# Drinking water and public health: Prevention, detection and response to waterborne outbreaks in Norway

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# Sammendrag

Forsyning av trygt drikkevann er helt avgjørende for å fremme god folkehelse. Globalt utgjør forurenset drikkevann fortsatt en stor bidragsyter til sykdomsbyrden i mange samfunn. Det er anslått at smitte fra drikkevannskilder forårsaket 1,6 millioner dødsfall i 2016, og mer enn en fjerdedel av de som ble rammet er yngre barn i Sør-Asia og Afrika sør for Sahara.

I høyinntektsland har innføringen av flere forebyggende tiltak i vannforsyningen ført til en minimumsbyrde knyttet til smittsomme sykdommer i samfunnet. Særskilt betydning er knyttet til utbyggingen av grunnleggende tjenester som tilgang til trygt drikkevann og sanitæranlegg. Imidlertid forekommer vannbårne utbrudd fortsatt over hele verden, også i høyinntekstland hvor vannforsyningssystemene har en høy teknisk standard. I Norge har det blitt implementert flere hygieniske barrierer i vannforsyningen. Likevel registreres det årlig vannbårne utbrudd og tilfeller med magetarmsykdommer som trolig er en følge av forurenset drikkevann.

Det er en økende bekymring knyttet til sårbarhet i distribusjonssystemene for drikkevann i Norge. Dette er systemer som er aldrende og har en lav fornyelsestakt, og dermed også økt risiko for innsug av forurenset vann under episoder med lavt trykk i ledningsnettet. I tillegg er det bekymring knyttet til beredskapen, spesielt blant små vannverksorganisasjoner, til å håndtere utfordringer som ending i klimaparametere og kritiske hendelser som kan føre til forurensning i vannforsyningen og smitteutbrudd. Hendelser med forurensning i distribusjonsnettet er spesielt utfordrende da det ikke er noen hygieniske barrierer med desinfeksjon før vannet potensielt eksponerer befolkningen. Og dette understreker behovet for lokale tiltak som råd om å koke vannet før det benyttes til drikke eller matlaging.

Vannbårne utbrudd som forårsakes av forurenset drikkevann i vannforsyningssystemer utgjør en kritisk risiko for folkehelsen på grunn av potensialet for at svært mange kan eksponeres på kort tid. Dette kan igjen føre til store helse- og samfunnsmessige konsekvenser med økning i sykdomstilfeller, tap av arbeidsdager og belastning i helsetjenester.

Utfordringene for å sikre trygt drikkevann i Norge er komplekse og involverer både tekniske, helsemessige, så vel som sosiale aspekter. Fordi det ikke er mulig å oppnå en helt sikker vannforsyning, er det nødvendig med tiltak som tidlig påvisning av utbrudd og en effektiv respons i befolkningen. Dette kommer i tillegg til en fortløpende innsats med forebyggende tiltak. I denne avhandlingen tar jeg en tverrfaglig tilnærming til mitt hovedmål om å forhindre

vannbårne utbrudd, noe jeg skal studere med å identifisere risiko i vannforsyningssystem, tidlig påvisning av vannbårne utbrudd og etterlevelse av gitte kokeråd for vann som benyttes i befolkningen.

I denne avhandlingen, er risikoer i vannforsyningssystemer identifisert ved å undersøke et stort vannbårent utbrudd, samt ved gjennomgang av spørsmål om faglige råd til en rådgivningstjeneste for vannverk for å se på trender i kritiske hendelser og forhold knyttet til beredskap. Syndrombasert overvåkning har blitt fremmet som et tiltak for tidligst mulig å påvise vannbårne utbrudd, samtidig har ikke nytteverdien av syndrombasert overvåking blitt oppdatert siden 2006. Vi utførte derfor en systematisk kunnskapsoppsummering med formål å informere om bruken av slike systemer til tidlig påvisning av vannbårne utbrudd. Etterlevelsen av kokeråd for vann til befolkningen er hittil lite studert. Vi gjennomførte en studie blant innbyggere som hadde mottatt kokeråd fra kommunen for å vurdere deres etterlevelse av rådet og oppfatningen av risiko knyttet til drikkevann som følge av kommunikasjonen om kokerådene.

Hvert år forekommer det hendelser i vannforsyningen som utgjør en helserisiko, og av og til skjer det store vannbårne utbrudd. Det er identifisert en stor risiko for forurensning av drikkevann knyttet til vannbassenger i distribusjonssystemet, og spesielt råsprengte fjellbassenger. I tilfeller der en hendelse med forurensning utvikler seg til et vannbårent sykdomsutbrudd, så er det imidlertid ikke holdepunkt for at syndrombasert overvåkning kan tjene som tidlig påvisning. I alle fall gjelder dette ikke for mindre og lokale sykdomsutbrudd med rask innsykning i befolkningen. Etterlevelsen av kokeråd er generelt høy når kjennskapen til rådet er høyt, men lavere når befolkningen ikke kjente til rådet. Etterlevelsen kan også bli påvirket av hvordan alvorlighetsgraden av situasjonen ble oppfattet eller fortolket. Etterlevelsen var lavere dersom risikoen for sykdom ble oppfattet som lav. Fra perspektivet til vannverkene, så kan resultatene tyde på at de er usikre på hvordan de skal reagere hensiktsmessig på funn av koliforme bakterier i vannanalyser når det samtidig ikke påvises *E. coli*.

Mulige helsekonsekvenser kan på kort sikt forebygges ved at tilstrekkelige hygieniske barrierer blir implementert i råsprengte fjellbassenger som har høy risiko for å bli forurenset. Funnene i denne avhandlingen understreker at langsiktige forebyggende tiltak og gjennomføring av risikobasert overvåkning av vannforsyningssystemene er avgjørende for å begrense samfunnsmessige konsekvenser ved vannbårne utbrudd.

Fremtidige studier kan omfatte bidrag av *Campylobacter* i tilsigsområder til vannforsyningen, studere effekten av endrende klimaparametere på distribusjonssystemet og helseutfall, samt undersøke etterlevelse av kokeråd og effekten av kommunereformen i 2020 på vannverkenes beredskap. I tillegg kan det gjøres kvalitative studier for å identifisere behov for kapasitetsbygging blant små vannverk.

# Summary

Drinking water is of high public health relevance. Globally, contaminated water remains a major contributor to the global burden of diseases, estimated to be responsible for approximately 1.6 million deaths in 2016, with more than a quarter, in particular, affecting younger children in South Asia and sub-Saharan Africa.

In high-income countries, several precautionary actions have resulted in a minimum burden associated with infectious diseases in society, particularly due to the implementation of basic services such as drinking water and sanitation. However, waterborne outbreaks still occur worldwide in high-income countries with high-standard water supply systems. Despite the minimum burden of waterborne diseases in Norway after implementation of several hygienic barriers, waterborne outbreaks still occur and cases of gastrointestinal linked to drinking water are registered yearly.

In Norway, it is a specific concern directed towards an aging and vulnerable distribution system prone for contamination. In addition, there is a concern related to the level of preparedness, particularly amongst small-scale water supply systems, when facing challenges such as changing climate parameters and critical events. Contamination events involving the distribution systems are particularly challenging, as there are no disinfection barriers before the water potentially exposes consumers, highlighting the need for measures such as boil water advisories (BWAs).

Waterborne outbreaks caused by contaminated water in the water supply system present a critical risk to public health due to the potential exposure of pathogens to a large population in a short period, which may result in large societal consequences in terms of sickness, loss of workdays and burden on the health system.

The challenges faced in Norway to ensure safe drinking water are complex, involving technical, health and social aspects. As achieving perfection in drinking water supply systems is not possible, measures such as early detection and effective public health response are called for, along with a continuous focus on preventive actions. In this thesis, I take a multidisciplinary approach to the overall objective of preventing waterborne outbreaks by examining the risks in the water supply systems, the early detection of waterborne outbreaks and public compliance with BWAs.

This thesis identifies risks in drinking water supplies by investigating a large waterborne outbreak and assesses requests for advice to a crisis service for water supplies for possible trends in critical events and response capacities. Syndromic surveillance systems have been suggested for use in the detection of waterborne outbreaks. As the effectiveness of syndromic surveillance has not been updated since 2006, we conducted a systematic review to inform the potential use of such systems for the early detection of waterborne outbreaks. Public response to BWAs has been sparsely examined to date; thus, we conducted a study among residents affected by such advisories to assess their compliance and perceptions of the risks.

Every year, events that may jeopardise drinking water safety occur in Norway, and occasionally severe outbreaks occur. A risk of contamination can arguably be linked to the distribution system, particularly to cavern reservoirs. In case of a contamination event evolving into a waterborne outbreak, however, there is no clear evidence that syndromic surveillance may serve as early detection, at least not for smaller and local waterborne outbreaks with an acute onset of illness. Public compliance with BWAs is generally high when the awareness is high, but lower in cases where the advice went unnoticed. Compliance could also be affected by the perception of the severity of the situation; compliance is lower if the risk of illness is perceived as low. Regarding the issuance of BWAs, water suppliers might be unsure how to respond properly based on the findings of coliform bacteria, while at the same time not detecting *E. coli*.

Possible implications in the short term involve ensuring that sufficient hygienic barriers are put in place in cavern reservoirs at high risk of contamination. The findings emphasise that preventive long-term precautionary actions and conducting risk-based surveillance of drinking water supplies are essential to limit societal consequences.

Future studies could include identifying the source attribution of *Campylobacter* in the watershed area to drinking water supplies, determining the effects of changing climate paramteres on the drinking water distribution system and health, investigating public compliance to BWAs and the effects of municipal reform on drinking water preparedness, and conducting qualitative studies to identify the capacity needs of small-scale drinking water supplies.

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# List of Papers Included in the Thesis

I. Hyllestad S, Iversen A, MacDonald E, Amato E, Borge BÅS, Bøe A, Sandvin A, Brandal LT, Lyngstad TM, Naseer U, Nygård K, Veneti L, Vold L. Large waterborne Campylobacter outbreak: Use of multiple approaches to investigate contamination of the drinking water supply system, Norway, June 2019. *Eurosurveillance*. 2020;25(35):2000011.

II. Hyllestad S, Amato E, Nygård K, Vold L, Aavitsland P. The effectiveness of syndromic surveillance for the early detection of waterborne outbreaks: A systematic review. (Submitted, December 2020)

III. Hyllestad S, Veneti L, Bugge AB, Rosenberg TG, Nygård K, Aavitsland P. Compliance with water advisories after water outages in Norway. *BMC Public Health*. 2019;19(1):1188.

IV. Hyllestad S, Lund V, Nygård K, Aavitsland P, Vold L. The establishment and first experiences of a crisis advisory service for water supplies in Norway. *Journal of Water and Health*. 2020;18(4):545-55.

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## List of Abbreviations

| | |
|---|---|
| BWA | Boil water advisory |
| CDC | US Centre for Disease Control and Prevention |
| CIM | Crisis Information Management |
| ECDC | European Centre for Disease Control and Prevention |
| EEA | European Economic Area |
| IHR | International Health Regulations |
| MSIS | Norwegian Surveillance System for Communicable Diseases |
| MLST | Multi-locus sequence type |
| NIPH | Norwegian Institute of Public Health |
| NorSySS | Norwegian Syndromic Surveillance System |
| NWG | National Water Guard |
| OECD | Organisation for Economic Co-operation and Development |
| OTC | Over-the-Counter |
| PICO | Participants-Intervention-Comparator-Outcome |
| PRECEPT | Project on a Framework for Rating Evidence in Public Health |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| QMRA | Quantitative Microbial Risk Assessment |
| RCT | Randomized Control Trial |
| ROBINS-I | Risk Of Bias In Non-randomised Studies - of Interventions |
| SDG | Sustainable Development Goal |
| SMS | Short Message Service |
| UV | Ultra Violet |
| VESUV | Norwegian Outbreak Surveillance System |
| WGS | Whole Genome Sequencing |
| WHO | World Health Organization |
| WSP | Water Safety Plan |

# 1 Introduction

In this introduction, I provide a backdrop to the topic of research, study context and overall objective of this thesis, and I describe the outline of the thesis.

## 1.1 Background and overall study objective

Delivery of safe drinking water has a high public health relevance. The outbreak of cholera in London in 1854 is widely referred to as the outbreak that, via its investigation, established the link between contaminated drinking water and health (1). The investigator behind the pioneer approach, medical doctor John Snow, was later perceived as the founder of applied epidemiology (2).

Globally, contaminated water remains a major contributor to the global burden of diseases, estimated to be responsible for approximately 1.6 million deaths in 2016, with more than a quarter, in particular, affecting younger children in South Asia and sub-Saharan Africa (3). The importance of drinking water – as a fundamental requirement to live a life in wellbeing and dignity – was further emphasised when access to drinking water was acknowledged as a basic human right (4).

The overall burden of diarrheal diseases, and challenges related to health and wellbeing, disproportionately affects the less-developed parts of the world where adequate water and sanitation services are limited (5). Combating this challenge, the global burden of diarrheal diseases and safe drinking water is reflected in the Sustainable Development Goals (SDGs). The aim of SDG 3.3 concerns combating waterborne diseases, while SGD 6 aims to ensure access to safe drinking water and adequate sanitation facilities (6). In 2017, according to the Joint Monitoring Programme, based on a definition of the level of service of drinking water, 785 million were lacking a basic level of service of drinking water and 144 million people used untreated surface water or unimproved sources (7). It is expected that 341,000 deaths among children younger than five years of age could be prevented every year if access to adequate water and sanitation facilities in low- and middle-income countries was put in place (8).

In contrast to the less-developed parts of the world, drinking water safety is largely taken for granted by many citizens of affluent nations (9). In high-income countries[1] (10), several precautionary actions have resulted in a minimum burden associated with infectious diseases in the society, particularly due to the expansion of basic services such as drinking water and sanitation (3). Under normal conditions, drinking water from supply systems is safe and represents a necessary and critical infrastructure for modern society on which the population depends and trusts (11). However, waterborne outbreaks still occur worldwide in high-income countries with high standard water supply systems (12, 13), were some incidences have had a devastating impact on human health (14-17). Waterborne outbreaks caused by contaminated water in a water supply system present a critical risk for public health due to the potential exposure of pathogens to a large population in a short time span, which may result in large societal consequences in terms of sickness, loss of workdays and burden on the health system (18-20).

Norway is among the highest ranking countries in terms of living standards according to Organisation for Economic Co-operation and Development (OECD) (21). Drinking water is mainly produced from surface water sources, serving 90% of the population who are connected to drinking water supplies (22). Since the middle of the 1990s, several hygienic barriers have been implemented to ensure safe drinking water in a targeted programme to improve the quality of the drinking water in Norway (23). Today, only a small proportion of the consumers of the public drinking water supply receive water that is not disinfected (23). In Norway, water is an abundant resource, and access to drinking water is a natural part of daily life. When we pour a glass of water from the tap in the kitchen, we rarely think of where the water comes from or why it is clear, chilled and tastes almost the same every day. Pouring a glass of water Norway is embodied as many things we do without thinking about or problematising it (24). However, despite the contextual benefits in Norway, studies reveal that waterborne outbreaks occur each year (25, 26), and many cases related to food- and waterborne pathogens are reported to the Norwegian Surveillance System for Communicable Diseases annually (27).

In addition, in the midst of my work on this thesis, a large waterborne outbreak occurred in a municipality of Norway, causing approximately 2,000 people to fall ill from *Campylobacter* (28). Although the overall objective of the thesis was to investigate risk factors for the

[1] The World Bank assigns the world’s economies to four income groups—low, lower-middle, upper-middle, and high-income countries. The classifications are updated each year on July 1 and are based on gross national income (GNI) per capita in current USD (using the Atlas method exchange rates) of the previous year.

prevention of exactly similar waterborne outbreaks, this outbreak was not a part of the initial project planning since waterborne outbreaks of such size are more or less infrequent in Norway. Initially, the risks in the water supplies were planned to be informed by assessing advice logs to a crisis water advisory service. However, the outbreak in Askøy represented a real-life, yet unwanted, experiment using the 'society as a laboratory' (29). Owing to my involvement in the outbreak investigations, the findings have been added to the empirical corpus to the thesis and thus extended the thesis.

The risk of contamination in the distribution system has become a growing concern in Norway in recent years, along with an awareness that an ageing pipe infrastructure is vulnerable to backflow of contamination during loss of pressure (30). A loss of pressure in the supply system can lead to pathogenic viruses, bacteria and parasites entering the water sources, distribution systems or both in various ways and may cause outbreaks (31). The risks of distribution system deficiencies are challenging since the pipes are difficult to inspect, there is no overall monitoring in real time to detect potential contamination, and there is no necessary efficient water treatment before the drinking water reaches the households.

In 2011, 120 water supply systems reported spontaneous or unintentional interruptions in their water supply, which were likely largely caused by breaches in the distribution systems (32). In 2012, the Norwegian Food Safety Authority audited the water distribution systems at 491 water supply systems; the audits revealed deviations in 81% of the inspected systems, mostly related to the design and condition of the distribution systems. A majority of water utilities also lacked proper plans for maintenance and renewal (33). A distribution system affected by frequent breaches and high levels of leakages is especially vulnerable to contamination under low-pressure situations. According to statistics reported from the water works, Norway has a leakage of approximately 33%, ranging from 20% to 80%, of the produced drinking water (34), which is significantly higher than other countries (35). In Sweden, the level of leakages is estimated to be 20%; in Denmark, it is approximately 10%; and in the Netherlands, it is as low as 5% (35). When anticipating the current pace of renewing drinking water pipes, it is estimated that it will require approximately 145 years to upgrade the drinking water pipe network in Norway (34).

Sudden events in the supply of drinking water are demanding in terms of response from the water suppliers (16). Reports from inspection campaigns by the Norwegian Food Safety Authority reveal that almost all the registered water supply systems in Norway have an emergency preparedness plan in place; however, recent national inspection reveals that two-thirds of them do not conduct practice exercises (36). The lack of preparedness creates uncertainties regarding the continuous delivery of safe drinking water during larger events that the organisational capacity is at play (36).

The effects of changing climatic factors are expected to act as stressors to vulnerable drinking water supply systems and health consequences (37, 38). Concern about the ability of small water supply systems to manage a water crisis for effective public health protection is also a concern (39), which highlights the need for early warning systems that can detect waterborne outbreaks to limit potential health consequences. The vast majority of the population is exposed to drinking water daily, and in the case of suspected contamination, one is prone to conduct measures, such as BWAs, that involve communication and adherence by the consumer to protect the public health for an effective response (40). Achieving perfection in terms of distributing drinking water is not possible; one needs to target preventive measures and search for the early prediction of outbreaks to minimise the potential consequences. The challenges related to the drinking water distribution system are complex and therefore need to be tackled from several angles with a specific need to address measures that reduce the risks of outbreaks of waterborne (41). I therefore take a multidisciplinary approach to the overall study objective of this thesis.

In addition, derived from the implementation of the International Health Regulation (IHR) in 2005 (42), an increasingly common approach to combat infectious diseases is ‘to prevent, protect against, control and provide a public health response’ to the spread of diseases, including the capacity to promptly detect health risks. The IHR’s purpose is to provide an overarching legal framework to handle public health emergencies that have the potential to cross borders, as disease outbreaks are often unpredictable and require a range of responses (42). The framework has been widely adapted and applied in the work of emergencies combating infectious diseases (43). In this thesis, I am inspired by the IHR framework since combating waterborne outbreaks also requires a holistic approach (49), taking into account that preparedness and response involve people and their perception of risks related to drinking water (44).

Water is an abundant resource in Norway, and safe drinking water is a largely ‘taken for granted’ commodity, yet several factors may jeopardise this perception since contamination events, such as waterborne outbreaks, may cause public health consequences. The objective of this study is to shed light on drinking water preparedness in Norway by investigating specific aims related to the prevention, early detection and effective response to waterborne outbreaks.

## 1.2 Study context: Drinking water in Norway

The context of the studies in this thesis is Norway in the 21st century. Norway is a relatively small country in the Nordic region, with approximately 5.4 million registered inhabitants, as of November 2020 (45). The population is distributed throughout the country, mainly divided around five of the largest urban settlements (Oslo, Bergen, Stavanger/Sandnes, Trondheim, Fredrikstad/Sarpsborg) and rural settlements (46). Norway is a high-income country, which ranks the highest living standard in the Organisation for Economic Co-operation and Development (OECD) area (21).

In Norway, drinking from regulated drinking water supplies serves approximately 90% of the population and is generally considered to be of good quality (23), reporting high levels of compliance with water quality standards (22). A typical water supply system in Norway makes use of surface water as a raw water source. Safe drinking water is ensured by establishing a deep and protected intake in the lake and filtration and coagulation to remove particles associated with parasitic protozoa, UV radiation and adjustment of pH for corrosion control in the pipelines (47).

Water supply systems in Norway serving more than 50 residents are regulated by legislation delegated to the Norwegian Food Safety Authority and are obliged to report on the performance of compliance with drinking water quality standards. the water supply systems are also subject to inspections, among other measures, to ensure safe drinking water (48). Around 10% of the Norwegian population relies on private water supplies, such as wells, which are not under official control (23).

There are approximately 1,500 water supply systems serving households in Norway widely spread geographically, many of which are managed by small organisations. Approximately 86% serve less than 5,000 residents, while a few large supplies serve the majority of residents (22) (Table 1).

Table 1 Number of water supplies by number of persons served and ownership, Norway, 2018.

| Size by residents served | Publicly owned | Privately owned | Total | Number of residents served | Percentage of population served |
|---|---|---|---|---|---|
| **51-500** | 467 | 341 | 808 | 154,000 | 2.9% |
| **501-5,000** | 332 | 84 | 416 | 675,800 | 12.6% |
| **5,001-50,000** | 137 | 5 | 142 | 2,024,100 | 37.6% |
| **50,001-500,000** | 22 | 0 | 22 | 1,179,700 | 21.9% |
| **500,001-** | 1 | 0 | 1 | 666,800 | 12.4% |
| **Unknown** | 22 | 10 | 32 | NI* | |
| **Total** | 981 | 440 | 1,421 | 4,700,400 | 87.3%** |

*No Information **The remainder have private water supplies, such as wells.

Approximately 70% (981/1,421) of the registered water supplies are owned by a municipality. The publicly owned water supplies is financed based on the principle of self-cost paid by the population served in terms of fees (49).

The average water consumption per person per day in Norway is estimated to be 178 litres (36); of these, up to five litres are assumed to be consumed directly as drinking water or for cooking purposes. The remaining is consumed for household appliances, approximately divided into 20 litres per person per day (l/p/d) for toilet flushing, 60 l/p/d for personal hygiene, 25 l/p/d for dishwashing machines, 40 l/p/d for washing machines and 20 l/p/d for other uses (50). In addition to the person specific consumption, on average, 33% of the treated drinking water is lost during distribution through leaky pipes (ranging from 20% to 80%) (34).

## Delimitations in the thesis

A delimitation in this thesis is that the water supply systems above serve approximately 50 residents. The study does not include private wells and small water supply systems serving entities, such as schools, cafeterias and similar, without any permanent residents connected to the supply system. My focus is on diseases where pathogenic agents have been introduced to the water supply system and the system has served as a vehicle for contamination, leading to waterborne outbreaks. Water-related diseases caused by contact with contaminated water or soil-transmitted diseases (such as helminths) or the growth of opportunistic bacteria, such as *Legionella*, in the internal pipelines and plumbing are not defined within the objective of this study. This choice has been made since such diseases are more associated with an environmental and contextual risk, and they have significantly different preventive measures compared to waterborne pathogens in drinking water supply systems. Diseases caused by harmful chemical substances introduced into the water supply system are not within the objective of study, although the data collection in one of the included papers also accounts for such events.

The main empirical information is collected in the Norwegian context in the period 2016-2019, except for information about surveillance systems for the early detection of waterborne outbreaks, which is conducted as a systematic review collecting data between 1990 and 2018.

## 1.3 Outline of the thesis

This thesis comprises an introduction chapter and four separate studies published as articles (Annex I).

Based on the backdrop of the research area and the overall objective presented above, in Chapter 2, I delve into the status of knowledge of the development of drinking water supply systems. The status of knowledge reports on the status of drinking water supply systems and highlights challenges related to health risks and the waterborne disease surveillance in the context of high-income countries. This chapter comprises five main parts. First, I provide a general introduction to drinking water and public health in terms of infection, classification and causative agents, and I carry out a review of the known risks of drinking water supply systems and some identified challenges. Second, since the main interest of this thesis is the prevention of waterborne outbreaks, I dedicate a sub-chapter to this topic, where I define waterborne outbreaks and review large waterborne outbreaks in what would be termed high-income countries. Third, in the following sub-chapter, I describe current preventive measures in terms of a safe drinking framework, including regulatory instruments, and some challenging issues in maintaining drinking water safety related to routine monitoring. Fourth, I describe the epidemic intelligence framework for the surveillance and detection of waterborne outbreaks, with the aim of reviewing the status of knowledge of syndromic surveillance for the early detection of waterborne outbreaks. Last, in the final sub-chapter I focus on response measures to the microbiological contamination of drinking water and the updated knowledge on public compliance with BWAs. Throughout Chapter 2, I have a special focus on the Norwegian drinking water supply sector and the national situation on gastrointestinal waterborne illness. Finally, I depict an identified knowledge gap in the prevention of waterborne outbreaks in Norway.

In Chapter 3, I state the aims of this thesis to bridge the identified knowledge gap, which is divided into three parts of investigation: prevention, detection and response to waterborne outbreaks and microbiological contamination events. While in Chapter 4, I argue for a multidisciplinary approach to my overall study objective of the thesis based on the reasoning that drinking water and public health are strongly interlinked. I also present the background of the included papers, data collected and methods used in the study, along with ethical considerations.

In Chapter 5, I present the findings from the included papers relevant to the overall study objective of the thesis and the three lines of studies that addresses specific aims. In the presentation of my findings, I focus particularly on the risks for contamination in the drinking water supply systems, the effectiveness of syndromic surveillance for the early detection of waterborne outbreaks and the public response to BWAs. I also focus on the response capacities observed among small-scale drinking water supply systems. Based on my the studies in the included papers to this thesis, I discuss my findings and examine how these address the aims of the thesis and whether there is a relevance to the overall objective of the study in Chapter 6. Finally, in Chapter 7, I highlight the main conclusions of the findings and determine the implications for the prevention of waterborne diseases in Norway. I also make suggestions for further research topics.

# 2 Status of Knowledge

In this chapter, I describe the status of knowledge of water and health in relation to drinking water supply systems and the risks for waterborne outbreaks in high-income countries. First, I elaborate on the understanding of the overall public health issues related to drinking water supply systems and briefly address the current understanding of infection and humans. I further highlight some emerging public health concerns related to drinking water supply systems. Then, I describe the status of knowledge related to measures for the prevention of waterborne outbreaks, syndromic surveillance and outbreak detection, and responses to microbiological contamination in drinking water.

## 2.1 Drinking water and public health

Public health is defined as 'the art and science of preventing disease, prolonging life and promoting health through the organized efforts of society' (51). The main learning points from Snow's findings when investigating the cholera outbreak in London in 1854 were significant for the future development of water supplies; only by understanding the 'mode of communication' of the cholera was it possible to prevent it (1). This finding led to a shift from focusing on the mode of communication explained by the miasma theory to the understanding that drinking water can be a vehicle for pathogens (52). Snow's findings greatly affected the water supply sector technically by ensuring the separation of sewage as a source of faecal pollution and introducing basic treatment measures such as filtration and chlorination (52, 53).

At present, the delivery of safe drinking water is a result of the developed understanding of drinking water and health, the management of risks, official control and the knowledge of the best available technology (35). For people living in high-income countries, it is difficult to imagine living in a modern city without having a functional water supply system serving safe water for drinking, personal hygiene, toilet flushing and critical societal functions, such as water for firefighting (47).

The development of water supply treatment and distribution systems has been referred to as – perhaps – the biggest improvement to public health in the 'Western world' (54). The 'sanitary revolution' was awarded the most important medical advance since 1840, closely followed by the discovery of antibiotics and anaesthesia by readers of the British Medical Journal (55).

However, despite precautionary actions in terms of water treatment in high-income countries, waterborne outbreaks still occur (56) and remains a recurrent threat to public health (57).

### 2.1.1 Contaminated water and infection in humans

The understanding of drinking water and infection in humans has evolved significantly since the link between the ingestion of contaminated drinking water and health was established. In general, infectious diseases result from the interaction of agents, host and the environment. This interaction of mixing patterns with other people, and with animals, influences the frequency of infectious diseases (5). These transmission dynamics of infectious diseases must be taken into account when investigating the spread of infectious diseases and the measures required for disease control (5). Diseases may be prevented by eliminating at least one of the links in the chain of infection (58).

The sources of contamination of pathogens to drinking water come from human or animal excreta (59). Water contamination by human waste originates, often from municipal sewage water systems or local septic tanks where, due to a malfunction, such as overflows, the discharge of human waste to the environment may occur (38). Animal waste from agriculture or wildlife is mainly associated with surface run-off to water bodies or through intrusion at vulnerable points in drinking water supply systems, particularly for small-scale water supply systems located in areas with farmland activities (38). Equivalent to the spread of infectious diseases across borders, there are concerns about the risk of waterborne outbreaks due to an increase in the hygienic load related to the import of new or re-emerging pathogens from persons travelling abroad, the pressure of expansion of dwelling areas, and activities near raw water sources (47).

#### Classification of water-related diseases

Classification within infectious diseases is an important tool when it enhances understanding, communication and effective action (65). Significant progress has evolved in describing infections related to water that impact how the diseases are prevented (60). In the area of water-related diseases, a range of factors affect the attempt to classify the disease, which include, for example, the mode of transmission, symptoms, behaviour within water and response to water treatment processes (59, 61).

Bradley's classification, proposed by White et al. in 1972, is a widely used classification of water-related diseases (61). The classification aids the understanding of the problem of water-related diseases in a worldwide context based upon epidemiologic considerations and permits generalisations about the likely effect of environmental changes and other actions on their incidence (Table 2) (60).

Table 2 Classification of water-related diseases, adapted from Bradley's classification

| **Class** | **Transmission route** | **Example of pathogens** |
|---|---|---|
| Waterborne diseases | Faecal-oral route | Cholera, typhoid |
| Water-washed diseases | Linked to poor hygiene due to lack of water | Trachoma |
| Water-based diseases | Infection through ingestion or by contact | Dracunculiasis, e.g. schistosomiasis and leptospirosis |
| Water-related diseases from insect vectors | Linked to the presence of a water body | Malaria, dengue, yellow fever and other arboviral infections |
| Water-engineered diseases* | Growth of opportunistic bacteria in in-house water pipes | *Legionella*, *Pseudomonas aeruginosa* |

*Addition suggested by Bartram et al., 2015 (62)

Waterborne diseases are transmitted through the ingestion of contaminated water, where water acts as the passive carrier of infectious or chemical agents. Classic waterborne diseases include the bacterial disease cholera and typhoid fever. However, as other bacteria, viruses, protozoa and helminths through the faecal-oral route of transmission may also cause waterborne diseases, it is a challenge to distinguish waterborne diseases from those caused by contaminated food and poor hygiene, which follow the same route (60).

Since White et al.'s (62) proposal, the awareness and knowledge of sources of contamination between the water source and point-of-use have evolved. For example, in high-income countries, it is now common knowledge that the distribution system may be vulnerable to contamination during low-pressure events (31). The same accounts for the knowledge of causative agents, which comprise several more agents now than when the classification was published (62).

