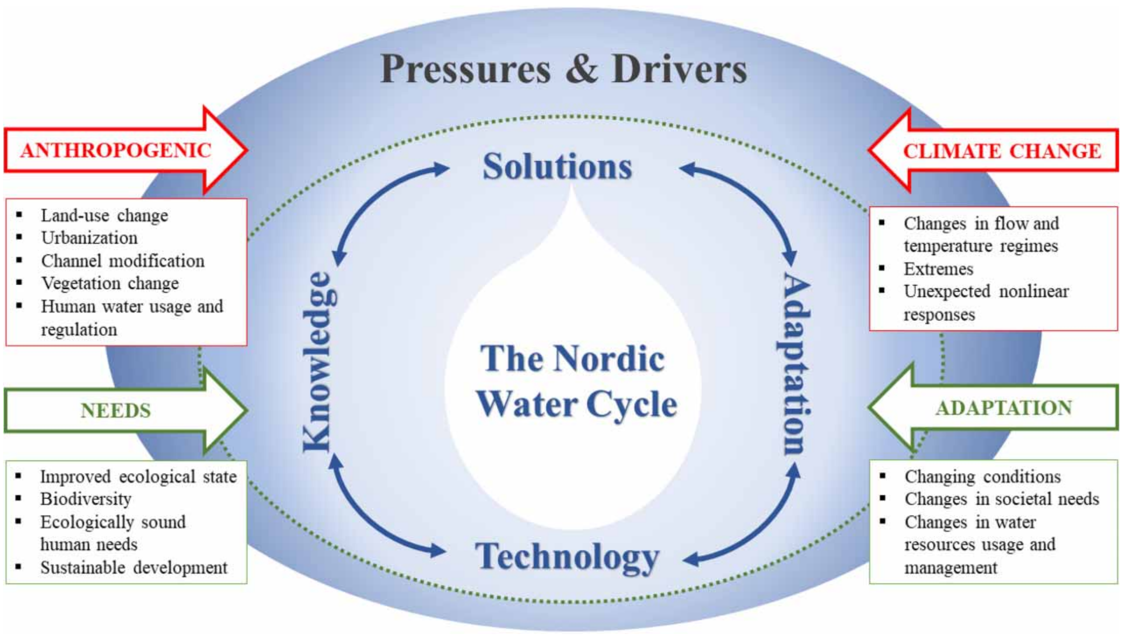

Figure 1 | Pressures, drivers, and their influence on the Nordic water cycle. Red indicates pressures coming from anthropogenic influences, including human interventions and climate change, whereas green indicates needs and adaptation. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2022.120.

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future of our water resources in these regions (Laudon *et al.* 2017). Although it is important to understand the complexity of the water cycle and its role in a wide range of risk assessments for societies and ecosystems, we highlight here a few key examples of research fields that we argue to be in great need of further attention in the future.

Climate change risk on Nordic water resources

Climate change causes various risk factors for society, human health, and the built and natural environment through a wide range of impacts. Flood risk management deals with current and future flood risk scenarios (Parjanne *et al.* 2018), showing how economic growth and urbanization play a major role in flood risk management. Climate change has led to severe impacts following an increasing number of extreme weather events (Silander *et al.* 2006; Akstinas *et al.* 2018), such as flash floods caused by extreme precipitation or wildfires caused by an extended dry period. These impacts call for immediate attention from society, including a shift from hazard forecasting to impact-based forecasting as recommended by WMO (2021). However, slow-onset risks and impacts have more long-term consequences, giving society more time to react. These can be associated with drivers, such as increasing temperatures, which can lead to an increase in evaporation and thus a reduction in water resources, loss of biodiversity, land and forest degradation, glacial retreat-related impacts, sea-level rise, and salinization, among others. The Nordic countries will continue to experience some of the most pronounced changes in terms of temperature and precipitation globally. The combination of large latitudinal gradients within the region, the wide range of altitudes, the coverage of three vital biomes (temperate, boreal, and tundra), and coastal ecosystems representing three different seas (Baltic Sea, Atlantic Ocean, and Arctic Ocean) create a large variety of characteristics, potential impacts, and future risks in the region. Risks can relate directly to water availability on the surface and underground (Kløve *et al.* 2014), or indirectly to a specific context where water is relevant, such as healthy ecosystems and human well-being (Assmuth *et al.* 2020). Hydro-climatological changes in water resources also impact energy production and demand, where both temperature (demand) and precipitation (hydropower production) play a role. The operation of water reservoirs will likely change in the future due to changing precipitation, temperatures, and seasonal patterns. Collaborative planning is a way to evaluate alternative regulation strategies (Söderholm *et al.* 2018). The mitigation of climate change favours renewable energy, which, in turn, requires larger short-term regulation of water resources. With an enhanced focus on bio-economy, forest, and agricultural land may be extended to marginal lands, affecting leaching and eutrophication. Additionally, we need to rethink reservoir operations and their role in water supply and energy production.

