Impacts of climate change on drinking water and health in Norway: A narrative literature review

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Sammendrag

Effekt av klimaendringer på drikkevann og helse i Norge: en narrativ litteraturgjennomgang. Klimaendringer vil sannsynligvis medføre en økning av vannrelaterte sykdommer globalt, spesielt i Arktis. I Norge får ca. 90 prosent av befolkningen drikkevann produsert fra overflatevann. Et aldrende vanndistribusjonssystem er et økende problem, som kan gi økt risiko for påvirkning av drikkevannet under ekstreme nedbørshendelser. Imidlertid er kunnskapsgrunnlaget om eventuelle sammenhenger mellom klimaendringer og drikkevannsrelaterte helseutfall i Norge mangelfullt. Vi gjennomførte en litteraturgjennomgang for å vurdere hvorvidt det finnes holdepunkter for at vannbåren sykdom er assosiert med klimaendringer i Norge, samt identifisere kunnskapshull og behov for fremtidig forskning. Vi inkluderte fire av 37 publikasjoner i gjennomgangen, hvorav to var basert på historiske overvåkingsdata, og de to andre artiklene var utbruddsundersøkelser. Funnene fra overvåkingsdataene tyder på at vannbårne utbrudd og ekstrem nedbør hovedsakelig er assosiert med små vannforsyningssystemer uten desinfeksjon. Resultatet av denne litteraturgjennomgangen er begrenset av det lave antallet publikasjoner. Det er behov for flere studier som kartlegger mulige effekter av klimaendringer på drikkevannskvalitet og helse i Norge. En videreutvikling av dagens overvåkingssystemer for hendelser knyttet til vannforsyningskjeden vil kunne gi bedre datagrunnlag for risikobasert overvåking, varsling og kartlegging av hendelser som kan ha helsemessige konsekvenser.

Summary

Climate change is expected to increase water-related diseases globally, particularly in the Arctic. In Norway, most of the population is served drinking water produced from surface water. An ageing water distribution system is a growing problem, which represents risk factors during extreme rainfall events. However, the impacts of climate change on drinking water in terms of health outcomes in Norway are not well documented. We conducted a literature review to assess evidence on waterborne diseases attributed to climate changes in Norway, and to identify knowledge gaps and future research priorities. We included 4 out of 37 publications in the review, 2 of which were based on historical surveillance data, and the other 2 articles were outbreak investigations. The findings from the

surveillance data suggest that waterborne outbreaks and extreme rainfall are mainly associated with small water supply systems without disinfection. The outcome of this literature review is limited due to the low number of publications identified. Further studies are needed to provide information on the impacts of climate change on drinking water and health in Norway. A further development of the current national surveillance systems for incidents affecting the water supply chain could provide a better data base for risk-based monitoring, notification and mapping of incidents that may have health consequences.

Introduction

Climate change is projected to impact hydrological systems (International Panel of Climate Change, 2022). In general, the effect of climate change is expected to increase the contrast in precipitation between wet and dry regions and between wet and dry seasons, although there will be regional exceptions (Hoegh-Guldberg, 2018). Climate change may affect human health in several ways, including water-related diseases (US Centers for Disease Control and Prevention (CDC), 2022, Romanello et al., 2021), and even small changes in the water cycle and availability of water may have substantial impacts on diarrheal diseases (Naghavi et al., 2017). In addition to mortality, climate change may have several other impacts, including impaired growth and cognitive development, and an increase is expected in susceptibility to other infectious diseases (World Health Organization, 2017). Climate change is anticipated to exacerbate an already high burden of waterborne disease in the Circumpolar North in particular (Harper et al., 2020). The Arctic is experiencing the fastest warming on the planet (M. Meredith et al., 2019), with an observed and projected annual average warming of more than twice the global mean and higher increases in winter (Arctic Monitoring and Assessment Programme (AMAP), 2019). Strong evidence points to an association between climatic factors, such as heavy rainfall, and food and waterborne diseases, such as *Salmonella* and *Campylobacter* infections, in the subarctic region (Hedlund et al., 2014).