Bradley's classification has had a great impact on our understanding and communication about water and infection. However, in a high-income context, such as Norway, water professionals would not associate closely with diseases in the Bradley's classification such as water-washed, water-based or water-related diseases from vectors, as they are perceived as not particularly relevant after several precautionary actions and hygiene improvements. Also, the classification does not fully cover the complete picture of water-related diseases as we know them today, particularly for the emerging issue of *Legionella* (62), for which the mode of transmission has become more understood (59). To accommodate aerosol-transmitted diseases, an additional class has been proposed; engineered water systems (62). The void in the classification, however, does not relate to a fundamental lack of understanding of water and infection but rather to the work of White et al. (62), which emerged from a rural setting in the developing regions of the world and thus has limited applicability in industrial or urbanised areas (62).

#### Causative agents in drinking water

Several agents have been identified as causes of waterborne disease, supported by strong evidence from epidemiological investigations and case stories (59). In addition, while several agents are suspected to cause waterborne disease, conclusive evidence is lacking (59). In general, the etiological agents in outbreaks may be multiple and not caused solely by a single agent (68). Previous outbreak investigations have revealed that some of the largest outbreaks in more recent times have been caused by agents such as *Cryptosporidium*, norovirus, *Giardia*, *Campylobacter*, and rotavirus (56). Some of these pathogens lead to severe and sometimes life-threatening diseases (typhoid, cholera, hepatitis A) and diseases caused by *Shigella spp*. and *E. coli* O157 (59). Others are typically associated with less severe outcomes, such as self-limiting diarrheal disease (e.g. noroviruses, *Cryptosporidium)* (59).

### 2.1.2 Hygienic barriers and critical control points in drinking water supplies

Drinking water supplies in high-income countries differ from those in low-income countries in terms of design and infrastructure. In urban areas a typical water supply systems have several residents connected and the general hygiene level is high, however, the drinking water supplies run the risk of contamination during production and distribution, thus exposing many residents in a short time span (63). In more remote areas, in particular in low-income countries, the risk for contamination and exposure to pathogens is more closely linked to challenges in maintaining sufficient hygiene due to the management of drinking water in households after collection and storage (64). Usually, urban drinking water supply systems comprise a raw water source, treatment and distribution network, which are typical ‘critical control points’ (65) (Table 3).

Table 3 Points of contamination with high risk in drinking water supply systems

| Point of contamination | Examples of hazardous events |
|---|---|
| **Source waters (surface or groundwater)** | • Runoff of animal and human waste and sewage into source water during wet weather<br>• Intrusion of contaminated water into groundwater aquifer through cracks in mountains or flooding of wells in gravels<br>• Contamination from activities such as small-scale sanitation facilities, hiking/camping and similar in influence areas to source waters |
| **Treatment process** | • Breakthrough in filtration beds<br>• Failure in coagulation/filtration process<br>• Failure in the disinfection process<br>• Flooding of buildings/protections for wells |
| **Distribution system** | • Intrusion of contaminated water through leaky pipes, under the situation of pressure drops<br>• Cross-contamination of drinking-water systems with non-potable systems (e.g. wastewater pipe)<br>• Resuspension of biofilms or sediments in pipes due to high-volume outtake of water (e.g. firefighting) |
| **Water storages** | • Intrusion of contaminated water through natural cracks or flaws in the building structure<br>• Entering of animals (rodents, etc.) in the storage through openings such as cracks, unprotected airing installations |
| **Building distribution systems** | • Back-flow of cross-connections with sewage systems<br>• Resuspension of biofilm growth |

In Table 3, the points at risk of contamination along the supply chain of drinking water is highlighted. In general, drinking water may be contaminated if the treatment process fails or becomes overwhelmed, or there is an intrusion of polluted water during distribution caused, for example, by pressure loss in pipelines or at points where the system is not protected by pressure (reservoirs, pump stations, etc.). In a review of waterborne outbreaks in Europe, North America and New Zealand, among 66 identified outbreaks, the causes were the contamination of raw water from surface waters (13/66) and groundwater (11/66), treatment deficiencies in the water treatment plant (18/66) and distribution system failures (26/66) (56). Most cases were attributed to the contamination of raw water sources or failure in disinfection, which is expected considering the exposure. In terms of these events, distribution failures accounted for more of the identified outbreaks than the contamination of raw water sources and treatment deficiencies.

## Management of risks: A multi-barrier approach

A core concept of the management of risks in drinking water supplies is the implementation of hygienic barriers. Hygienic barriers may be defined as 'natural or implemented barrier, or measures that remove or inactivate pathogenic microorganisms; or dilute, remove or convert chemical substances to a level that do not represent a harm to humans' (66). The concept of hygienic barriers has been subject to change, moving from a more static perspective of counting the number of barriers and ensuring a minimum of two independent operating barriers to a more risk-based approach that takes all possible risks into account: a ‘multi-barrier approach’. The idea of a multi-barrier approach is to remove or manage all identified risks continuously, thus reducing the risk of the potential contamination reaching the consumer, although the risks will never be eliminated (67).

### Risk of contamination in the drinking water distribution system

Of the listed critical control points in Table 3, much emphasis has been placed on implementing hygienic barriers in the raw water source, for example, by limiting activities and protecting areas against contamination, and in the treatment process by designing two independent processes in case one of them malfunctions (59). However, there is increased awareness that the distribution system in itself represents a risk factor for gastrointestinal illness (30). Due to loss of pressure in the supply system, pathogenic viruses, bacteria and parasites may enter the distribution systems in numerous ways, representing a public health risk for infectious diseases to consumers (68).

Three key susceptibility conditions must be met for an accidental intrusion to occur in a distribution system: adverse pressure gradient, intrusion pathway, and contaminant source (69). Theoretically, this requirement implies that residents served by a water supply system are protected from contaminated water as long as positive pressure in the pipelines is maintained. However, in practice, pressure loss is unavoidable due to sudden pipe breaks or planned outages during maintenance. In a systematic review and meta-analysis, an association between distribution deficiencies and gastrointestinal illness indicated a three times higher risk if affected by a water outage (31). In terms of outbreaks, it is estimated that, in North America, the distribution system could account for approximately 30% of waterborne outbreaks (70). The pathway of contamination – the intrusion of polluted water – is established through epidemiologic studies. However, there is a knowledge gap regarding how factors such as dose response and the environment influence gastrointestinal illnesses through the consumption of drinking water after a water outage (68). A methodological approach using a quantitative microbial risk assessment (QMRA) has been applied to overcome such challenges and to inform decision-making (71).

### 2.1.3 Climate change, drinking water and implications for human health

An emerging concern for public health and drinking water is the effect of changing climate parameters. Climate change is expected to affect human health in several ways, including water-related diseases (72). 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 (73). Because of the projected impacts of climate change on hydrological systems, water-related diseases are among the primary expected health impacts of climate shifts, and since water-related diseases contribute significantly to the global burden of diseases (3), even small changes in the water cycle and availability of water may have substantial impacts on diarrheal diseases. In addition to mortality, including impaired growth and cognitive development, an increase is expected in susceptibility to other infectious diseases (74).

The main climate change parameters are often referred to as heavy rainfall, floods, ambient temperature and droughts (75). It is reported that heavy rainfall and flooding were the most common events preceding outbreaks associated with extreme weather (76). 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 ground water sources, and overwhelming water and sanitation infrastructure (75). Outbreaks following extreme water-related weather events is reported to often be the result of contamination of the drinking water supply (76). Considering that the effects of changes in climate parameters are intertwined and not linked to a single event, heavy rainfall may lead to more turbidity in the raw water, resulting in an overwhelmed water treatment process. As a result, the water is not treated adequately, and the risk of contaminating the drinking water and the ingestion of pathogens and diarrheal incidences increases (75).

It is anticipated that heavy rainfall and flood events will affect the context of Norway (77). Strong evidence points to an association between climatic factors, such as heavy rainfall, and food and waterborne diseases, such as *Salmonella* and *Campylobacter*, in the sub-arctic region (37). An association was also found between heavy precipitation events and waterborne outbreaks in the Nordic countries for single households, with groundwater as the raw water source during summer (78). Vulnerabilities related to small-scale water supplies are a particular concern, which will be discussed in the following chapter.

### 2.1.4 Small-scale drinking water supply systems

Drinking water safety from small-scale supplies plays an important public health role worldwide since such supplies serve a significant number of people (7). Small-scale drinking water systems are not a feature of low-income countries only. An assessment in the European region of WHO found that 23% (207 million individuals) are served by drinking water supplies serving populations of less than 5,000 people (39). On a national basis, approximately 1,000 of the 1,450 water utilities in Finland are classified as small-scale, serving up to 500 inhabitants, while in Hungary, 75% of the 1,650 water supplies serve less than 5,000 inhabitants (39). In Norway, in 2018, 86% (1,224 of 1,421) of water supplies under official control served less than 5,000 inhabitants, and approximately 5,500 very small water supplies were registered (serving less than 50 inhabitants, or self-registered by owners of small supplies) (22).

The definition of a small-scale drinking water supply system varies, and no one set of official criteria of a ‘small-scale’ drinking water supply system exists (39). However, smaller-scale drinking water supplies have been identified as being particularly vulnerable to a failure to provide a continuous supply of safe drinking water (79) as they share a range of common managerial, financial and institutional challenges and particularities that make them more vulnerable to inadequate management and breakdown, which may impair the provision of sustainable services (39). The true burden of disease associated with small-scale drinking water supplies is not known; however, according to a study of gastrointestinal illness in the Nordic countries, 4 to 18 outbreaks are reported each year, mainly affecting a few people and linked to single supplies (78).

### 2.1.5 Burden of waterborne disease in Norway

Based on the increased knowledge of pathogens causing waterborne diseases as described in the previous sub-chapter, Table 4 presents the cases of waterborne diseases reported as notifiable diseases to the Norwegian Surveillance System for Communicable Diseases (MSIS).[2]

[2] The MSIS is an indicator-based surveillance system for notifiable diseases. The system is operated by the Norwegian Institute of Public Health since 1977.

Table 4 Pathogens transmitted through water supplies that are notifiable in Norway by cases reported per year in the period 2000-2019[a]

| **Pathogen** | **Health significance[b]** | **Persistence in water supplies[c]** | **Resistance to chlorine[d]** | **Relative infectivity[e]** | **Cases reported per year 2000-2019[f], mean (range)** |
|---|---|---|---|---|---|
| **Bacteria** | | | | | |
| *Campylobacter (C.coli, C.jejuni)* | High | May multiply | Low | Moderate | 2,870 (2,160-4,154) |
| *E.coli* enterohaemorragic (E.coli O157) | High | Moderate | Low | High | 390 (27-1,553) |
| *Francicella (F.tularensis)* | High | Long | Moderate | High | 49 (3-183) |
| *Salmonella (S. enterica, S. bongori)* | High | May multiply | Low | Low | 1,373 (866-1,942) |
| *Shigella (S. dysenteriae)* | High | Short | Low | High | 128 (77-194) |
| *Vibrio (V.cholerae* O1 and O139) | High | Short to long | Low | Low | Sporadically imported |
| Picornaviridae (Enterovirus, parechovirus, hepatitis A virus) | High | Long | Moderate | High | 61 (22-180) |
| **Protozoa** | | | | | |
| *Cryptosporidium (C. hominis/parvum)*[i] | High | Long | High | High | 191 (4-379) |
| *Giardia (G. intestinalis)* | High | Moderate | High | High | 394 (179-1,580) |

[a]Adapted from WHO drinking-water guidelines for pathogens for which there is some evidence of health significance related to their occurrence in drinking water supplies.
[b]Health significance relates to the incidence and severity of disease, including associations with outbreaks.
[c]Detection period for the infective stage in water at 20°C: short refers to up to one week; moderate refers to one week to one month; and long refers to over one month.
[d]Within pathogen species and groups, there are likely to be variations in resistance, which could be further impacted by characteristics of the water supply and operating conditions. Resistance is based on 99% inactivation at 20°C where, generally, low represents a $Ct_{99}$ of < 1 min.mg/L, moderate 1–30 min.mg/L and high > 30 min.mg/L (where C = the concentration of free chlorine in mg/L and t = contact time in minutes) under the following conditions: the infective stage is freely suspended in water treated at conventional doses and contact times, and the pH is between 7 and 8.
[e]From experiments with human volunteers, from epidemiological evidence and from experimental animal studies. High means infective doses can be 1-102 organisms or particles, moderate 102-104 and low > 104.
[f]Number of cases reported in the National Register for Notifiable Diseases in the period 2000-2019.
[g]Reported outbreaks linked to drinking water.
[h]Suspected in several outbreaks in the period.
[i]Cryptosporidiosis became notifiable in 2012, and the data represent the period 2012-2019.

In Norway, 4,000-8,000 cases related to pathogens with evidence for transmission through drinking water (59) have been registered annually in the last 20 years. The majority of these cases are imported from abroad and include infections caused by *Salmonella*, *Shighella*, *Campylobacter*, *Giardia* and *Vibrio cholera*.

The MSIS includes only laboratory-confirmed cases. Although several implemented measures have improved the surveillance of waterborne illness, the true burden of waterborne diseases in high-income countries is not perfectly known. This is linked to the phenomenon that notified cases only represent the 'tip of the prevalent ice-berg' (5). In Norway, we anticipate that only a fraction of the cases of gastrointestinal illness are reported in the MSIS (Table 2) since

- a person experiencing gastrointestinal illness may not seek health care for treatment;
- or if he does, he may not be examined for pathogens by stool sample;
- or if he does, the pathogen may not be identified or reported.

Several studies have been conducted to shed light on the disease burden attributed to drinking water in high-income countries (80, 81). However, it is a general challenge within gastrointestinal illnesses to rule out other reasons for the disease than drinking water, such as food or lack of hygiene. Confounding factors are well known to be present in epidemiological studies, which must be accounted for in the results (82). To overcome confounding factors, randomised control trials (RCTs) have been conducted in Canada (83), the United States (US) (84) and Australia (85), reporting different results on the association between tap water consumption and illness. Where a positive association was reported in Canada, it was not in the US and Australia. A possible explanation for these differences may relate to the study design and contextual study area, thus highlighting the challenge in estimating the burden of waterborne diseases; although randomised controlled studies are regarded as the 'gold standard' in study design, they do not necessarily provide results relevant for drinking water supplies in general (86).

Few population-based studies have investigated the burden of gastrointestinal illness in Norway (87, 88); however, both studies provide estimates based on the subjective indication of an association to consume drinking water. Currently, there is an ongoing prevalence study to estimate the burden of disease linked to the consumption of drinking water in Norway, with the expected outcome to be finalised in 2021 (89).

Although knowledge of the burden of disease associated with waterborne illnesses in Norway is incomplete, there exist a more substantial overview of outbreaks linked to drinking water due to systematic recording and reporting. In the following sub-chapters describe waterborne outbreaks, with a particular focus on high-income countries and Norway.

## 2.2 Waterborne outbreaks in high-income countries

Since the main interest of this thesis is waterborne outbreaks, I here establish an understanding of the term and current investigation methods. Further, I provide a review of the investigated outbreaks that have been linked to drinking water supply systems. The aim is to describe the extent and causes of outbreaks that have occurred in settings with urban pipe supply systems that are often associated with high-income countries. The review has a particular focus on waterborne outbreaks in Norway.

### 2.2.1 Investigation of waterborne outbreaks

An outbreak is often defined as an increase of a disease above expected levels in a particular location or population in a given period (5). An outbreak is also commonly defined, which is the case in Norway, as a) some cases of an infectious disease that clearly exceeds the expected level within a given time and area, or b) two or more cases of the same infectious diseases where a common source is suspected (90). Typical features associated with waterborne outbreaks, particularly those in large water supply systems, are the sudden onset of cases, clustering in water supply zones with fewer in adjacent zones often with the occurrence of cases relative to the distribution pattern of drinking water (91).

Common challenges when facing waterborne outbreaks are (91)

- difficulties assessing exposure information since water is the second common exposure and during one day almost everyone is in contact with water,
- an effect on the whole community in terms of pressure on health system and media attention, and
- drinking water supply systems are often technically complicated.

A systematic approach for the timely detection, assessment, investigation and control of an acute outbreak situation is required to ensure the best public health outcome (5). An outbreak investigation is a multidisciplinary exercise, and it is necessary to collect sufficient triangulating data from epidemiological, microbiological and environmental investigations to explain a plausible causal relationship between the exposure and the illness observed (92). By the time a waterborne outbreak is detected, the population has probably already been exposed; thus, control measures are crucial to prevent further cases (91). The implementation of response measures may therefore often be based on preliminary investigations without establishing a definite causal relationship (59).

The investigation of an infectious disease outbreak, including waterborne outbreaks, will generally follow the same framework consisting of epidemiological, microbiological and environmental investigations (91). The steps in an outbreak investigation are a part of a dynamic process; however, the chronological order of the steps may vary or be conducted simultaneously, where hypotheses of the source of contamination are tested, revised or rejected along with the incoming new information (90).

### Epidemiological investigations

In epidemiological investigations, traditional study designs for observational studies are applied. Observational studies are often used where it would be ethically unacceptable to conduct an experimental trial that involves exposure to disease (82). However, observational studies are prone to confounding factors since the outcome of a variable of interest is intermixed with the effects of other variables (82). Adjusting for confounding is therefore necessary to estimate the effect of the variable of interest.

In outbreak situations, observational studies are conducted in a rapid manner, which does not imply that the studies are inaccurate, but rather that it is appropriate and necessary to collect essential information to manage the outbreak (91). The common designs used for epidemiological studies are cohort studies, which may be applied to compare the occurrence of illness among exposed and non-exposed groups of people, allowing for the calculation of relative risks and attack rates among the groups. Cohort studies are often used when the outcome of interest is common. Usually, the cohort study is prospective, but it may also be used to study cause and effect historically (93). Another common study design is a case-control study, which is a classic approach to identify the cause of disease by comparing ill subjects (cases) with corresponding healthy subjects (controls). The purpose is to determine how cases and controls differ in regard to a number of possible etiological factors (82). Case-control studies are relatively inexpensive (due to a low number of participants), rapid and suited to the study of rare diseases (82). Other study designs, but maybe to a lesser extent, applied to waterborne outbreaks are cross-sectional studies and surveys that are conducted within a source population at a particular point in time, and ecological studies that measure the outcome and the exposure at the group level (94).

### Microbiological investigations

Microbiological investigations, which are needed in outbreaks to confirm the pathogen involved to ascertain the infectious disease (93), should be conducted in parallel with epidemiological investigations (91). The etiological diagnosis, which suggests the pathogen involved in the outbreak, provides important information in the investigations (90). This information contributes to establishing and testing the hypothesis about the source of infections and hygienic failures and possible specific measures (90). A comparison of pathogens isolated from the cases and sources of contamination is needed to confirm or reject a possible relationship in the outbreak. However, isolating the pathogen in the drinking water is difficult since the drinking water is in constant flow and the contaminated water may have passed when the outbreak is detected. A relatively large volume also makes the analysis of microbes difficult (53).

The technical advances in terms of whole genome sequencing (WGS) have played a greater role in microbiological investigations in infectious disease outbreaks than conventional methods such as pulse-field gel electrophoresis (PFGE) and multi-locus sequence typing (MLST) (95). The subtyping resolution and evolutionary context provided by WGS data allow investigators to connect related illnesses that would be missed (96). Genotypic analyses are based on characterising DNA- or RNA-profiles (90), and these findings allow for differentiating between outbreaks that may be caused by the same agent but from a different genotype. The detection of the same pathogen in cases and the environment (e.g. drinking water) is not always sufficient evidence to determine an epidemiological relationship if the pathogen is at the same time a common species in other sources (90).

### Environmental investigation and assessment

The objective of the environmental assessment in waterborne outbreaks is to identify the source of contamination in the water supply system. This includes evaluating the effectiveness of the existing control measures and possible both internal and external system failures that may have compromised system safety (91). The water supply personnel in the organisation are key sources of system performance and historical and outbreak-related information, including flow diagrams of the supply system, routine monitoring results and documents such as water safety plans (WSPs) or project plans (91). Other relevant data obtained in environmental investigations are weather reports, such as rainfall, snow thaw and drought that may have triggered faecal contamination to the system and visual inspections of the system in general or points suspected as a source of contamination (91).

Environmental investigations and assessments of waterborne outbreaks need some special considerations. The drinking water supply systems in high-income countries are typically complicated systems compared to those in low-income countries, which may require expertise to support the outbreak situation. If the pathogen is known and waterborne, the investigation can focus on investigating possible failures in the supply system, and an additional spatial investigation may be useful to identify the potential sources (91).

### Cause of the outbreak

Based on the investigations, generating and evaluating the hypothesis is essential for identifying the sources of the outbreak and providing strong evidence to justify the targeted control measures (91). Although finding the direct cause of a waterborne outbreak is imperative to end the outbreak and ascertain the control measures, an understanding of the indirect causes is also important to prevent future outbreaks. For example, if the contamination event that resulted in an outbreak was caused by a malfunction disinfection process, the managerial and technical factors need to be assessed (16). Reducing the cause to a purely technical issue would miss the structural context affecting the risk of failures (16, 41).

### 2.2.2 Historical documentation of waterborne outbreaks up to the 1990s

Historical documentation of public health effects due to waterborne diseases caused by the contamination of drinking water supply systems is generally lacking worldwide, and mainly only present where health structures are in place (63). The most comprehensive source of information probably originates in the US (54), where national reporting started in the 1920s. Reporting after 1971, when the US Environmental Protection Agency (EPA) Centers for Disease Control and Prevention (CDC) was established, is more systematic and contains information on water system deficiencies, which provide a benefit in assessing risks.

Although the reporting in the period from 1920 to 1970 is subject to errors (e.g. due to inadequate outbreak investigations) and underreporting, the characteristics of waterborne outbreaks in this period show an increasing trend in the number of waterborne outbreaks overall up to the 1950s. In the post-war decades, from 1950 to 1970, the total number of waterborne outbreaks decreased significantly (97). However, in the US after 1971, the number of waterborne outbreaks started to peak (97). One likely explanation for this peak is the increase in the systematic and comprehensive surveillance of waterborne outbreaks conducted by the CDC, and not due to an increase of outbreaks *per se* (60). Another likely explanation is the emergence of new risks in water supplies, for example, the increasing awareness of chlorine-resistant parasitic protozoa (98). Without such a long-term systematic collection and analysis of data and outbreak investigations, the existing and emerging risks would be challenging, if not impossible, to spot (59).

### 2.2.3 Review of large waterborne outbreaks

Several serious water emergencies in the 1990s and at the beginning of 2000, mainly in the US and Canada, placed risks related to drinking water on the agenda yet again, leading to an increased focus on the management of risks in drinking water systems to protect public health (99). Some of these outbreaks have been thoroughly investigated, and I elaborate on some of the most significant ones before focusing on waterborne outbreaks in Norway.

#### Waterborne outbreaks outside of Norway

The outbreak in Milwaukee, Wisconsin, in 1993 is the largest documented waterborne outbreak in US history (16). The outbreak was detected when the health authorities were contacted after reports of numerous cases of gastrointestinal illness that had resulted in widespread absenteeism among hospital employees, students, and schoolteachers (14). An outbreak investigation was initiated, which revealed that approximately 403,000 individuals had been infected by *Cryptosporidium*, and 69 deaths, mainly among immunocompromised patients, were suspected to be linked to the outbreak (16). The outbreak had gone undetected due to compliance with water-quality standards, and the testing of patients for cryptosporidiosis was not adequate to detect the outbreak (14). The magnitude of the outbreak in Milwaukee was subject to several studies and discussions in the aftermath.

Following the outbreak in Milwaukee, two outbreaks in Canada occurred, which have also been thoroughly investigated (16). In Walkerton, Ontario, in May 2000, a waterborne outbreak occurred after the drinking water system became contaminated due to heavy rains, most probably from manure that had been spread on a farm near the well (15). The first indications of the outbreak were absentees from school (15). The outbreak investigation revealed that *Escherichia coli* O157:H7.1 and *Campylobacter* in the drinking water caused 2,300 people to be ill and seven to die (15). The inquiries into the outbreak revealed that operators lacked the training and expertise necessary to identify either the vulnerability of well to surface contamination or the resulting need for continuous chlorine residual and turbidity monitors (15). The inquiries to the outbreak were substantial, including direct and indirect causes to the outbreak and included recommendations to improve water safety for the region as a whole (15). Despite the lessons-learned, less than one year after the Walkerton outbreak, another severe outbreak occurred Canada. In North Battleford, Saskatchewan in 2001 (17), an estimated 5,800 to 7,100 people from the Battleford area were ill from *Cryptosporidium parvum*. The most likely cause was treatment deficiencies following maintenance work because of increased turbidity (16).

During the same period, several other large outbreaks were reported in the US. In 2004, in Ohio, 1,450 people became ill from *Campylobacter* and norovirus due to the contamination of the groundwater aquifer from septic systems, the application of sludge and the infiltration of run-off to the well (100). In the same year in Ohio, another outbreak caused illness among 1,450 people from multiple etiology (*Campylobacter*, *E. coli* and norovirus), where the source contamination originated from distribution deficiency related to untreated ground water (101). An outbreak of unknown etiology occurred in Florida in 2007, most likely due to operation and maintenance deficiencies in the drinking water treatment causing 1,650 people to get sick, while an outbreak in 2008 in Colorado, likely caused by animal contamination of a reservoir tank, caused 1,300 cases of unknown etiology (102).

Since the beginning of 2000, a number of outbreaks linked to drinking water have been recorded in the United Kingdom (UK) and Ireland, which have been mainly due to *Cryptosporidium* after contamination of waters, treatment deficiencies or deviations in the distribution system (56).

A series of large waterborne outbreaks have also put the risks and health consequences on the agenda in the Nordic countries. In Nokia, Finland, in 2007, a waterborne outbreak was caused by a valve in the wastewater plant connecting the drinking water line with a wastewater effluent line. As a consequence, the drinking water network became contaminated with sewage effluent, causing 8,453 persons to be ill from multiple etiology (norovirus, *Campylobacter* and *Giardia*) (103).

In Sweden, three sever waterborne outbreaks have been reported in less than 15 years. In Lilla Edet, in 2008, approximately 2,400 of the 13,000 inhabitants became ill from norovirus gastroenteritis caused by contaminated municipal drinking water (19). The source of the contamination was probably linked to heavy rainfall events that had led to sewer overflows both upstream of Lilla Edet and in Lilla Edet (19). In Östersund in 2010, approximately 27,000 inhabitants were affected by a waterborne outbreak of cryptosporidiosis, which made it the second largest reported waterborne outbreak of cryptosporidiosis globally. The outbreak was probably caused by insufficient reduction of parasites by the municipal water treatment plant (104). Only six months later, another outbreak caused by *Cryptosporidium* occurred in Skellefteå in 2011, a neighbouring municipality to Östersund (105). Approximately 18,500 individuals were affected by a waterborne outbreak of cryptosporidiosis. The outbreak went unnoticed by authorities for several months; it had likely had started in January the same year, and although possible sources of contamination were investigated and discussed, no conclusive information could be found (106).

Two waterborne outbreaks occurred within a relatively short period in the small town of Koge in Denmark. The first in 2007 led to 140 cases of *Campylobacter*, *E. coli* and norovirus after a technical and human error at a sewage treatment allowed wastewater into the drinking water system. The second in 2010 was caused by *Campylobacter jejuni* and resulted in approximately 400 cases of illness; however, the source of the contamination was inconclusive (107).

### Waterborne outbreaks in Norway

Waterborne outbreaks have been thoroughly investigated in Norway. In the period 1988-2003, 72 waterborne outbreaks were registered, representing 10,616 cases (108). The main causative agents were *Campylobacter* (86%, 19/72), norovirus (18%, 13/72) and the remaining had unknown etiology. The main cause (62% of the reported outbreaks) was due to the lack of disinfection, where none of the privately owned water supply systems in the study had implemented disinfection measures (108). Outbreaks registered in the outbreak surveillance system to the Norwegian Institute of Public Health, which were suspected to be caused by drinking water, were examined in the period 2003-2012 (25). Twenty-eight of those waterborne outbreaks representing 8,060 cases were reported (25). In half of those cases, the outbreaks were linked to drinking water from water supply systems (16/28 outbreaks, 57%), and a relatively high number were linked to single household drinking water supplies (12/28 outbreaks, 43%) (25). While the majority of the outbreaks resulted in less than 100 cases, two of the outbreaks involved more than 1,000 cases. A *Campylobacter* outbreak in Røros resulted in an estimated 1,500 cases (109), and a *Giardia* outbreak in Bergen had an estimated 5,000-6,000 cases (110).

The outbreak in Bergen in October 2004 was detected after an increase in laboratory-confirmed cases of giardiasis was reported. The outbreak investigation indicated that the first cases had already fallen ill at the end of August, and it was estimated that 5,000-6,000 persons became ill with giardiasis. The most likely source of the contamination was leaking sewage pipes combined with insufficient water treatment. Prior to the outbreak, a water treatment plant with filtration and disinfection by UV radiation had already been commissioned for the affected water supply, with the planned start of operation in 2007. Late detection contributed to the huge public health impact of the outbreak (110). In Røros in 2007, about 1,500 cases were reported due to *Campylobacter* (109). The first hypothesis was that the contamination happened due to a failure in the distribution system, but a later investigation after the snow had melted revealed that one well, which was unprotected during the construction work under establishment, may have been contaminated by birds resting on top of the pipe.

Similar thorough examinations of waterborne outbreaks have not been conducted since the period described above. However, the Norwegian Outbreak Surveillance System (VESUV),[3] has reported one to two outbreaks suspected to be caused by drinking water annually between 2013 and 2019.

The plausible causes in the most sever reported outbreaks in Norway, based in available information, both peer reviewed and non-peer reviewed, demonstrate a variety from

[3] The VESUV is an event-based alert portal, which was established in 2005 and is operated by the Norwegian Institute of Public Health. The system is designed to take care of the obligations of the local health and specialists and the Norwegian Food Safety Authority to report outbreaks.

contamination of raw water source, lack of disinfection or contamination during distribution (Table 5).

Table 5 Overview of plausible causes for contamination in waterborne outbreaks involving more than 1000 cases in Norway based on historically available information and peer reviewed publications, 1981-2019.

| Year | Estimated cases | Causative agent | Plausible cause/explanation | Reference |
|---|---|---|---|---|
| **2019** | 2,000 | *Campylobacter* | Contamination of water reservoir, probably due to heavy rainfall | (28)* |
| **2007** | 1,500 | *Campylobacter* | Contamination of raw water source (wells) during construction (unprotected) | (109) |
| **2004** | 6,000 | *Giardia* | Use of raw water source with chlorine as only treatment (lack of hygienic barrier) | (110) |
| **1994** | 2,000 | Norovirus | Use of reserve water source which had inadequate water quality, while at the same time, the chlorine pump failed | Internal** report |
| **1992** | 2,000 | Norovirus | Leakage from polluted river water to drinking water storage | Internal** report |
| **1981** | 2,000 | *Campylobacter* | Gulls present in water storage, no disinfection | Internal** report |

*The reported waterborne outbreak is included in the empirical corpus in this thesis.

**Reports from the Norwegian Surveillance System for Notifiable Diseases.

A certain underreporting of waterborne outbreaks in Norway suggests that either they are not detected or they are detected but not reported or investigated (26).

## 2.3 Prevention of waterborne outbreaks

The previous chapter elaborated on the knowledge gained about water and infections in humans and the public health implications of contaminated drinking water. In this section, I describe the current preventive measures, in terms of the 'best practice' and regulatory instruments, towards waterborne outbreaks in high-income countries.