Catchment management and hydrological extremes

Nordic catchments are already experiencing signs of more frequent extreme hydrological conditions, such as droughts and floods, directly influencing our society and ecosystems. An increase in heavy rainfall events poses an increasing challenge for both rural and urban areas in handling such extremes when the inflow of stormwater exceeds the capacity of the drainage system. Adapting underground stormwater systems might be possible in some parts of the Nordic area but cannot fully manage the increase in rainfall intensity; thus so-called 'green infrastructures' become part of the solution. Stormwater management in urban catchments aims to reduce construction impacts on urban water cycle, restore some of the natural hydrologic processes, and improve biodiversity and amenity in population centres (Khadka *et al.* 2021). In crop production and forested areas, soil moisture conditions during prolonged dry spells and increased evaporation losses due to global warming challenge traditional catchment management (Veijalainen *et al.* 2019; Bakke *et al.* 2020; Levia *et al.* 2020). More frequent periods of wet soils and changes in surface runoff processes will likely result in enhanced nutrient and DOC leaching patterns (Kämäri *et al.* 2018) as well as greenhouse gas (GHG) emissions and transportation processes of suspended sediments (Kämäri *et al.* 2015; Wenng *et al.* 2021a, 2021b).

Overall, more frequent flooding and a shift from spring snowmelt flooding to less predictable flash floods challenge both our current hydrometric monitoring and water management approaches and tools. Future climate and new social needs demand comprehensive catchment management plans. Catchments (and aquifers) should be seen as one management unit with very specific conditions, meaning that similar actions cannot be 'copy-pasted' from one catchment to another. Novel water protection methods and nature-based solutions are required to change baseline conditions. We need to set new targets for catchment mitigation measures, such as drainage, adaptive buffer strips, the restoration of rivers and wetlands, and land-use actions, to not only improve the retention of water and solutes but also restore natural hydrological conditions, support carbon sequestration, improve biodiversity, and enhance ecosystem services such as flood protection.

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Conserving hydrological function is key in any restoration action and should be stressed for sustainable catchment management. The restoration of river channels, floodplains, peatlands, etc., is increasingly done in Nordic landscapes to conserve critical ecosystems and their functions. Although landscape restoration is being carried out globally, there is still a long way to go in mitigating the loss of rivers and wetlands as ecosystems. The slow progress is not primarily due to a lack of scientific understanding of physical and ecological processes but rather due to limited local-scale restoration actions not leading to basin-scale changes. As a result, there is a substantial gap between society's actions and expectations (Wohl *et al.* 2015). Ongoing programmes in the Nordic region support large-scale restoration actions (e.g., the River Skjern in Denmark; Kristensen *et al.* 2014), but the long-term hydrological impact of these actions is yet to be seen and evaluated. Future directions are focused especially on peatland conservation and headwater restoration actions that need much greater attention. Altogether, this raises important questions about whether active restoration can help to mitigate human pressures and restore ecosystems and the functions and services they provide.

