

Small water supplies in Nordic countries: climate change effects, risks and contingency planning

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ABSTRACT

Climate change (CC) is altering the working conditions for water suppliers. To enhance preparedness, CC has been emphasised in the risk-based approach (RBA) and water safety planning guidelines. We studied how the RBA approach has been applied in small water supplies in the Nordic countries to mitigate CC related risks and impacts. We interviewed small water supply operators and authorities in each country, followed up by government-level queries on guidelines and legislation. We found that small water supplies have experienced consequential incidents associated with a changing climate. Heavy rains, drought, changes in cold climate hydrology, and landslides were most frequently mentioned. Many of the supplies, however, had not experienced any effects, possibly because groundwater is the main water source for small water supplies in the region. Importantly, the effects of a changing climate were scarcely discussed, and CC receives limited or no attention in governmental guidelines. However, in Norway, the CC preparedness was analysed on a municipal level, and Finland and Sweden have tools for CC preparedness, but separately from the RBA. Small suppliers are concerned about over-burdening with multiple guidelines, frameworks, and tools. Therefore, we conclude that CC would be best addressed through integration into RBA and water safety planning regulation and implementation.

Key words: Arctic, climate change, national water supply guidelines, risk-based approach, small water systems, water safety planning

HIGHLIGHTS

- Study of risk-based approach on climate change (CC) and small water supplies in Nordic countries
- Environmental effects of CC were recognised, but effects on the water supply were scarcely discussed.
- National guidelines lacked the CC theme.
- Recommend including CC in guidelines and regulations for small water supplies.

1. INTRODUCTION

Extreme weather, associated with climate change (CC), may affect water resources and drinking water supplies. Adverse effects arise from temperature extremes, intense rainfall, landslides, flooding, coastal erosion, saltwater intrusion due to rising sea levels, drought, storms, wildfires, loss of permafrost, loss of glaciers and associated meltwater flows, reduced

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river flows and lake or groundwater levels, and microbial growth, e.g., blooms of cyanobacteria (Kellerer-Pirklbauer *et al.* 2012; Seneviratne *et al.* 2012; Patton *et al.* 2019; Zepernick *et al.* 2023; Grimes *et al.* 2024). The consequences of these events include destruction of infrastructure assets, interruption of drinking water supply, contamination of water resources and supplies (Rosenbom *et al.* 2010; Ma *et al.* 2016), and disease outbreaks (Curriero *et al.* 2001; Cann *et al.* 2013).

The eight Nordic countries are Denmark, Finland, Iceland, Norway, and Sweden, together with three self-governing nations, the Faroe Islands and Greenland under the external sovereignty of the Kingdom of Denmark, and the Åland Islands under the sovereignty of Finland. In the Nordic region, climate conditions are changing faster than global averages, especially in the Arctic (Zhou *et al.* 2024). In Norway, annual precipitation has increased by 20% in the last hundred years (1910s–2000s), and intense rainfall events and landslides have increased in frequency (Hanssen-Bauer *et al.* 2009). Increased precipitation is predicted across northern regions by the Intergovernmental Panel on Climate Change (IPCC 2018). In the Icelandic mountains, landslides have been traced to the melting of permafrost (Saemundsson *et al.* 2018; Morino *et al.* 2019). Porous postglacial near-sea areas of Iceland will be at high risk of saltwater intrusion due to predicted sea rise (Egilsson & Stefánsdóttir 2014). Some adverse effects are indirect: temperature rise will prolong the growing season. This will affect agriculture – likely increasing use of fertilisers and pesticides and consequential aquifer contamination. It will likely also lead to blooms of harmful cyanobacteria (Gobler *et al.* 2024). Similarly, extreme rainfall can overload wastewater treatment facilities and degrade treatment efficiency – increasing sewage discharge risks and the likelihood of water source contamination. Changes in hydrology can also drive intrusion of contaminated surface water into groundwater, and flooding of water supplies, e.g., during storm surge in low-lying land close to the coast.

Water supply management approaches considering CC in the Nordic region have been developed and studied in previous years from the national to local level. Refsgaard *et al.* (2013) approached Danish national water management, including water supply, from the perspective of uncertainty reduction through knowledge increase and discussion on CC. On a city level, Rudberg *et al.* (2012) studied the adaptive space of Stockholm (capital of Sweden) water supply and sanitation for CC, also emphasising knowledge, but also refer to rules to pinpoint the requirement for adaptation. Boholm & Prutzer (2017) recalled in their semi-structured interview study of Swedish experts that the lack of political saliency is also an obstacle for developing robust CC adaptation strategies. Mohammed & Seidu (2019) implemented a quantitative microbial risk assessment model for selected Norwegian drinking water plant processes for future climate-driven risks from surface water sources. Considering quantitative issue studies, Lindqvist *et al.* (2022) presented a socio-hydrological model for Fårö Island, Sweden, to avoid groundwater depletion for future decades in different climate scenarios.