Extreme rainfall events increase the risk of failures in water and sanitation infrastructure, and therefore the risk of infectious diseases associated with the lack of safe management of sewage (Harper et al., 2020), particularly in ageing reservoirs (Renwick et al., 2019). Heavy rainfall and flooding are the most common events preceding outbreaks associated with extreme weather (Cann et al., 2013). Heavy rainfall may cause a number of changes in the hygienic load in the environment, such as the resuspension and transport of pathogens to other areas, surface run-off from land to water, contamination of groundwater sources, and overloading water and sanitation infrastructure (Levy et al., 2016). Concerns about the ability of small water supply systems to manage a water crisis for effective public health protection are also increasing (World Health Organization Regional office for Europe, 2016).

It is anticipated that heavy rainfall and flood events will be more frequent in Norway (Noregs offentlege utgreiingar (NOU), 2010). In Norway, water is an abundant resource, with 88 % of the population supplied by a water service provider that must comply with the Norwegian Drinking Water Regulation (Norwegian Institute of Public Health, 2020). A typical Norwegian water supply system uses surface water as a raw water source. Roughly 60 % of water supplies use surface water for drinking water production, serving approximately 90 % of the population. Several steps are taken to ensure safe drinking water, for example: deep raw water intakes in lakes, filtration and coagulation to remove particles associated with parasitic protozoa, UV radiation for disinfection, and adjustment of pH for corrosion control in pipelines (Norwegian Institute of Public Health, 2016). Norwegian drinking water is generally considered to be of good quality, reporting high levels of compliance with water quality standards (Norwegian Institute of Public Health, 2022b). Nevertheless, data from the national outbreak system reveal that waterborne outbreaks occur each year (Guzman-Herrador et al., 2016b), and many cases related to food-borne and waterborne pathogens are reported annually to the Norwegian Surveillance System for Communicable Diseases (Norwegian Institute of Public Health, 2022a).

The risk of contamination of ageing distribution systems, especially the vulnerability to backflow during loss of pressure, has become a growing concern in Norway in recent years (Nygård et al., 2007, Ercumen et al., 2014). According to data reported from the water works, approximately 33 % of produced drinking water at the national level is lost to leakages (Statistics Norway, 2020), which is significantly higher than that of many other countries (EurEau, 2017). Audits have revealed that 120 water supply systems have reported spontaneous or unintentional interruptions in the drinking water supply, likely caused by failures in distribution systems (Norwegian Institute of Public Health, 2015). In 81 % of the inspected systems, this was mostly related to the design and condition of the distribution systems. A majority of water utilities also lacked proper plans for maintenance and renewal of the distribution systems (Norwegian Food Safety Authority, 2012), and two-thirds of water utilities do not conduct preparedness exercises, which creates uncertainties regarding the continuous delivery of safe drinking water during events in which organisational capacity is at play (Norwegian Food Safety Authority, 2016).

The impacts of climate change are high on the agenda among politicians, public health practitioners, and the scientific community in Norway. Several reports and non-peer review publications have been made available (Norwegian Environment Agency, 2022, Norwegian Meteorological Institute, 2022, CICERO, 2022), along with scientific publications that highlight the risk of the impacts of climate change (Mohammed & Seidu, 2019, Mohammed et al., 2019, Bruaset & Sægrov, 2018, Robertson et al., 2021, Guzman-Herrador et al., 2021). However, the impact of climate change on drinking water in terms of health outcomes is–to the best of our knowledge–assessed to a lesser degree. Considering the severity of predicted climate change impacts on drinking water and health, and the challenges with the Norwegian drinking water distribution system, we conducted a narrative literature review to assess evidence on waterborne disease attributed to climate changes, and to identify knowledge gaps and future research priorities.