Groundwater and surface water interactions

The glacio-fluvial landscape of the north consists of a mosaic of aquifers, lakes, and wetlands that depend partially or fully on groundwater interactions. Here, groundwater seepage and upwelling zones sustain specific hydrological processes that are critical for ecosystems. Although there has been a large number of studies of groundwater and surface water interactions in the Nordic countries, ranging from groundwater-dependent ecosystems (Kløve *et al.* 2014; Isokangas *et al.* 2015, 2017), to nutrient leaching management (Skarbøvik *et al.* 2020), glacier meltwater interactions (Dochartaigh *et al.* 2019), and riverine processes (Jansson *et al.* 2007), it is still an understudied topic in many other aspects, including urban areas and groundwater-dependent lakes (Kidmose *et al.* 2015; Vainu *et al.* 2015). Because of their critical importance as drinking water reservoirs and natural ecosystems, aquifers should be better identified and protected from pollution and the effect of land-use changes and management practice. Groundwater seepage should be especially considered in riparian management in agriculture and forestry. Strong links between the biodiversity of riparian areas, nutrient leaching and GHG emissions have been documented, and adaptive riparian management has been suggested (Kuglerová *et al.* 2014; Lind *et al.* 2019). Sustainable land use and catchment management should increasingly consider hydrological conditions using hydro-smart design and assess ecosystem services and local biodiversity when investigating groundwater and surface water interaction. A clear limitation for sustainably managing these various interactions at the landscape scale is the inability of most hydrological models to identify critical locations. Examples that ignore basic hydrological knowledge are mine structures that have been built on top of groundwater discharging areas, thus challenging the sustainability of the mining operations and water protection measures (Isokangas *et al.* 2019). Hence, future environmental impact studies need to integrate surface and groundwater flow better with state-of-the-art integrated modelling (Ala-aho *et al.* 2015).

Cryosphere

Snow cover and volume changes, the depth and spatial extent of soil frost (including permafrost), and glacier, river and lake ice conditions all influence Nordic hydrological processes in many ways. Under changing climate and snow conditions, we expect situations with (1) a greater variability in snow cover season with mid-winter snowmelt and rain-on-snow events increasing the risk of winter flooding and (2) a reduction in snow (cover and depth) promoting colder soils and deeper soil frost conditions and thus affecting surface flow patterns (Walsh *et al.* 2020). Additionally, the presence of snow influences albedo and thus, the regional energy balance. Snow and soil frost also influence the overall hydrological conditions of the region, and the role of soil frost in catchment-scale hydrology is understudied and poorly understood (Ala-Aho *et al.* 2021), and little is known on how it should be taken into account in land-use management and mitigation measure plans. Snow is also a critical resource for societies and ecosystems in winter and is a major source of flooding in the Nordic landscape. However, we still miss critical snow information, especially related to, snow depth and snow water equivalent (SWE). There is, therefore, a challenge to improve predictions of the duration of spring flood periods. The seasonality of snow and its dependence on air temperature make it sensitive to global warming. With the exception of high mountain areas, less snow has led to an overall earlier snowmelt flood period. Winter warming events may cause snow-free areas, exposing vegetation to frost damage and winter flooding, whereas Rain-On-Snow (ROS) events can lead to the formation of ice layers and can often play a role in the formation of extreme flood events (Pall *et al.* 2019). Additionally, the rapidly diminishing of glaciers has a major influence on seasonal hydrology (Flett *et al.* 2017), water resources, and water security, especially in mountainous regions. The processes by which enhanced glacial melt feeds the hydrological cycle need to be better understood (Flowers

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et al. 2003). These are areas where more research is greatly needed to reduce societal and ecological impacts. Furthermore, urban snow processes are lacking in attention, and solutions for reducing the environmental impacts of polluted urban snowmelt have not been properly covered, which is then reflected in inadequate urban snow management practices. Additionally, river and ice conditions need further attention (Gebre *et al.* 2014; Yang *et al.* 2020). River ice is important for shaping channels, storing water, causing ice jams, controlling instream and riparian ecology, and the utilization of water resources. A warming climate also increases the stream water temperature, affecting ecology and biodiversity (Jyväsjärvi *et al.* 2015).

Lakes, wetlands, and coastal water levels

The Nordic region is a region with one of the greatest numbers of lakes and wetlands in the world. These wetlands and lakes maintain water quality, regulate groundwater levels and soil moisture, help mitigate floods, sequestrate carbon, and support natural habitats for biodiversity. Lakes and wetlands are also a cornerstone for achieving sustainable development as part of Agenda 2030 (Jaramillo *et al.* 2019). However, wetlands are under pressure and have been in decline over the last 200 years due to the expansion and intensification of agriculture and forestry. They are now facing accelerated change due to global warming. However, currently, very few lakes and wetlands are monitored *in situ* for water level changes, or other hydrological components requiring better opportunities to observe and quantify recent and future hydrological changes of these critical systems.