Small water supplies are defined in the Nordic countries as those with fewer than 500 consumers or serving less than 100 m³ water/day. They are the most abundant water supply by number in the Nordic region, though serving only approximately 10% of inhabitants (Gunnarsdottir *et al.* 2020b; Maréchal *et al.* 2022). Geography and history explain some of this abundance. Parts of the Nordic countries are sparsely populated, with long distances between small communities, enhancing independent water supplies. In previous decades, some of the countries had incentives or cheap loans to build community wells and/or to start community-level water supplies. Generally, their management differs from that of larger supplies in often having few and/or voluntary staff, being user-owned or cooperatives, and applying less processing of water. In most countries, they have less comprehensive monitoring requirements (e.g., sampling usually yearly in Finland and Iceland).

These factors are consequential. For example, Hyllestad *et al.* (2023) concluded based on a literature review of publications from the Nordic countries and the Arctic that waterborne outbreaks during extreme rainfall in Norway were directly related to less disinfection of water in small supplies. Similarly, Gunnarsdottir *et al.* (2020a) found that all but 1 out of 15 registered waterborne outbreaks (1998–2017) in Iceland were in small water supplies and were frequently associated with use of reserve water resources because of drought. Skaland *et al.* (2022) concluded that impacts of CC on drinking water in Norway might especially affect small water supplies, but the lack of data from the small supplies made this conclusion uncertain.

Adaptation to anticipated climate has long been emphasised. Extreme weather events are emphasised as hazardous events to be planned for in the World Health Organization's (WHO) drinking water guidelines and associated water safety plans (WSP, WHO 2017); and risks stemming from CC are highlighted in the European Union Drinking Water Directive (EU DWD, Directive 2020/2184). However, studies for adaptation in practice and at scale are sparse and fragmented in the current scientific literature (Harper *et al.* 2020), especially considering small water suppliers. This study aims to fill this gap from the Nordic perspective.

To increase knowledge on CC adaptation, especially in at-risk small water supplies, we explored associated perceptions, experiences, regulations, and planning through stakeholder interviews across the Nordic countries. This study is part of a

large Nordic project on improving drinking water quality in small water supplies with an emphasis on risk-based approach (RBA) initiated by the new EU DWD and higher non-compliance with microbes in small water supplies. We have studied the current conditions and interviewed stakeholders about challenges and possible solutions in improving drinking water quality. Previous results are presented in [Gunnarsdottir et al. \(2020b, 2023\)](#) and [Bayona-Valderrama et al. \(2024\)](#) and analysis of lessons learnt on COVID-19 effect and the surveillance and inspection challenges are in process. The following research questions were related to CC and are studied here: (1) What are the views of the small water suppliers and regulators regarding the consequences of CC now and in the future? (2) What is the regulation concerning CC adaptation in Nordic countries – in particular for the smaller supplies?, and (3) How are the plans to adapt to CC applied and are there constraints for smaller water supplies inhibiting adaptation?

2. METHODS

We set out to explore progress with adaptation to future climate in the Nordic region, especially for small water supplies, as outlined in our logical framework, from directing documents and legislation to what has been implemented ([Figure 1](#)). EU directives are an overarching legislation in the region: Åland, Denmark, Finland and Sweden all follow the EU DWD as part of the EU, which is also the case for Iceland and Norway (with the exception of Svalbard) as members of the European Economic Area (EEA). As exporters of processed seafood, the non-EU members – the Faroe Islands and Greenland – are interested in meeting the EU DWD requirements. We interviewed key stakeholders in the eight Nordic countries, about (i) perceptions and experiences of environmental effects of CC among small supply system operators and regulators; (ii) the expected impacts of CC to small water supplies; (iii) how CC adaptation is addressed in national legislation and regulation, and (iv) how CC is reflected in guidelines for risk-based approaches and their implementation in practice.

This study was a part of a larger qualitative study on how to improve drinking water quality from small water supplies in the Nordic region, as mentioned earlier. We studied water quality status, a preventive RBA in water safety management, and training in how to secure drinking water quality. Overall methods are presented in [Gunnarsdottir et al. \(2023\)](#).