### 2.3.1 Framework for safe drinking water

Several serious water emergencies in the 1990s and beginning of 2000, as described in the previous sections, led to an increased focus on the management of risks in drinking water systems to protect public health (99). A common feature of the outbreaks investigated in these water emergencies was parasitic protozoa as the causative agents. Investigations into the outbreaks showed that parasitic protozoa, particularly *Giardia* and *Cryptosporidium,* were a risk factor in drinking water from the early 1980s through to the 1990s, as experiences revealed that they were particularly resistant to conventional disinfection processes such as chlorine (98). Hence, public health was not adequately protected, and other approaches were needed. As a result, a framework for safe drinking water was developed. According to the WHO, the basic and essential requirements to ensure the safety of drinking water comprise ‘health-based targets established by a competent health authority, adequate and properly managed systems (adequate infrastructure, proper monitoring and effective planning and management) and a system of independent surveillance’ (59). A key message in this framework to ensure safe water is to have a knowledge of risks – and eliminate them – all the way ‘from source to [the] consumer’s tap’ (99).

#### Water Safety Plans (WSPs)

Since the middle of the first decade of 2000, the WHO has advocated WSPs (99, 111). The concept of water safety planning comprises system assessment and design, operational monitoring, and management plans, including documentation and communication (112). The elements of a WSP build on the multiple-barrier approach principle, the principles of hazard analysis and critical control points, and other systematic management approaches. The plans should address all aspects of the drinking water supply and focus on the control of abstraction, treatment and delivery of drinking water (64). The approach has been widely implemented, both in practice and in legislations, yet the effects in terms of health outcomes have not been systematically demonstrated. A study from Iceland reported a decrease in microbiological content in the drinking water, indicating that the population was 14% less likely to develop diarrhoea (113). A similar study was conducted in France and Spain, where the changes in water quality remained the same and gastrointestinal disease was only observed in one of the locations studied (114).

### 2.3.2 Regulatory instruments

An essential preventive measure for waterborne outbreaks, along with proper technical design, is the use of regulative instruments that ensure management and follow-up actions for the continuous supply of safe drinking water. The WHO describes four distinct types of health-based targets applicable to all types of hazards and water supplies (59):

1) Health outcome targets (e.g. tolerable burdens of disease)

2) Water quality targets (e.g. guidelines values)

3) Performance targets (e.g. log reductions of specific pathogens)

4) Specified technology targets (e.g. application of defined treatment processes)

These targets are common components of existing drinking water guidelines or standards that are used to improve drinking water quality and, consequently, protect human health (59). Health-based targets based on a health outcome, if often measured in established methods such as disability-adjusted life years (DALYs), are mostly used in less-resource settings. In high-income countries and in the European Union member states, regulatory instruments based on water quality targets are more common, followed by obligations related to the daily operation, long-term planning, and internal control system and preparedness measures. The more common and publicly available references of such regulatory instruments are from the US (115), Canada (116), Australia (117) and the European Union (118).

### The Norwegian drinking water legislation

The Norwegian drinking water legislation have undertaken an incremental development. The first Norwegian drinking water legislation came into force in 1951, providing the mandate for official control to the health authorities. The first legislation comprised guideline values and technical requirements for filtration and chlorination. The first harmonisation with the European Economic Area (EEA) Agreement (119) occurred in 1995, introducing the concept of hygienic barriers. Still, chlorination was mandatory, but the water supply system was required to have a minimum of two independent hygienic barriers.

In Norway, UV radiation has been applied since the 1970s, although this was more for practical reasons than because of an awareness of the risks of parasitic protozoa. Hygienic barriers for parasites were not foreseen as particularly relevant for Norway at the beginning of the 1990s. A mapping of their presence revealed low numbers in the surface water, and the risks were more or less viewed as an issue for the more ‘exotic’ areas of the world (120). However, in the 2001 revision of the Norwegian Drinking water legislation, the notion of disinfection as a hygienic barrier expanded from only chlorination to include UV radiation, ozone and membrane filtration. In terms of content and function, Norwegian Drinking water regulations have developed from technical requirements (e.g. application of defined treatment processes) to require compliance with quality standards, hence, addressing the responsibility for technical solutions to the water suppliers and not at the authorities.

After a further administrative revision due to the EEA Agreement in 2001, the responsibility for official control of the water supply was transferred from the health authorities to the newly established Norwegian Food Safety Authority in 2004. A part of the reasoning for this shift was to avoid that the decisions concerning water supply were made auspices of municipalities, which were the authority for both approval and control.

The drinking water legislation was last updated in Norway in 2017 (66). One of the overarching elements in the Norwegian Drinking water legislation is an obligation to conduct a hazard assessment that informs all decisions to ensure safe drinking water, applying a multiple barrier approach. Another area that has been strengthened in the last revision is the obligation to focus on the renewal and safe management of the distribution system and the duty to inform the residents in case of suspected, harmful water quality. The EU drinking water regulation is under a major revision as of November 2020 (the first since it was implemented in 1998). Significant changes are expected to be the inclusion of *Legionella* and a stronger emphasis on the human right to water. The Norwegian Drinking water legislation will be revised accordingly to harmonise it with the changes resulting from the EEA agreement.

### Protocol on Water and Health

Of other instruments implemented to ensure safe drinking water is the United Nations Economic Commission for Europe (UNECE) and WHO regional Office for Europe Protocol on Water and Health, which was adopted in 1999 and entered into force in 2005 (121). This protocol is the first international agreement of its kind adopted specifically to attain an adequate supply of safe drinking water and adequate sanitation for everyone and to effectively protect water used as a source of drinking water (121). The Protocol aims to protect human health and wellbeing by improving water management, including the protection of water ecosystems, and by preventing, controlling and reducing water-related diseases (121). The driving factor to achieve this ambition is the obligation to establish national goals, designed according to the situation in the country, for safe drinking water and to systematically implement actions for improvements. Norway ratified the agreement in 2005 and formally adopted national goals in 2014 (122). Several actions have been implemented in Norway under the auspices of the Protocol for Water and Health for the prevention of waterborne outbreaks and illnesses, of which the most important are the Drinking Water Study (89) and the National Water Guard (NWG), a crisis advisory service for water supplies (123).

### 2.3.3 Surveillance of drinking water supplies

Routine drinking water quality monitoring serves an essential function as verification, operational and validation in water supplies to oversee the effect of the safe measures implemented (66). Faecal indicator bacteria monitoring is used to check the presence of potential pathogens in the drinking water. The presence of *E. coli*, for example, indicates whether the drinking water may have been contaminated with faecal matter from humans or animals (53). Moreover, routine monitoring results are needed for the assessment of compliance with drinking water standards laid out in the regulations and for reporting to authorities. Long-term assessment of reported data from routine monitoring makes it possible to spot new or re-emerging risks (59).

Routine monitoring data is a key source of information for water supplies in Norway (22). The water supplier reports drinking water data, such as routine monitoring data, along with administrative and internal control system management information to the Norwegian Food Safety Authority in a one-off yearly campaign. However, in case a breach of faecal indicator bacteria is detected, the water suppliers would normally prompt action to rectify the situation to bring it back to normal. Such an event is notifiable to the Norwegian Food Safety Authority (66).

Although traditional routine monitoring conducted by the water works serves an important function in terms of performance of the water supply system, it does not serve the purpose of monitoring imminent health risks in the distribution system or detecting outbreaks or disease surveillance (124). Microbial monitoring is an end-product testing for faecal indicator bacteria, and since the analysis needs 24 to 48 hours, by the time the test results are available, the water will already have been consumed (125). Contamination events may not necessarily be detected due to infrequent sampling. In that respect, faecal indicator bacteria analyses represent a retrospective check rather than a proactive demonstration of safety (125). In addition, faecal indicator bacteria are not always indicative of other important microbial parameters (e.g. the ones that may be resistant to chlorine or viruses). Therefore, when assessing the outcome of faecal indicator bacteria in isolation, little information is provided about the system as it does not alone create an understanding of the hazards, hazardous events and control measures in the water supply system (125).

Risk-based drinking water surveillance has been suggested as the best practice within the framework for safe drinking water (59). The approach represent a shift in focus from an overreliance on the compliance testing of a predetermined list of water quality parameters to promoting a proactive approach to identifying, controlling and monitoring critical risks in the water supply (125). A core element of risk-based surveillance is to conduct a hazard assessment; by knowing the existing risks, one is better able to manage these risks. Important components of risk-based surveillance are water quality monitoring, on-site inspections, hazard identification and risk and trend analysis. By applying a risk-based approach in drinking water surveillance, it is expected that countries will focus more on the issues that are most important for the protection of public health and maximise the benefits that they can accrue from limited resources (125).

A risk-based approach is, to various degrees, formalised in drinking water legislations, for example, the last amendment to the EU Drinking water directive, which allows for the derogation of monitoring parameters if documented as not needed (125). Norwegian Drinking water legislation differentiates requirements for water suppliers after size (i.e. the larger the amount of drinking water produced, the higher the frequency of the water sampling in the routine monitoring schemes), which is an interpretation of the 'risk-based' approach. The Norwegian legislation incorporates risk-based elements informed by the hazard assessment, which in practice means that the water supplier's responsibility is to identify hazards that should be monitored beyond the minimum requirements laid out in the drinking water legislation.

## 2.4 Surveillance of waterborne diseases and outbreak detection

In the previous sections, I described current preventive measures for waterborne outbreaks, which are often based on lessons learned from outbreak investigations. In this chapter, I elaborate on the core functions of surveillance of waterborne disease and outbreak detection, with a particular focus on the status of knowledge of syndromic surveillance.

### 2.4.1 Core function of surveillance

Surveillance is the ongoing systematic collection, analysis and interpretation of health-related data for use in planning, implementing and evaluating public health policies and practices (126). In terms of water supply, surveillance serves a core function for the continuous public health assessment and review of the safety and acceptability of water supplies (125).

The surveillance of waterborne disease may have some objectives at both national and regional/local levels, which involve the coordination and cooperation between disease surveillance agencies and drinking water suppliers to ensure a timely response to possible waterborne outbreaks (91) (Table 6).

Table 6 Purposes of surveillance at different administrative levels

| Administrative level | Purpose |
|---|---|
| **National** | • Temporal trends in the incidence and prevalence of waterborne diseases<br>• Identify new and re-emerging pathogens, estimate the burden of disease<br>• Inform national priorities, policies and regulation |
| **Regional and/or local** | • Detect possible waterborne disease outbreaks<br>• Identify groups and communities who are at higher risk of waterborne diseases<br>• Inform local or regional policies<br>• Target control measures |

A waterborne outbreak is often detected when there is an increase of a disease above expected levels in a particular location or population in a given period (5). Detecting waterborne outbreaks early is challenging, since at the time the first cases are identified, a large proportion of the population is likely already exposed (91). Early detection is therefore crucial for the possible implementation of control measures, which may be in conflict with processing the data from identifying cases to obtaining information on the diagnosis, pathogen and confirmation of cases (91). In the following, I describe elements in an epidemic intelligence framework, with a particular focus on syndromic surveillance and implications for the early detection of waterborne outbreaks.

### 2.4.2 Indicator- and event-based surveillance

The main components of an epidemic intelligence framework for outbreak detection are indicator-based surveillance and event-based surveillance (127). Indicator-based surveillance reports structured standardised data such as laboratory-confirmed infections, while event-based surveillance reports unstructured data from any source, such as media reports or a health facility reporting an excessive number of cases presenting at the emergency department (91). These may also be described as passive and active surveillance systems. Passive surveillance systems are easy to set up and require fewer resources, but underreporting is common and there might be a lack of motivation to report among health professionals (5). Active systems provide more timely and complete reporting and reflect a true change in disease activity, but they require more resources to obtain the information and the timeliness is limited by frequency of reporting prompts, in addition to difficulties to sustain the system for longer periods (5). Experience has shown that relying on the passive surveillance of laboratory-confirmed cases is not sufficient for the timely detection of waterborne outbreaks of non-endemic infections and may contribute to late detection and worse health impacts (110).

### 2.4.3 Syndromic surveillance

The evolving need to detect bioterrorism promptly has led to the utilisation of information sources other than diagnostics for the early prediction of infectious diseases – syndromic surveillance (128). Syndromic surveillance is defined as the real-time (or near real-time) collection, analysis, interpretation and dissemination of health-related data (128), such as indicators of clinical signs and symptoms, as well as proxy measures, such as over-the-counter (OTC) pharmaceutical sales, hospital admission reports or infectious disease surveillance (129-131). Syndromic surveillance, which is broadly applicable to many public health issues, identifies a threshold number of early symptomatic cases and allows the detection of outbreak days earlier than would conventional reporting of confirmed cases (132). The theoretical benefits of syndromic surveillance include potential timeliness, increased response capacity, the ability to establish baseline disease burdens, and the ability to delineate the geographical reach of an outbreak. However, the approach has been questioned in terms of the resources needed to evaluate the signals and distinguish them from false outbreak alarms (133).

Implications of syndromic surveillance for detecting waterborne outbreaks were reviewed in 2006 (133), with the recommendations that syndromic surveillance should not be implemented at the expense of traditional surveillance, but that syndromic data sources such as OTC drug sales of anti-diarrheal medications for detection should be evaluated. Some studies assessing data sources, such as OTC drug sales for anti-diarrheal medications, demonstrate promising results (134, 135), while others report the opposite (136). Drug sales data analysis for outbreak detection for infectious diseases was reviewed in 2014 with the conclusion that OTC sales are a useful tool for identifying gastrointestinal and respiratory diseases (137). Several studies published after the 2006-review have shown a promising correlation between syndromic surveillance and signals – such as contact for advice – within the health care system (106, 138). Regarding climate change, some studies recommend the use of syndromic surveillance based on meteorological data for predicting the impacts of climate change, but the main aim of the review was not to evaluate syndromic surveillance *per se* (37). The potential use of syndromic surveillance has also been qualitatively assessed among individuals utilising such systems in Europe, who express that syndromic surveillance based on data sharing and good communication with the water utilities would be desired to improve surveillance, leading to more astute estimates of the waterborne disease burden (139). Syndromic surveillance may have the potential to prevent outbreaks and burden lives and society; however, there is reported inconsistency in terms of its effectiveness. Despite the increasing implementation and expressed promising use of the application of syndromic surveillance, there is not an updated review of the effectiveness of such an approach in terms of detecting waterborne outbreaks.

### Timeliness, sensitivity and specificity in early warning surveillance systems

A number of factors are needed to evaluate the public health surveillance system, including the resources needed, usefulness, acceptability and distinguishing an outbreak from a 'false alarm' (140). Some technical core assets to evaluate a surveillance system's ability to detect a true outbreak are its timeliness, sensitivity and specificity (126).

Timeliness is a measure of whether data are submitted in time to begin investigations and implement control measures. The timeliness of a surveillance system (particularly an early warning system) will depend on how often the data are retrieved – daily, weekly, monthly or annually. The surveillance system should ideally process the information within a useful time frame (5). Sensitivity is the proportion of actual cases in a population that are detected and notified through the system. Sensitivity is particularly important in an early warning system designed to detect outbreaks. It is usually impractical to obtain highly accurate estimates of sensitivity, as this requires the true number of cases in the population to be known – something that is almost impossible – and for the diagnosis of reported cases to be confirmed to eliminate 'false positives' (126). Sensitivity has a link to the positive predictive value (PPV). The PPV reflects the probability that a case reported in the surveillance system is a real case (141), while specificity refers to the proportion of persons without the disease that are considered by the surveillance system as not having the disease. Very low specificity would result in the surveillance system indicating many ‘false’ outbreaks, and the staff using a lot of resources to verify and investigate (126). Useful surveillance systems for detecting a true outbreak are a balance between timeliness, sensitivity and specificity: high sensitivity and specificity express the surveillance systems to detect a true outbreak, however, in reality, this would require less timely detection.

### Epidemic intelligence surveillance in Norway

Several elements in the epidemic intelligence framework for Norway have been implemented that allow for the surveillance of waterborne cases and outbreak detection. For example, the MSIS is an indicator-based surveillance system for notifiable diseases (27), and the VESUV is an event-based alert portal. The MSIS, which has been operated by the Norwegian Institute of Public Health since 1977, monitors infectious diseases and contributes to international surveillance. For the time being, medical microbiological laboratories and clinicians report to MSIS with full patient identification reports on 71 diseases. Of these diseases, some are caused by pathogens transmitted through drinking water, such as *Campylobacter*, *Cholera*, Enteropathogen *E.coli*, *Giardia*, Hepatitis A, *Salmonella*, *Shigella* and *Francicella tularensis*. VESUV, which was established in 2005 and is operated by the Norwegian Institute of Public Health (26), is designed to take care of the obligations of the local health authorities and the Norwegian Food Safety Authority to report suspected outbreaks. In terms of waterborne outbreaks, several other relevant pathogens involved in an outbreak may be the causative agents other than the notifiable diseases to MSIS. In addition, systems for surveillance of media reporting and international reporting, for example from the European Centre for Disease Control (ECDC), are also implemented at the Norwegian Institute of Public Health.

After the severe outbreak of *Giardia* in Bergen in 2004, one of the recommendations was to implement syndromic surveillance as a part of epidemic intelligence. The Norwegian Syndromic Surveillance System (NorSySS), which is the syndromic surveillance system for infectious diseases, was thus established in 2006 and is operated by the Norwegian Institute of Public Health (142). The system is based on national diagnosis codes (ICPC-2) D11-Diarrhoea, D70-Gastrointestinal infection and D73-Gastroenteritis for presumed infections. These codes are obtained via both telephone and face-to-face consultation data from general practices in

Norway on a bi-weekly basis, based on the control and payment of health reimbursement from general practitioners (GPs) to the Norwegian Health Directorate (142). Historical data from 2006 have been made available in NorSySS; however, only a few waterborne outbreaks are recorded, mainly in retrospect, and NorSySS has not presently been demonstrated to detect a waterborne outbreak.

## 2.5 Response measures to microbiological contamination in drinking water

As mentioned at the beginning of this status of knowledge, a prompt public health response is imperative to prevent public health consequences. However, ensuring a prompt public health response depends on the capacity of the local health authorities or the water supplier to respond adequately to an emergency. In the following, I briefly elaborate on response measures in general, focusing on the BWA as a measure to address microbiological contamination.

### 2.5.1 Contingency plans and crisis management

Sudden events in the distribution of drinking water require resources from the water supplier to respond to an emergency. If a microbiological contamination results in cases of gastrointestinal illness and an outbreak is detected, an outbreak investigation is normally initiated and control measures implemented. In the case of a response to operational breaches in the drinking water supply system, an assessment of the risk and mitigating measures to rectify the situation are conducted. These situations are quite different depending on the level of emergency and the actors involved. In an outbreak situation, the outbreak is normally detected by the health departments, who then initiate a municipal crisis management team to handle the investigations, media and monitoring. In case of a breach of faecal indicator bacteria, it is – normally – the technical water suppliers' response measures that handle the situation by notifying the affected residents and effecting repairs, without involving health personnel.

Contingency planning, which includes instructions on how to obtain a continuous supply of safe drinking water, should be present and regularly practiced in case of an emergency or unplanned event (59). Almost all the registered water supplies in Norway have an emergency preparedness plan in place; however, a national inspection in 2018 revealed that two-thirds of the water supplies do not conduct training exercises (36). The main outcome of the recent national audit is that – although the quality of water is good – there are shortcomings especially related to prevention and precautionary measures (36). This shortcomings create uncertainties regarding the continuous delivery of safe drinking water during larger events in which the water supplies' organisational capacity is at play (36).

### 2.5.2 BWAs and public compliance

The issuance of BWAs to consumers is a widely used measure to prevent waterborne illness in the case of microbiological contamination in drinking water (59). Boiling, which effectively kills microbes if present in the water (143), has a protective effect on the prevention of gastrointestinal illness among consumers (144). The WHO recommends issuing a BWA if the water quality has deteriorated, the water supply has been disturbed by an outage, following a failure to disinfect the water, faecal indicator bacteria is detected or if a waterborne outbreak is declared (59).

An awareness of the risks of gastrointestinal illness associated with the main breaks and water outages, without the detection of faecal indicator bacteria, has led to a practice where *precautionary* BWAs are defined for certain events, while *emergency* BWAs are associated with the detection of faecal indicator bacteria, for example, in Canada (145). In the US, guidance on the communication of precautionary and emergency BWAs has been developed, such as for a temporary loss of pressure (146). Providing health advice in an uncertain situation is a dilemma often faced by decision-makers (40, 59). There is a fear that exposing the public to too many precautionary BWAs would make the public either lose trust in the water company or not give the BWA adequate attention, whereas waiting too long to issue a BWA could be a potential hazard to public health (40). The WHO suggests that BWAs can also increase consumer anxiety and alter perceptions about drinking water (147).

Issuing a BWA is an important part of risk communication in a waterborne outbreak. Emerging from barely communicating with the public, risk communication has evolved as an approach to communicate with the public about issues that pose a threat to health, safety or the environment (148). Risk communication differs from traditional communication models – where there is a one-way message to warn or motivate behavioural change – as the risk communication approach is a two-way process, with active participation both from the sender and the audience, including elements such as caring and empathy, dedication and commitment, competence and expertise, and honesty and openness (148). In waterborne outbreaks and water quality incidences, the role of communication has evolved using new technology such as the internet and SMS, where social media, such as Facebook, is used to communicate with the affected population of a water incident. Although issuing a BWA is an important measure to protect public health, a meta-study on compliance with BWAs suggests that compliance with BWAs is sparsely examined (40). The effectiveness in terms of protecting public health depends on how the public changes its practices according to the advice given. Therefore, more research on the perception and adherence to BWAs is needed for effective communication with consumers (149).

Activities in parallel to this thesis have shed more light on the topic of BWAs in Norway. In terms of the numbers of BWAs, in 2018, there were approximately 90 BWAs, of which 68 were issued due to the detection of faecal indicator bacteria and 22 were due to suspected contamination, reported to the Norwegian Food Safety Authority (22). The issuance of BWAs in Norway was descriptively and qualitatively assessed in a cross-sectional study among municipalities in 2018. The main findings showed that the majority of municipalities sent no or few BWAs; however, some municipalities sent out more than 100 BWAs a year due to the routine issuance of a BWA for every water outage (150). A discrepancy was also found in the routines of BWAs, despite complying with the same legislation. Of the 139 responses from the 417 municipalities invited, only two respondents represented the municipal doctors (local health authority) (150). In addition, the outcome of an investigation into public compliance with a BWA following a water contamination incident in a residential area indicated high compliance among those aware of the BWA. The few non-compliers reported not drinking the water and having a lower trust in the water supplier compared to the compliers (151).

## 2.6 Summary: A knowledge gap

Based on the status of knowledge, this chapter has described drinking water supply in high-income countries regarding its status and challenges. Despite several precautionary regulations have been implemented and technical advances have been made in the drinking water supplies in Norway, waterborne disease surveillance reveals a yearly detection of waterborne illnesses and outbreaks. The occurrence of waterborne outbreaks, regardless of multiple hygienic barriers and precautionary actions, demonstrates that a fraction of risks of waterborne outbreaks will always remain, and knowledge of how to combat these risks is still lacking. There are concerns related to the preparedness level, particularly among small drinking water supplies, in Norway, to manage risks due to an increasingly aging and vulnerable water infrastructure and the predicted changes in climatic parameters.

This calls for gaps in drinking water preparedness to be bridged, particularly related to early detection systems for possible waterborne outbreaks and effective responses, to prevent waterborne outbreaks and societal consequences.

# 3 Overall study objective and specific aims of the thesis

This thesis examines the risks in water supplies to fill the knowledge gaps in drinking water preparedness in Norway for the future prevention of waterborne outbreaks. Specifically, the study has the following three aims:

a) Identify risks for the prevention of outbreaks.

b) Examine the early detection of waterborne outbreaks.

c) Examine effective response measures and public compliance with BWAs.

The three specific aims of the study are inspired by the IHR's framework of 'prevention, detection and response' to combat infectious diseases and outbreaks (42).

# 4 Materials and Methods

## 4.1 A multidisciplinary approach to the overall study objective

This thesis brings together several disciplines to shed light on drinking water preparedness in Norway. Drinking water is an important public health topic, which comprises many aspects within a society, including natural, contextual, technical, cultural and political factors. When studying drinking water, we need to consider that drinking water preparedness involves people who are agents with history; man is alive, with bodily functions, lives in a given environment and has his history (152). We cannot overlook such conditions when we want to explore phenomena in society (24, 153). For this reason, I take a multidisciplinary approach to the overall study objective of the thesis. Applying multiple disciplines has long been emphasised in health research, services and policy (154). The objectives of multiple disciplinary approaches are several and include resolving a ‘real world or complex problem’ within public health (154) because real-world problems are rarely confined to the artificial boundaries of academic disciplines (154).

Multidisciplinary is often defined as using the competence obtained in solving a common problem, but staying within the boundaries of the discipline (154). It has become more accepted within medical science that for certain topics, qualitative methods are needed to gain insight that experimental and quantitative methods are unable to (24). To study health in a societal context, topics of humanities such as history, philosophy and ethics are integral to the understanding of the observation (24). The combination of quantitative and qualitative methods has a long practice, which in later years has been conceptualised as a mixed method (155). It has been claimed that mixed methods research occurs when ‘a researcher or team of researchers combines elements of qualitative and quantitative research approaches for the broad purpose of breadth and depth of understanding and corroboration’ (155). However, despite the popularity of a mixed methods approach, a more rigorous evaluation of mixed methods research is needed (155). To what extent the study is ‘trustworthy’ depends on the methodologies used and the potential biases in the study (155). The topics included in this thesis could, and are, studied in isolation; however, investigating the improvement in drinking water treatment processes will ensure more certain hygienic barriers, but it will not account for the human factor when there is a potential breach in the process and the residents are obliged to boil the water for public health protection. I therefore examine these issues in one context in this thesis.

## 4.2 Study designs

The papers included in the thesis are presented in Annex I. Several study designs have been applied to address the aims of the study: the investigation of a waterborne outbreak (Paper I), a cross-sectional study of a population (Paper III), a systematic review of clinical information (Paper II) and a review of historical documentation (advice logs) (Paper IV).

## 4.3 Background, data collection and methods in the included papers

### 4.3.1 Large waterborne *Campylobacter* outbreak in Norway in 2019 (Paper I)

Outcomes from outbreak investigations provide important information in terms of understanding threats and preventing future outbreaks (16). To inform future preventive measures, we used the outcome of a waterborne outbreak investigation from a large waterborne *Campylobacter* outbreak occurring in Askøy in June 2019 to identify the risk factors of the source of contamination in the water supply systems (direct causes) and indirect factors (28).

Askøy is a medium-sized municipality located west in Norway and home to approximately 27,000 residents. The outbreak affected a large part of the drinking water supply system serving the administrative centre of the municipality consisting of approximately 12,000 residents. We conducted epidemiological investigations, such as pilot interviews of cases, a survey of childcare centres and an SMS-based cohort study of households. In parallel, we conducted WGS on *Campylobacter* isolates from patients and in water samples. We also analysed water samples in the distribution system for faecal indicator bacteria to identify the affected areas. The operational drinking water system information and historical data from the drinking water supply system were reviewed, including the results from drinking water routine monitoring schemes before the outbreak. We assessed critical points and possible sources of contamination (including system failures and unusual events) through interviews with water supply staff and visual inspections of selected areas of the water supply system, including the suspected reservoir. Other environmental data, such as local rainfall, were assessed using data from the national meteorological website (www.yr.no).

### 4.3.2 Review of syndromic surveillance for waterborne outbreaks (Paper II)

Considering the evolvement and popularity of syndromic surveillance, potentially using different sources of data signals, we considered it sensible to assess already existing knowledge to inform our secondary aim. Systematic reviews gather and examine what is known from existing research (156) to address precisely defined research questions using all available studies in a specific field (157). The implications of syndromic surveillance to detect outbreaks were last reviewed in 2006 (133), and our aim was to update this knowledge to inform future decisions on surveillance and early warning systems.

Our PICO in the systematic review were (Paper II):

- Participants/population: The general population (connected to the water supply).
- Intervention(s), exposure(s): Syndromic surveillance/early warning systems.
- Comparator(s)/control: Traditional surveillance (laboratory-confirmed).
- Outcome(s): Syndrome/data, sources for surveillance, outcomes/causative agents of outbreaks, affected populations, outbreak causes, study periods, study designs, study objectives, regions/countries. Measures of effect were mainly sensitivity, specificity and timeliness of the syndromic surveillance system.

To inform the effectiveness of early detection of waterborne outbreaks, we reviewed published literature on syndromic surveillance used for waterborne outbreak detection in the period 1990-2018 to inform the effectiveness of syndromic surveillance for the early detection of waterborne outbreaks. We searched Cochrane Library, Medline/PubMed, EMBASE, Scopus and Web of Science for relevant published articles using a combination of the keywords ‘drinking water’, ‘surveillance’ and ‘waterborne disease’, and we screened the reference lists of identified articles for full-text record assessment and conducted random searches using the same keywords. Since our studies are mainly observational studies, the risk of bias was assessed using the ROBINS-I tool (158). We also used PRECEPT to evaluate the cumulative body of evidence (159).

### 4.3.3 Public compliance with BWAs (Paper III)

Despite the importance of obtaining public health protection, public compliance with BWAs is rarely monitored (40). We therefore examined compliance and the perception of risks to BWAs among the consumers of drinking water in Bærum municipality (Paper III), which had issued routine precautionary BWAs to the affected consumers of water outages (160). Every year, some 12,000-22,000 residents served by the water supply system receive a precautionary BWA in Bærum.

We used strategic sampling of the participants (161) from records kept by the municipality of issued BWAs to residents in the study period to identify the study population. We studied the compliance and perception of risks among the public who received BWAs by conducting a cross-sectional study of the residents who had received BWAs via SMS in the municipality of Bærum between January and September 2017. We conducted a survey of the population affected by BWAs during the year prior to the study and two focus group discussions, one consisting of families and one of elderlies. The focus groups were used to inform the survey questionnaire (155).

The data from the focus groups were recorded discussions that were transcribed into a written document. Participants' quotations were categorised and coded in different colours according to the research questions in the study. We conducted descriptive analyses and calculated odds ratios (OR) using logistic regression to identify associations of compliance and awareness with demographic characteristics, using Stata version 15.1 (by StataCorp).

### 4.3.4 Requests to a crisis advisory service for water (Paper IV)

To identify the risks and response capacities in water supplies in Norway, we used data from the water supplier's requests for advice in water incidents to identify the needs in response measures among the suppliers (Paper IV). Data on critical events in water supplies were collected from a 24-hour crisis advisory service, the NWG (National Water Guard), which was established in 2017 to provide advice on national water supplies (123). The purpose of the service is to provide advice for water suppliers and support during events that can affect the water supply and have health consequences for the population. We used data from 2017 to 2019 to examine the frequency and main topics of the requests based on the advisory service's log of all requests in a Crisis Information Management tool (CIM).

A request was considered relevant to the service and data synthesis if it was (a) directed by a leader of a water supplier and/or in collaboration with a municipal doctor, (b) acute in nature, and (c) severe enough to be referred to the leadership of the water supplier. Requests that originated from private individuals, private building owners, lawyers seeking expert opinions, municipal doctors who sought general advice on how to answer water-related questions, and water suppliers that sought advice on general questions regarding non-acute water hygiene in the offshore oil industry were filtered out and excluded from the dataset to ensure that only organisational capacities were monitored.

## 4.4 Ethical considerations

Ethical considerations in medical research are imperative since the research involves patients or other informants of health status (162). The major ethical issue in epidemiology and public health is the tension between concern for the individual and the good of society (2). Typically, there is an asymmetric relation in terms of power and knowledge between the participant and the researcher, where the researcher has the benefit of the input from the participant for research purposes (162). Informed consent from the participants is therefore a core element of medical research to maintain general ethical principles of respect for self-determination (162).

In outbreaks, the health consequence of not implementing action while waiting for ethical approval would be serious, and the rapid outbreak response is in the public interest; however, an ethical consideration of the study is always required. These ethical considerations respect the rights of individuals’ freedom, privacy, and confidentiality (163). In the large waterborne *Campylobacter* outbreak (Paper I), approval by a regional committee for medical research was not needed, as the Norwegian Institute of Public Health is authorised to access and use personal identifiable information for communicable disease outbreak investigations in the public interest.