Understanding the ecohydrological and hydrodynamic changes in coastal wetland systems affected by upstream human interventions requires extended hydroclimatic monitoring networks of water level. These networks should monitor discharge in river and stream tributaries, tidal variation, and local precipitation. These data can then be used for hydrologic and hydraulic wetland modelling and to design rehabilitation programmes and projects aiming to restore natural hydrologic wetland conditions. However, hydrologic monitoring in coastal systems is a challenging task as these networks are costly to install and maintain and cannot be used to monitor the full extent of the coastal systems.

River regulation and flood control

River regulation is used for electricity production, water management, inland navigation, agricultural production, and flood control purposes. Hydrology plays an important role in operational flood management through forecasting inflow and planning reservoir operation to mitigate flooding through releases of water prior to the flood event (Killingtveit *et al.* 2021). In a green transition and fossil fuel-free future, hydropower has a fundamental role in balancing stochastic solar and wind energy production capacities due to the flexibility of operation, and dynamic water reservoir regulation can play an important role in this. The utilization of hydropower systems for balancing production can lead to fluctuating flows in receiving water bodies (hydropeaking), which is shown to have increased over recent years (Ashraf *et al.* 2018). Several studies in the Nordic countries have shown the negative effect of peaking operations on ecology and the utilization of water bodies (e.g., Bakken *et al.* 2016; Bejarano *et al.* 2018; Akstinas *et al.* 2021). Accordingly, mitigation strategies are needed to protect the environment from adverse effects. Recent studies have found under-utilized potential in the renewable energy sector that could be achieved by considering better climate services such as the seasonal forecast of inflow (Halsnæs *et al.* 2021). As hydropower is the dominant renewable energy source in the region, continued collaboration between hydrologists and the energy sector will be essential for a sustainable future through the sustainable operation and effective utilization of resources. Collaborative planning and adaptive river regulations are needed to meet the future demands of the environment, society, and hydropower (Söderholm *et al.* 2018; Kasvi *et al.* 2019; Virbickas *et al.* 2020). Mitigation of hydropower impacts requires a cross-disciplinary endeavour. Environmental design and environmental flow requirements (Forseth & Harby 2014) are key in the management of Atlantic salmon, and the methodology could be adapted to other species and applications. Future assessments of impacts and mitigation measures need to focus on ecosystem services and incorporate the multiple users of watercourse, rather than focussing purely on fish (e.g., Aroviita & Hämäläinen 2008; Barton *et al.* 2020). Since several hydropower systems are currently undergoing revision processes, a larger focus on the environment is expected, and hydrological knowledge will play a key role in this process.

Regions that are projected to experience increased floods in the future require adaptation depending on the type of flooding (Akstinas *et al.* 2018), with the scenario changing based on whether it is traditional spring snowmelt flooding or flash floods following extreme precipitation. The latter is more difficult to forecast and predict compared to a larger flood caused by a frontal system or snowmelt (or a combination of the two). Both traditionally engineered flood control structures and nature-based solutions can play an important role in such adaptation strategies. There is a need to ensure that the flood

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control measures do not infringe on other important measures to protect biodiversity, habitats, and land use (Juárez *et al.* 2021). Knowledge of the interaction between hydrology, ecology, and other river ecosystem services will be necessary in the planning and design of flood mitigation measures for the future.

3. EMERGING TECHNOLOGIES AND POTENTIAL OPPORTUNITIES

As hydrologists gain access to new data, tools, and knowledge about our changing environment, it is important to ask what the major research gaps and potential leaps forward are in hydrology, and especially in management, interdisciplinary communication, modelling and monitoring, and what this means for Nordic communities and societies. Our first step would be to critically evaluate the status of the network for hydrological monitoring, and its functioning, most importantly assessing whether it fulfils Nordic expectations from scientific and societal points of view. Second, we need to re-evaluate risks and possible changes in the water cycle and consider whether our existing monitoring and analysis tools are able to capture the projected changes in our observations. Third, we need to broadly welcome emerging technologies and models, and evaluate the opportunities they may bring. The fourth step addresses data and observational design, and how it should be targeted to the questions and needs at hand and can be included as a service to other communities (e.g., the climate community) to foster cross-disciplinarity.

In all the steps above, the Nordic hydrological science and management community should guide and lead the way forward while asking the question: 'What should be kept and what should be changed?'. Although hydrological monitoring networks have been intensively used in the Nordic countries, we still lack systematic monitoring in rural and remote locations and of many essential processes in the hydrological cycle. There is a clear systematic mismatch between hydrological, biogeochemical, and ecological monitoring that includes all parts of the water balance and its components (meteorology, soil processes, vegetation, groundwater, and surface water). When the future aim is to gain a more comprehensive and dynamic understanding of our environment and the role of hydrology, we must also rethink and improve our monitoring networks.