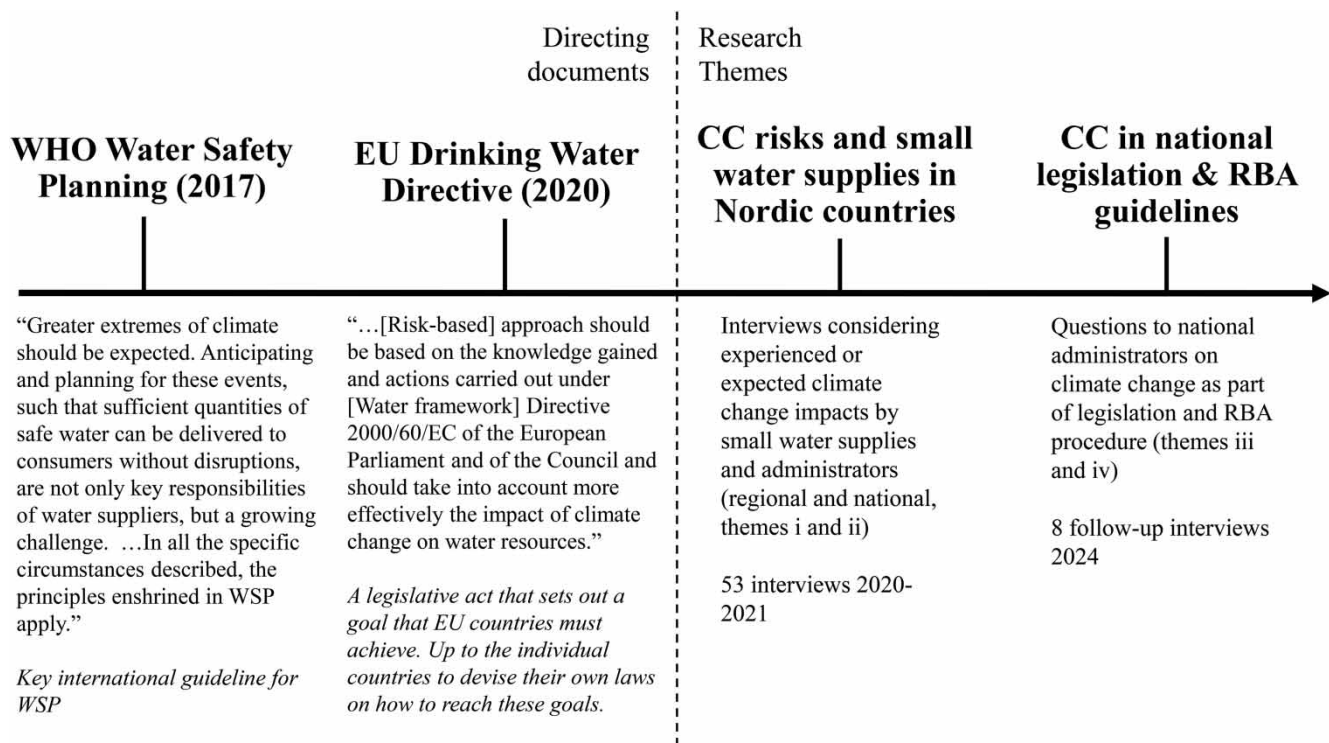


Figure 1 | The study logical framework, from directing documents (role of each in italic) to research topics, and connections to interview themes.

In each country, key personnel from small water suppliers ($n = 27$), associations of water suppliers or similar ($n = 5$), and government authorities, including surveillance agencies and ministries ($n = 21$), were identified for a total of 53 initial interviews. Through these interviews, information concerning water quality challenges in small water supplies, experience, and hindrances to implementing RBA, and possible solutions to improve the situation was collected.

Interviewees were sent an introduction to the project and an interview outline when they had agreed to participate, and both interviewees and supplies were anonymised. Interviews were performed in the local languages during 2020–2021 and were conducted mostly via a web-based conference platform or by face-to-face meetings or by telephone. Interviews lasted on average 1 h and were transcribed. We analysed themes appearing in each category of the interview outline and made a codebook including the theme, explanation and direct code. Codebooks were collated from local language transcripts manually by a country-specific researcher. Then, codebooks for each country were translated into English to facilitate inter-country pooling. For the present work, we searched the codebooks for all climate and extreme weather mentions and analysed these alongside the CC-specific questions.

For CC, the direct questions were ‘Has climate resilience of water supplies been evaluated in your country and if so, what are the main challenges related to safe water supplies, that you know of?’, ‘Are there any interruption or risk to supply of water in your area e.g., scarcity due to drought, risk to water quality due to heavy rain, or other?’, and ‘Is there a contingency plan for action in place in case of non-compliance incidents?’

The status of implementation of CC risk assessment in the RBA was investigated in late 2023. In early 2024, we conducted follow-up interviews with local administrators and ministry representatives, asking ‘Is climate change mentioned/taken into account in water supply/water resources legislation or regulations of your country. If yes, how so (reference)?’, and ‘Is climate change included in your countries RBA?’. In total, eight follow-up interviews, one for each country, were conducted.