When we examined public compliance with BWAs in a municipality in Norway (Paper III), ethical approval was not needed since the study did not collect personal health data and the participants in the survey remained anonymous. However, there was a need to make the informants in focus groups anonymous in the data analysis and reporting. At the beginning of the focus group discussions, the objectives of the study and means of data collection were explained to each participant in the focus groups. The participants were assured of the anonymity and confidentiality of their responses. They were also informed that their participation was voluntary and that they could withdraw without consequences at any time.

Using the data from the advice logs originating from the NWG (Paper IV) does not require ethical approval since that data does not include personal health data. However, the existence of advisory service credibility and loyalty among the water suppliers falls to a large extent on discretion. This discretion is imperative, even though the water suppliers have, according to the Norwegian drinking water regulations enforced in 2017 (66), an obligation to notify customers and the Norwegian Food Safety Authority about events that may have implications for human health. Most notifications also have to be copied to the municipal medical officer responsible for infectious disease control measures. However, such events were few and could easily be traced back to specific water suppliers. Information on lack of competence or vulnerability should not be subject to communicating elsewhere unless approved for use as case studies and should be synthesised under more general terms while reporting in articles.

No ethical approval was needed in the systematic review (Paper II).

# 5 Results

Here, I present the main results from the papers included in this study, which shed light on the overall study objective of this thesis. The full text papers are included in Annex I.

## 5.1 Large waterborne *Campylobacter* outbreak in Norway in 2019 (Paper I)

In reporting the outcome of the waterborne outbreak in Askøy, I focus on the findings on the causes, how the outbreak was detected, and the public's compliance with BWAs. The waterborne outbreak in Askøy in June 2019 (28) was detected on 6 June 2019 due to a rapid onset of cases presenting with gastrointestinal symptoms in the open-hours emergency room, creating an alarm of an outbreak. The clinicians made note of the geographical relation among the cases because of the proximity of their home addresses, which further led to suspicion about the drinking water supply system and, in particular, to one of the drinking water reservoirs in the supply system. At the same time, one patient was confirmed with *Campylobacter*. For that reason, a BWA was issued when the outbreak was detected on 6 June 2019 and the water reservoir was taken out of service on 7 June before the outbreak investigation started.

The investigations revealed that 1,573 respondents met the case definition in the cohort study, leading to an attack rate of 26%. The relative risk of illness among those residents served by the suspected reservoir was estimated to be 4.6 times higher than other water supply zones. The microbiological and environmental investigations also pointed towards the suspected reservoir. For example, cracks where contamination could enter were observed and *Campylobacter* was detected in both water samples and patients, which were identical by WGS.

During the environmental investigations, the water operators reported several delays in the planned long-term precautionary actions, and several operational challenges were recorded in the later years, which had resulted in some precautionary BWAs and a crisis regarding a dry summer in 2018.

No unusual malfunctions in the distribution system were reported before the outbreak by the water operators, except a heavy rainfall event prior to the outbreak. Weather data obtained from a nearby weather station indicated heavy rainfall, which coincided with registered consultations of gastroenteritis in the NorSySS (Figure 2).

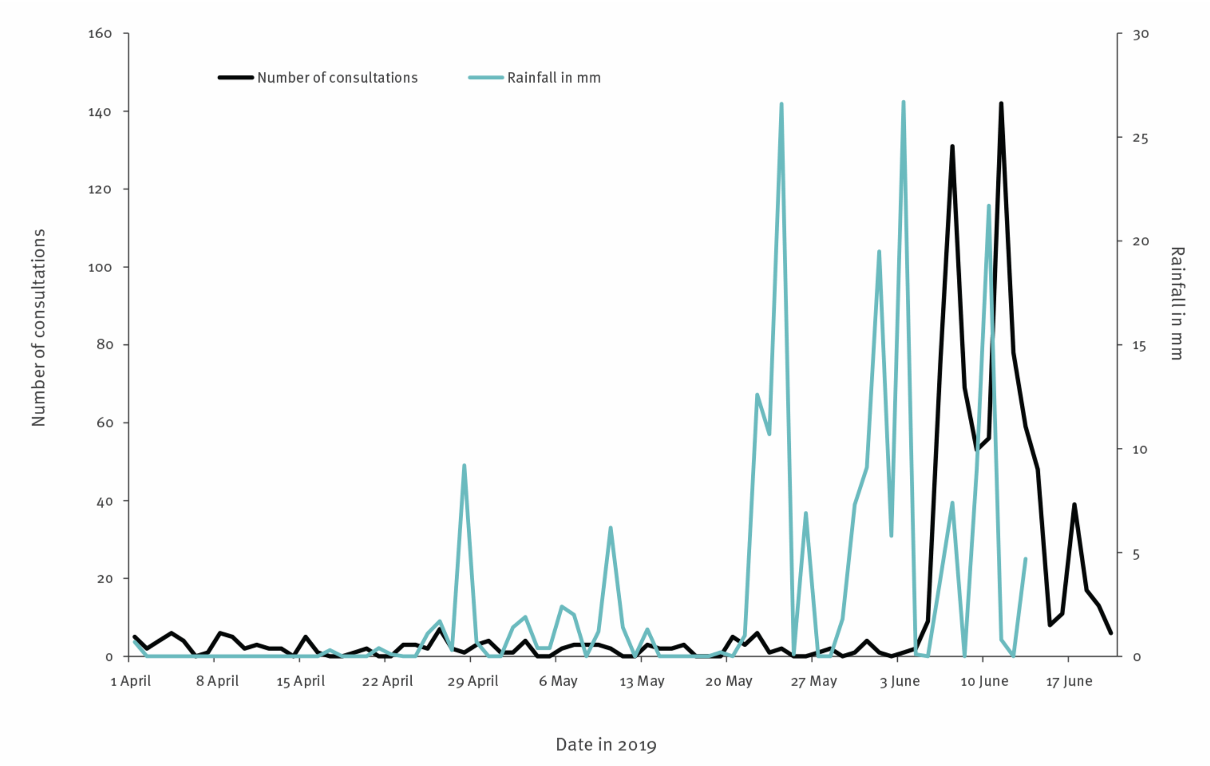


Figure 1 Rainfall data from a nearby weather station and onset of consultations for gastroenteritis registered in the NorSySS, Askøy, 1 April-20 June 2019.

Regarding the notification of the BWA via SMS, 88% of households (2,223 of 2,526) reported that they had received an SMS with the BWA, while 179 (7%) did not receive the BWA and 124 (5%) were unsure. Of all households, 2,384 reported having complied with the BWA (compliance rate: 95%: 2,384/2,526). Reasons for non-compliance were reported by 142 of the households; the main reasons were purchasing bottled water (n = 76), considering that the risk of becoming ill was low (n = 9) and drinking little or no tap water (n = 4). Reasons for non-compliance with the BWA were not reported for the remaining 53 households.

## 5.2 Review of syndromic surveillance for waterborne outbreaks (Paper II)

We identified 1,955 articles in the literature search for our defined PICO in Paper II. We reviewed 52 articles, of which 16 met the eligibility criteria. Of these included articles, 10 were retrospective studies assessing either historical outbreaks or register data on gastrointestinal illness and data signals for early detection, and six simulation studies evaluated system performance.

The included studies originated from Sweden (n = 2), France (n = 5), the US (n = 4), the UK (n = 4) and one study assessing data from several European countries, covering a study period from 1997 to 2013 overall with multiple agents causing waterborne outbreaks or illness. When reported, sensitivity in retrospective studies included in the systematic review was below 50%, with one exception reporting a sensitivity of 89% (135). In simulation studies, the sensitivity was reported to be above 70% using different aberration adjustments.

Among the excluded articles, the majority were association studies with various data signals. Examples include water quality data with signals being telehealth or emergency department visits (164-170) or disturbances in the water supply to gastrointestinal illness either by self-reporting or by telehealth (171-173). One study used web queries to estimate the burden of gastrointestinal illnesses related to pipe breaks (131), while another study assessed the relationship between precipitation and waterborne diseases (174). Common to these studies is that despite demonstrating promising correlations, they failed to report on an experienced effectiveness or value of using the same signals in surveillance explicitly. Other excluded studies dealt with syndromic surveillance systems but described or reviewed the systems in a general manner (175, 176).

## 5.3 Public compliance with BWAs (Paper III)

Of the 2,764 residents in Bærum who had received BWAs by SMS between January and September 2017, 611 responded to our survey.

Among the respondents, 67% reported that they had received a BWA. The effective compliance rate with safe drinking water practices, either by storing clean drinking water or boiling tap water, after a water outage was 72% among those who remembered receiving a notification and 49% among all participants. Compliance with safe drinking water advisories was lower among men than women, but was independent of age, education and household type.

Of those respondents who were aware of the advice but did not follow it (n = 231), 45% reported that they did not boil the water because they had stored clean water in advance (regarded as compliance with safe drinking water). According to 28%, the water was visually clear and, therefore, they saw no need to boil it; 9% considered the risk of getting ill by drinking the water to be very low; 6% forgot to boil the water; and 5% reported that they generally drank small amounts of water from the tap. The remaining 20% could not remember why they had not followed the advice.

In the focus groups, the main reason for respondents' non-compliance with safe water practices was that they perceived the water to be safe to drink after letting it flush through the tap until it became clear. They also reported that the awareness of the notified BWA could easily get lost in all the other information from the municipality that was issued as an SMS. Some of the participants in the study also reported that they perceived a 'boiling recommendation' as vague advice, assuming that the risk was low and more or less up to their choice to follow. On the other hand, several agreed that they trusted the municipality to notify them if the risk was high.

In general, the participants, both in the focus groups and to the survey, had a high degree of trust in the drinking water and the municipalities' management of the drinking water, and the communication (the issuance of BWAs in the water outage notifications) contributed to an increased level of trust.

## 5.4 Requests to a crisis advisory service for water (Paper IV)

From the assessment of the advice logs to the NWG in the period 2017-2019, we found that 50 (41%) of 122 requests were considered relevant to inform the overall study object of this thesis. Of the 50 requests, 14 came to the service outside office work hours, and most callers were from small to medium water suppliers (serving less than 5,000 inhabitants). The number of requests per year were 10 (2017), 22 (2018) and 18 (2019), respectively, where most of the requests came in the summer. Dividing the 50 requests by topics, 36 (72%) were microbiological, 6 (12%) were chemical related and 8 (16%) were related to operational issues.

Usually, the callers sought advice on proper measures to take, such as whether to issue a BWA or whether to flush the pipe distribution system or use emergency chlorination. There were several specific questions about the issuing of a BWA, based on the findings of a coliform bacteria test, which did not detect *E. coli* in the water samples. The reason for the request was uncertainty about the health consequences if the number of coliform bacteria was high and the significance of measuring coliform bacteria in the absence of clear action points for this parameter. Typical requests for advice regarding chemical spills concerned the risk to human health due to the possible consumption of pollutants by residents.

# 6 Discussion

In this chapter, I discuss points relevant to the three lines of studies in the thesis as described under the aims of the study. To recall, the specific aims were to a) identify risks in the drinking water supplies to inform future preventive measures, and b) examine the effectiveness of syndromic surveillance for the early detection of waterborne outbreaks and c) the effective response to protect the public health in terms of compliance with BWAs. In the following discussion, I examine the results highlighting these specific aims and reflect on the extent to which my results may be generalised to a larger context.

## 6.1 Identifying risks in drinking water supplies

### 6.1.1 Risk of reservoirs in the distribution system

The hypothesis in the outbreak in Askøy was that environmental contamination through cracks in the suspected reservoir most likely occurred during heavy rainfall following a long dry period. Rainfall events have been a factor in several serious waterborne outbreaks (15, 56, 76) and smaller outbreaks (177), where *Campylobacter* has frequently been identified as the cause of the outbreaks (107, 178). We were unable to conclusively determine how the reservoir became contaminated, however, the triangulation of epidemiological, genomic, geographical and water systems data was essential for confirming the role of the reservoir in the outbreak in Askøy and 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' (179) since the pathogen identified in clinical cases was also found in water and evidence from the analytical epidemiological study demonstrates an association between water and illness. In addition, the WGS of *Campylobacter* of the four positive water samples had the same DNA profile as in the human samples.

The hypothesis – intrusion of contaminated water due to heavy rainfall – is a plausible explanation considering the frequent reporting on waterborne outbreaks (180). 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 the external conditions of the reservoir. According to the water operators during the environmental investigations, the weather pattern had been particularly unusual prior to when the outbreak was detected. A period of approximately two months of almost completely dry weather, which in itself is not common on the west coast areas of Norway, was followed by hard rains. Rainfall is, on the other hand common, in the west areas of Norway, however, the rainfall was so hard that it had been, according to the water operators, a topic of conversation in the community. Predicted changes in climate parameters such as rain and drought are expected to affect the overall situation of waterborne diseases; however, this does not imply that one can say that 'climate change was the cause of the outbreak' since such a statement is not supported by a causal relationship (152). It is merely an assumption that uncertain weather patterns represent stressors to water supply systems (82), in particular aging reservoirs (181). Whether the combination of weather conditions resulted in a contamination event in the spring of 2019 as opposed to other seasons where it had not been experienced will require more in-depth examination.

### 6.1.2 Indirect causes of the outbreak in Askøy

During the outbreak, the immediate focus was directed towards the fault of the technical management of the water operators related to, for example, the monitoring of the suspected reservoir. However, a risk analysis of the water supplies systems in Askøy conducted in 2004 pointed out the vulnerability of the cavern reservoirs in the municipality. In that regard, the outbreak was foreseeable (57). Previous reporting of the causes of waterborne outbreaks is often technical or operational, for example, a poor design or a 'human error' (16). Such statements are an example of a one-sided statement – and an unreasonable individualisation of the water operator, without taking into account that the water operator is part of a larger system in its historical context (182). In the environmental investigations, several financial, bureaucratic and political factors led to delays in the implementation of long-term preventive measures.

In the analysis of societal aspects, it has been suggested that a three-level perspective accounting for the individual, institutional and historical aspects is needed to differ between individuals, institutions and traditions (182). An in-depth study of the indirect causes of the outbreak in Askøy was not a part of the outbreak investigation, but investigating the indirect causes of the outbreak in Askøy further could contribute to a more substantial understanding of the risks and barriers to prevent waterborne outbreaks at a structural level for other water supply systems. For example, in Norway, in 70% of the cases, the water supplies systems are publicly owned by the municipalities in Norway (22), where the development of the water supply is a political decision (183). The investments in the drinking water sector are financed by fees paid by the citizens served by the water supply system (49). This ensures an ‘earmarked’ and stable financial income, as the funding cannot be used for other budgetary purposes in a municipality and allows for long-term investments in precautionary actions. The level of fees is, on the other hand, up for political decision, and there exists a general political will to keep the fees related to drinking water services as low as possible for their residents, stated more explicitly among certain political parties. This creates a tension between the need for investment and the willingness to make decisions that affect the residents.

### 6.1.3 Requests to the Norwegian Water Guard

In Paper IV, examining requests to the NWG did not reveal a clear trend. However, the data from the first three years of operation of the NWG demonstrated that events in the drinking water supply in general are occurring, representing different severities and needs for crisis management and response. Although few, some vital events recorded involved, for example, sabotage to a drinking water reservoir with contamination of an unknown substance resulting in a complicated crisis management handled by the municipality, prompting the investigation into the introduction of a bioweapon, such as anthrax, into the drinking water. Other examples of severe events were a critical main pipe break due to a landslide after heavy rains affecting a whole city and petroleum spills into a river that could have destroyed the municipal’s only well serving the majority of its residents. Although these are isolated events that represent only the problems experienced by the respective water supply systems, it may also be argued that the events are not unique to water supply systems that requested assistance from the NWG (16). Despite no clear trends in the data, it is worth mentioning that some requests came after normal working hours, demonstrating the need for round-the-clock availability.

### 6.1.4 Taking drinking water for granted in Norway

Drinking water is an abundant resource in Norway. For example, today, no one in Norway fears cholera, and relatively few have experienced gastrointestinal illness, except the reported cases shown in Table 2 and as depicted in the review of the waterborne outbreaks in the previous chapters. This is something which in 1853 was not the case, when 2,484 deaths were registered as a result of cholera, representing half of all deaths in in Norway the same year (52). However, even though we do not completely know the true burden of waterborne disease in Norway today, it is reasonable to assume, based on estimates from the global burden of disease project, that it is not a major cause of sick leave or deaths. Using estimates such as the global burden of disease, the focus is directed towards diseases such as ischemic heart diseases, cancer and mental health issues (184), and not on the *low* levels of waterborne disease present in Norway. Behind this depicting of priorities, enormous efforts are being made to implement long-term precautionary investments, which are not depicted explicitly in the analysis of the burden of disease.

The combination of easy access to safe and abundant water, pressurised systems and low fees may, to a certain extent, contribute to the fact that our collective memory may have forgotten the need to be thrifty in the use of water, work to get it or the pain of gastroenteritis. It may have evolved into a notion that drinking water is so cheap that we do not appreciate it as an essential good for life and wellbeing, but rather something that we can let go to waste. An example is the high level of leakages in Norway, where a third of the treated drinking water disappears during distribution. This leakage is far higher than in other countries, yet it is largely 'accepted' on both the individual and political levels. Although efforts are being made to reduce such leakages, the political ambitions are set to 25%, which is still very high compared to other countries such as Denmark and Netherlands where the level of leakage is below 10% (122). In a less-developed setting, it would be unethical to use resources to treat water to be safe for drinking and to then let it flow down the drain. A body, regardless of geography, needs 1-2 litres a day for drinking and 5-10 litres per person per day is recognised as a minimum requirement in less-developed areas. However, in Norway, we estimate that 150-200 litres a day per person is needed to cover our consumption.

Drinking water has in many ways become a service for which we have expectations in the same way as other commodities. The administrative shift from public health responsibility to the Food Safety Authority may be argued for in the event of this decoupling. Today, the drinking water supply is the work of water engineers and not public health specialists. This transition – from access to safe drinking water as a public health issue – is ultimately a more technical activity disconnected from the health aspect. For instance, the drinking water legislation in Norway refers to the technical sector and does not describe the role of the health authorities in the municipalities (66).

## 6.2 Early detection of waterborne outbreaks

### 6.2.1 Syndromic surveillance for the early detection of waterborne outbreaks

The popularity of a syndromic surveillance system has increased since the beginning of 2000, and the theoretical benefits for detecting waterborne outbreaks (133) have led to a number of implemented syndromic surveillance systems, including the NorSySS (142). The increase of consultations in the Askøy outbreak, however, was not detected by the NorSySS. The observant clinicians at the emergency department detected the outbreak by recognising the increasing number of patients presenting with gastrointestinal symptoms and the proximity of their home addresses (Paper I).

In Paper II, the review of identified articles reported from different syndromic surveillance systems showed, in general, low sensitivity and specificity in detecting waterborne outbreaks, particularly of smaller and local outbreaks with an acute onset of cases, which corresponded with the experience of the outbreak in Askøy (Paper I). There was one exception among the articles, reporting a sensitivity of 89% and a specificity of 89%, to distinguish acute gastrointestinal cases based on drug sales (135). Other studies reporting from the same French syndromic surveillance system, which is based on the reimbursement of drugs from a health insurance administrative database, do not report such results (185).

The studies identified in Paper II include a variety of syndromic surveillance systems using different signals, such as OTC pharmacy sales, 'telehealth', administrative databases for reimbursement of health expenditures, and emergency room visits, either alone or in combination with environmental data. Because surveillance systems vary widely in methodology, scope, and objectives, characteristics that are important to one system may be less important to another. Comparing such systems is therefore challenging. Efforts to improve certain attributes – such as the ability of a system to detect a health event sensitivity – may detract from other attributes, such as simplicity or timeliness (140).

The effectiveness of a syndromic surveillance system is a balance among sensitivity, specificity and predictive value, and timeliness (141). Timeliness is influenced by the frequency of an outtake of signal for outbreak evaluation. In the NorSySS, the data on health consultation may have a lag up to 14 days before being entered into the surveillance system, which will not be timely enough for outbreaks with a more or less acute onset. To increase the sensitivity, and hence the potential for the timely detection of local outbreaks, the outbreak algorithm could be increased to, for example, operate on a daily basis. However, doing so has the drawback of reduced specificity, since there will be a risk of more false positive outbreak signals being generated due to randomness, especially for geographical regions where the population size is small (106).

Outcomes from publications with simulation studies imply that multiple sources of signals, combined with spatial information, may increase the sensitivity of detecting waterborne outbreaks and reducing false alarms (186). However, deploying such systems may be challenging since it will most likely involve two different fields of expertise (health and technical), and the processing of data to health decisions must still account for local outbreaks that are usually short-lived (28).

### 6.2.2 Early warning systems based on water quality parameters

Among the excluded articles in the systematic review included in this thesis (Paper II), the majority of included studies were data signals such as water quality data. Water quality parameters are often considered to be an early warning signal for risks in water supplies, and technological advances in terms of real-time monitoring of water distribution supply systems suggest the potential for an earlier warning of the potential risk of outbreaks. However, deploying such measures may be challenging linking monitoring data to operational response (187).

There are examples of combined approaches, which were not identified in Paper II. A study of failure events in conventional drinking water systems in potable reuse schemes showed promising results from using a combined approach of multiple barriers, online instrumentation and operational measures in mitigating the events that resulted in waterborne outbreaks (188). Another example of a combined approach – which aims to address the risk of contamination of drinking water systems – consists of components combining online water quality monitoring and public health surveillance (e.g. OTC pharmacy sales, hospital admission reports or infectious disease surveillance), field and laboratory analysis, enhanced security monitoring and customer complaint data in real time (187). This approach also provides benefits, such as improved water quality management, to drinking water utilities (187). However, none of these examples reported on effectiveness in terms of timeliness, sensitivity and specificity for the possible evaluation of public health benefits.

Berger's review on syndromic surveillance for waterborne outbreaks in 2006 argued that water quality parameters were helpful and more timely since they are often the first initial indication that something is wrong (133). However, measuring this signal in terms of disease – without any other indications of disease – in the population may not necessarily be termed 'syndromic' since the development of disease in the population has not occurred. It is more likely to be a false alarm for an outbreak since water quality parameters will have a low sensitivity and specificity for gastrointestinal illness (141). On the other hand, traditional regular obligations require action to mitigate a breach in the monitoring of microbiological parameters – if detected – and often the mitigating action is the issuance of a BWA to protect the population from evolving a potential outbreak (59). The risk of developing a waterborne outbreak is when a contamination event goes *undetected* from day-to-day-operation and routine monitoring, which is a common factor for several waterborne outbreaks and not necessarily when an exceedance in water quality parameters is detected (124).

### 6.2.3 Risk-based drinking water surveillance

In general, since there will always be a risk of water contamination going undetected, the emphasis on prioritising long-term preventive measures should not be underestimated, despite promising reports on syndromic surveillance or early warning systems. The main goal must be to prevent contamination or to have the earliest possible detection of contamination. Risk-based surveillance of drinking water quality is performed to gain an understanding of hazards, hazardous events and the effectiveness of control measures throughout the water supply system (125). However, water supply is a dynamic system under constant changes, and the risks in the water supply system also need to be continuously assessed (59). To do so, one needs to have holistic approaches that imply a high degree of flexibility to foresee, and preferably prevent, the potential challenges. For example, in Askøy, knowing the risk to the reservoir in hindsight, one could question whether this conclusion could have been foreseen following a more proactive surveillance approach by, for example, conducting visual inspections or having a higher preparedness during heavy rainfall events. Sanitary inspections are a vital element of drinking-water quality surveillance, particularly for small-scale water supplies (125). Onsite fact-finding enhances the knowledge of supply system conditions, provides information about immediate or ongoing risks to contamination and enables the prediction of future water quality changes (125).

## 6.3 Response to microbiological contaminations in drinking water

### 6.3.1 Public compliance with BWAs

The effect of a BWA is highly dependent on the awareness of and adherence to the advice (40), which underlines the importance of including social science aspects and qualitative methods in public health issues (24). Among the residents in Bærum (Paper III), one-third reported not remembering having received a notification of a BWA from the municipality, which is lower than that found in a systematic review and meta-analysis, where the awareness was calculated as a mean of 85% and median of 97% (40). The rate of awareness in the study may relate both to recalling an SMS as long ago as one year prior to the study, as well as the reported causes in the focus groups that such messages could easily get missed along with other information from the municipality. The communication and uptake of the advice therefore has implications for the overall public health, as the adherence by the population can only be measured by those who were aware of the advice (40).

However, compliance with the BWA among the participants in the study (Paper III) who were aware of the advice was higher (above 80%) than that reported in a systematic review, resulting in a mean of 68% and a median of 76% (40). When factoring in awareness, the effective compliance rate becomes just above 50% of the reached population. Awareness and compliance are reported to vary whether the BWA is issued in an emergency setting (up to 100%) (40) or in a more or less peaceful situation (as low as 43%) (40, 149). This was also observed in the in Askøy (Paper I), where 88% of households in the cohort study reported that they had received an SMS with the BWA, while 12% did not receive it or were unsure. Factoring in the awareness, the compliance rate was calculated to be 95% (2,384/2,526), which is a higher compliance rate than that in Paper III. A particular aspect of the study in Paper III is that the BWA was part of a planned maintenance operation, which prepared the residents for the upcoming event and advised the residents to store safe drinking water in advance. This was a reason why some of the residents did not follow the BWA, since they had already stored a sufficient amount of safe water to last throughout the BWA. Another reason for not complying with the BWA reported in the focus groups was that the drinking water was perceived as clean and safe to drink.

### 6.3.2 Risk perception and trust

In the initial phase of the outbreak in Askøy, the crisis management team was concerned about the effectiveness of the BWA due to a history of issued precautionary BWAs and about whether they would face a 'cry-wolf' scenario when notifying the residents. Since 2017, several precautionary BWAs related to the water supply system in Askøy have been issued due to necessary upgrades to the treatment process (hygienic failures) and sudden failures in the technical installations at the treatment plant. However, despite this concern, the compliance rate was high (95%). In the study in Bærum (Paper III), the residents reported high trust in the management of the municipality and the drinking water, despite repeated BWAs. These findings are in contrast to claims that BWAs have negative consequences, such as increasing consumer anxiety and altering perceptions of water quality (59).

The role of the consumers is an important but challenging issue when discussing risks in drinking water supply (67). There is an established relationship between acceptance trust and risk perception; however, little research on this relationship has been conducted in the domain of safe water supplies (189). While waterborne outbreaks are a serious threat to the water suppliers' trust in the consumers, it is suggested that the pre-existing trust in the institution plays a role in regulating the perceived risk (16). For example, Bratanova et al. reported that trust in the regulatory institutions, and not prior attitudes towards a contamination event, defines the public's risk evaluation and acceptance of post-incident water use and supply (16). This could be a possible factor at play in the Askøy outbreak (Paper I), where the compliance was high, despite the frustration of previous water precautionary BWAs (although no contamination had been detected). A better understanding of the processes involved in public perception of water quality, may – amongst several gains – help to improve services and satisfaction and prevent conflict (44).

It might be that the difference in the observed compliance with BWAs in Papers I and III is related to the reporting that the public tends to trust different sources of information depending on the context and reason for issuing the BWA, whether it is an emergency or a routine situation (190). Aakko (2004) argued that risk perception significantly affects risk communication, as people view risks differently for different reasons based on the factor, as the risk is perceived to be familiar, voluntary, natural and under the person's control (148). It is also suggested that good communication with the water utility is interpreted as a form of control by the consumer (44), which may have been a factor in the study in Paper III.

### 6.3.3 Response capacities and small-scale drinking water systems

Drinking water safety is dependent on the management and decisions involved in all levels of the water supply (9, 41), and in their daily operation, those responsible for the water supply must preserve regulations and manage multiple perception risks, irrespective of their tangible health impacts and consumer trust (191). Doing so requires well-functioning drinking water supply systems, including adequate hygienic barriers and a sufficiently staffed organisation with competency.

In Paper IV, when reviewing the request for advice to the NWG, most of the requests for advice came from small-to-medium water suppliers (serving less than 5,000 inhabitants). This does not necessarily imply that the capacity among the small-scale water supply organisations is lower than larger ones, but rather confirms that there are many smaller-scale water supply systems in Norway. In Norway, the majority (approximately 70%) of the water supplies in terms of numbers serve less than 5,000, which also may explain the frequent requests from smaller-scale water supplies. However, the types of requests provide insights into the needs that may benefit the general understanding of obstacles to timely and proper responses to water incidents.

The requests for support from the water suppliers varied from microbiological to chemical spills with no clear trend; however, one recurring question observed was whether the water supplier should issue a BWA based on the results of microbiological analysis for coliforms, while at the same time not detecting faecal indicators bacteria such as *E. coli* and intestinal enterococci. Microbiological questions can be expected to recur, as they are of obvious health significance and the value of guidance (zero occurrence of *E. coli*) is attested by the Norwegian drinking water regulations enforced in 2017 (66). However, no explicit official guidance exists on remedial actions by the water supplier following an analysis of the results of coliform. In Denmark and Sweden, guidance on levels of coliform, alongside an assessment of the situation, indicates when it is necessary to issue a BWA (192, 193). The findings in reviewing the logs of requested advice to the NWG may thus support that more detailed guidance on assessing levels and situations when coliform is detected is needed, either in the interpretation for drinking water legislations or as a part of the guidance for issuing BWAs.

## 6.4 Methodological considerations

### 6.4.1 Strengths and limitations of addressing a broad study objective

I have taken a multidisciplinary approach to shed light on the overall object of my topic in the thesis. Using perspectives from multiple disciplines and several methods in medical science, including quantitative, qualitative and microbiological, both as a self-standing researcher and in collaboration with others, I have attempted to answer a 'real world problem' and provided different perspectives on how we can prevent waterborne outbreaks (154). However, while multiple disciplinary teamwork has become an increasingly emphasised and accepted approach within health research, it does not necessarily imply that the approach is without limitations or that it was always necessary in every project (154). Although I could claim that there is a fruitful triangulation within the single studies included in this thesis, it could be argued that when bringing these methods together in a thesis by one researcher, I run the pitfall of 'spreading myself thinly' (194). Multidisciplinary research is popular – and often called for, in particular, by politicians and research funding institutes. However, to be multidisciplinary in the fruitful sense, researchers also need to bring their competence to shed light on the topic of interest (194). In this thesis, I have made use of the competence and methods served by other researchers, which was needed to fill an identified knowledge gap in drinking water preparedness in Norway. This knowledge gap involves several aspects, such as natural, contextual and technical factors, and actors from different sectors such as health and the technical side of drinking water supply (41).

### 6.4.2 Internal and external validity

In the following, I discuss factors that may influence the internal and external validity of the papers included in the thesis, and I examine to what extent the outcome of the thesis is relevant for drinking water preparedness in Norway. Validity is a measure of how well we have measured what we intended to measure (2). It usually differs between external and internal validity, where the internal validity refers to the study's ability to measure the relation between, for example, illness and treatment, without the interference of systematic errors or by chance (195). This could be obtained in randomised controlled studies (RCTs), where the randomisation and blinding of participants avoids confounding factors. However, regardless of how 'well conducted' a randomised study is, it does not always imply that it is relevant in a larger context, which is the external validity (195). External validity is also linked to the generalisability of the study, meaning the extent to which the outcome may be generalised to a larger population (152). An evaluation of the errors introduced in the study is essential when assessing the internal and external validity. Within epidemiology, the sources of bias are traditionally selection bias, information bias and confounding (82). Two of the studies in this thesis are observational studies: the cohort study in Paper I and the cross-sectional study in Paper III.