Materials and methods

We conducted a literature search in Ovid MEDLINE, Embase, Cochrane Database of Systematic reviews, Web of Science, Global Health, and CAB abstracts using combinations of keywords, such as "drinking water", "tap water", "climate change", "extreme weather", "waterborne diseases", "waterborne infections", "Norway", "Scandinavia", "Nordic countries", and "Arctic region", to identify peer review publications within the scope of this review. We used the same search terms to conduct additional searches on Google Scholar and on selected websites (WHO, ECDC, CISERO, NIPH, and opengrey.eu) to capture relevant grey literature. The complete search strategy is shown in the supplementary material (Additional File 1). No time periods or language restrictions were imposed on the search. Further, the references of identified articles were retrieved, and a hand search was conducted using the keywords "climate change", "drinking water", and "Norway" in Google Scholar.

We included studies if they primarily investigated the link between health outcomes (waterborne disease) and changing climatic parameters, using different methods, such as epidemiological studies and modelling/simulation. However, we also included reports of outbreak investigations in which the cause or part of the cause could be attributed to extreme weather events, such as heavy rainfall.

We synthetized the outcomes of the included publications in a narrative review to highlight the current knowledge of the impacts of drinking water and health in Norway.

Results

Peer-reviewed publications

The literature search identified 37 publications, four of which met the criteria for inclusion in the literature review (Table 1). We excluded 31

Table 1. Publications included in this study, with brief summaries of scope, results and conclusions.

Publication Id/reference	Title	Study period	Study population	Study context	Aim of study	Design/ Method	Results	Conclusions	Knowledge gap/suggested further studies
Guzman-Herrador et al., 2021	Heavy weather events, water quality, and gastroenteritis in Norway	2006 -2014	Approx. 2.8 million residents	26 waterworks in Norway	Generate new knowledge on the effect of extreme weather conditions and climate change on drinking water and waterborne disease Influence of extreme weather events on raw and drinking water quality, and subsequent risk of waterborne disease	Statistical analysis of relationship between precipitation, runoff, water quality, and gastroenteritis	Extreme weather events affect raw water quality but has less effect on treated drinking water Increased maximum temperature is associated with an increased risk of disease for the whole year Heavy rain and high runoff associated with a decrease in risk of gastroenteritis for several age groups and time periods throughout the year	No evidence that increased precipitation and runoff trigger gastroenteritis outbreaks. This may be due to the robust treatment methods in large Norwegian waterworks that prevent waterborne disease	Modelling future climate scenarios is necessary to assess the need for improved water treatment capacity in future climate change
Hyllestad et al., 2020b	Large waterborne Campylobacter outbreak: use of multiple approaches to investigate contamination of the drinking water supply system, Norway, June 2019	April- May 2019	Approx. 12,000 residents	Kleppe waterwork in Askøy municipality, Norway	Outbreak investigation to confirm the source, extent of the outbreak, and effect of control measures	Epidemiological, microbiological, and environmental investigations	The results of epidemiological, microbiological, and environmental investigations support that contaminated water from a drinking water reservoir caused an outbreak of more than 1,500 cases of campylobacteriosis in Askøy in June 2019	The diversity of data sources used to investigate this outbreak supports the hypothesis that environmental contamination through cracks in a reservoir most likely occurred during heavy rainfall following a long dry period	The cause of the pollution event remains unknown and need further studies