3. RESULTS AND DISCUSSION

Based on the questionnaire codebook of the 53 interviews, the experienced and expected effects of CC were collated (Figure 2). The main environmental phenomena mentioned as having been experienced were heavy rains, landslides, flooding, and drought. Hydrological changes connected to cold climate conditions (such as snow conditions, melting glaciers) were reflected in several interviews. Mentions of experienced effects were evenly distributed between administrators and water supply representatives. However, expected impacts on water supply due to CC were mentioned less frequently (Figure 3).

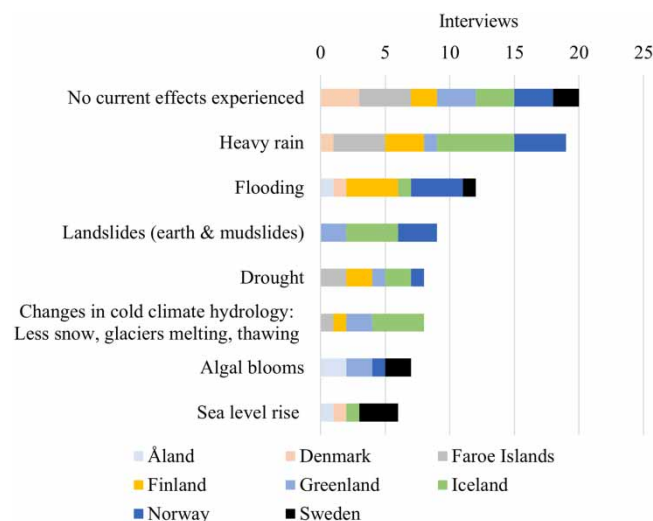


Figure 2 | Experienced or expected climate change-related environmental effects mentioned by operators in small water supplies and administrators in Nordic countries. Frequency by number of mentions from 53 interviews.

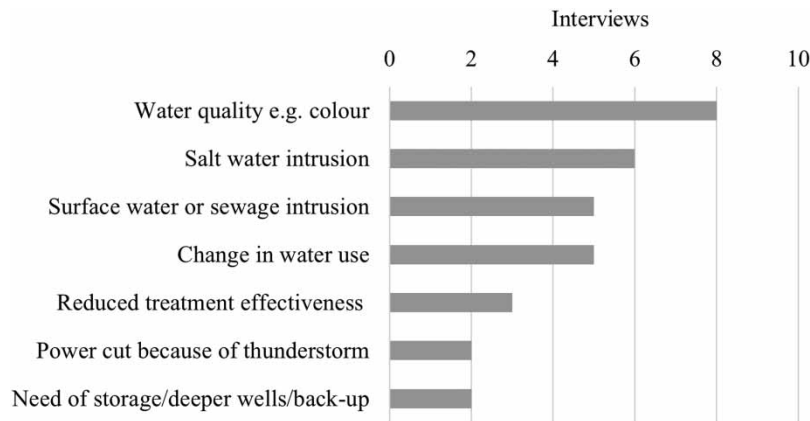


Figure 3 | Expected effects on water supplies directly associated with climate change mentioned by operators of small drinking water supplies, system regulators and inspectors in Nordic countries. Frequency by number of mentions from 53 interviews.

3.1. Several small water supplies had not experienced environmental effects associated with CC

Excerpt from the interviews: *‘There has been no, to my knowledge, any hint of climate change impact on our water supply. I do not know if climate change could pollute groundwater. I do not know how it could happen. One can of course say that if one has not protected the surroundings around his waterworks well enough, then it could well cause some pollution if it suddenly becomes ‘heavy rain’.*

Many interviewees mentioned that they had no experience with CC effects. Such responses were mainly from small water supplies (15 of 27 interviews) compared to administrators (5 of 26 interviews). In every country, except for Åland, at least one respondent indicated that they had seen no effects of CC.

Most small water supplies in the study region use groundwater as their water source (Figure 4 (a) and (b), updated from Gunnarsdottir *et al.* 2020b). Quantitatively, the abstraction rates of small water supplies are generally small compared to aquifer volumes and therefore abstraction might not be so prone to aquifer storage variance. Qualitatively, groundwater is a protected source of water because the soil and other geological layers function as covering and filtering layers, reducing polluting effects unless contamination is direct. For this reason, especially where aquifer recharge is slow compared to storage volume, groundwater quality deterioration is slow and difficult to reverse. Thus, it is of concern that changes in the hydro-geological regime in the region have been observed (e.g., Jyväsjärvi *et al.* 2015; Nygren *et al.* 2021), even though the effects have not necessarily affected the water supplies.