Selection bias is a systematic error in a study that arises when the association between exposure and disease differs between those who participate and those who do not, which skews the effect estimates as a result since the participants are not representative of the study population (195). Selection bias often occurs when there is a low response rate. In the cohort study in Paper I, conducted as a retrospective cohort study, we reached a response rate just above 50%, while in Paper III, the response rate in the cross-sectional survey was only 22%. Although we encouraged all the invited participants in Paper I to report on their experiences with illness in the defined period reflecting the outbreak – and considering the media attention in the outbreak – the response rate is lower than expected. In the study in Paper III, the low response rate was largely expected, as the topic is more or less insignificant in everyday life challenges, along with an anticipated decreasing interest in participating in surveys. We believe that the participants may have had an interest in the topic in both studies; hence, the outcome of the data may be estimated in a positive direction (196). In cohort studies, we are often not familiar with the reason why some participants leave the study or how this influences the outcome of the study (93). We were unable to conduct an analysis of the non-responders in Papers I and III, which could have informed the effect of selection bias in the results. Regarding the compliance of BWAs in Papers I and III, the low response rate may have overestimated the outcome, along with the possible effect of recall bias, for example, by the participants' tendency to overestimate their own positive behaviour. The latter may be more relevant for Paper III than Paper I, where the high compliance may also reflect recall bias based on the severity of the situation.

In Papers I and III, the outcomes have been triangulated using multiple methodological approaches. In Paper III, we used focus groups to understand insights regarding the questions, language and expressions that are relevant to a target audience (197). We anticipated that by discussing the topic in groups, we would generate a discussion and reflection with different viewpoints on the experience more than we would by conducting interviews. Focus groups may be applied to almost every topic of interest, but not where sensitive information is expected to be revealed. The drawback with focus groups is that the participants could orient towards consensus with the group rather than provide their own viewpoints and perhaps in less depth due to the presence of several participants, compared to individual interviews (161).

Information bias may have influenced the outcome of the assessment of the requests to NWG (Paper IV). The requests are few, and there is a risk of having wrongly classified the types of requests. If the requests are systematic, there will be a high precision of an outcome, but it will not necessarily be the topic of needed advice among the water supplies (2). The use of information from the advice logs has for such reasons been used to support the overall objective in the thesis, rather than a self-standing finding. The identified insecurity of action points based on coliform bacteria in the drinking water distribution systems is somehow triangulated during informal settings, such as in seminars for water operators and other practitioners, and is not the subject for research studies for the ones included herein in particular. Several data from the NWG, along with more comprehensive studies of capacities among small-scale drinking water suppliers, are needed to confirm this assumption.

### Errors in systematic reviews of observational studies

Evidence-based research has become an accepted and required approach in medical research (157). Traditionally, questions about the effects of treatment have been answered using systematic reviews and a meta-analysis of RCT design. RCTs are regarded as the 'gold standard' within medical research due to the possibility of limiting confounding factors in the study design, while the reporting from case reports and case series are regarded as the lowest of scientific evidence (157). However, systematic reviews are becoming increasingly applied to other study designs, such as observational and qualitative studies (156). The use of systematic reviews in study designs where confounding factors and selection bias are introduced, such as observational studies, creates some challenges that need to be addressed to evaluate the evidence (157). Another concern is publication bias (or reporting bias), which is a bias caused by a discrepancy between published studies of 'negative' results, as it is likely that research with results are mainly accepted for publication (157).

To avoid bias in the systematic review in this study, we applied preferred guidelines to ensure rigorous reporting (PRISMA) (198) and used tools to assess the risk of bias in our single included studies (158) and cumulative body of evidence (159). However, these tools were not without their challenges and may have affected the outcome of the study, particularly the assessment of risk of bias. For example, the concept of ROBINS-I is based on assessing the risk of bias from single studies based on a 'mimic' hypothetical randomised trial for the effect or effectiveness sought in the systematic review (158). In our systematic review, we assessed the effect of 'intervention' syndromic surveillance compared to traditional surveillance systems (Paper II). Although the hypothetical randomised trial for PICO is assumed to be pragmatic according to Sterne et al., it is challenging to imagine a randomisation of countries or nations, the several signals used for syndromic surveillance (133), and the ways the signals are calculated for surveillance purposes. This difficulty may have influenced the accuracy when assessing the risk of bias in the single studies in the systematic review (Paper II), especially since we were able to judge the risk of bias within each domain in the ROBINS-I tool (158).

### 6.4.3 Generalisability of the thesis

Based on reflections on the internal validity in the papers included in this thesis, I discuss to what extent the findings in this thesis may be generalised to shed light on drinking water preparedness in Norway.

Since Paper I concerns a particular waterborne outbreak, one could question how relevant the findings are to other drinking water supply systems in Norway. Case reports, or case studies, are often ranked in medical science as low in evidence and generalisability (194). Both direct technical causes and indirect causes have been identified in the outbreak: the intrusion of contaminated water into a cavern reservoir and barriers to implementing long-term precautionary actions. The reservoir in the Askøy outbreak is a cavern storage, which is a design where the reservoir is blasted in the mountain. This is a widely used construction for water storage in Norway; however, the numbers or conditions of the cavern reservoir are not known since they are not part of the routine reporting to the Norwegian Food Safety Authority. The cavern reservoirs in use in Norway most likely vary in terms of risks due to their feature of natural protection or precautionary actions among water suppliers in Norway. However, information on whether they are cavern reservoirs or constructed sealed reservoirs would improve the knowledge largely compared with the current surveillance system, and potentially benefit to spot new or re-emerging risks allowing for the planning of targeted preventive measures (59).

Cavern reservoirs have in general been associated with a certain risk of contamination from the environment (181, 199). Since they are established in a natural environment, it is a challenge to ensure proper hygienic conditions in general due to the lack of an overview of cracks where polluted waters may enter the drinking water storage. There exist technical measures such as lining or establishing waterproof sealing covers to avert possible dripping waters from reaching the drinking water; however, a risk will most probably still be present. One could argue whether cavern reservoirs are compatible for storing treated drinking water, knowing that they are not completely sealed, thus ruling out the risk of intrusion of polluted water from the environment or being generally unhygienic. The public health effects have severe consequences since no hygienic barriers to contamination, such as disinfection, are normally implemented in the distribution system or in water reservoirs. The reservoir itself is not protected with pressure, as the piped network is kept under normal conditions (181). Phasing out cavern reservoirs completely would entail high costs for the water sector and would be technically complicated, requiring time for planning and implementation. Knowing that there exists a risk to cavern reservoirs that could potentially cause a breach in the water quality, temporary solutions, such as implementing disinfection on the outlet of such caverns, may be needed to obtain a multi-barrier effect to ensure safe drinking water from source to tap in a safe drinking water framework (59).

Regarding the indirect causes identified in the outbreak, it might be argued that these are mainly associated with the administrative and political structure in Askøy and are not applicable to other water supply systems. However, the majority of drinking water supplies in Norway are organised in a manner like that of Askøy and adhere to the same regulations, which are largely expected to be interpreted in similar ways. On the one hand, the Norwegian Drinking water legislation refers to the water supplier as the main supplier responsible for the delivery of safe drinking water regardless of publicly or privately ownership (66). However, in 70% of the cases, the water supplies systems are publicly owned by the municipalities in Norway (22), where the development of the water supply is a political decision. The low fees mean that access to finance for long-term precautionary actions in the drinking water sector varies: in small municipalities, there are too few residents 'to share the cost', and in urban areas, the maintenance of the distribution system is technically complicated (183).

Several events in the drinking water supplies systems have triggered the need for advice every year in Norway; however, our results only incorporate the requests recorded by the NWG and cannot necessarily be generalised to all water supply-related events. An observation is that the need for advice mainly originates from smaller scale water supply systems. Organisations of small-scale water supplies have expressed challenges obtaining sufficient finance and competence (183). Recently, a new municipal administrative reform has been implemented in Norway, reducing the total number of administrative municipalities effective from 2020. This reform has led to a smaller reorganisation in the drinking water sector, where some of the new municipalities are responsible for several, also smaller, water supplies assuming that access to competence may have increased. In the future, this intervention could be studied in terms of drinking water preparedness or health effects.

Reliability (or replicability) refers to the possibility of reproducing the study and obtaining the same results (2). In our study, the use of a qualitative approach has been used to study a particular group of interest, and the generalisability of the findings may be claimed to not be an expected attribute (200). The reliability of this study may be argued to be of high relevance in the quantitative parts of this thesis, but of less relevance within the qualitative parts since the definition of reliability refers to the exact replicability of the processes and results (201). In qualitative research, replication of this study could not produce the same attitudes as social phenomena inevitable change over time (202). In addition, an attempt to repeat the study, the participants in the second interview would be influenced by the first interview, would imply challenges in the data (203). Of more relevance is the demonstration of the accurate handling of data in terms of form and context with constant comparisons either alone or with peers, resulting in a triangulation of the data from several methodological aspects (200).

# 7 Conclusions, Implications for Policy and Further Research Topics

The overall objective of this study was to shed light on factors that may add to the knowledge gap in drinking water preparedness in Norway. The specific aims were to identify the risks and examine the opportunities for early detection and effective response measures.

I found that, every year, events that may jeopardise drinking water safety occur in Norway, and occasionally severe waterborne outbreaks occur, as one did during my work on this thesis. A risk of contamination is arguably linked to the distribution system, particularly to cavern reservoirs. In the case of a contamination event evolving into a waterborne outbreak, there is no clear evidence that syndromic surveillance may serve as early detection, at least not for smaller and local waterborne outbreaks with an acute onset of illness. The lack of systems for the early detection of waterborne outbreaks emphasises that preventive long-term precautionary actions and conducting risk-based surveillance of drinking water supplies are essential to limit societal consequences. In the case of microbiological contamination events, which are likely to occur, or in the case of issuing a precautionary BWA, I found that public compliance with BWAs is generally high when awareness is high, but lower when advice goes unnoticed. The compliance could also be affected by the perception of the severity of the situation – lower compliance if the risk of illness was perceived as low. In general, the communicated BWAs increased consumers' trust in the municipality and the safety of the drinking water. Regarding the issuance of BWAs, the water suppliers might be unsure about how to respond properly based on the findings of coliform bacteria, while at the same time not detecting *E. coli*.

The findings could entail implications for improving drinking water safety in Norway. Drinking water supply systems widely use cavern reservoirs in the distribution of drinking water. However, such cavern reservoirs are not mapped in terms of the number or risk assessed in Norway. A closer assessment of the risks related to cavern reservoirs in Norway is needed to determine which are at more risk than others. This assessment should be prioritised since the cost of replacing is high and is, in general, very technically complicated and time-consuming. Geological hazard assessment is largely complicated and requires qualified competence to conduct. However, a tool or guideline that enables water suppliers to report the risks related to their cavern reservoirs in their water safety planning should be developed. Owing to the natural features of cavern reservoirs, they are assumed to not be compatible with the hygiene levels required for safe drinking water, which prompts the need for measures to obtain a multiple barrier approach. A technical solution is to provide disinfection on the outlet of such reservoirs until they are replaced or otherwise considered not to jeopardise the safe drinking water quality.

The outbreak in Askøy is also a reminder that ageing infrastructure is a concern, particularly in terms of water reservoirs. In Norway, much emphasis has been directed towards the increasing age of the piped network due to a relatively slow pace in renewing leaky pipes, which is reflected in the national goals for water and health. The risk has been associated with low-pressure events due to sudden outages or planned maintenance in the pipelines and less towards the risks related to water reservoirs.

Whether a safe drinking water supply is high enough on the administrative and political agenda in Norway to ensure the implementation of precautionary actions could be questioned. This is a challenging point, since drinking water could largely be argued to have become a 'taken for granted' commodity, and it could easily lose priority over other emerging issues such as education and commerce interests. Measures such as bureaucratic 'fast-tracks' in planning processes or re-organising the drinking water sector could be elaborated to propose the future management of safe drinking water.

A system for the early detection of waterborne outbreaks is somewhat missing. Although the astute clinicians will probably be the first to detect local outbreaks with an acute onset in Norway, improvements to the established NorSySS in terms of daily updates of signals might improve the detection of slowly evolving outbreaks. Local and short-lived waterborne outbreaks with an acute onset will probably not be detected in a national system, and an evaluation of the cost-effectiveness should be conducted before implementing possible fruitful systems combining water supply zones and environmental and health data, even at the local level. Improvements to NorSySS by, for example, including a daily update may serve to detect slower evolving outbreaks by assessing trends in gastroenteritis.

Communication of the risks during response measures to microbiological contamination events is an important factor in compliance with BWAs. Along with a certain uncertainty identified in situations regarding when to issue a BWA, it could be explored whether a national guideline for BWAs should be developed. Such a guideline should be to sort out dilemmas on when and how to distribute a BWA to support a timely and suitable response to microbiological contamination events and ensure the highest public compliance with BWAs.

The conclusions and implications for policy in this thesis are made based on the studies conducted mainly within the context of Norway. Although some aspects, such as the use of cavern reservoirs and municipal ownership of drinking water supplies, may be assumed to be most relevant to Norway, other aspects could be relevant to similar contexts of drinking water supply systems. These aspects could include the findings from the review of syndromic surveillance, which is based on published literature both internationally and nationally, and is the first updated systematic review on syndromic surveillance for the detection of waterborne outbreaks since 2006. The studies on compliance to BWAs add to a general knowledge gap on the topic , which also addresses dilemmas faced by responsible health authorities and water supply systems outside of Norway. In addition, the risk of contamination due to an ageing infrastructure, limited capacities in small-scale drinking water supply systems and expected negative effects of climate change – including uncertain weather patterns – are risk factors that are relevant to contexts similar to Norway.

The following topics could be studied to shed further light on drinking water preparedness in Norway:

- The source attribution of *Campylobacter* to fill a gap in knowledge of the risk factors for the drinking water distribution system, particularly pressure-less installations such as reservoirs

- The effect of climate change on distribution networks to gain more specific knowledge on where and how to focus preventive measures

- Qualitative studies on the perception of risks in water supplies to improve BWA compliance, with a particular focus on non-compliers

- The effect of municipal re-organisation launched in 2020 to assess whether access to new competence has led to an improvement in drinking water safety

- Qualitative studies of the response capacities of small-scale drinking water suppliers to inform future competence building activities and to target counselling, for example, to the NWG.

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# Annex I

# Paper I

# Large waterborne *Campylobacter* outbreak: use of multiple approaches to investigate contamination of the drinking water supply system, Norway, June 2019

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On 6 June 2019, the Norwegian Institute of Public Health was notified of more than 50 cases of gastroenteritis in Askøy. A reservoir in a water supply system was suspected as the source of the outbreak because of the acute onset and geographical distribution of cases. We investigated the outbreak to confirm the source, extent of the outbreak and effect of control measures. A case was defined as a person in a household served by Water Supply System A (WSS-A) who had gastroenteritis for more than 24 h between 1 and 19 June 2019. We conducted pilot interviews, a telephone survey and an SMS-based cohort study of residents served by WSS-A. System information of WSS-A was collected. Whole genome sequencing on human and environmental isolates was performed. Among 6,108 individuals, 1,573 fulfilled the case definition. Residents served by the reservoir had a 4.6× higher risk of illness than others. *Campylobacter jejuni* isolated from cases (n = 24) and water samples (n = 4) had identical core genome MLST profiles. Contamination through cracks in the reservoir most probably occurred during heavy rainfall. Water supply systems are susceptible to contamination, particularly to certain weather conditions. This highlights the importance of water safety planning and risk-based surveillance to mitigate risks.

## Background

Campylobacteriosis is a common cause of bacterial diarrhoeal illness worldwide [1] and *Campylobacter jejuni* is the most common species in human infections [2]. Patients typically experience self-limiting diarrhoeal illness lasting 5 to 7 days [2]. Immunocompromised and elderly patients are at highest risk for prolonged illness and death [2]. Faecal-oral transmission to humans can occur through consumption of contaminated food and water, contact with animals and person-to-person contact [3]. In Norway, outbreaks of campylobacteriosis have been associated with consumption of untreated or contaminated drinking water, unpasteurised milk, mutton, contact with farm animals and with butchering, preparation and consumption of poultry [4-6].

Despite advances in water management and sanitation in high-income countries, waterborne outbreaks still occur and may acutely infect many people simultaneously [7]. Several waterborne outbreaks have been caused by contamination of the raw water source and inadequate hygienic barriers in the treatment process [8,9]. Updated regulations have improved safety at the treatment stage with a multiple-barrier approach in many water supply systems [10,11]. However, the distribution network is increasingly being identified as at risk for contamination through pipe breaks, cross connections and wastewater intrusion between the water treatment plant and the households [5,10,12,13]. Campylobacteriosis is the most commonly reported gastrointestinal disease in humans in Europe [14]. In Norway, waterborne outbreaks are detected every year [15,16], including two large waterborne outbreaks with more than 1,000 cases in the past 20 years. In 2004, an outbreak of giardiasis caused 1,300 confirmed cases and affected an estimated 6,000 residents in Bergen [17] and in 2007, an outbreak of campylobacteriosis associated with contaminated drinking water in Røros caused 1,500 cases [5].

## Outbreak detection

On the evening of 6 June 2019, the Medical Officer in Askøy reported an outbreak of gastroenteritis to the NIPH. In a 24 h period, 10 people had been hospitalised with fever, abdominal pain and diarrhoea, and ca

**Figure 1**

Water supply zones of water supply system WSS-A defined by different reservoirs, Askøy, Norway, 2019


Zones 6, 7 and 8 were served by Reservoir X.

30 individuals had sought medical attention from out-of-hours primary healthcare services (OPHS). At least one person had tested positive for *Campylobacter*. Staff of the OPHS noted that many patients presenting with gastroenteritis had home addresses near each other, which led to a suspicion that drinking water could be the source of the outbreak. A joint investigation was carried out by the municipal services, the Norwegian Food Safety Authority and the Norwegian Institute of Public Health (NIPH), with the aim to confirm the source, extent of the outbreak and effect of control measures.

# Methods

## Outbreak context

The 29,500 inhabitants of the island municipality Askøy receive water from three different water supply systems, of which the largest, Water Supply System A (WSS-A) from the 1950s, serves ca 12,000 people in the south of the island. WSS-A has nine reservoirs, including three built as unlined mountain caverns. Its Reservoir X was early on suspected to be the source of the outbreak because of the geographical distribution of cases that clustered in two areas.

## Epidemiological investigations

### Outbreak monitoring

In order to determine the extent of the outbreak, we collected data on in-person and telephone consultations with the International Classification of Primary Care (ICPC-2) codes for diarrhoea (D11), gastrointestinal infection (D70) and gastroenteritis (D73) that occurred at the OPHS and general practitioners' (GP) offices in Askøy between 3 June and 15 June. We mapped all consultations by household address and water supply zone.

Several of the initial cases with confirmed *Campylobacter* infections were interviewed using a standardised 19-page trawling questionnaire in order to exclude possible exposures other than drinking water. The questionnaire included detailed questions about food consumption and purchases, animal contact and environmental exposures in the week before the onset of symptoms, as well as clinical and demographical information.

### Survey of childcare centres

In order to rapidly ascertain the start and geographical areas of the outbreak, we contacted all childcare centres in the municipality on 11 and 12 June to document absence for illness. As children normally attend childcare centres close to their homes, it was likely that the household and childcare centre water supply zones would be the same. For the childcare centre survey, a case was defined as any person absent from the childcare centre (child or employee) because of the symptoms diarrhoea or vomiting between 28 May and 7 June. We then mapped the childcare centres by water supply zones served by the different reservoirs and compared the attack rates in childcare centres served by Reservoir X against those served by other reservoirs.

### Cohort study of households

We included all residents who received water from WSS-A in a retrospective cohort study, and identified eight different water supply zones (Figure 1).

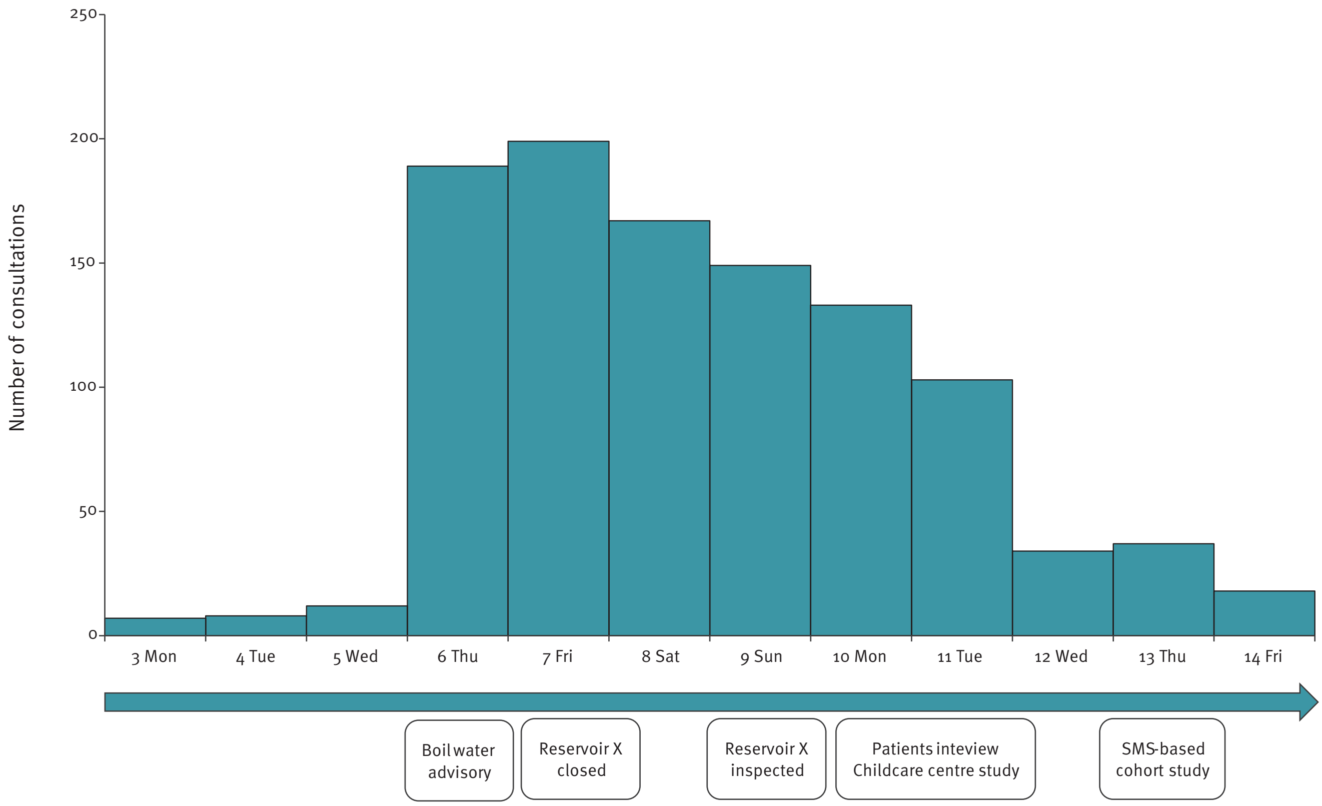
People in households that partially or exclusively received water from Reservoir X were defined as exposed. We defined a case as a person with gastroenteritis (defined as having symptoms of (i) diarrhoea only or (ii) vomiting and at least one of the following: abdominal distention, fever, stomach pain or nausea, with duration of illness of more than 24 h), with symptom onset between 1 and 19 June 2019.

We sent all households served by WSS-A an SMS with a link to our questionnaire on 13 June 2019 and posted the link on the municipality's website. We requested that one person should respond on behalf of all household members. We asked about household illness, clinical presentation, tap water consumption and whether the household had received and followed the boil water advisory (BWA). The survey was closed on 20 June.

We used R version 3.6.0 (2019–04–26) for statistical analyses.

**Figure 2**

Number of gastroenteritis consultations (including telephone consultations) at OPHS and GP offices, Askøy, Norway, 3–14 June 2019 (n = 1,056) and timeline of action points




GP: general practitioner; OPHS: out-of-hours primary healthcare services.

## Microbiological investigations

The primary diagnostic laboratory sent Campylobacter isolates from patients to the National Reference Laboratory for Enteropathogenic Bacteria (NRL) for confirmation and genotyping.

We extracted DNA on MagNAPure 96 (Roche Molecular Systems Inc., Pleasanton, United States (US)) and used KAPA HyperPlus (Kapa Biosystems, Wilmington, US) for library preparation and Agencourt AMPure XP (Beckmann Coulter Life Sciences, Indianapolis, US) for removal of adaptor dimers. Whole genome sequencing was performed as paired-end (250 bp × 2) sequencing on the MiSeq platform (Illumina Inc., San Diego, US) aiming for coverage of› 50×. Quality control of the raw reads was done through FastQC.

We used SeqSphere+ software, version 5.1 (Ridom GmbH, Münster, Germany) for analysis. Briefly, multilocus sequence typing (MLST) of the *Campylobacter* isolates was performed using the seven-gene scheme developed by Keith Jolly at PubMLST [18]. Core genome MLST was performed using SeqSphere+ integrated scheme for *Campylobacter* of 637 core and 958 accessory genome targets modified from Cody et al. [19,20].

According to the routine sampling and analysis plan for WSS-A, water samples are collected and tested for faecal indicator bacteria: weekly for *Escherichia coli* and coliform bacteria and for heterotrophic plate count, and monthly for intestinal enterococci and *Clostridium perfringens*, according to standard methods described in the national drinking water legislation [21].

After the outbreak was detected, we started extra sampling of the water in WSS-A and analysed it for faecal indicator bacteria at an accredited laboratory using standard methods. On 6 June, we also took water samples from Reservoir X and several other points along the distribution system and immediately analysed it for *Campylobacter* using semiquantitative and quantitative determination in foods and drinking water (NMKL 119, 3.Ed., 2007) with pre-incubation on enrichment broth of filtered sample followed by plating on a selective medium [22]. The presence of *Campylobacter* was confirmed by phase contrast microscopy.

## Environmental investigations

We reviewed operational system information and historical data from WSS-A, including results from drinking water routine monitoring schemes before the outbreak. We assessed critical points and possible sources of

**Figure 3**

Estimated incidence rates for gastroenteritis consultations linked to reservoir supply zones, Askøy, Norway, 6 June 2019


IR: incidence rate.

The three zones with IR › 1 are the ones served by Reservoir X.

contamination (including system failures and unusual events) through interviews of WSS-A staff and visual inspections of selected areas of WSS-A, including Reservoir X. Local rainfall was assessed using data from the national meteorological website (www.yr.no).

## Ethical statement

Approval by a regional committee for medical research was not needed as the NIPH is authorised to access and use personal identifiable information for communicable disease outbreak investigations in the public interest. All persons invited to the pilot interviews and childcare centres study provided oral consent to be a part of the study. They were informed that they could withdraw at any time during the study and that their data would be deleted. The SMS questionnaires were distributed by Askøy municipality and personal identifiers were not a part of the dataset.

## Results

## Epidemiological investigation

### Outbreak monitoring and timeline of action points

A BWA was issued when the outbreak was detected on 6 June. Reservoir X was taken out of service on 7 June and inspected on 9 June by representatives from Askøy municipality and NIPH. The pilot interviews and childcare centre survey were conducted on 11 June, and the SMS-based cohort study started on 13 June.

Data collected at the OPHS and GP offices revealed a sharp increase in the number of consultations for gastroenteritis (from 12 to 182 consultations) on Thursday 6 June (Figure 2). The consultations were evenly distributed among all age groups, although in-person consultations were primarily for children.

The gastroenteritis patients' residences were geographically concentrated in two areas of the municipality, which coincide with three water supply zones served by Reservoir X. These zones had higher incidence rates (IR) for consultations than other supply zones in WSS-A at the time of the outbreak detection (Figure 3).

### Pilot interviews with confirmed cases

We interviewed five of the first cases with confirmed *Campylobacter* infection. They reported diarrhoea, stomach pain and fever with onset on 4 June (n = 1) or 5 June (n = 4). They lived in areas that received drinking water from WSS-A and had consumed tap water at home or used tap water for brushing teeth in the week before symptom onset. Other reported exposures, such as attendance at common dinners or events, consumption of food items, contact with animals or recreational water exposure, were not common to all five cases.

### Survey of childcare centres

All 27 childcare centres in the municipality participated in the study; eight (with 769 children and employees) were in areas supplied by Reservoir X and 19 (with 1,761 children and employees) were in areas supplied by other reservoirs. The overall attack rate was 20% for the childcare centres in affected areas and 2% for the childcare centres in unaffected areas. Absences started to increase at the childcare centres in affected areas on Monday 3 June (n = 26) and peaked on Friday 7 June with 81 absences (11%).

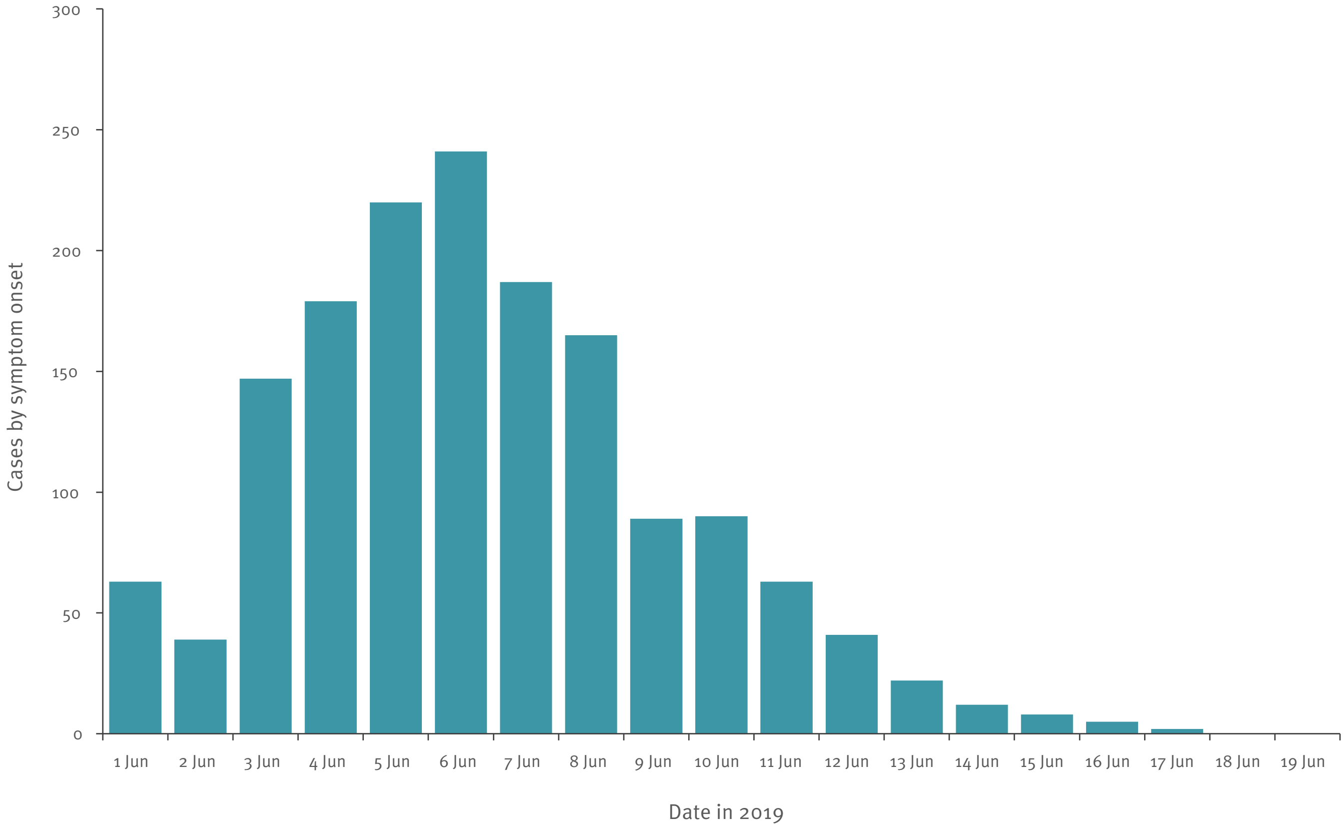
### Cohort study of households

The SMS with the questionnaire was sent to 4,409 persons with mobile phone numbers registered to residences in the supply area of WSS-A. Data from 6,192 individuals were reported through the online questionnaire, of whom 1,913 reported illness. We excluded data for 79 household members who reported onset of illness before 1 June and for five who reported onset of illness after 19 June. After this exclusion, data were available from 2,526 persons who responded on behalf of 6,108 household members, which yields a coverage of 51% (6,108/11,995) of the residents supplied by WSS-A. Mean age of the included household members was 34 years (range: 0 to 93 years) and 50% were female.