As data are becoming more affordable and available, open-access is strongly promoted, and we should rethink the utilization of spatial mapping not only in operational hydrology but also in hydrological education and scientific documentation. New approaches should consider the 'monitoring network' aspect when combining data (data assimilation) at all levels, from remote sensing, point scale high resolution, and infrequent grab samples (solutes and ecology), to citizen science.

How to monitor missing elements in the hydrological cycle?

Currently, there is a lack of high-frequency spatial and temporal coverage of several hydrological storages and fluxes in our monitoring networks. Hydrologic science needs the implementation of new kinds of observations and main hydrological components. There are many reanalyzed (forcing) datasets that are constantly improving in resolution and quality. Big data does open new opportunities for regional and continental scale distributed hydrological modelling approaches. Technologies are rapidly developing and creating possibilities, especially for automated spatial and temporal monitoring of the hydrological cycle (McCabe *et al.* 2017; Njue *et al.* 2019) and for modelling water movement over land (Beven 2019). Emerging earth observation technologies, such as microsatellites and unmanned aircraft systems (UAVs) will continue to provide game-changing research opportunities for future hydrologists.

Satellites, especially microsatellites and UAV methods offer flexible tools to address hydrological questions. Remote sensing provides opportunities to measure environmental change and hydrologically relevant parameters at much larger scales than previously feasible. Satellite technologies in Nordic hydrology have so far been limited, but microsatellites from the Nordic countries like ICEYE-X1 (SAR Microsatellite-X1) have opened up new opportunities, such as mapping of flood areas. There will also be new satellites providing more details about runoff and deep soil moisture. Another methodology, termed Interferometric Synthetic Aperture Radar (InSAR), employs the differences in the path length of two satellite acquisitions taken from the same orbital point to estimate changes in water level, for example, in wetlands (Wdowinski *et al.* 2004), and soil moisture conditions (Manninen *et al.* 2021). In general, satellites and UAV technologies are already used for the detection of variables such as precipitation, temperature, snow cover extent and depth, soil moisture in the surface layers, soil frost/thaw status, water levels, ET, flood extent, flow velocity, river discharge, and land water storage over regional/global areas (Crétaux *et al.* 2016; Salminen *et al.* 2018; de Niet *et al.* 2020; Duan *et al.* 2021; Vélez-Nicolás *et al.* 2021). The Gravity Recovery and Climate Experiment, known as GRACE, measures the variability in the mass of the earth system and can be used to infer large-scale changes in water storage, visualizing the heavy toll of human activities on the

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world's aquifers. Nevertheless, it has a coarse spatial resolution that limits its application, and it requires complicated algorithms to differentiate surface water changes from other changes. The application of space observations like InSAR has the potential to improve our assessment of Nordic water resources and their changes. Despite this data being mostly freely available in the Nordic countries (in contrast to many other European countries) (Waylen *et al.* 2019a, 2019b), it is still not taken full advantage of for studying Nordic water resources and ecosystems, one obstacle being their large data storage capacities and processing time requirements. Furthermore, there is still little information of climate change influences on ET at the Nordic scale despite its key control on the water balance. Increasingly available eddy covariance towers and actual measured ET open new possibilities to reveal ecosystem-scale feedbacks and reduce the rather large uncertainties that prevail in the current estimate of regional evaporation.

Increased temporal resolution and the improved robustness of high-frequency sensors together with new optical (e.g., multispectral) and chemical (e.g., redox potential) detectors open new possibilities for monitoring the water quality of our waters (Rode *et al.* 2016) on a continuous basis. Many commercial sensors are already capable of measuring DOC, nitrate (N_2-N), and suspended solids (SS) among others, but sensors are still relatively unexplored in national monitoring networks. This is often related to costs or inability to analyze high-resolution datasets, thus hiding the true potential of high-frequency sensors for improving national monitoring. High-frequency sensors can improve our capability to understand diurnal variations as well as the influence of extremes and their immediate (high sudden peaks) or long-lasting tails on water quality. High-frequency water quality monitoring supports catchment model evaluation and enhancement (Kämäri *et al.* 2019).