3.2. Observed local environmental effects associated with CC

CC-associated effects vary with the geographical origin of the interviews. This is unsurprising because Nordic geography and climate conditions vary widely from mountains to plains, oceanic to semi-continental, and from Arctic to Hemiboreal.

3.2.1. Heavy rain and flooding

‘It feels like more extreme rain now compared to the past.’

Of all experienced effects, rain and flooding were most mentioned. They affect water quality directly and through intrusion into wells. Most mentions were from the Faroe Islands, Iceland, and Norway, which have oceanic climates and the highest precipitation of the region.

Even though the changes in precipitation are more uncertain than those in temperature in CC models (O’Gorman 2015), more frequent extreme precipitation events are expected in Nordic regions (Lind *et al.* 2023). Interviewees most-mentioned heavy rainfall, which has caused challenges, and the rainfall seems to have changed over time. In the application of RBA, this is important because extreme rainfall events are a key contributor to waterborne outbreaks in the region (Kløve *et al.* 2017).

In Norway, for example, several of the recent floods have occurred due to sudden heavy rain or sudden melting of large amounts of snow. In some cases, water supplies have been affected by flooding of pumping stations, by water contamination,

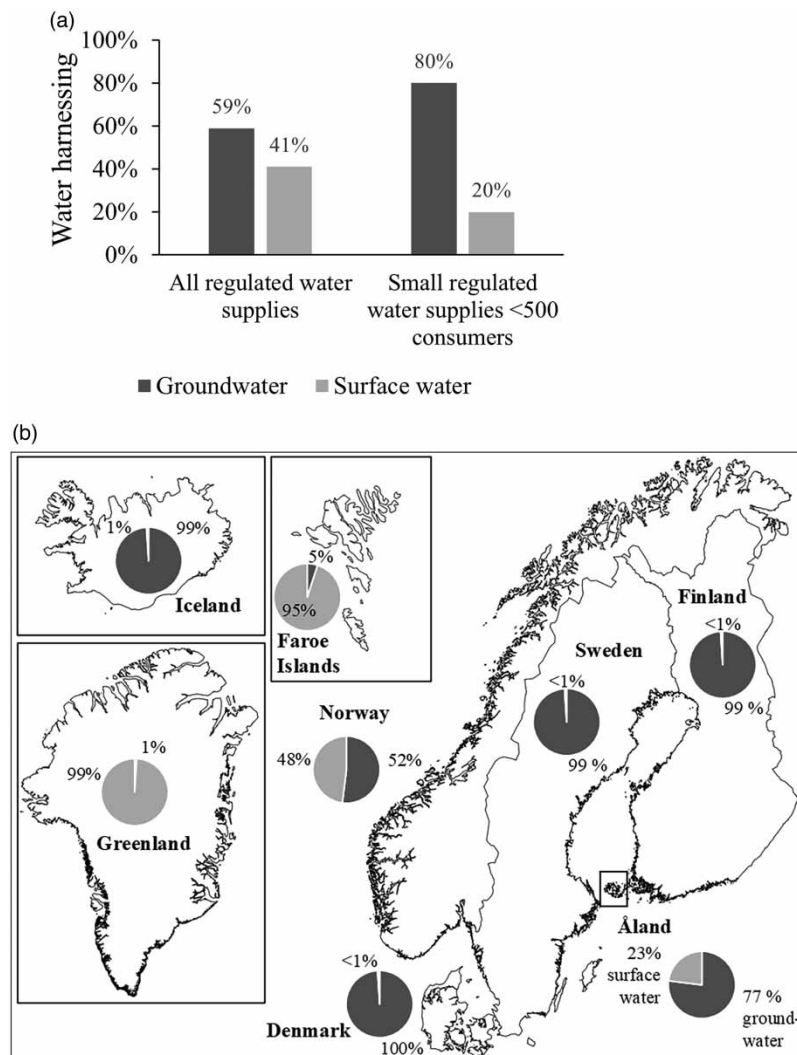


Figure 4 | Water harnessing in eight Nordic countries (a) all countries and (b) water source in small (<500 consumers), regulated water supplies by country (based on data from Gunnarsdottir *et al.* 2020b, updated by the authors). Maps of different regions are not in scale to each other.

and in one case by transformer shut-off, causing the water system to close down. Nevertheless, the general impression is that in Norway, water suppliers have maintained their services due to preventive implementation of hygienic barriers, including enhanced disinfection (Skaland *et al.* 2022).

3.2.2. Landslides

'Flood and landslide are the biggest problems in our area and every supply should have a reserve drinking water source, but not all have that.'