A total of 1,829 persons reported at least one of the following symptoms: diarrhoea (n = 1,626; 89%), abdominal pain (n = 1,347; 74%), headache (n = 959; 52%), nausea (n = 935; 51%), fever (n = 868, 48%), abdominal distention (n = 639; 35%), vomiting (n = 286; 16%) and bloody stool (n = 113; 6%). In total, 1,573 respondents

**Figure 4**

Distribution of cases by date of symptom onset, Askøy, Norway, 1–19 June 2019 (n = 1,573)




Most respondents sent their response on 13 June, numbers after this date may be uncertain.

met the case definition, leading to an attack rate of 26%. The number of cases by date of symptom onset peaked on 6 June and decreased gradually thereafter (Figure 4). The mean duration of symptoms was 4.6 days (range: 2–16 days).

Residents who were supplied from Reservoir X had a 4.6× higher risk of illness than residents served by other reservoirs in WSS-A (Table 1).

Among residents supplied by Reservoir X, the risk of illness increased with the amount of daily consumption of tap water (p value $< 0.001$) (Table 2).

Regarding the notification of BWA via SMS, 88% of households (2,223 of 2,526) reported that they had received an SMS with the BWA, while 179 (7%) did not receive the BWA and 124 (5%) were unsure.

A total of 2,384 households reported having complied with the BWA (compliance rate: 95%: 2,384/2,526). Reasons for non-compliance were reported by 142 of the households; the main reasons were purchasing bottled water (n = 76), considering that the risk of becoming ill was low (n = 9) and drinking little or no tap water (n = 4). For the remaining 53 households, reasons for non-compliance to the BWA were not reported.

## Microbiological investigation

### Analysis of *Campylobacter*

The Norwegian Surveillance System for Communicable Diseases (MSIS) registered 181 laboratory-confirmed cases of campylobacteriosis linked to this outbreak. The NIPH received 24 isolates of *C. jejuni* from persons served by Reservoir X. All isolates were sequence-typed as ST1701, which is part of the clonal complex ST-45, and all had identical cgMLST profiles, cluster type 97 (0 allelic differences). Two representative sequences have been submitted to the European Nucleotide Archive (ENA) (ERS4574581, ERS4574582). When comparing publicly available ST1701 *C. jejuni* sequences to the outbreak strain, we did not observe any close genetic relationships, although poultry or birds were identified as a possible source.

### Analysis of water

In the 3 years before 3 June 2019, the routine monitoring programme for WSS-A did not detect any faecal indicator bacteria in WSS-A or in Reservoir X, except for occasional findings of coliform bacteria. The samples collected during routine monitoring for WSS-A on 3 June were also negative for faecal indicator bacteria, including samples located near Reservoir X.

**Table 1**

Estimated attack rates and risk ratio for areas supplied by Reservoir X and other areas, gastrointestinal illness, Askøy, Norway, 2019 (n = 6,108)

| Reservoir | Households | Individuals | Cases | Attack rate | Risk ratio (95% confidence interval) |
|---|---|---|---|---|---|
| Other reservoirs in WSS-A (zones 1–5) | 1,653 | 4,098 | 481 | 12% | Reference |
| Reservoir X (zones 6–8) | 873 | 2,010 | 1,092 | 54% | 4.6 (4.2–5.0) |

**Table 2**

Risk of gastrointestinal illness by consumption of tap water, Askøy, Norway, 2019 (n = 6,108)

| Daily tap water consumption | Individuals | Cases | Attack rate | Risk ratio (95% confidence interval) |
|---|---|---|---|---|
| 0 glasses | 381 | 27 | 7% | Reference |
| 1–3 glasses | 2,562 | 586 | 23% | 3.2 (2.2–4.7) |
| 4–6 glasses | 2,255 | 654 | 29% | 4.1 (2.8–5.9) |
| ≥ 7 glasses | 910 | 306 | 34% | 4.7 (3.3–6.9) |

Of eight water samples taken on 6 June, five were collected from Reservoir X and areas supplied by Reservoir X and were faecally contaminated, while the remaining three samples from other areas were not. Seven water samples collected from the distribution system at the same locations on 9 June, after Reservoir X was taken out of service on 7 June, were negative for faecal indicator bacteria. One sample taken inside Reservoir X on 9 June was positive for faecal indicator bacteria, as were all samples collected in Reservoir X during the week of the outbreak (until 13 June).

Four of seven water samples were positive for *Campylobacter* (7 June). The positive samples had been taken from Reservoir X, two households and one school supplied by Reservoir X. *Campylobacter jejuni* isolates from cases (n = 24) and water samples (n = 4) were identical by WGS.*

## Environmental investigation

### Description of the water supply network

Under normal conditions, Reservoir X supplies a defined zone (zone 6) of 1,350 residents. However, before the outbreak, a valve had been opened from Reservoir X to ensure replacement of water in response to customer complaints about the water quality in the area. This led to a connection between zone 6 and zones 7 and 8 (Figure 1), serving in total 3,558 residents with drinking water from both Reservoir X and other reservoirs. Zone 6, 7 and 8 were all considered zones affected by water supplied by Reservoir X and consultations indicated a higher IR in these zones initially in the outbreak detection (Figure 3). The valve was closed on 6 June.

### Visual inspection of Reservoir X

Reservoir X is a basin constructed as an unlined rock cavern with an entrance sealed by a locked door. It holds ca 400 $m^3$ of water and is located above a residential area in mountainous terrain. The inflow and outflow of Reservoir X is through the same pipe. Because of the design of the reservoir, the chosen sampling location for routine monitoring samples did not capture the water flowing out of the reservoir. Potential contamination introduced to the reservoir would therefore not necessarily not be detected.

During the visual inspection of Reservoir X, we observed natural cracks located in the back of the reservoir. There were leaks in the concrete construction and we observed water running from inside the roof. A large antenna is also located above the reservoir, with power lines running over the closed cavern, were birds could potentially gather and increase the risk of bird faeces contaminating the area below. Although varied wildlife is reported in the area, we did not observe this during our inspection of the area.

No unusual malfunctions in the distribution system were reported before the outbreak. In weeks 21 and 22, three episodes of extreme rainfall (24 May, 1 June and 3 June) occurred in the area after a long dry period from 1 April to 20 May. Weather data obtained from a nearby weather station (Skredderdalen) indicated heavy rainfall which coincided with registered consultations of gastroenteritis in the Norwegian Syndromic Surveillance System (NorSySS) (Figure 5).

## Outbreak control measures

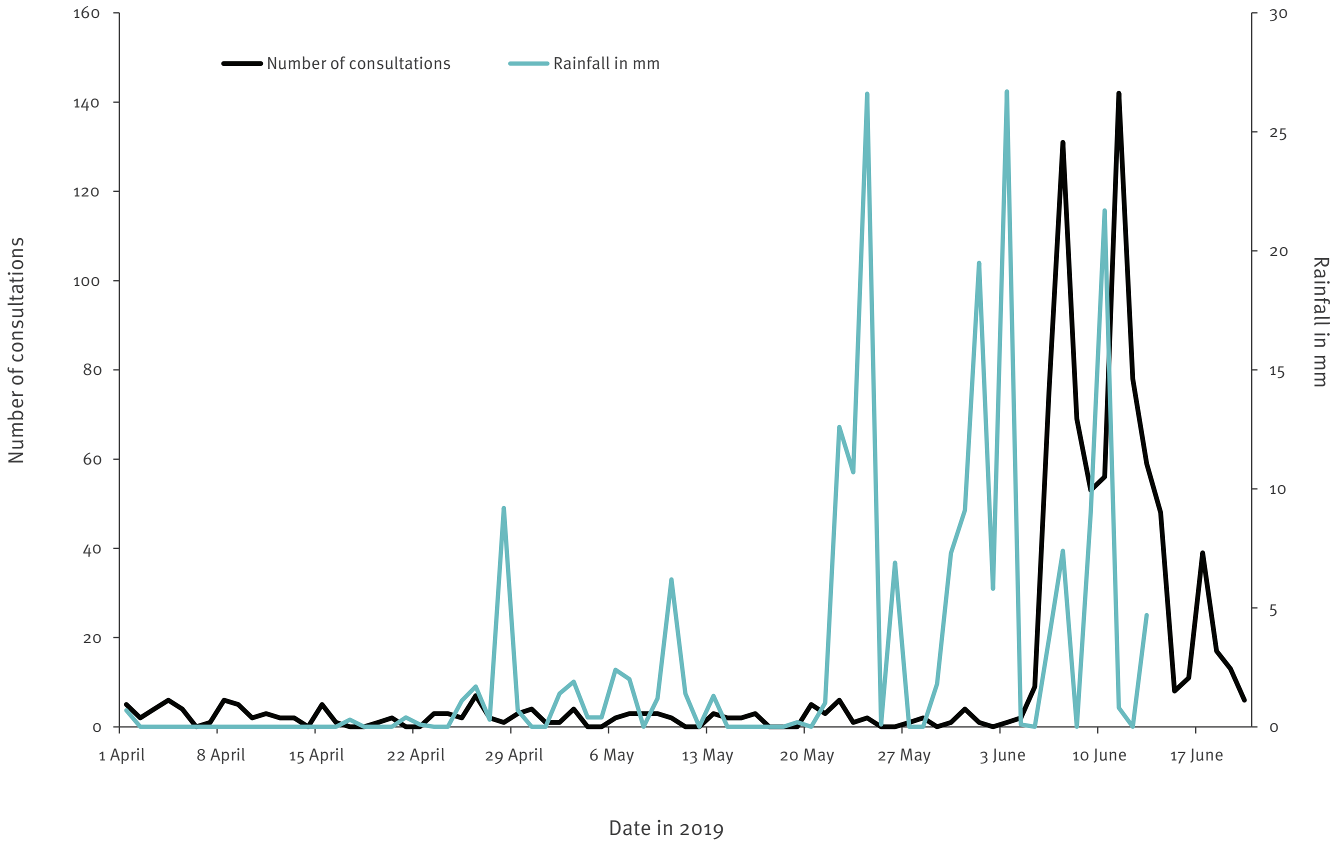
In addition to issuing a BWA and closure of Reservoir X (Figure 1), emergency water supply distribution started on 8 June from water tanks located in public areas such as school and parking lots, and infection control measures in public services were strengthened, as a measure to address the concern in the population.

## Discussion

The results of epidemiological, microbiological and environmental investigations support that contaminated water from Reservoir X caused an outbreak of more than 1,500 cases of campylobacteriosis in Askøy in June 2019. The triangulation of epidemiological, genomic, geographical and water systems data was essential for confirming the role of Reservoir X in the outbreak and determining the extent of exposure

**Figure 5**

Data on rainfall from a nearby weather station and onset of consultations for gastroenteritis registered in the Norwegian Syndromic Surveillance System (NorSySS), Askøy, 1 April–20 June 2019 (n = 948)




within the community. The rationale for the decisions early in the phase of the outbreak was based on local knowledge and mapping of cases rather than epidemiological studies. This observation gave a hint towards the drinking water supply system as the source to the outbreak. The use of multiple approaches and use of mixed methods also allowed us to identify contributing factors, such as inclement weather conditions, and ensure that the implemented control measures had successfully stopped the outbreak. While we were unable to conclusively determine how the reservoir became contaminated, the diversity of data sources used to investigate this outbreak support the hypothesis that environmental contamination through cracks in Reservoir X most likely occurred during heavy rainfall following a long dry period.

*Campylobacter* has frequently been identified as the cause of waterborne outbreaks [10,23], often associated with heavy rainfall [24,25] and intrusion of contaminated surface water either into source water [26-30] or into the distribution network [31,32]. In 2006, a risk analysis of WSS-A pointed out the vulnerability of unlined reservoirs established in mountains. Reservoir X was therefore scheduled to be taken out of service, as a part of long-term precautionary actions, and replaced by a newly built reservoir in the area in February 2019, several months before the outbreak. However, work to connect the new reservoir was delayed and only a limited number of households had been connected to the new reservoir at the time of the outbreak. Given the identified vulnerabilities, the occurrence of an outbreak under these conditions was foreseeable [33] and serves as a reminder that the drinking water is susceptible for contamination at any time, even during transition phases [5,17]. Continuous risk assessment, followed by implementation of long-term precautionary actions, is essential to protect the drinking water from contamination, while simultaneously ensuring day-to-day operation [34].

There was no indication of contamination with faecal indicator bacteria before the outbreak from routine sampling conducted on 3 June. This is a common finding in many waterborne outbreaks in which routine monitoring was neither the source of early detection nor able to prevent the occurrence of an outbreak [7]. Although traditional routine monitoring conducted by the waterworks serves an important function in terms of assessing the performance of the water supply system, it does not reliably allow for monitoring imminent health risks in distribution systems, surveillance of diseases or prediction of outbreaks [35,36]. To allow early detection of deviant water quality in the distribution system, technological advances are being made in terms of real-time monitoring of water distribution supply systems. However, it may still be difficult to link the results to public health monitoring systems and operational response [37]. This highlights the need to focus on water safety planning to protect the water supply from contamination and to conduct risk-based surveillance, rather than detecting the contamination in retrospect [38]. This is particularly relevant when external risk factors to the water supply systems are changing, such as unexpected rainfall patterns, and the existing infrastructure may not be designed to adapt or is vulnerable because of lack of maintenance and upgrading.

Timely detection of waterborne outbreaks is crucial in preventing widespread exposure of the population and limiting the negative health consequences. Although the exposure to contaminated drinking water may be almost instantaneous for the supplied residents, the detection may be delayed, particularly in large areas served by the same water supply [17,39], while the time between exposure and detection may be shorter in more limited contexts [5]. To overcome delays in detection that may occur when relying on surveillance of laboratory-confirmed cases, syndromic surveillance of real-time (or near to real-time) clinical signs and symptoms as well as proxy measures [40,41] may be useful, especially if health data can be linked to water supply system information [42,43]. In Askøy, the outbreak alert was generated by astute healthcare workers on the evening of 5 June and on 6 June, information on the geographical distribution of the consulting patients' addresses were manually plotted on maps, demonstrating a link to Reservoir X. Although there are theoretical benefits of a surveillance system based on epidemiological indicators, either on an ongoing basis or triggered by spatio-temporal exceedances it is unlikely that this would have led to a more timely detection in Askøy. However, having systems in place that allow for rapid combined analysis of health and water systems data may have simplified the investigation of the outbreak and monitoring of the efficacy of the control measures.

This investigation has several limitations. Initially, it was difficult to determine the scale of the rapidly developing outbreak. Although campylobacteriosis is a notifiable disease in Norway, only a small proportion of sick residents were tested and laboratory-confirmed cases were not reported rapidly enough to follow the progression of the outbreak. For this reason, consultations for gastroenteritis were tracked manually through the GP and OPHS offices on a daily basis for outbreak monitoring until monitoring with NorSySS was possible. The SMS-based cohort study corroborated the onset and duration of the outbreak, but since only one person in the household was asked to respond on behalf all members of the family, this may have led to an underestimation of cases. In addition, the specific case definition excluded more than 500 people who reported illness possibly linked to the outbreak. On the other hand, the widespread media attention may have affected the results of the SMS-based cohort study by overestimating illness among the respondents. However, we chose to use a specific case definition to avoid including people that were ill for other reasons.

## Conclusions

A large waterborne outbreak leading to more than 1,500 cases of campylobacteriosis occurred in Askøy in Norway in June 2019. Through multiple data sources, we were able to determine that contamination of drinking water occurred through cracks in a mountain reservoir, probably because of heavy rainfall after an extended dry period. This is a reminder that water supply systems, in particular ageing infrastructure, are generally vulnerable and susceptible to contamination that may result in an outbreak, especially as external risks such as climate factors are changing. This investigation highlights the importance of conducting water safety planning, updating the infrastructure and performing risk-based surveillance to mitigate risks.

### *Author's correction

On request of the authors, the sentence "*Campylobacter jejuni* isolates from cases (n = 24) and water samples (n = 4) were identical by WGS" was added on 28 October 2020 to the chapter on the Microbiological investigation.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### Conflict of interest

None declared.

## Authors' contributions

SH participated in the environmental outbreak investigations and wrote the first draft of the manuscript; AI, BÅSB and AB were responsible for the local outbreak management in Askøy; EM was leading the epidemiological studies during the outbreak investigations; EA and KN participated in the outbreak monitoring and epidemiological studies; AS participated in the outbreak investigations during pilot interviews; LTB and UN participated in the microbiological and molecular outbreak investigations; TML and LVe participated in the epidemiological investigations and statistical analysis; LVo was coordinating the outbreak investigations. All authors contributed to the manuscript, revised it and approved the final version.

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# Paper II

# The effectiveness of syndromic surveillance for the early detection of waterborne outbreaks: a systematic review

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**Abstract:**

Background: Waterborne outbreaks are still a risk in high-income countries, and their early detection is crucial to limit their societal consequences. Although syndromic surveillance is widely used for the purpose of detecting outbreaks days earlier than traditional surveillance systems, evidence of the effectiveness of such systems is lacking. Thus, our objective was to conduct a systematic review of the effectiveness of syndromic surveillance to detect waterborne outbreaks.

Method: We searched the Cochrane Library, Medline/PubMed, EMBASE, Scopus, and Web of Science for relevant published articles using a combination of the keywords 'drinking water', 'surveillance', and 'waterborne disease' for the period of 1990 to 2018. The references lists of the identified articles for full-text record assessment were screened, and random searches using the same key words were conducted. We assessed the risk of bias in the included articles using the ROBINS-I tool and PRECEPT for the cumulative body of evidence.

Results: From the 1,955 articles identified, we reviewed 52 articles, of which 16 met the eligibility criteria. Ten were retrospective studies, whereas six were simulation studies. There is no clear evidence for syndromic surveillance in terms of the ability to detect waterborne outbreaks (low sensitivity and high specificity). However, one simulation study implied that multiple sources of signals combined with spatial information may increase the timeliness in detecting a waterborne outbreak and reduce false alarms.

Conclusion: This review demonstrates that there is no conclusive evidence on the effectiveness of syndromic surveillance for the detection of waterborne outbreaks, thus suggesting the need to focus on primary prevention measures to reduce the risk of waterborne outbreaks. Future studies should

investigate methods for combining health and environmental data with an assessment of needed financial and human resources for implementing such surveillance systems.

**Keywords:** Syndromic surveillance, early detection, gastrointestinal illness, waterborne outbreaks

## Background

Waterborne outbreaks have a particular high risk for public health, as exposure to drinking water that has been contaminated with pathogens could affect a large population in a relatively short period of time (1). The early detection of infectious diseases is crucial to prevent related consequences, such as the loss of life, adverse health events, and societal burdens (2). Moreover, experience has shown that relying only on the passive surveillance of laboratory-confirmed cases is not sufficient for the timely detection of waterborne outbreaks of non-endemic infections and may contribute to late detection and worse overall health impacts (3). Syndromic surveillance (SyS), which aims to identify a threshold number of early symptomatic cases and facilitate the detection of an outbreak days earlier than conventional surveillance, has been implemented worldwide (4). SyS is defined as the real-time (or near real-time) collection, analysis, interpretation and dissemination of health-related data (2), such as indicators of clinical signs and symptoms, as well as proxy measures such as over-the-counter pharmaceutical sales, hospital admission reports or infectious disease surveillance (5-8).

Although SyS has theoretical advantages in detecting waterborne outbreaks, the approach has been questioned in terms of the resources needed to evaluate the signals and distinguish them from "false alarms", i.e. the specificity (9). A number of factors is needed for evaluating public health surveillance system, including resources needed, usefulness, acceptability amongst other, in particular distinguishing an outbreak from a "false alarm" (10). Some of the technical core assets to evaluate a surveillance system's ability to detect a true outbreak is timeliness, sensitivity and specificity (11). Useful surveillance systems for detecting a true outbreak is a balance between the timeliness, sensitivity and specificity, where the ideal situation is to have high values of sensitivity and specificity. However, in reality, this would require a less timely detection (9).

SyS systems for detecting waterborne outbreaks were reviewed in 2006 (12), with the recommendation that such surveillance should not be implemented at the expense of traditional surveillance. On the other hand, Berger et al. (12) also suggested that syndromic data sources, such as the over-the-counter sales of anti-diarrheal medications for detection of waterborne outbreaks, should be further evaluated (12). In the aftermath of this aforementioned review, several articles were published in the field of SyS for waterborne illness and early outbreak detection. However, these articles have not yet been reviewed for the purpose of assessing SyS effectiveness, indicating an updated knowledge gap in this field.

With this review, we aim to provide a knowledge update on the use and effectiveness of SyS approaches to detect waterborne outbreaks among populations connected to water supply systems earlier than traditional surveillance. We have specifically examined reported timeliness, sensitivity and specificity using implemented SyS approaches in contexts where health structures in place. An updated evidence for the effectiveness of the application of SyS will contribute to the evaluation and decision-making processes related to the implementation of this approach.

# Methods

## Literature search

We searched the Cochrane Library (http://www.thecochranelibrary.com/), Medline/PubMed (https://pubmed.ncbi.nlm.nih.gov/), EMBASE (https://www.embase.com/login), Scopus (http://www.Scopus.com), and Web of Science (https://apps.webofknowledge.com) for relevant published articles using a combination of the keywords 'drinking water', 'surveillance', and 'waterborne disease'. A research librarian conducted the search between January to March of 2019, and the search strategy is described in Additional File 1. The publication period was set from 1990 to 2018, and only peer-reviewed publications in English, German, French, Spanish, and Scandinavian languages (Norwegian, Swedish, and Danish) were included in the search. The bibliographies of the eligible articles were screened to identify additional studies. We also searched Google Scholar for articles using the same key words.

## Selection criteria

We included studies on the early detection of waterborne outbreaks using signals from data sources other than diagnostic data. Descriptive and analytical studies or simulation studies on waterborne outbreaks were included in the review. Studies aiming at demonstrating a general association between gastrointestinal illness and drinking water exposure were excluded from the data synthesis. Publications that were included in the review by Berger et al. (12) were also excluded in addition to studies reporting health surveillance due to temporary emergency settings or as a response to natural disasters.

## Data extraction and analysis

The literature search output was uploaded in Rayyan (13), where the publications were screened for removing duplicates and processed for further screening. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (14) were followed in the reporting of this review. Two reviewers independently screened the publications' titles and abstracts against the inclusion criteria using the 'blind-on' function in *Rayyan*. Eligible studies for full-text review were further screened independently by two reviewers, and the following summary information was extracted and analysed from publications fulfilling the aim of the review: region/country, objective of study, study design, study period, outbreak cause, affected population, causative agents in the outbreak, and syndrome/data source for surveillance. A list of excluded studies with reasons for their non-inclusion is presented in Additional File 1.

The protocol of this systematic review was also approved by the National Institute of Health Research with the registration number PROSPERO 2019 CRD42019122332 and is available online (https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=122332).

### Data synthesis

The information regarding effectiveness of the SyS in detecting waterborne outbreaks (i.e., timeliness, sensitivity, specificity) reported in the included articles was not suitable for pooling due to heterogeneity; therefore, a meta-analysis was not possible. A narrative summary of the findings of the timeliness of detection is presented as a summary in tabular form. Two researchers were involved in the data synthesis.

### Risk of bias in the individual studies and cumulative evidence

We used the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) assessment tool to assess the risk of bias in the individual studies (15). The resulting body of evidence of the cumulative result was assessed by the Project on a Framework for Rating Evidence in Public Health (PRECEPT), which was developed by the European Centre for Disease Prevention and Control (ECDC) in 2012 (16, 17).

## Results

### Descriptive summary of study characteristics

From the 1,955 articles identified in the literature search, screening of bibliographies (of the 27 articles found eligible for full-text screening in the literature search), and random search, 16 articles were included in the review (Figure 1). A summary of the study characteristics of the included studies is presented in Additional File 1. Of these included articles, 10 were retrospective studies assessing either historical outbreaks or data of cases of gastrointestinal illness and data signals for early detection of waterborne outbreaks (18-27), and six were simulation studies evaluating the system performance of different SyS systems (28-32). The included studies originated from Sweden (n = 2), France (n = 5), the USA (n = 4), and the United Kingdom (n = 4), with one study assessing data from several European countries suggesting a common surveillance approach (25), covering an overall study period of 1997 to 2013, with multiple agents causing waterborne outbreaks or illness. All of the included studies were published in the period 2010 to 2018—except for one that was published in 2006 (21) (Additional File 1).

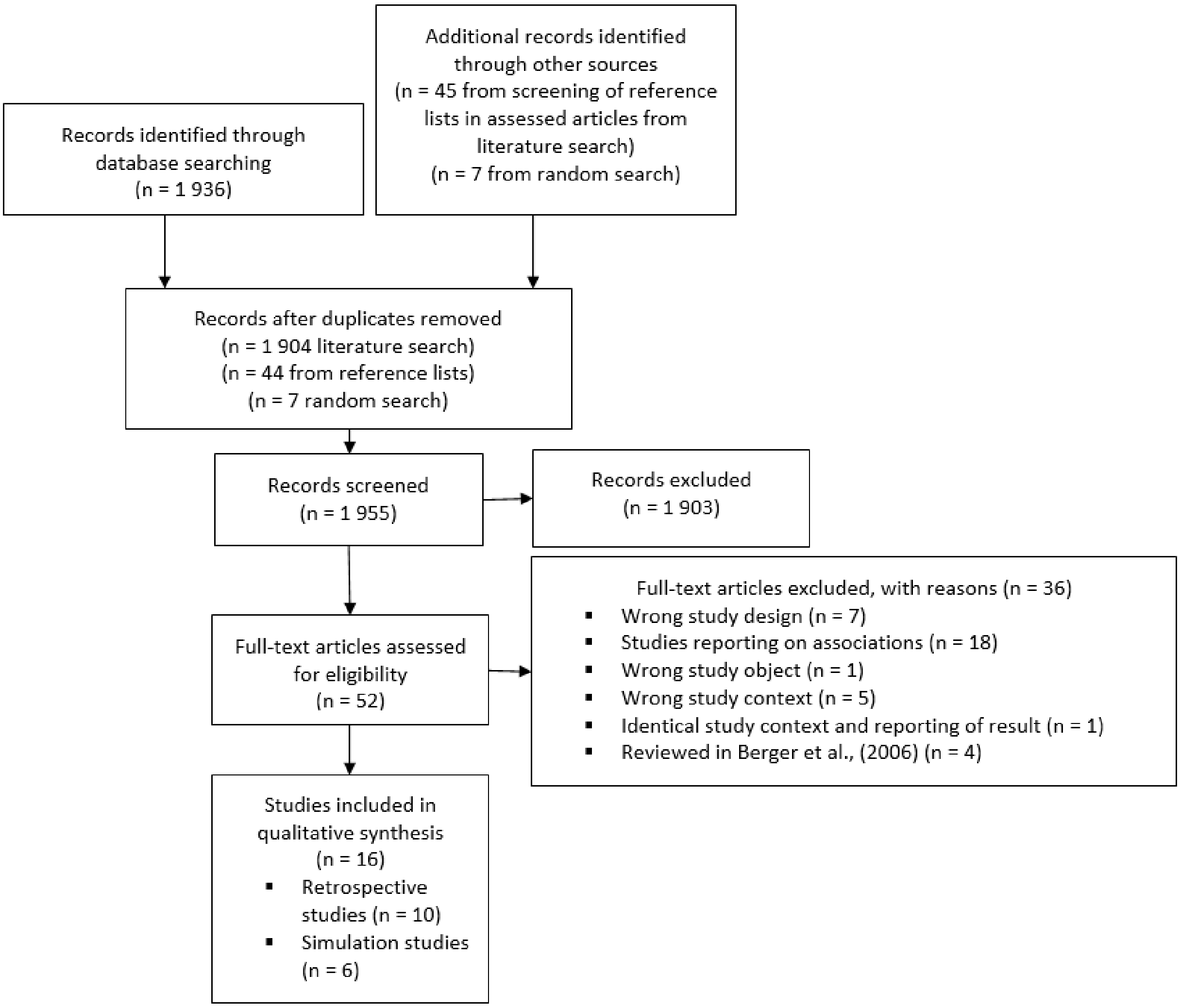


*Figure 1. Flow of studies identified and screened in the review*

Among the excluded articles, the majority were data signal studies, including investigations of water quality data or disturbances in the distribution systems, in combination with other signals from the health sector (33-42). One study used web queries to estimate the burden of disease due to gastrointestinal illness related to pipe breaks (7), while another study assessed the relationship between precipitation and waterborne diseases (43). Common in these studies was the fact that, despite that they demonstrated promising correlations, they did not report on the experienced effectiveness or value of using the same signals in their surveillance system explicitly. The other excluded studies addressed SyS but in the context of describing or reviewing such systems in a general manner (44, 45) (Additional File 1).

## Data synthesis

The data extracted from the included articles is synthesized in Table 1. When reported, the sensitivity of the SyS in the retrospective studies was below 50%, with one exception reporting a sensitivity of 89%

(19). In the simulation studies, the sensitivity was reported above 70% when using different aberration adjustments.