Table 1 continued

Publication Id/reference	Title	Study period	Study population	Study context	Aim of study	Design/ Method	Results	Conclusions	Knowledge gap/suggested further studies
Guzman-Herrador et al., 2016a	Association between heavy precipitation events and waterborne outbreaks in four Nordic countries, 1992–2012	1992-2012	Unknown population size. A total of 186 notified waterborne outbreaks between January 1st, 1992 and December 31st, 2012 in Norway, Sweden, Finland, and Denmark had information about municipality and onset month and were included in the analyses	The Nordic countries	Examine the association between heavy precipitation events and waterborne outbreaks by linking epidemiological registries and meteorological data	Matched case-control study	Among waterborne outbreaks with known onset date (n = 89), exceedance rainfall on two or more days was associated with occurrence of outbreak, compared to zero exceedance days Stratified analyses revealed a significant association with single household water supplies, ground water as a source for outbreaks occurring during spring and summer	The results suggest an association between waterborne outbreaks and heavy precipitation in the Nordic countries The results highlight single household supplies as particularly vulnerable to extreme weather events	More sensitive epidemiological registries could also be used. Syndromic surveillance systems, for example, consultations due to gastroenteritis, or notifications of waterborne micro-organisms, could help to better assess the influence of heavy precipitation events and runoff on waterborne diseases
Nygård et al., 2006	A large community outbreak of waterborne giardiasis-delayed detection in a non-endemic urban area	Oct.- Dec. 2004	48,000 people exposed to contaminated drinking water	City of Bergen (limited water supply area)	Outbreak investigation to confirm the source, extent of the outbreak, and effect of control measures	Epidemiological, microbiological, and environmental investigations	The risk of infection for persons receiving water from the water supply serving Bergen city centre was significantly higher than for those receiving water from other supplies	Leaking sewage pipes combined with insufficient water treatment was the likely cause of the outbreak. Heavy rainfall during a short period in September may have been a factor in overloading the sewage system, thus causing leakage to the lake	No further studies suggested than recommendations for future prevention of waterborne outbreaks

publications since they did not include data from Norway (wrong study context) and/or they did not assess waterborne disease as a health outcome (wrong study outcome) (n = 28) (Astrom et al., 2007, Astrom et al., 2009, Brown et al., 2014, Charnley et al., 2022, Dudley et al., 2015, Fisk et al., 2005, Greer et al., 2008, Gurcan, 2014, Holmner et al., 2010, Nilsson et al., 2013, Overgaard et al., 2021, Rautio, 2010, Klove et al., 2017, Kvitsjoen et al., 2021, Mohammed & Seidu, 2019, Raposo et al., 2021, Robertson et al., 2021, Sirocko et al., 2016, Tryland et al., 2014, Tornevi et al., 2013, Whittington et al., 2003, Altuna et al., 2021, Bazzicalupo et al., 2018, Caminade et al., 2019, Carroll et al., 2020, Chashchin, 2010, Cheshmehzangi et al., 2021, Eisen & Moore, 2013), duplication (n = 2) (Holmner et al., 2010, Eregno et al., 2016). One publication, although thematically relevant, was excluded because it was a review and thus fell outside the scope of this study (Guzman Herrador et al., 2015).

Grey literature

Grey literature search yielded seven publications (five reports, one doctoral thesis, and one book chapter) that were found relevant for the scope of this review. However, none met the criteria for inclusion in the literature review.

Discussion

Two of the publications included in this study used historical data from national infectious disease surveillance systems together with weather data to analyse the possible association between drinking water and weather with health outcomes in terms of waterborne infections. Two were reports following outbreaks with extreme weather events in combination with a lack of hygienic barriers as the probable cause. The four publications cover a combined study period of approximately 20 years, with the study population ranging from 12,000 to 2.8 million Norwegian residents. The health outcome in all the studies was waterborne outbreaks caused by different aetiologies.