Landslides related to CC were mentioned in the interviews, especially in mountainous regions (Figure 2). In Iceland, warming is causing permafrost thawing and triggering landslides (Czekirda *et al.* 2019). A risk assessment of 179 water intakes in mountainous North-East Iceland estimated that 40 (22%) are at medium to high risk of damage from landslides (Gunnarsdottir *et al.* 2019). In Greenland, landslides have caused tsunamis and the evacuation of villages (Svennevig 2019). Nevertheless, there has as yet been no overview of the future risk of similar incidents and their potential impact on water resources.

Several landslides have destroyed water intakes in Iceland following heavy rain in mountainous areas where small water supplies are mainly gravity-fed from mountain slopes. In July 2010, large landslides occurred in Búlandsdalur, destroying the intake for the small town of Djúpavogur. Subsequently, faecal bacteria, including *Campylobacter*, were detected in drinking water. At the end of June 2014, a landslide affected two water sources in the north: Vatnsveita Árskógssandur and Hauganes, where faecal coliforms were subsequently detected in the water supplies. In both cases, residents had to boil the water for several weeks. The same heavy rainfall event caused landslides from a mountain above a farm at Vellir in Svarfaðardalur, which destroyed the farm's water source. (Gunnarsdottir *et al.* 2019). Similarly, in July 2024, a landslide in northern Norway blocked a river that is impounded for drinking water, leaving 200 households without water (Wilhelms *et al.* 2024).

3.2.3. Drought

'Everything is soon forgotten when it rains again after a drought-period.'

'Four years ago, there was drought and farmers were without water. One farmer had just installed a new well intake for a spring and it dried up.'

In some of the cases mentioned in the interviews, the water supply depended on reservoir water storage, and drought had dramatically decreased the level of the source water. Such issues can be particularly severe in supplies that are island-operated, being in many cases dependent on a single source (not only a single source type) and lacking emergency alternatives (such as connection to a nearby system).

In rural regions, severe effects had been experienced with droughts increasing agricultural water use. Similar to extreme rain, the extreme dry events – including but not restricted to drought – should be considered carefully in the RBA: What are the consequences of a prolonged dry season to the water source or water usage by the serviced community? In Arctic conditions, there is also another dry circumstance not mentioned in interviews that should be taken into account: cold-season precipitation accumulates as snow, and no groundwater recharge occurs. CC might alter this in other ways (see cold climate hydrology, below).

During dry conditions, wildfires contaminate drinking water as significant amounts of diverse contaminants are released, which can pollute pristine environments (Muir and Galarneau 2021) and contaminate water supplies. Wildfires are becoming more frequent because of CC, more so in the northern hemisphere, as the landscape has become increasingly overgrown by shrubs and trees due to milder temperatures (Fernandez-Anez *et al.* 2021). Gosden *et al.* (2022) studied wildfires in western Greenland for the period 1995–2020 and identified 21 tundra fires, most of which occurred in July or August and during warm, dry weather periods. A case study of a wildfire in May 2021 after a long period of drought on the drinking water catchment of the capital area in Iceland showed that several polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) had reached the groundwater source soon after the fire (Gunnarsdottir *et al.* 2024).

3.2.4. Changes in cold climate hydrology

'We can feel the climate change. When the ice is melting, we get water from the well, and we are getting it sooner (in the spring) now.'

The coldest regions of the study area are experiencing consequences of the changes in the cryosphere. Greenland and Iceland had experienced changes in glacier melt and frost thaw, and their consequences were conspicuous in answers from water suppliers. These align with previous studies, for example, studies in the Arctic region on permafrost thaw effects on infrastructure (Medeiros *et al.* 2017); increasing landslide risks (see below) and with the release of nutrients and organic matter leading to excessive algae growth in surface water sources and release of microbial contaminants (Ayala-Borda *et al.* 2021).

Elsewhere, snowpack changes were mentioned as altering water source recharge patterns – in Finland and Sweden, the snow cover period is becoming shorter and changing groundwater conditions (Nygren *et al.* 2021). Affected regions should update their RBA because groundwater storage patterns might critically change in the coming decades.

The Svalbard archipelago is sensitive to CC due to the relatively low altitude of its main ice fields and its geographical location in the high latitude North Atlantic. Increasing summer temperatures, above the melting point, have led to increased glacier melt. There is only one water supply in Svalbard, and its infrastructure and water source are already challenged by CC.

3.2.5. Algal bloom

‘Over the last couple of years, we have seen a clear change, with the most visible being larger and earlier algal blooms.’