Table 1 Synthesis of data from the included articles (n = 16)

| Data signal | Reference | Timeliness | Sensitivity/Specificity | Pros | Cons |
|---|---|---|---|---|---|
| Over-the-counter (OTC) sales of pharmacy sales | Kirian et al., 2011 | NI | Sensitivity: 4-14%, specificity: 97-100%. | It may capture symptoms in the population before a person with gastrointestinal illness seeks health care. | It does not necessarily indicate the buyer's location, their demographic status, or the reason for the purchase. Those who purchase OTC medications for their illness may not be representative of the sick population as a whole. Hoarding behaviour will also affect the outcome. |
| Reimbursement of prescription drugs | Bounoure et al., 2011 | NI | Reported sensitivity of 89% and specificity 89% to distinguish acute gastrointestinal cases based on drug sales. | Prescription drug data can be considered for the development of a detection system of waterborne outbreaks given its ability to describe an epidemic signal. It could support authorities in slow developing outbreaks. | The algorithm cannot be used directly in other countries because of their different health systems, types and sources of data, and medical practices. The accuracy depends on the medical consultation rate in the impacted population. |
| | Mouly et al., 2016 | NI | Sensitivity: 6% and 21% for two examined outbreaks. | | |
| Calls to health advice line ('telehealth') | Bjelkmar et al., 2017 | ~ 6 days | NI | It may capture symptoms in the population before seeking health care. | The alarm does not contain information regarding the cases' medical status to validate the cause of the alarm. Moderate and low outbreaks (< 1000 cases) are unlikely to be detected. The detection ability varies seasonally. Telehealth may, in general, be driven by media bias. |
| | Cooper et al., 2006 | Unlikely to detect local outbreak | NI | | |
| Emergency care data; medical dispatch, ambulance medical service, emergency department chief complaints | Ziemann et al., 2014 | NI | NI | This system could detect changes in local trends and clusters of statistical alarms. | It is not likely to detect local gastrointestinal outbreaks with few, mild, or dispersed cases. The probability of detecting an outbreak increases with the outbreak size. The results cannot be generalized to region-level data or very sparse time series. |
| Over-the-counter (OTC), web queries, calls to health advice line | Andersson et al., 2014 | NI | Calls to health advice line: sensitivity: 40-50%, specificity: 99%, web queries and OTC: no signal. | SyS can serve as an early warning, especially with telephone triage data with sufficient temporal and spatial resolution. It may be suited to detecting widespread rises in syndromes and, rarely, small-scale outbreaks. | The alarm does not contain information on the cases' medical status to validate the cause of the alarm. Moderate and low outbreaks (< 1000 cases) are unlikely to be detected. |

| | | | | | |
|---|---|---|---|---|---|
| Telehealth, in-hours and out-of-hours GP, ED visits | Smith et al., 2010 | Peak of calls coincides with outbreak (95% CI) in one area | NI | Multiple syndromic data streams are an advantage. | Telehealth may, in general, be driven by media bias. |
| Combined health, spatial and environmental data | Coly et al., 2017 | NI | Detected outbreaks < 100 cases. | Increases sensitivity and timely detection of waterborne outbreaks. | These systems are expensive in terms of resources and shared expertise in incorporating local knowledge regarding both environmental and health data. |
| | Rambaud et al., 2016 | NI | NI | Combining two complementary methods protects against false positives, e.g. confusion of cases stemming from exposure from other types of food or swimming, for example. | Pilot-study and not tested on a larger scale. |
| Multiple SyS and environmental data | Burkom et al., 2011 | NI | Sensitivity: 80%, specificity: 99% | Use of multiple syndromic data streams is an advantage. The number of false alarms is greatly reduced. | Simulation results must generally be improved with real epidemiological data. |
| | Colón-Gonzales et al., 2018 | Unlikely to detect outbreaks < 1000 cases | NI | Framework applicable for other SyS systems. | The detection ability varies seasonally. |
| | Mouly et al., 2018 | NI | Sensitivity: 73%, PPV: 90.5% | Space-time increases the likelihood of detecting outbreaks. | The probability of detecting outbreaks increases with the outbreak size. |
| | Noufaily et al., 2012 | NI | Unknown | Able to reduce the number of false alarms and, in some cases, increase the sensitivity. | Week-to-week variation in outbreaks may prove unhelpful. |
| | Zhou et al., 2014 | 3.3 to 6.1 days | When reported, the sensitivity ranged from 24 to 77%, and the PPV was 90.5%. | Sensitivity and timeliness increase with stratification. | Study population perhaps not representative. |
| | Xing et al., 2011 | NI | Of the simulated models, the regression method had higher sensitivity (range 6–14% improvement of sensitivity in the surveillance system). | Demonstrates possible improvement in the surveillance system to increase sensitivity. | Simulations based on small number of data points. |

Note: NI = not identified, PPV = positive predictive value

Some of the included studies addressed the same surveillance system but with different study purposes. In France, a national surveillance system based on administrative health data from the French National Health Insurance on the reimbursement of prescriptive drugs has been functioning since the late 1990s (19). The system contains information on the medications for gastrointestinal illness, which are reimbursable, prescribed by a general practitioners (GPs) and dispensed in a pharmacies covering approximately 98% of the French population. (24). All the included articles originating from French study data were related to this health administrative database.

In the UK, the SyS at Public Health England (PHE) is based on four National Health Service (NHS) healthcare settings: telehealth, in- and out-of-hours, unscheduled care general practitioner consultations, and emergency department (ED) attendances (30). This system has been examined, together with the of the Health Protection Agency (HPA) and QSurveillance, a national surveillance system set up by the University of Nottingham, and the Egton Medical Information System, which consists of a network of GPs (23). Meanwhile, Noufaily et al. assessed weekly counts of samples sent to the HPA. One of the studies in this review included an older version of the SyS in the UK (21).

In the US, several surveillance systems exist (39, 44, 45), and, in this review, we included publications addressing the Electronic Surveillance System for the Early Notification of Community-Based Epidemics (ESSENCE) (28). Additionally, two studies assessed the US Centers for Disease Control and Prevention BioSense surveillance system using emergency department chief complaint data (32) and daily syndrome counts from the outpatients of the U.S. Department of Veteran Affairs' Veteran Health Administration (31). Moreover, both of the two included studies from Sweden addressed data signals from Swedish Health Care Direct 1177 (Vårdguiden 1177), along with signals such as web queries and over-the-counter pharmacy sales in one of the study (18, 22).

### Single data signal SyS system

Five of the included studies addressed a single preclinical data signal for outbreak detection and gastrointestinal illness. Kirian et al. (2011) evaluated the ability of drug sales in predicting endemic and epidemic gastrointestinal disease in the San Francisco area and found no significant correlations between drug sales and illness case counts, outbreak counts, or the number of outbreak-associated cases and reported a low sensitivity (4-14%) and high specificity (97-100%) in the study (26).

In the UK study included in this review, calls made to the health helpline (NHS Direct) were assessed based on whether the number of calls about diarrhoea exceeded a statistical threshold (21). The authors of the study predicted a 4% chance of detection when assumed that one-twentieth of cryptosporidiosis cases telephoned the helpline, which rose to a 72% chance when assumed nine-tenths of cases telephoned. They concluded that NHS Direct was currently unlikely to detect an event similar to the cryptosporidiosis outbreak used in the study and may be most suited to detecting more widespread increases in symptoms (21).

Bjelkmar et al. (2017) extended on such a system for nurse health calls proposed by Andersson (18). The authors compared phone call patterns to the Swedish Health Care Direct 1177 during the outbreak in Skellefteå in different water distribution areas, suggesting that the systematic monitoring of phone calls made to health services could have limited the outbreak from 18,500 cases to approximately 2,300 cases by detecting the outbreak approximately six days earlier than actually detected (22).

### Multiple data signal SyS systems

For establishing a national SyS system, Andersson et al. (18) evaluated the efficiency of alternate data sources for the early detection of nine investigated outbreaks in Sweden, including telephone triage, web-queries, and over-the-counter (OTC) pharmacy sales. The authors suggested that SyS can serve as an early warning of waterborne outbreaks, especially with telephone triage data with sufficient temporal and spatial resolution (40-50% sensitivity and 99% specificity); however, data was lacking for outbreaks of moderate size (300-1,000 cases) (18).

Smith et al. (23) evaluated the value of SyS in monitoring small waterborne outbreaks using data from a SyS system featuring a direct telephone helpline and QSurveillance national SyS using clinical diagnosis data extracted from the GP clinical information system (23). The authors reported that, for the first time, such a SyS system was helping to monitor a small-scale waterborne outbreak; however, the peaks of calls to the helpline observed may have been influenced by the media as a boil water advisory was issued during the outbreak (23).

Using routine emergency data based on an inventory of sub-national emergency data available in 12 European countries, Ziemann et al. (2013) proposed a framework of definitions for specific symptoms and a SyS system design applying cumulative sum and spatial-temporal cluster analyses for the detection of local gastrointestinal outbreaks in four countries. Based on the suggested system, the authors identified two gastrointestinal outbreaks in two countries, and 1 out of the 147 confirmed outbreaks in the studied countries was detected (25).

### Combined SyS systems with environmental data

Two articles included in this review combined water quality data and information on supply zones in the SyS in France. A pilot study was conducted to assess the utility of using a health insurance database for the automated detection of waterborne outbreaks of acute gastroenteritis (27). Overall, 193 clusters were identified, with 10% of the municipalities involved in at least one cluster and less than 2% in several (27). To improve the detection of waterborne outbreaks, Coly et al. (24) developed an integrated approach to detect any study clusters of acute gastrointestinal infection in geographical areas with a homogeneous exposure to drinking water. They used data from the French SyS system, geographical and population data, and environmental data based and the application of a space-time detection method identified 11 potential waterborne disease outbreaks. The outbreaks identified were not investigated, but the risk factors of exposure were examined (24).

### Method evaluations via simulations

Three of the included articles concerned simulations of SyS systems in the US. Burkom et al. (28) studied an integrated approach for the fusion of water quality data (e.g., faecal indicator bacteria, chlorine, pH, conductivity, and turbidity) with health monitoring data (ESSENCE) using probabilistic Bayesian networks. The simulations indicated a sensitivity of 80% and specificity of 99% for the symptoms "nausea/vomit" (28), however, further component simulations and the multidisciplinary development of realistic data scenarios would be needed (28). Xing et al. (32) compared timeliness of the SyS system using five regression models, and found that the sensitivity for 'nausea and vomiting' was calculated to approximately 55% (32). The simulations in the study of Xing et al (32) had a number of limitations, including a low number of data points.

Zhou et al. (31) examined the performance of the U.S. Centers for Disease Control and Prevention's BioSense SyS system by injecting multi-day signals stochastically drawn from lognormal distributions into time series of aggregated daily visit counts for the outpatients at the Department of Veterans Affairs' Veterans Health Administration (VHA) (31). The authors reported that, with a daily background alert rate of 1% and 2%, the sensitivities and timeliness in the SyS ranged from 24 to 77% and 3.3 to 6.1 days, respectively (31).

In the UK, two published studies presented measures to improve the method performance of national SyS systems. Noufaily et al. (46) reviewed the performance of aberrances among the weekly counts of isolates reported to the Health Protection Agency. By simulating different contrasting scenarios, the authors suggested several improvements related to the treatment of trends, seasonality, and the re-weighting of baselines. They claimed that the suggested system was able to reduce the number of false reports while retaining good power to detect genuine outbreaks. However, no explicit results regarding sensitivity and specificity related to detection of waterborne outbreaks were reported in the article (46).

Colón-Gonzales et al. (30) investigated how the characteristics of different outbreaks affected outbreak detection and the utility of SyS in detecting outbreaks using modelling and probability/statistics for two possible scenarios, including a localized outbreak of cryptosporidiosis. The authors reported that small gastrointestinal outbreaks (e.g., cryptosporidiosis) were unlikely to be detected unless the number of cases was over 1,000, with the detection of waterborne outbreaks varying by season (30). Multiple data streams (e.g., emergency attendance) are an advantage of influenza detection but not for outbreaks of cryptosporidiosis. However, the proposed framework of Colón-Gonzales et al. (2018) could, according to the authors, be applicable for the evaluation of any SyS system (30).

Mouly et al. 2018 (29) evaluated the performance of an algorithm using the French SyS system for waterborne outbreak detection through a simulation-based study using multivariate regression to identify the factors associated with outbreak detection. Almost three-quarters of the simulated outbreak were detected (sensitivity of 73%), and more than 9 out of the 10 detected signals corresponded to a waterborne outbreak (positive predictive value of 90.5%). The probability of was found to increase with the outbreak size (29).

### Risk of bias and cumulative body of evidence

The risk of bias of the included studies was overall assessed to be moderate to serious (Additional File 1). Due to the heterogeneity of the articles included, the cumulative body of evidence was partly assessed using the PRECEPT framework. The evidence was graded as high due to the low risk of publication bias.

## Discussion

In this systematic review, we identified 10 articles assessing the detection of waterborne outbreaks using different syndromic surveillance systems and six articles simulating a detection using a variation of statistical methods for the system performance improvements. The articles originated from four countries and represented five systems.

### Effectiveness of SyS systems in detecting waterborne outbreaks

The results reported in the included articles are generally modest (sensitivity below 50%) in their ability to detect waterborne outbreaks regardless of data signals. However, the simulation studies included in this review imply that multiple sources of signals combined with spatial information may increase the sensitivity in the SyS system of detecting waterborne outbreaks and reduce false alarms. The effectiveness of a SyS is a balance between sensitivity, specificity and predictive value, and timeliness, implying that high sensitivity may lead to a less timely detection (9). Because surveillance systems vary widely in terms of methodology, scope, and objectives, the characteristics that are important to one system may be less important to another. Efforts to improve certain attributes, such as the ability of a system to detect a health event (sensitivity), may detract from other attributes, such as simplicity or timeliness (10).

The use of over-the-counter pharmacy sales have been reported as not useful to detect waterborne outbreaks (26), while others have reported its usefulness (8). Drug sales data analysis for the outbreak detection of infectious diseases was reviewed in 2014 by Pivette et al (8), with the conclusion that over-the-counter sales appear to be a useful tool in detection trends gastrointestinal disease (8); however, the review may have been prone to publication bias. Only a few studies have shown promising correlations between SyS and signals, such as that origin from contact for health consultations in the health care system (22, 47). Such conflicting reporting of results should not be surprising, since the SyS systems included in the review are context-specific and not directly comparable. Although this review provides an updated overview of published articles assessing the effectiveness of SyS in detecting waterborne outbreaks, the synthesis of the articles was challenging, since they varied greatly in terms of administrative and geographical context, the data signals and algorithms used, and how the results were reported. The effectiveness of SyS system, in general, also largely relies on the methods used to detect aberrations.

The timeliness of surveillance approaches for outbreak detection is the amount of time from exposure to the disease agent to the initiation of a public health intervention (10). Berger et al. scored environmental data in terms of timeliness from a range of typical data used for SyS (12). However, when observing a change in for instance environmental data that may affect public health, disease in the population is likely to have been developed. In drinking water supply systems, there is an obligation of the water supplier to prompt action to mitigate a breach exceedance in the monitoring of microbiological parameters. Often, the mitigating action is the issuance of a boil water advisory to protect the population from a potentially evolving outbreak (48). The risk of developing a waterborne outbreak is higher when a contamination event goes undetected during day-to-day-operations and routine monitoring, which is a common factor in several waterborne outbreaks (49, 50). In some of the identified articles included in this review, the benefit of combining the surveillance system to geographical supply zones to increase the likelihood of detecting a waterborne outbreak was highlighted. On the other hand, deploying such systems may be challenging, since it will most likely involve two different fields of expertise (health and technical), and the processing of data to inform health decisions must still be accounted for, since local outbreaks are usually short-lived (51).

The association between gastrointestinal illness cases and water quality data, such as turbidity, has been reviewed by de Roos et al. (52) in an attempt to discern the presence of waterborne gastrointestinal illness. However, the utility of turbidity as a proxy for microbiological contamination may be context-specific (52). Several of the excluded articles (Additional File 1) examined the potential of strengthening surveillance by including water quality data. In particular, these included, turbidity, disturbances in the distribution network, and calls to an alarm centre, among others. However, none of the excluded studies reported on analysis linked to real or simulated outbreaks. One of the most reported causes of waterborne outbreaks is heavy rainfall, which represents a future increasing risk (53) and implies a greater call for a risk-based approach to surveillance for water supply systems (51). In general, since there will always be a risk of water contamination going undetected, prioritizing long-term preventive measures and risk-based surveillance should not be underestimated despite promising reporting on SyS systems.

### Strengths and limitations

There are several limitations related to our review. First, the rather wide scope of the review resulted in a variety of articles that may have been of interest to the study topic but were excluded due to a lack of eligibility. Still, the included articles were also different from each other in many ways and did not allow for an accurate comparison of the reported results and assessments of the risk of bias. We also only found articles from four countries representing five surveillance systems, which limited the possibility of generalizing the results in terms of effectiveness to detect waterborne outbreaks.

In general, observational and retrospective studies are more prone to bias than randomized controlled studies due to a lack of randomization and blinding, hence jeopardizing their external and internal validity, which also affected the general outcome of the review. The ROBINS-I tool used in this review could only be partly used for the assessment of the risk of bias. We assessed risk of bias on a more-or-less hypothetically manner of the studies since developing the mimic RCT according to Sterne et al. (15), was challenging. Studies examining the detection of waterborne outbreaks based on real investigated outbreaks generally were assessed as having a lower bias due to confounding than those only using data on water quality deviations as a risk factor for waterborne illness. Bias in the selection of participants was, in general, a problem in the observational studies. In this review, all the studies using register data were assessed as having a lower risk of bias have been rated as having a moderate or serious risk of bias. . Moreover, bias in the classification of interventions was different among the studies examining outbreaks as serious due to the risk of differential misclassification (recall bias), while studies using register data with confirmed aetiology had a decreased risk of classification bias; however, there was a lack of evidence on illness attributed to drinking water. Bias in the domains of deviation from the intended interventions, missing data, and the measurement of outcomes were regarded as not applicable to this review. Bias in the selection of the reported results was assessed as serious in cases in which only one data signal was studied.

A strength of this review is its comprehensive search of published peer-reviewed articles using multiple databases, the screening of bibliographies, and a random search of the topic of SyS systems' effectiveness in detecting waterborne outbreaks. The screening of bibliographies is a 'snow-balling' technique that entails a targeted assessment of the topic.

## Conclusion

Waterborne outbreaks still represent a risk in developed countries, and their early detection is crucial for the prevention of societal consequences. SyS systems with different features are widely used for the detection of waterborne outbreaks; however, in this review, we did not find evidence for syndromic surveillance in terms of their ability to effectively detect waterborne outbreaks (low sensitivity and high specificity), especially small and localized outbreaks. There are, on the other hand, promising development towards surveillance systems combining health, geographic, and water quality data; however, such systems must be evaluated in a cost-benefit context. This review demonstrates that there is no conclusive evidence regarding the effectiveness of SyS for the detection of waterborne outbreaks, which also emphasizes the need to focus on primary prevention measures to reduce the risk of waterborne outbreaks and risk-based surveillance. Future studies should include methods for combining health and environmental data with an assessment of the resources required for operating such a system.

## Author contributions

SH and PAA screened the publications identified in the literature search. EA screened the reference lists in the identified articles. SH conducted the random search for other studies. SH and EA assessed the identified studies from the three searches for eligibility. SH drafted the first version of the manuscript. EA, PAA, LV, and KN critically reviewed the drafted manuscript and approved its final version.

## Ethical considerations

None

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# Additional file 1

## Literature search strategy

Database: MEDLINE

Date: 27.03.2019

Number of identified articles: 687

| # | Searches | Results |
|---|---|---|
| 1 | Drinking water/ or Water supply/ or Water*.tw,kf. | 763557 |
| 2 | Sentinel surveillance/ or POPULATION SURVEILLANCE/ or (syndromic surveillance* or Sentinel surveillance* or (early adj2 outbreak*) or "early warning*" or "risk based surveillance*").tw,kf. | 68165 |
| 3 | Waterborne Diseases/ or (outbreak* or waterborne or "water borne" or infection* or infectious* or "water related disease*").tw,kf. | 1481492 |
| 4 | 1 and 2 and 3 | 687 |

Database: Embase

Date: 27.03.2019

Number of identified articles: 999

| # | Searches | Results |
|---|---|---|
| 1 | drinking water/ or water supply/ or Water*.tw,kw. | 886634 |
| 2 | sentinel surveillance/ or health survey/ or (syndromic surveillance* or Sentinel surveillance* or (early adj2 outbreak*) or "early warning*" or "risk based surveillance*").tw,kw. | 192928 |
| 3 | water borne disease/ or (outbreak* or waterborne or "water borne" or infection* or infectious* or "water related disease*").tw,kw. | 1821962 |
| 4 | 1 and 2 and 3 | 999 |

Database: Scopus

Date: 10.04.2019

Number of identified articles: 111

| | | |
|---|---|---|
| 5 | #4 AND NOT INDEX ( medline ) | 111 |
| 4 | #1 AND #2 AND # 3 | 287 |
| 3 | ( KEY ( "Waterborne Diseases" OR "Waterborne Disease" OR "Water borne Diseases" OR "Water borne Disease" ) OR TITLE-ABS ( outbreak* OR outbreaks OR waterborne OR "water borne" OR infection OR infections OR infectious* OR "water related disease" OR "water related diseases" ) ) | 1,807,212 |
| 2 | ( KEY ( «sentinel AND surveillance» OR «population AND surveillance» ) OR TITLE-ABS ( "syndromic surveillance" OR "syndromic surveillances" OR "Sentinel surveillance" OR "Sentinel surveillances" OR ( early W/1 outbreak ) OR ( early W/1 outbreaks ) OR "early warning" OR "early warnings" OR "risk based surveillance" OR "risk based surveillances" ) ) | 30,482 |
| 1 | ( KEY ( «drinking AND water» OR «water AND supply» ) OR TITLE-ABS ( "water*" ) ) | 3,287,810 |

Database: Web of Science Core Collection

Dato: 10.04.2019

Number of identified articles: 740

Comment: Database covers the period 1987-2019 (=all years)

**# 4740#3 AND #2 AND #1**
Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=All years

# 31,497,422TS=( "Waterborne Diseases" OR "Waterborne Disease" OR "Water borne Diseases" OR "Water borne Disease" OR outbreak* OR outbreaks OR waterborne OR "water borne" OR infection OR infections OR infectious* OR "water related disease" OR "water related diseases")
Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=All years

# 257,077TS= («sentinel surveillance» OR «population surveillance» OR "syndromic surveillance" OR "syndromic surveillances" OR "Sentinel surveillance" OR "Sentinel surveillances" OR «early NEAR/1 outbreak» OR «early NEAR/1 outbreaks» OR "early warning" OR "early warnings" OR "risk based surveillance" OR "risk based surveillances" )
Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=All years

# 12,273,034TS=( «drinking water» OR «water supply» OR water$)
Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=All years

## Characteristics of included articles (n=16)

| | Study ID | Country | Study design | Study period | Outbreak cause (aetiology) | Affected population | Syndrome/data for surveillance/detection for the outbreaks |
|---|---|---|---|---|---|---|---|
| 1 | Andersson et al., 2013 | Sweden | Retrospective | 2007-2011 | Gastrointestinal symptoms, food and waterborne outbreaks | Swedish population | Telephone triage<br>Web-queries<br>OCT pharmacy sales |
| 2 | Bjelkmar et al., 2017 | Sweden | Retrospective | Spring 2011 | Cryptosporidium | Skellefteå municipality | Phone calls to a health advice line |
| 3 | Bounoure et al., 2011 | France | Retrospective | Two period pool: 1mth (2000) and 6 mths (2006) | Acute Gastroenteritis | 3 major cities and 2 small town in the same region | Reimbursement of expenses for health care and drugs |
| 4 | Burkom et al., 2011 | USA | Simulation | NI | Waterborne diseases | American population | Fusion of water quality data (faecal indicator bacteria, chlorine, pH, conductivity and turbidity) with health monitoring data (“ESSENCE”) |
| 5 | Colón-Gonzales et al., 2018 | UK | Simulation | NI (må sjekke) | Big pandemic influenza outbreak and localized outbreak of Cryptosporidiosis | England | Telehealth,<br>in-hours GP and out-of-hours, ED visits |
| 6 | Coly et al., 2017 | France | Retrospective | 2009-2012 | Acute gastrointestinal infection due to water exposure | Population in municipalities in a French region grouped by ‘geographical water supply network’ | Reimbursement of expenses for health care and drugs, geographical and population data, and environmental data based on common water exposure and water network |
| 7 | Cooper et al., 2006 | UK | Retrospective | Outbreak February – April 1997 | Cryptosporidium | London | Data from a health helpline (NHS Direct) |
| 8 | Kirian et al., 2011 | USA | Retrospective | Jan 2004 – Jul 2005 | Gastrointestinal illness | Population in the San Francisco Bay Area | Diarrheal remedy sales data<br>Diarrheal case counts from Health department |
| 9 | Mouly et al., 2015 | France | Retrospective | Waterborne outbreak in 2010 and 2012 | Campylobacter jejuni, norovirus | Two cities in France | Health administrative databases, reimbursment of expenditures for medication (SNIIRAM) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 | Mouly et al., 2018 | France | Simulation | 2010-2013 | Waterborne illness | France | Daily baseline counts of acute gastrointestinal infections |
| 11 | Noufaily et al., 2012 | UK | Simulation | Simulated of outbreaks | Multiple waterborne agents | England and Wales | Health Protection Agency (HPA) |
| 12 | Rambaud et al., 2016 | France | Retrospective | 2009–2012 | Unknown | Three French districts | Health administrative data (SNIIRAM) |
| 13 | Smith et al., 2010 | UK | Retrospective | June-July 2008 | Cryptosporidium | Northamptonshire | Dats from syndromic surveillance system from direct telephone helpline and QSurveillance national surveillance system using clinical diagnosis data extracted from GP clinical information system |
| 14 | Xing et al., 2011 | US | Retrospective | May 2008 to April 2009 | GI | 16 cities in the US | Emergency department chief complaint data |
| 15 | Zhou et al., 2015 | US | Retrospective | January 2010 through May 2011 | GI (according to diagnosis codes) | Population of US (Department of Veterans Affairs' Veterans Health Administration (VHA)) | Outpatient VHA daily syndrome counts |
| 16 | Ziemann et al., 2013 | Europe | Retrospective | 2006-2009 (muliptle countries) | GI (from diagnosis codes) | Population in Europe (several countries) | Routine emergency data |

## Assessment of Risk of Bias according to ROBINS-I

| **Agent**<br>**Citation** | **Bias due to confounding** | **Bias in selection of participants** | **Bias in classification of interventions** | **Bias due to deviations from intended interventions** | **Bias due to missing outcome data** | **Bias in outcomes measurement** | **Bias in selection of results reported** | **Overall risk of bias** |
|---|---|---|---|---|---|---|---|---|
| Andersson et al., 2013 | Low/moderate | Moderate/ serious | Low/moderate | N/A | N/A | N/A | serious | Moderate |
| Bjelkmar 2017 et al., 2017 | Low/moderate | Moderate/serious | Moderate | N/A | N/A | N/A | serious | Moderate |
| Bounoure et al., 2011 | Moderate/serious | Serious | Serious | N/A | N/A | N/A | serious | Moderate/serious |
| Burkom et al., 2011 | Moderate | NI | Moderate/serious | N/A | N/A | N/A | serious | Serious |
| Colón-Gonzales et al., 2018 | Low | NI | Low/moderate | N/A | N/A | N/A | Moderate | Moderate/serious |
| Coly et al., 2017 | Moderate/serious | NI | Serious | N/A | N/A | N/A | Serious | Moderate/serious |
| Cooper et al., 2006 | Low/moderate | Moderate | Moderate | N/A | N/A | N/A | Serious | Moderate |
| Kirian et al., 2011 | Moderate/low | Moderate | Moderate | N/A | N/A | N/A | Moderate | Moderate |
| Mouly et al., 2015 | Moderate/low | Moderate | Moderate | N/A | N/A | N/A | Serious | Moderate |
| Mouly et al., 2018 | NI | NI | Moderate | N/A | N/A | N/A | Serious | Moderate/serious |
| Smith et al., 2010 | Moderate | Low | Moderate/serious | N/A | N/A | N/A | Moderate | Moderate |

## Table excluded articles with reasons

| Reason | Articles From literature search: | Screening of reference lists | Random search | Number |
|---|---|---|---|---|
| Wrong study design | Paladini, 2004<br>Risebro et al, 2007<br>Naumova et al., 2008<br>Beaudeau et al., 2008 | Lombardo et al., 2003<br>Neill 2009<br>Haas et al., 2011 | | n=7 |
| Wrong outcome (association/relationship) | Elliott et al., 2016<br>Drayna et al., 2010 | Beaudeau 1999<br>Beaudeau 2012<br>Curreiro et al., 2001<br>Egorov et al., 2003<br>Frosst et al., 2006<br>Hunter et al., 2005<br>Morris et al., 1996<br>Tinker et al., 2010<br>Derby et al., 2004<br>Jackson et al., 2007<br>Todkill et al., 2016<br>Hsieh et al., 2015<br>Edge et al, 2006<br>Gilbert et al., 2006 | Malm et al., 2013<br>Shortridge et al., 2014 | n=18 |
| Wrong study object | | Kulldorff 2005 | | n=1 |
| Wrong study context | El-Khatib et al., 2019<br>Nelesone et al., 2006<br>Pirard et al., 2015<br>Rosewell et al., 2013<br>Worwor et al., 2016 | | | n=5 |
| Covered in review of Berger | Edge et al., 2004<br>Heffernan et al., 2004<br>Proctor et al, 1997 | Balter et al., 2005 | | n=4 |
| Duplication | Kirian et al., 2010 | | | n= 1 |
| Total | | | | n=36 |

# Paper III

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BMC Public Health

RESEARCH ARTICLE Open Access

# Compliance with water advisories after water outages in Norway

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## Abstract

**Background:** Water advisories, especially those concerning boiling drinking water, are widely used to reduce risks of infection from contaminants in the water supply. Since the effectiveness of boil water advisories (BWAs) depends on public compliance, monitoring the public response to such advisories is essential for protecting human health. However, assessments of public compliance with BWAs remain sparse. Thus, this study was aimed at investigating awareness and compliance among residents who had received BWAs in Baerum municipality in Norway.

**Method:** We conducted a cross-sectional study among 2764 residents who had received water advisories by SMS in the municipality of Baerum between January and September 2017. We analysed data from two focus group discussions and an online survey sent to all residents who had received an advisory. We conducted descriptive analyses and calculated odds ratios (OR) using logistic regression to identify associations of compliance and awareness with demographic characteristics.

**Results:** Of the 611 respondents, 67% reported that they had received a water advisory notification. Effective compliance rate with safe drinking water practices, either by storing clean drinking water or boiling tap water, after a water outage was 72% among those who remembered receiving a notification. Compliance with safe drinking water advisories was lower among men than women (OR 0.53, 95% CI 0.29–0.96), but was independent of age, education and household type. The main reason for respondents' non-compliance with safe water practices was that they perceived the water to be safe to drink after letting it flush through the tap until it became clear.

**Conclusions:** Awareness of advisories was suboptimal among residents who had received notifications, but compliance was high. The present study highlights the need to improve the distribution, phrasing and content of water advisory notifications to achieve greater awareness and compliance. Future studies should include hard-to-reach groups with adequate data collection approaches and examine the use of BWAs in a national context to inform future policies on BWAs.

**Keywords:** Boil water advisories, BWAs, Public compliance, Water supply interruptions, Adherence, Drinking water, Communication, Consumer trust

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## Background

Water-related diseases remain a major contributor to the global burden of disease, with 842,000 deaths annually in low- and middle-income countries [1]. In high-income countries, several outbreaks of disease associated with drinking contaminated water are reported yearly despite precautionary actions taken by water suppliers [2]. Contamination of water sources and lack of adequate water treatment are common causes, but there is increasing awareness that deficiencies in water distribution systems also represent a risk factor for (re)contamination of treated drinking water [3], not only during intermittent supply or sudden breaks [3] but also during routine maintenance operations [4]. Furthermore, measures aimed at ensuring hygienic conditions during operations to reduce the risk of gastrointestinal illness when reconnecting the water supply have been inadequate at times [5].

Boil water advisories (BWAs) are widely used to prevent the spread of illness via contaminated water. However, their effectiveness is highly dependent on public compliance [6]. A recent review of compliance with BWAs evinced 97% awareness and 76% compliance based on 11 studies [6]. The studies mainly focused on acute water incidents [7–10] or natural disasters [11–13] and rarely on planned or less acute issues with the water supply system [14]. For instance, an ageing water distribution network that is vulnerable to breaks and leakages contributes to increases in the distribution of BWAs [15].

Detection of *E. coli* in a routine monitoring scheme is the most obvious trigger of a BWA. Other situations that may trigger a BWA [16] include substantial deterioration in source water quality, major failures in treatment processes or main breaks resulting in zero or negative pressure [15]. The World Health Organization (WHO) advises water suppliers and public health authorities to develop protocols for BWAs before an emergency event occurs to avoid having to develop a response during an event, as this may complicate decision-making, compromise communication and undermine public confidence [16]. Canada, Australia and the United States [17–19] are among the few countries with a national policy on BWA use. In Canada, BWAs are categorised by cause; the detection of pathogens or indicator bacteria is often termed as an *emergency* boil water advisory, whereas water main breaks or maintenance that leads to pressure loss would be termed a *precautionary* boil water advisory [6, 14]. Evidence from Canada suggests that BWAs are more often issued due to failures in water processing and distribution than due to the detection of *E. coli* [6, 20]. The United States Environmental Agency has suggested formulating BWAs for various scenarios, such as pipe breaks [19, 21]. In Norway, the decision to issue a BWA is made by the water supplier usually in conjunction with the municipal public health authority. The Norwegian Institute of Public Health has issued general advice on the use of BWAs [22], but a comprehensive policy and national monitoring of BWA use are lacking.