Of the two studies using health data from registries and climate data, the results diverge. One of the studies applied data from the largest water utilities in Norway and found a positive association between extreme rainfall events and a change in raw water quality, but not with GI (Guzman-Herrador et al., 2021). Large water utilities have implemented advanced treatment methods that are likely to manage weather-related changes in raw water quality. The authors pointed out that it was not clear whether the negative association between heavy rainfall events and waterborne infections was due to the ability of the water treatment plants to remove pathogens, or if it was due to inadequate data on waterborne outbreaks. The other study found a positive association between waterborne outbreaks and extreme precipitation, mainly for small water supply systems, such as private wells (Guzman-Herrador et al., 2016a). Outbreaks associated with small water supply systems are likely due to limited water treatment and disinfection. These systems are unable to protect consumers from abnormally contaminated drinking water following extreme weather events. Analysis based on waterborne infections data can also be challenging, considering the difficulties in differentiating waterborne infections from drinking water and infections from other sources, such as food and hygiene. Available data may also be sparse, as registered waterborne infections cases are known to represent the tip of the "prevalence iceberg". In addition, using data from syndromic surveillance systems, as in the referred study, may not be effective in detecting outbreaks due to factors such as timeliness, sensitivity, and specificity (Hyllestad et al., 2021, Hyllestad et al., 2022).

The hypothesis in the outbreak detected in Askøy was that the suspected drinking water reservoir most likely got contaminated by water from the outside through cracks in the bedrock, during heavy rainfall following a long dry period. Rainfall events have been a factor in several serious waterborne outbreaks (O'Connor, 2002, Cann et al., 2013, Moreira & Bondelind, 2017) and smaller outbreaks (Guzman-Herrador et al., 2016a), in which *Campylobacter* has frequently been identified as the cause of the outbreaks (Pitkanen et al., 2008, Gubbels et al., 2012). Although it is difficult to determine the exact mode of contamination, the triangulation of epidemiological, genomic, geographical, and water system data proved essential for confirming the role of the drinking water reservoir in the Askøy outbreak and for determining the extent of exposure within the community. When assessing these three main tracks of the investigation, the outbreak in Askøy could be classified as 'strongly associated with water' (Tillett et al., 1998), since the pathogen identified in clinical cases was also found in water. Evidence from the analytical epidemiological study demonstrates an association between water and illness. In addition, whole genome sequencing of *Campylobacter* in the four positive water samples matched the DNA profile of the human samples.

The hypothesis—the intrusion of contaminated water due to heavy rainfall—is a plausible explanation, considering the frequent reporting of waterborne outbreaks (Auld et al., 2004). However, it might be relevant to question why this outbreak occurred in Askøy in June 2019. The reservoir had been in operation since the 1960s, with no known changes in the construction of the reservoir or in the external conditions of the reservoir. According to the water operators, the weather conditions were unusual in the period prior to the outbreak: There was a long dry period of approximately two months, which is uncommon on the Southwest coast of Norway, before an extreme rainfall event occurred in the days before the outbreak. Predicted changes in climate parameters, such as rain and drought, are expected to affect the overall situation of waterborne diseases. However, we cannot conclude that climate change was the cause of the outbreak, since such a statement is not supported by a causal relationship (Hofmann & Holm, 2015). It is merely an assumption that uncertain weather patterns represent stressors to water supply systems, particularly ageing reservoirs (Renwick et al., 2019). Whether the combination of weather conditions resulted in a contamination event in the spring of 2019, as opposed to other seasons in which it had not been experienced, will require more in-depth examination.

Similar circumstances preceded the 2004 outbreak of giardiasis in Bergen (Nygard et al., 2006). A period of intense precipitation overloaded the sanitation infrastructure, resulting in the contamination of a nearby drinking water source. Faecal indicator organisms, that is *E. coli*, in routine samples from the raw water, offered some warning signs. However, there were no deviations in the drinking water samples, probably due to chlorination in the water treatment plant. Chlorination, while proven effective against indicator organisms, has a limited effect on *Giardia* (Adeyemo et al., 2019). In addition to a temporary failure in chlorination, this contributed to the onset of a significant giardiasis outbreak. It is worth noting that UV disinfection is more effective than chlorination for inactivating and removing *Giardia* (Li et al., 2008), and in fact, UV irradiation is now the primary disinfection method in most Norwegian water works (Norwegian Institute of Public Health, 2022b).