In some parts of our study region, water supply relies on surface water reservoirs (river impoundments), because groundwater is inaccessible or insufficient, and river flows are insufficient to sustain the supply (Figure 4(b)). These include the majority of regions in Åland and Greenland, where algae were mentioned as a growing problem. River impoundments are a major source of water for both Åland and Greenland. This is because parts of Åland consist of rocky islands with little land area. In Greenland, many communities are located similarly on small rocky islands, and the country faces the combination of permafrost and surface bedrock, limiting groundwater use for large and small water supplies alike. Small water supplies in Sweden generally use groundwater as a source, and algae were mentioned by one administrator as a regional issue for larger water supplies. In Norway, small supplies use both groundwater and surface water, and a few surface water sources have problematic levels of cyanobacteria (Norwegian Water Association 2022). However, these organisms are detected in an increasing number of lakes in Nordic regions due to rising water temperatures and runoff from the surroundings with higher concentrations of nutrients (Urrutia-Cordero *et al.* 2016). Indeed, observations of cyanobacteria in 198 lakes located in all regions of Sweden during 1995–2018 showed higher occurrences in the warmer and more heavily populated southern regions compared to northern regions (Li *et al.* 2021). These factors will, therefore, necessitate preparedness for harmful cyanobacteria blooms, and these will extend northwards.

3.2.6. Sea level rise

‘Most worrying is the saltwater intrusion.’

Issues regarding rising sea levels were mentioned by water suppliers located close to shorelines. Low-lying countries, such as Denmark, are especially concerned about this, leading to increasing saltwater intrusion into groundwater aquifers.

Globally, saltwater intrusion is cited as a key problem for groundwater-based water supplies in shoreline regions (e.g., Barlow & Reichard 2010). However, the local effects due to sea level rise are complex (Chang *et al.* 2011; Rasmussen *et al.* 2013). Proper adaptation of groundwater abstraction, including adjustment of volumes to local conditions, is critical to these water supplies to avoid excess seawater in their wells.

3.3. Representability of the interview results on the environmental effects

The interviewee responses we document have parallels with the following previous national studies and reports. Interestingly, our results can be compared to those of a national survey study in Finland by Meriläinen *et al.* (2019) on CC effects on water supply and sanitation. This study received responses from 695 water utilities (from the total of 1,100 utilities in Finland). Of these, 558 were from small- and medium-sized utilities producing water quantities of less than 1,000 m³/day, and 95% were from groundwater-based systems. The utilities were asked about expected future weather and CC. Most mentioned were heavy winds, mild winters, and heavy rainfall, which align with our results, except for heavy winds. In Sweden, the handbook for climate adaptation of drinking water supply by Livsmedelverket (2019) lists similar effects as examples for water supplies to consider. A Swedish public inquiry for safe water supply (SOU 2016) listed several preventive measures for water supply adaptation to CC. These highlighted technical analyses of temperature, precipitation, hydrologic regimes and water consumption patterns, and the need for legal and administrative support on national and regional levels. Some have been implemented, but much remains to be done, particularly for small water supplies.

Even though Finland and Sweden represent only a part of the climatic and geographic regime in the Nordic region, the similarities in the study by Meriläinen *et al.* (2019) and Swedish handbook strengthen the basis for recommendations to enhance preparedness; especially in the Arctic region, where the temperature increase is on a at least three-fold pace from global average (Rantanen *et al.* 2022; Zhou *et al.* 2024) – which accelerates changes in conditions and effects (Figure 3).

3.4. Expected impacts on water supply mentioned in the interviews

The effects of CC on water supply operation were less discussed in the interviews compared to the environmental effects. The mentioned topics were, however, logically connected to (i) storms through power outages; (ii) changes in source water altering water quality, saltwater intrusion near-sea or other surface water source intrusion to wells, or needed changes in water

treatment, and (iii) changes in source quantity requiring in water consumption changes or enhancement of water sources such as deeper wells, new reservoirs or supplementary sources.

While effects were less discussed in the interviews, themes again reflected the earlier mentioned study by Meriläinen *et al.* (2019), the climate handbook by Livsmedelverket (2019) and the Swedish public inquiry (SOU 2016). However, the Swedish handbook has a comprehensive list of effects for water supplies to consider, including, for example, wildfire risk, brownification of surface waters, qualitative changes in groundwater due to warmer soil, corrosion, and increased microbial activity in networks.

3.5. Contingency plans for CC are generally lacking

Even though water suppliers broadly acknowledged changes in conditions due to CC and, to some extent, their potential impacts, a few interviewees mentioned contingency plans reflecting CC. In fact, eight interviewees specifically mentioned having no such plan, and only three (from Norway and Sweden) mentioned existing preparedness for future climate. The Swedish mentions are probably attributable to the climate handbook (Livsmedelverket 2019), which describes steps towards preparedness. In Norway, on a national level, 75% of municipalities have made decisions on climate adaptation; however, allocation of financial and human resources to this work seems to be lacking. In total, 60% of the municipalities in Norway have implemented some measures against CC (Arnslett & Skjeflo 2023).