In addition to providing higher resolution spatial and temporal data, new technologies open new hydrological parameters to be measured and make more data available. Spatially distributed and the use of ensemble meteorological forcing can improve hydrological predictions, while better use of spatially distributed parameters (e.g., soil, vegetation, and topography) can account for landscape heterogeneity. Multi- and hyperspectral monitoring in UAVs or point scale high frequency can reveal new unexplored processes, for example, from DOC quality. In general, future hydrological monitoring should focus on improving both the quantity and quality of data. It is important that novel high-frequency monitoring is linked to advanced modelling, including both numerical models and data-driven approaches. Artificial intelligence and machine learning will have an increasingly important role as they allow searching for dominant patterns and unknown connections. Additionally, in future studies, hydrological monitoring should be directly linked to cross-disciplinary studies, including ecological status, biodiversity, and ecosystem service monitoring, providing insights into important socio-economic cases such as hydropower, land use, and water supply.

How to improve our hydrological models?

Hydrological models are key tools that hydrologists use to analyze various spatial and temporal processes, predict operational hydrology, and assess climate change or land-use change impacts. Although hydrological models can simulate different runoff components, soil moisture, and many other relevant variables, they still greatly lack fully hydrologically integrated components, such as groundwater for detecting groundwater-dependent ecosystems (Jansson *et al.* 2007; Kløve *et al.* 2014), tracer aided hydrological modelling (Ala-aho *et al.* 2017) or the links between catchment hydrology and detailed river hydraulic processes (Lotsari *et al.* 2020). With more information about vegetation cover, land use, hydrogeological soil structure, and farming and forestry practices becoming available (e.g., Kmoch *et al.* 2021), it is also a question of how to make use of this data to improve our model parameters. This is an area where the climate, land surface modelling, and hydrological communities can collaborate closer, through combining simulations of land-atmosphere interactions (energy and water balance) and soil moisture (interface where the two modelling communities meet). A collaboration example is the combination of high spatial resolution information from precipitation radars to hydrological models simulating flashy hydrological behaviour of urban catchments (Niemi *et al.* 2017).

Additionally, we are lacking higher time resolutions in our hydrological measurements to meet the requirement by more complex models (minutes and hours), and real-time data assimilation with high-frequency sensors has not yet been fully developed. In general, new computer capacity and data assimilation possibilities call for an improvement in our models, allowing (1) more detailed process representation, (2) larger spatial domains, (3) finer spatial and temporal resolutions, and (4) reduced uncertainty and improved predictions. We should also see beyond hydrological or hydraulic modelling and consider integrating our models into a cross-disciplinary context to be coupled with ecosystem functions and services, decision-making, and/or bio-economy (Huttunen *et al.* 2021; Lötjönen *et al.* 2021). Our hydrological models and their output need to be more user-friendly, enabling better interaction with stakeholders with less hydrologic knowledge. Additionally, models should be

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associated with the statement of uncertainty using an ensemble modelling approach and greater interactions between the user, the model, and the modeller (Singh 2018).

What do we need to do?

To enable Nordic societies to adapt, we need to foster new technological approaches, engage in interdisciplinary research efforts, and bring novel hydrological knowledge to stakeholders (Figure 2). To do this, we need to have clear national policies and roadmaps for improving hydrological infrastructure and ensure funding for high-quality hydrological education. Increased collaboration is encouraged, for example, by online, net-based courses combined with joint fieldwork or intense teaching weeks across universities. The Nordic hydrological community is encouraged to utilize newly available tools and approaches as well as to develop the hydrological science further in a joint effort.

4. THE NEED FOR A COMPREHENSIVE SYSTEM WHICH UNDERSTANDS AND CHALLENGES TRADITIONAL HYDROLOGY AND GUIDES TOWARDS CROSS-DISCIPLINARY APPROACHES

Hydrological understanding and processes are essential information for many scientific fields. In the 21st century, the hydrological community should aim to achieve more comprehensive system understanding and solve environmental and societal problems and challenges alongside other disciplines. An important task is to link ecosystem functioning with the critical components of our water cycle. Close collaboration with the climate community to improve the representation of hydrological processes in land surface models ultimately leading to improved climate projections is also needed. Improved integration between hydrological analysis, mapping, modelling, and practical management is needed to find a better balance between water usage and protection targets. Integrated ecosystem–scale hydrological approaches are essential in the future to sustain biodiversity, optimize carbon sequestration, and develop natural-based solutions in water management.