This study has limitations, which are mainly related to the nature of the few published studies identified in the literature search providing data on health outcomes due to the impacts of climate change or extreme weather events on drinking water. Therefore, it is challenging to state conclusive findings on the health outcomes linked to drinking water and climate change in Norway. Nevertheless, this review may be useful for highlighting knowledge gaps and research priorities.

Guzman-Herrador et al. (2016) expressed the need for more sensitive data on disease outcomes than registries, such as syndromic data based on consultations (Guzman-Herrador et al., 2016a). Such data was used in a follow-up study, which did not demonstrate any association between health outcomes and extreme precipitation, most likely because the syndromic surveillance data were not sufficiently sensitive for analysis/future modelling (Herrador et al., 2021). Although it is challenging to assess the impacts of climate change on drinking water and health in Norway, further studies should include health data that are adequate for analysis. Further, the studies included in this review addressed the effects of climate change on source water. Given the risk related to the pollution of drinking water distribution systems (Ercumen et al., 2014, Renwick et al., 2019), we also highlight the need for studies addressing the effect of climate change on distribution networks to gain more specific knowledge on where and how to focus preventive measures. Traditionally, outbreak studies offer recommendations for the prevention of future outbreaks rather than filling knowledge gaps within the field of future research. However, in the Askøy outbreak, the researchers suggested further investigations to highlight the source of the pollution (Hyllestad et al., 2020). More insight could be highlighted by assessing the source attribution of *Campylobacter* to fill a gap in the knowledge of the risk factors for the drinking water distribution system, particularly pressure-less installations, such as reservoirs.

Some of the excluded studies assessed the effects of heavy rainfall and/or future scenarios on source water quality (Mohammed & Seidu, 2019, Klove et al., 2017), demonstrating a negative effect with, for example, increased levels of indicator bacteria for faecal pollution. These findings are also supported by recent findings in Norway (Skaland et al., 2022). Deterioration of source water quality represents a risk of waterborne disease cases and outbreaks, in the case that the drinking water treatment is exceeding its capacity or is malfunctional at the time of source water pollution. Studies assessing the risks for pollution due to climate change are relevant for such reasons, although they do not address health outcomes. This is particularly relevant for Norway, considering the concern of vulnerabilities linked to an ageing distribution system, and the anticipation of more frequent extreme rainfall events in Norway. A drinking water distribution system comprises several critical points (Havelaar, 1994), which are vulnerable to pollution, despite continuous preventive measures. This highlights the need for knowledge in effective methods of risk-based surveillance and early-warning systems, for example, on-line monitoring and/or surveillance systems combining several information sources, such as weather data/rainfall forecasting, water supply zones, and/or health data. The consequences of other extreme weather events, such as drought, are not addressed in the publications retrieved from the literature search, which may indicate a knowledge gap.

Conclusion

In this study, we reviewed the available information on the impact of climate change on drinking water and health in Norway. The findings from the identified studies suggest that waterborne outbreaks and extreme rainfall are associated with small water supply systems without disinfection, while larger water supplies are not, probably due to adequate drinking water treatment processes or inadequate data on disease for proper analysis. Waterborne outbreaks are also reported after extreme rainfall due to a lack of hygienic barriers. The findings of this literature review are limited due to the low number of publications identified. Further studies are needed to provide information on the impacts of climate change on drinking water and health in Norway. A further development of the current national surveillance systems for incidents affecting the water supply chain could provide a better data base for risk-based monitoring, notification and mapping of incidents that may have health consequences.

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Authors' contributions

SH initiated and led the study. SH and EHM contributed equally to the search strategy and screened the literature for eligibility. SH extracted the data from peer-reviewed publications. EHM summarised the grey literature. SH developed the first draft of the manuscript. AB critically read and contributed to the manuscript. All authors read the final manuscript.

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