Our results indicate that current RBA processes lack incentives and procedures to induce actions in small water supplies in the Nordic countries on the impacts of CC. This lack of preparedness is worrisome in the context of accelerating changes in conditions.

3.6. A gap between directing documents and national guidelines

Authorities from all the studied countries provided information on the legislation and national RBA guidelines. None of the replies included or mentioned CC. The answers from Denmark and Greenland indicated that, because water supply planning and risk assessment should be holistic, sustainable, and pay attention to long-term changes, CC impacts, and adaptation were implicit. In Finland, the national WSP tool was updated in 2024, including enhanced extreme weather effect estimation. However, CC as a theme was not mentioned. A project started in 2024 by the Finnish Environmental Institute to create a risk assessment tool for climate impacts on water supply, and aimed to connect with WSP tools where possible. In Sweden, the handbook of CC (Livsmedelverket 2019) has a step-by-step guide for climate risk assessment for water supplies, but it is not integrated in the RBA approach in Sweden. In Norway, the civil protection act guides municipal level RBA, including events resulting from CC (Act relating to Norway's climate targets 2018), a ministerial white paper states that CC must be included in water supply vulnerability analysis (Norwegian Ministry of Climate and Environment 2013), and water supply RBA guidelines, while omitting mention of CC, it points to heavy rain and milder winter climate (Mattilsynet 2021).

Our study revealed a gap between the directing documents (e.g., the WHO guidelines and the EU Drinking Water Directive) and national implementation. CC is referred to substantively in the guiding documents, but at the national level, holistic approaches are emphasised and CC is relegated to one of several factors to be considered, but not separately listed. In Sweden, and somewhat in Finland, there is a separate tool for climate risk assessment for water supplies. Despite these observations, CC consideration may be implemented in RBA for small water supplies (see Sections 3.2 and 3.4, on interview results). However, this raises the question whether water supplies would be more prepared for possible future impacts if CC were listed as a separate point in the RBA?

Parallel arguments and evidence concern contingency plans and WSP. Whether hazards and risks derived from CC are adequately addressed in either, without explicit specific guidance, and if not, whether separate contingency planning would enhance the resilience of small water supplies, are critical questions. Scenario exercises for CC impacts as part of WSP are reported to efficiently enhance readiness (Deere *et al.* 2017), and in Sweden, this is part of the handbook guidelines.

In other parts of our RBA interview research (Gunnarsdottir *et al.* 2023) an emerging risk was noted for RBA implementation: the small water supplies sometimes consider the RBA as additional paperwork, especially if no support is available. If climate risk assessment is separate from the RBA process – as in Sweden and possibly Finland – this might increase paperwork further. This risk could be decreased if the climate issues are discussed as part of the RBA process.

4. CONCLUSIONS

The small water supplies and authorities we interviewed had in many cases experienced or anticipated changes in environmental conditions – caused by CC, that will affect water supply. However, the effects of these changes on water supply were less well-considered, and they received little attention in RBA, in WSP and in contingency planning. This might result from CC being subsumed as one of several contextual factors without specific recommendations or guidance in associated guidelines.

To enhance the preparedness and resilience of small water supplies, we recommend incorporating CC into the RBA national guidelines and regulations. This is emphasised by WHO in its guidelines and by the European Commission in its Drinking Water Directive. In addition, ensure that the RBA guidelines are approachable by small water supplies. Scenario exercises may contribute to clarifying the CC part. Note that separate climate guidelines from the RBA might excessively burden small utilities with limited staff and encourage documentation over action, with the potential unintended consequence of hampering implementation.

Our study reveals the situation as it is experienced by and appears to be a small water supply management issue. Here, locally-specific conditions ('contextual factors') – such as whether the water source is groundwater or surface water, the climatic and the hydrogeological settings determine outcomes. Thus, the recommendations and guidance that we call for should be sufficiently relevant to be applicable in diverse contexts, and should be accompanied by guidance adequate to steer their application under specific conditions.

Small water supplies are disproportionately represented in the contamination cases. This global truism includes several Nordic countries. Improved preparedness of these small water supplies has the potential to both improve the management of risks arising from emerging climate and to enhance the protection of water safety and of health more widely.

Climate conditions in the North, including the Nordic countries, will change more rapidly than in other regions of the world. Anticipating and responding to the water supply challenges due to CC will enhance regional health and preparedness and yield new lessons that may assist other regions in their management approaches.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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