Water is critical for societies and humans, and social–hydrological approaches are needed to solve conflicts between human water use and ecosystems needs. To accomplish these tasks, we need to open our minds to cross-disciplinary collaboration to better understand processes and consequences (research and educate), develop our monitoring network to allow the detection of rapid changes and use new knowledge when modelling to allow for society and ecosystem adaptation. Again, all of this hydrological information and how it is used are essential for maintaining the livelihood of the Nordic countries.

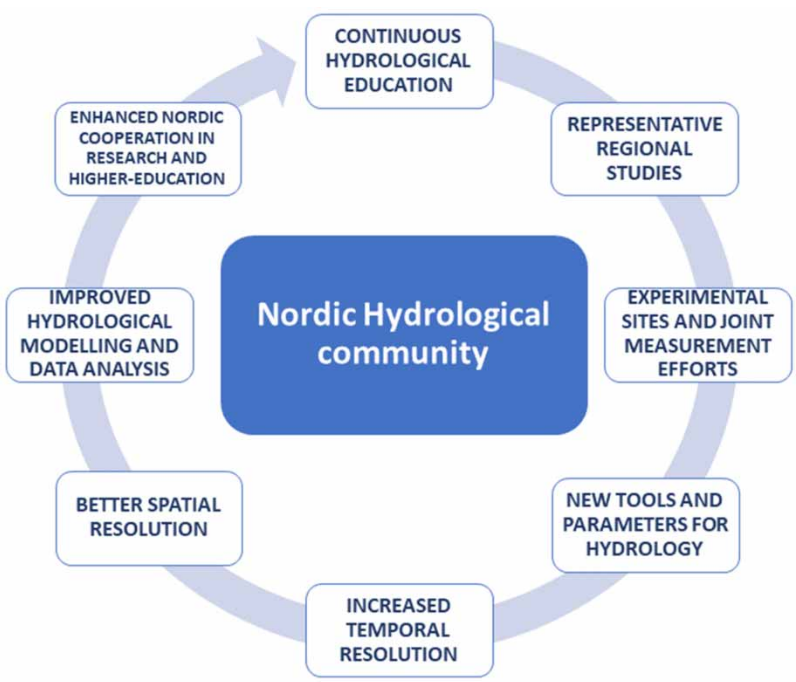

Figure 2 | Conceptual graph highlighting new technology possibilities for hydrological use.

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We need to identify new societal needs along with a better understanding of the limits set by nature in hydrological analysis, monitoring, and water usage. For example, river regulation has traditionally been dominated by electricity production and flood protection, whereas modern society today also considers recreational aspects and other river corridor usages. Water is not just a resource but an invaluable component in the support of biodiversity and carbon-rich ecosystems as it improves the resilience of nature and humans to a changing climate. The hydrological community should also adopt messages from the Bern convention and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) relating to biodiversity and the United Nations (UN) focus on restoring ecosystems. The messages from these actions should guide us in planning the sustainable use of water resources and encouraging greater use of our knowledge of hydrology and cross-disciplinary cooperation to provide the foundations for the restoration of water systems such as wetlands and river regulations.

Land use is one of the most influential human interventions in Nordic catchments, causing direct and nonlinear changes to the hydrological cycle and responses. Traditionally, hydrologists have mostly focused on the local and short-term effects of land-use change to meet human needs. However, we should be increasingly concerned about human-made long-term hydrological changes and how the changed hydrology then generates secondary human reactions (Sivapalan 2019) or impacts ecosystems in a longer perspective. This stresses the need for long-term observation networks and a willingness to ask the right questions in order to fully understand long-term changes. Long-term monitoring has shown its importance in identifying thresholds and unexpected nonlinear responses, for example, revealing the legacy of peatland drainage in Finland and Sweden (Nieminen *et al.* 2018), nutrient stores in soils, or climate change overriding actions done in water protection. The combined use of new technologies and long-term monitoring enables the detection of new unknowns and explanations, which can then be directly transferred to support sustainable water use. We should have a specific focus on conserving our soil resources using hydrological understanding, for example, to support improved carbon sequestration in farming.

5. OUR VISION FOR THE NORDIC HYDROLOGICAL FRONTIER IN THE 21ST CENTURY

Nordic hydrological society should adapt and renew in the 21st century and find societally important frontiers and ways forward. In our commentary, we have pinpointed new possibilities and have suggested the next steps needed. Providing a common direction is hoped to increase awareness, and thus accelerate progress not only in the hydrological community but for society at large. We hope that our vision and the opportunities identified will provide ideas and inspiration for assisting in the long-term development of the Nordic hydrological frontier.

An improved understanding of the role of thresholds, tipping points, and other nonlinear hydrological processes is central for assessing the consequences of future environmental change. Detecting, understanding, and predicting such responses and changes require improved empirical studies and evaluation tools that go well beyond the current approaches. A prerequisite for understanding and predicting future changes in the hydrological cycle is a good understanding of the processes controlling it currently. The least understood components are evaporation, transpiration, and interception losses, either from rain or snow. As the climate continues to warm, precipitation is projected to increase, and so is evaporation. The net effect on the hydrological cycle is highly uncertain with potentially large impacts on water management and sectors like the hydropower sector.

New data are central for new knowledge, and novel technology facilitates both higher spatial and temporal data collection and the easier transfer of data. Infrastructures that combine field measurements from a multitude of disciplines in the same catchment provide a valuable source for interdisciplinary studies. A few such Nordic examples currently are Krycklan in Sweden (Laudon *et al.* 2021), Pallas in Finland (Marttila *et al.* 2021), the River Skjern in Denmark (Jensen & Refsgaard 2018), and Finse in Norway (Finse EcHO 2021). A further improvement would be a joint Nordic network of sites with easy data sharing, knowledge exchange, and collaboration. The Nordic countries have one of the most extended time series of hydrologic and climatic data, collected over the last centuries, which should be exploited to generate comparisons of hydrological regimes, signatures, and effects from different drivers across the heterogeneity of the Nordic landscape. Although hydrological studies using large numbers of catchments exist for particular countries (e.g., Veijalainen *et al.* 2010; Jaramillo *et al.* 2018), hydrological assessments combining data from several Nordic countries are more rare (e.g., Tallaksen & Hisdal 1997). Such studies are important to understand the large-scale context of the Nordic region or even viewed in a larger European context (e.g., Stahl *et al.* 2010). Creating a common Nordic and Baltic reference dataset of near-natural catchments for analyzing the effect of climate change on hydrology would be a great benefit to the

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hydrological community and society at large. Such efforts go well beyond what one research group can achieve and require a well-coordinated infrastructure that can support and combine the collection of critical long-term monitoring data, provide large sets of ancillary empirical information, and host complementary long-term/large-scale experiments that are crucial to achieving a mechanistic understanding of ecosystem responses to environmental change.

Coordinated Nordic hydrologic scientific efforts are needed to advance knowledge development and monitoring. There is a tremendous amount of new sensor technologies at the point and spatial scale, combined with big data analysis and machine learning methods available for scientific and stakeholder needs. New empirical data feed to support the improvements of predictive models vital for future projections in the short- and long-timescale of our hydrological cycle. Hydrological processes will play an increasingly important role in meeting the great challenges that Nordic countries will face in the 21st century, such as water security, ecosystem security, food security, energy security, sustainable development, and the use of new concepts and approaches such as water–food–energy nexus. We propose the following focus areas and opportunities for 21st-century Nordic hydrology:

- Continue to highlight the importance of hydrology in society by being active in public discussion, searching for ways for collaboration, and fostering cross-disciplinary science.
- Acknowledge the importance of long-term monitoring and national research infrastructures that combine field measurements from a multitude of disciplines in the same catchment.
- Critically review the existing hydrological monitoring network and utilize new technological and analytical innovations.
- Improve open data towards easy data sharing and more comprehensive use of open data platforms.
- Initiate model intercomparison projects with participants, data, and models from several Nordic and Baltic countries addressing different research questions.
- Use already available emerging and current technologies and big open data to solve current research questions.
- Constantly develop hydrological education to provide lifelong learning opportunities at all educational levels.
- Enhance Nordic cooperation in research and higher education.
- Improve networking and contributions to global hydrology research.
- Work towards governmental bodies and research organization to increase awareness and funding opportunities for hydrological research.

To achieve these goals, we need collaboration among Nordic hydrological colleagues and joint efforts in education, datasets, or undertaking intercomparison of national hydrological models. New digital tools and platforms offer many possibilities for this, we just need the willingness to take the first steps forward. We challenge the Nordic hydrological community to continue discussions about the future of Nordic hydrology.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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