In addition to concerns about BWA effectiveness, BWAs may have negative consequences, such as increased consumer anxiety and altered perceptions of drinking water quality [16, 23]. Thus, there have been calls for more monitoring and reporting of the public response to BWAs to increase understanding and improve compliance [6], particularly regarding reasons for non-compliance and perceptions of the notifications [14].

In the municipality of Baerum, Norway, the water supplier issues precautionary BWAs after planned and unplanned water outages. Between 2003 and 2016, SMS notifications were sent to residents in affected areas due to 150–200 interruptions per year in the water supply. The present study was aimed at assessing awareness, compliance, reasons for non-compliance and perceptions among residents of Baerum municipality who had received BWAs in 2017.

## Methods

We conducted a cross-sectional study among residents of the municipality of Baerum who had received water advisories by SMS between January and September 2017. We analysed the findings from two focus group discussions and data from an online survey that was administered to all residents who had received water advisories.

### Study site

The municipality of Baerum is located near Norway's capital, Oslo, and has 124,000 residents. The municipality's drinking water is produced in three water treatment plants – two large and one small. Although the drinking water in Baerum is considered to be of good quality, episodes of pressure drops due to breaks and maintenance occur. Municipal health authorities issue a BWA concerning water outages that last longer than 30 min, advising consumers to boil tap water for drinking and food preparation for the next 24 h. The notice reaches consumers mainly by SMS or voice message, and sometimes on the internet, and it announces any planned outages in the water supply (e.g. for maintenance) and advisories regarding the use of tap water.

The content of a message about a water outage follows a standard format and includes the time and place of the water outage, four action points (water advice), a link to more information on the municipality's website and a contact phone number (Fig. 1).

### Study population

The study population included individuals belonging to households connected to the public water supply in

"This is a notification from Baerum municipality. On Monday 12th June at 8.30 am to 2.30 pm, the water supply will be closed due to planned work in XX Street. Store clean water for necessary consumption in advance. If the water is discoloured when it is connected again, let cold water flush until it is clear. Do not use washing machine or dishwashing machine until the water is completely clear. The water supply may be connected at any time. During the first 24 hour after the water is connected, we recommend to boil the water intended for food and drinking. For more information see www.baerum.commune.no/va or call 12345678."

**Fig. 1** Example of a precautionary notification of a planned water outage in Baerum municipality (translated from Norwegian)

Baerum, Norway, who had been sent a BWA due to a water outage from the municipality between January and September 2017. During this period, 8091 residents of Baerum (including children) were registered as affected by 153 water outages in the municipality. Of the 153 water outages recorded, 83% were due to planned maintenance work. About 6285 notifications were sent to residents (excluding children); specifically, 5222 (83%) were sent via SMS and 1063 (17%) were sent via voice message to residents registered with landline phone numbers.

The affected population was identified by a geographic information system (GIS), and the municipality obtained contact information from the National Registry. The municipality had a list of issued notifications, which consisted of names, addresses, phone numbers and the mode of communication (SMS or voice message). From this list, we removed those who had received only voice messages to a landline. We also removed notifications sent to addresses belonging to schools, businesses and other non-individual recipients. Finally, we included persons only once even if they had received more than one notification during the period under study. After completing this process, 2764 persons remained on the list.

### Data collection and analysis of focus group discussions

From the list, residents over 70 years of age and those with children under 12 years of age were randomly invited to participate in the discussions. The group profiles were selected to represent priority audiences for the notifications. These were divided into two focus groups – one with elderly participants and one with families with children – with seven participants in each group. Both groups participated in one focus group discussion session.

A researcher moderated the discussions using a focus group discussion guide. The group discussions began by sending the participants a notification by SMS that resembled an actual notification sent from the municipality. Each focus group discussion lasted 1.5 h and was tape-recorded. After the data collection was completed, a public health/water supply researcher observed the discussions and answered questions that had been raised during the discussions.

Both of the taped discussions were transcribed into a written document. Participants' quotations were categorised and coded in different colours according to the research questions in the study.

### Data collection and analysis of the survey

We employed the findings from the focus groups to develop an online survey about awareness of, and compliance with, BWAs. The questionnaire was developed for this study (Additional file 1 Questionnaire). The survey was sent as a link via SMS to all 2674 residents on the list. More than one person per household was invited, and up to three reminders were sent to non-responders.

We conducted descriptive analyses and calculated odds ratios (OR) using a logistic regression to identify associations of compliance and awareness with demographic characteristics. A statistical analysis was performed by Stata version 15.1 (by StataCorp).

The Data Protection Officer at the Norwegian Institute of Public Health waived the need for ethical approval according to national regulations (The Act on medical and health research of 20 June 2008) since the study did not collect personal health data and the participants to the survey remained anonymous. The need for ethical approval for the conducting the focus groups was waived to the same act. The respondents to the survey consented by filling out the questionnaire after reading the introductory text. No participants below 16 years were invited to the study. The need for written consent for the participants in the focus groups was waived according to the Act of 14 April 2000 relating to the processing of personal data (Personal Data Act) since the data collection did not contain any person sensitive data. The participants in the focus groups provided verbal consent and an email with confirmation of the verbal consent was sent to each participant who had given the consent to be a part of the study. In this email, the object of the study was repeated and the procedures for the data collection (tape recording) in the focus group was explained. The correspondence of the email with conformations of verbal consent were filed on a secure server only accessible for the responsible recruiter. The participants and their contact information provided to the study, were decoded and the file connecting the participant to their contact information were stored separately and deleted 6 months after the data collection had found place. At the beginning of the focus group discussions, the objectives of the study and means of data collection were explained again to each participant in the focus groups. The participants were assured of the anonymity and confidentiality of their responses. They were also explained that their participation were voluntary and that they could withdraw at any time.

## Results

### Findings from the focus group discussions

#### *Sample characteristics of the focus groups*

The two focus group discussions were held in September 2017 in the municipality of Baerum: one with seven individuals over 70 years old and one with seven families with children (below 12 years). The first focus group was composed of four women and three men ranging in age from 71 to 84 years. Four participants had higher education (university level) and three had completed high school. In the group of families with children, five were women and two were men ranging in age from 29 to 51 years. All participants in the family group had higher education (university level) and were married or cohabitants.

#### *Communication, compliance and trust*

Both focus groups expressed that they used smartphones actively and preferred SMS as a communication mode. The participants with children mentioned that they also received other information from the municipality at the same number, making it difficult to determine important information from the municipality. Therefore, messages about water outages were easily missed. Most participants were satisfied with the content of the messages and found them understandable with a sufficient amount of information. However, some called for more details about why the water should be boiled, but elderly women did not want more such information because they claimed that it would create 'unnecessary fear'. Participants in the elderly group revealed uncertainties about how they should in fact 'boil the water'.

A desire for accurate information about BWAs was expressed more clearly in the family group than in the elderly group. Few had visited the municipality's website to obtain additional information. However, both groups appreciated that the SMS contained a link to retrieve more information from the municipality in case questions arose. As one participant expressed, 'For the majority, knowledge gains trust… for many – that is – not for all'.

Several participants had stored sufficient amounts of clean water for drinking to last throughout the first day of a water outage. However, some believed that it was 'not vital' to boil tap water and did not perceive the word 'recommendation' as strong advice. Other participants stated that it was important to avoid becoming 'too anxious'. In both groups, several participants had chosen not to boil their water, as they believed that letting it flush through the tap for some time was sufficient to make it safe to drink.

The participants in both groups expressed that they generally had a high degree of trust in the drinking water in Norway and, thus, had little concern related to this. They perceived the water to be 'fresh, clean and with good taste'. However, some older participants suggested that work on the water pipes might hamper water quality. Both groups clearly expressed that the messages conveyed by the municipality did not decrease their trust; rather, the communication increased trust in the municipality regarding the water supply.

### Survey results

#### *Sample characteristics*

Out of the 2674 residents that were invited to complete the survey, 611 responded (response rate of 22%). Of these 611 respondents, 47% were men, 70% were above 45 year old and 85% had higher education. Regarding household type, the majority were couples with (45%) or without (37%) children in the home and 15% of the households had at least one child under the age of five (Table 1).

Furthermore, 412 respondents (67%) remembered receiving a BWA during the period under study (Table 1).

The majority (69%) remembered receiving an advisory one or two times during the period in question and only 2% remembered receiving more than five notifications.

#### *Communication of the notifications*

The majority (97%) of participants who remembered receiving a notice reported that they had received it by SMS. However, some participants had also learned about the water outage from a leaflet in their mailbox (22/412, 5.3%), from other persons in the household (11/412, 2.7%), acquaintances/neighbours (8/412, 1.9%) or other sources (5/412, 1.2%). Only a few reported learning about the water outage on social media (1 respondent) or in the newspaper (2 respondents).

SMS was the most preferred method of communication (97%). Moreover, SMS was preferred slightly more among participants who remembered receiving a message (99%) than those who did not (93%) (Table 2).

#### *Awareness and compliance with water advice in the notification*

The notification contained four pieces of advice of which awareness and compliance were assessed (Table 3). Of those who remembered receiving a notification (412/611), approximately 66% were aware of the advice to store water in advance, 51% to let the water flush until it was clear, 43% to not use the washing machine until the water was clear and 65% to boil the water before consuming it (for cooking and drinking). Compliance was 82% for the advice to store water in advance, 92% to let the water flush until it was clear, 91% to not use the washing machine until the water was clear and 81% to boil the water before consuming it (for cooking and drinking). For both awareness and compliance (effective compliance), the proportion was around 50% for each piece of advice given, except for the advice to not use

**Table 1** Demographic characteristics of survey participants, municipality of Baerum, Norway, 2017 ($N = 611$)

| Characteristics | Survey population # (%) |
|---|---|
| Gender | |
| Male | 285 (47) |
| Female | 327 (54) |
| Total | 611 (100) |
| Age group | |
| 16–35 | 65 (11) |
| 36–45 | 120 (20) |
| 46–65 | 328 (54) |
| > 65 | 98 (16) |
| Total | 611 (100) |
| Highest level of education completed | |
| Primary school | 8 (1) |
| High school | 84 (14) |
| University/college (1–3 years) | 171 (28) |
| University/college (4 years or more) | 348 (57) |
| Total | 611 (100) |
| Household type | |
| Single without children in the household | 69 (11) |
| Single with children in the household | 41 (7) |
| Couples without children in the household | 223 (37) |
| Couple with children in the household | 278 (45) |
| Total | 611 (100) |
| Household members | |
| Pregnant | 5 (1) |
| Children < 5 years old | 89 (15) |
| Breastfeeding | 15 (3) |
| None of the above | 517 (85) |
| Total | NA |
| Number of notifications received during the previous 12 months* | |
| 1–2 times | 284 (69) |
| 3–5 times | 81 (20) |
| > 5 times | 9 (2) |
| Does not know how many notifications | 38 (9) |
| Total | 412 (100.0) |

*412 of 611 reported to have received a notification from the municipality

the washing machine (#3), for which effective compliance was 39%.

Compliance regarding safe drinking water – either by drinking stored clean water, boiled water or commercially bottled water – was 72% among participants who remembered receiving a notification and were aware of its message, and 49% among all participants.

### *Behaviour of response to BWA*

Of those who chose to boil their water ($n = 182$), the main reason mentioned for following the advice was to avoid getting sick from drinking the water (80%), and 37% reported that they had no specific reasons, but trusted the advice. A smaller proportion (13%) reported following the advice due to a health condition in the household (small children, pregnancy, immunocompromised). Of those respondents who were aware of the advice, but did not follow it ($n = 231$), 45% reported that they did not boil the water because they had stored clean water in advance (regarded as compliance with safe drinking water). According to 28%, the water was visually clear and, therefore, they saw no need to boil it. Nine per cent considered the risk of getting ill by drinking the water to be very low, while 6% forgot to boil the water and 5% reported that they generally drank small amounts of water from the tap. Twenty per cent could not remember why they had not followed the advice. The survey allowed multiple choices for adherence and non-adherence to the advice. Consequently, some participants (16/412) reported both following the advisories and being unaware of the advice that they had followed.

Compliance with safe drinking water advisories (combined BWA or stored clean water in advance) was lower among men than women (OR 0.53, 95% CI 0.29–0.96), but was independent of age, education and household type.

### *Perception of risks of drinking water and trust in the water supplier*

Most respondents reported that they generally had a high degree of trust in the municipality's drinking water. Only 5% (31/611) reported the quality of the water as 'bad or very bad'. The majority had a high degree of trust in the municipality, and only 2% (12/611) reported having low or very low trust. Four per cent (24/611) expressed concern about getting ill from drinking the water, whilst the majority reported that this was something about which they had little or very little concern. The survey allowed multiple choices for adherence and non-adherence to advice. All respondents reported on trust, although some reported not remembering receiving a notification. Almost half (48%, 293/611) reported that the communication led to increased trust in the municipality's water supply services, and 31% (189/611) reported a small increase in trust. Seventeen per cent (104/611) reported that it did not change their perception of the municipality, and only 1% (6/611) reported that the communication decreased their trust.

## Discussion

In the present study, effective compliance with safe drinking water practices by either drinking clean water stored in advance or boiling tap water was 72% among

**Table 2** Preferred sources of water advisories for future communications, municipality of Baerum, Norway, 2017

| Information media | Preferred way to be informed in the future | | |
|---|---|---|---|
| | Number (%) out of all participants, $N = 611$ | Number (%) out of people who remembered receiving a notice, $n = 412$ | Number (%) out of people who did not remember receiving a notice, $n = 199$ |
| Mobile (SMS) | 590 (97) | 406 (99) | 184 (93) |
| Leaflet in the mailbox | 28 (5) | 20 (5) | 8 (4) |
| Municipality website (www.) | 30 (5) | 21 (5) | 9 (5) |
| Social Media (e.g., Facebook, Twitter) | 14 (2) | 10 (2) | 4 (2) |
| Email | 123 (20) | 78 (19) | 45 (23) |
| Letter | 6 (1) | 4 (1) | 2 (1) |
| Digital mailbox | 10 (2) | 6 (2) | 4 (2) |

Note: more than one option could be selected

participants who reported receiving a notification from the municipality. Since 412 of the 611 participants reported receiving a notification, the notification reached 67% of the study population. When factoring in the coverage of communication, the effective compliance rate for all survey respondents becomes 49%. Given awareness, the main reason for non-compliance was the perception that the water was safe to drink after flushing it until it was clear. The notification did not hinder the respondents' long-term perceptions of drinking water quality but increased their trust in the municipality's water supply services.

### Awareness and compliance with BWAs

There was an awareness rate of 65% for BWAs relating to water outages from the municipality, which is lower than reported in a meta-analysis on BWAs, where awareness was calculated to a mean of 85% and median of 97% [6]. It is less likely for routine maintenance operations on the water supply distribution network – the reason for 83% of the notifications in our study – to reach the press and contribute to public awareness as compared to what would occur in severe water incidents [8, 24]. However, awareness of the advice to store clean water in advance or boil tap water was higher than BWA alone (85%).

Eighty-one per cent compliance with BWAs was reported among participants who were aware of the notification, and effective compliance of 53% was reported when awareness was factored in. Compliance is higher than in a meta-analysis (reported mean of 68% and median of 76%), but effective compliance is lower (mean of 66% and median of 68%). We found similar results for storing water for necessary consumption in advance. Compliance with the recommendation to store clean water for drinking adds to the number of respondents who drink safe water during a water outage (here 72%); however, this is only possible in situations where there is a planned water supply interruption. In an emergency, consumers would need alternatives, such as delivered water or bottled water, and could not rely on advice to store clean water in advance.

**Table 3** Awareness and compliance rates for advice received, municipality of Baerum, Norway, 2017

| Water advice in the notification | Awareness[a] % (n) | Compliance[b] % (n) | Effective compliance rate[c] (Awareness x Compliance) % |
|---|---|---|---|
| #1 Store clean water for necessary consumption in advance | 66% (273) | 82% (224) | 54% ($82 \times 0.66$) |
| #2 Let cold water flush until clear if discoloured | 51% (211) | 92% (195) | 47% ($92 \times 0.51$) |
| #3 Do not use washing machine or dishwasher until the water is completely clear | 43% (178) | 91% (161) | 39% ($91 \times 0.43$) |
| #4 Boil water before use for food and drinking | 65% (269) | 81% (218)* | 53% ($81 \times 0.65$) |

[a]:awareness is measured among participants who remembered receiving a notice ($n = 412$)
[b]:compliance rate is measured only among respondents who were aware of each advice (number provided in the first column)
[c]:effective compliance rate is the product of awareness and compliance and capture the effect of the ones being unaware of the BWA
*Note: 169 boiled water and 49 did not boil water because they used bottled water for food and drink

### Communication coverage

SMS was the main notification method and the most preferred method for future communication. Coverage with this communication mode was 67%, implying that 1/3 of the study population was not reached, which affects effective compliance if factored in. Findings from the focus groups also indicate that BWA messages could easily be missed among other information from the municipality. Furthermore, it is likely that participants did not recall receiving a notice 12 months prior to the survey, even though they had, in fact, received an SMS from the municipality. In addition, technical errors in sending out the notifications or with residents' mobile phones may be a factor. An SMS may not reach persons not acquainted or comfortable with newer technology, non-Norwegian readers or travellers not registered with a permanent address in the municipality [16]. These groups rely more on personal networks to become aware of public health messages [24]. Effects of tiredness to repeated notifications ('message fatigue') [16, 25] seem less relevant for our study, as the recommendation is restricted to 1 day after the reconnection of the water supply.

### Behavioural change and perception of risks

Many focus group participants perceived that 'recommendations' are not strong advice and leave the evaluation of risk to the individual. Furthermore, survey respondents believed that it was sufficient to let the water either run until it was clear or to allow a short time for it to be safe to drink. Even though messages issued by an authority may seem very specific and precise, recipients may not perceive the risks in the same way that experts do [26]. Thus, we suggest that a better description of the risk is needed to enable the public to make informed choices for themselves [26]. Similarly, the message to 'boil the water' may not be specific enough [26]. More information on health risks may have a positive effect on behavioural changes and increase compliance at the household level [27].

### Effect on trust in the water supplier

BWAs pose some dilemmas for decision-makers: exposing the public to too many precautionary BWAs could make the public lose trust in the water supplier, diminish the BWA's credibility ('cry wolf' scenario) or other negative consequences, such as increasing consumer anxiety and altering perceptions of water quality [6]. These findings contrast with our findings indicating that communication served as a trust-building measure. We believe that prompt and accurate information is a mitigating measure [28]. Consumers interpret extensive communication from the water supply agency as a form of control [28], which corresponds with the findings of our study.

### Strengths and weaknesses of the study

One strength of this study is the combined data collection methods of focus group discussions and a survey. The combination of qualitative and quantitative data provides different insights to the same problem (triangulation) and enhances the validity of the study [29, 30]. The focus group discussions provided valuable insights regarding the questions, language and expressions that are relevant to a target audience [31]. The findings were triangulated by researchers with different fields of expertise in the application of qualitative methods and water supply [30].

The rather low response rate (22%) may be of concern. In terms of generalisability, one might question the extent to which our results are valid for the general population that has received and SMS in Baerum municipality. Low response rates are becoming an increasing challenge in conducting surveys, yet it has been argued that the response rate of a survey may not be as strongly associated with the quality or representativeness of the survey as generally believed [32]. The low response rate in our study may have affected the results. Participants were recruited on a voluntary basis and may not represent the general population of the municipality who have received a BWA notification (selection bias). Furthermore, they may have had a greater interest in the study topic, thus affecting the results in a positive direction [33]. Recall bias may also be relevant, particularly in the survey, due to a tendency to overestimate one's own positive behaviour. Another weakness is that the findings may not be representative of some groups, such as older individuals without mobility, non-Norwegian speakers, illiterate individuals and those without smartphones. However, this is not a result of sampling representativeness but is, instead, related to the design of the study [34]. Data collection in the form of personal interviews in participants' homes could have contributed to filling this gap.

In our study, we used qualitative approaches to examine a particular group or phenomenon of interest – namely, the uptake of the communication of BWAs based on one municipality's practice. Therefore, the generalisability of the findings may be claimed to not be an expected attribute of the study per se [30]. Although the results of a quantitative study may not be directly generalisable, we believe that the results of our study are of general interest to a larger audience – in particular, water supply agencies. The study illustrates that BWAs, when issued in an informative and transparent way, may increase public trust. This is in contrast to other reported effects of BWAs [16]. The findings of the study also provide a better understanding of adherence to BWAs – an area where data are sparse [6] – and may make a valuable contribution to increasing interest in knowledge synthesis in qualitative research [30].

### Implications of the study and future research

A suboptimal awareness of BWAs affects effective compliance and implies that there exists a health risk due to possible infection. Therefore, efforts to improve awareness of BWAs are needed.

In Norway, no national policy on the use of BWAs as a precautionary measure to avoid infection risk from the water supply exists, except when *E. coli* is detected in water samples. As the health effects of an ageing water infrastructure are of national concern, there is a need to consider adopting an overarching policy regarding the use of BWAs in situations where drinking water contamination is suspected. If the water suppliers are reticent to use precautionary BWAs due to concerns about decreasing the population's trust in the water supply, this study provides a reassuring response to such concerns. As we do not have knowledge of the practices of BWAs elsewhere in Norway, the findings of this study may not be relevant to other water suppliers. An assessment of the use of BWAs among water suppliers in Norway would make a valuable contribution when considering a possible national policy on the use of BWAs. Included in such an assessment would be the practice of issuing BWAs; reasons for not considering the use of BWAs; and the wording, content and communication methods for the notifications.

## Conclusions

In our study, awareness was suboptimal among residents who had received water advisories, but compliance with the advice in notifications of the advisories was high. The study highlights the importance of the distribution, phrasing and content of water advisory notices to achieve greater awareness and compliance. The public positively perceives information on interruptions in the water supply and precautionary recommendations to boil tap water, and such information aids in fostering greater trust in water supply authorities. Future studies should include hard-to-reach groups with adequate data collection approaches and examine the use of BWAs in a national context to inform future policies on BWAs.

## Additional file

**Additional file 1:** Questionnaire (DOCX 26 kb)

#### Abbreviations

BWAs: Boil water advisories; OR: Odds ratio; SMS: Short message service

#### Acknowledgements

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#### Authors' contributions

SH led the study project, participated in the data collection, analysed and interpreted the data, and drafted and revised the manuscript. LV conducted the statistical analysis. ABB contributed to the design of the study, development of the survey, interpretation of the data and drafting of the manuscript. TGR contributed to the collection of qualitative data and analysis of these data. KN conceived of the study, participated in the overall design of the study and contributed to the revision of the manuscript. PAA contributed to the revision of the manuscript. All authors read and approved the final manuscript.

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No funding was granted for the study.

#### Availability of data and materials

Data from this study may be made available upon request to the corresponding author. As the original participant consent process did not explicitly state that raw data might be provided to others outside of the original study team, access to raw data will only be considered after an institutional ethics review by the requesting researcher/research team. The raw data exist in Norwegian only. The questionnaire developed for the survey in the study is found in a translated version under Additional files.

#### Ethics approval and consent to participate

The Data Protection Officer at the Norwegian Institute of Public Health waived the need for ethical sapproval according to national regulations (The Act on medical and health research of 20 June 2008) since the study did not collect personal health data and the participants to the survey remained anonymous. The need for ethical approval for the conducting the focus groups was waived to the same act. The respondents to the survey consented by filling out the questionnaire after reading the introductory text. No participants below 16 years were invited to the study. The need for written consent for the participants in the focus groups was waived according to the Act of 14 April 2000 relating to the processing of personal data (Personal Data Act) since the data collection did not contain any person sensitive data. The participants in the focus groups provided verbal consent and an email with confirmation of the verbal consent was sent to each participant who had given the consent to be a part of the study. In this email, the object of the study was repeated and the procedures for the data collection (tape recording) in the focus group was explained. The correspondence of the email with conformations of verbal consent were filed on a secure server only accessible for the responsible recruiter. The participant and their contact information provided the study, were decoded and the file connecting the participant to their contact information were stored separately and deleted 6 months after the data collection had found place. At the beginning of the focus group discussions, the objectives of the study and means of data collection were explained again to each participant in the focus groups. The participants were assured of the anonymity and confidentiality of their responses. They were also explained that their participation were voluntary and that they could withdraw at any time.

#### Consent for publication

Not applicable.

#### Competing interests

The authors declare that they have no competing interests.

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## Publisher's Note

# Paper IV

# The establishment and first experiences of a crisis advisory service for water supplies in Norway

Susanne Hyllestad, Vidar Lund, Karin Nygård, Preben Aavitsland and Line Vold

## ABSTRACT

Water supply systems, in particular small-scale water supply systems, are vulnerable to adverse events that may jeopardise safe drinking water. The consequences of contamination events or the failure of daily operations may be severe, affecting many people. In Norway, a 24-hour crisis advisory service was established in 2017 to provide advice on national water supplies. Competent and expert advisors from water suppliers throughout the country assist other water suppliers and individuals who may be in need of advice during an adverse event. This paper describes the establishment of this service and experiences from the first three years of its operation. Since the launch of the service, water suppliers across Norway have consulted it approximately one to two times a month for advice, in particular about contamination events and near misses. The outcomes have helped to improve guidance on water hygiene issues at the national level.

**Key words** | crisis management, drinking water, water contamination

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## HIGHLIGHTS

- Prevention of drinking water emergencies.
- Sharing of experience on novel prepardness measures.
- Effective and low-cost solution which is replicable elsewhere.

## INTRODUCTION

The delivery of safe drinking water is an important public health issue (Bain *et al.* 2014). When pathogens or harmful chemicals contaminate drinking water, many individuals suffer adverse health effects (Nygard *et al.* 2006; Pitkanen *et al.* 2008; Widerstrom *et al.* 2014). Several serious water emergencies have led to an increased focus on risk management for drinking water systems (Mac Kenzie *et al.* 1994; O'Connor 2002). For more than ten years, the World Health Organization (WHO) has repeatedly advocated water safety plans (WSPs) (World Health Organization 2004). Safe drinking water does not necessarily imply zero risk (Hrudey *et al.* 2006); regardless of multiple hygiene barriers and precautionary actions, there will always be a small remaining risk of waterborne illnesses or diseases (Hrudey & Hurdey 2007). Since unwanted events will inevitably occur, learning from incidents and near misses concerning water supplies is imperative for preventing future events (Hrudey & Hurdey 2014).

Drinking water safety is highly dependent on management decisions at all levels of the water supply sector (Hrudey *et al.* 2006; Rizak & Hrudey 2007). The water



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suppliers must manage multiple perceptions and risks to maintain regulatory compliance and consumer trust (Jalba *et al.* 2014). Small-scale drinking water supplies have been identified as particularly vulnerable to failure to provide a continuous supply of safe drinking water (WHO 2011). They share a range of common managerial, financial and institutional challenges and particularities that make them more vulnerable to inadequate management and operational breakdowns, which may impair the provision of sustainable services (WHO 2016). Residents in the Nordic countries rely widely on small-scale systems serving fewer than 500 people, where performance information generally is lacking for these systems. However, a study implies that non-compliance of faecal indicators occurs more frequently among small-scale drinking water supplies than larger systems (Gunnarsdottir *et al.* 2017).

The safety of small-scale drinking water supplies plays an important role in terms of ensuring public health, worldwide and in Europe, since such small-scale supplies serve a significant number of people (UNICEF 2019); for instance, in Norway, 86% (1,224 of 1,421) of the regulated water supplies serving permanent residents in 2018 served fewer than 5,000 inhabitants (Hyllestad *et al.* 2019). This is similar to the statistics for other countries in the region, for example, France, Austria, Finland and Spain (WHO 2016). Although the true burden of waterborne diseases in the WHO European region, which stretches from Europe to Central Asia and includes a number of low- and middle-income countries, is unknown due to the underreporting or underestimation of water-related diseases (Kulinkina *et al.* 2016), it is believed that they constitute a leading contributor to the global disease burden. Despite the fact that the water supply sector in Norway is of general high technical standard, 28 waterborne outbreaks resulting in 8,060 cases were reported in the period 2003 to 2012, implying that outbreaks occur almost every year (Guzman-Herrador *et al.* 2016). Some of these outbreaks are large, such as the Giardia outbreak in Bergen in 2004 with an estimated 6,000 cases (Nygard *et al.* 2006), the outbreak of campylobacteriosis in Røros in 2007 with an estimated 1,500 cases (Jakopanec *et al.* 2008) and the recent outbreak of campylobacteriosis in Askøy in 2019 with an estimated 2,000 cases (Norwegian Institute of Public Health 2019). In addition, breaches in the supply, such as main breaks, drought and contamination events, are each year notified to the Norwegian Food Safety Authority, and some also reach the media.

In early 2017, a 24-hour advisory service – the National Water Guard (NWG) (in Norwegian: Nasjonal vannvakt) – for water emergencies that could affect water utilities was introduced in Norway to address the challenges of inadequate managerial capability in the water supplies. The primary aim of the NWG is to strengthen emergency preparedness measures in the sector. An expected outcome of the NWG is data collection on events that challenge the organisational capacities of the water supplies in order to shed light on necessary preparedness measures, and ultimately reduce the risk of waterborne illnesses. The objective of this paper is to present the experiences for the first three years of the NWG's operation, with the objective of describing the background and enabling factors relating to the establishment of the NWG, including an analysis of the registered requests for advice to manage adverse events.

## METHODS

The methods used to address the objective in this paper are two-fold: methods used to design a crisis advisory service in the Norwegian context, and methods used to present the experience of three years of operation.

### Establishment of a crisis advisory service for water supplies

In the establishment of the crisis advisory service for water supplies in Norway, several methods and approaches were used to explore and design a crisis advisory service that would be suitable for the Norwegian context.

In the design phase for the service, the researchers assessed the documented experiences of similar crisis services for water supplies, here, particularly in Sweden. In Sweden, a crisis group (VAKA) addressing emergencies in water supplies was launched in 2004 after experiencing several severe events of flooding in 2001 and 2002 which affected the water supplies. Since the launch, representatives of VAKA have been involved in addressing crisis events in the water supplies, approximately every month, in Sweden. Consultations with key representatives of the

Norwegian Water Association were conducted to determine potential types of advice that might be needed and the expectations of such an emergency service among the water supplies. The Norwegian Water Association collected their input from workshops with representatives from several water suppliers of various sizes. Other official services, such as the Infectious Disease Control Service at the Norwegian Institute of Public Health, were consulted about their experiences of the 24-hour advisory service. Principal discussions regarding enabling factors, roles, responsibilities, and funding were conducted with the Ministry of Health and Care Services, the Norwegian Food Safety Authority, the Norwegian Water Association and the Norwegian Institute of Public Health.

In the launch phase of the advisory service and during the development of procedures, a project group consisting of personnel from the Norwegian Institute of Public Health and the Norwegian Water Association was formed to execute the planned actions. VAKA in Sweden and the Norwegian Poison Center (administered by the Norwegian Institute of Public Health) were consulted about their experiences of procedures, codes of conduct relating to sensitive and detailed information obtained from water suppliers, and practical issues concerning staffing and incentives for the service. Workshops involving unpaid volunteers from water suppliers and personnel from the Norwegian Institute of Public Health were held to discuss issues pertaining to the operation of the service, and to test procedures using tabletop simulations. A two-month pilot period was assigned at the beginning of 2017 to test the service's functions and procedures.

### Data collection and analysis

The advisory service logs all requests in a crisis incident management tool (CIM). We used data from 2017 to 2019 to examine the frequency and main topics of the requests.

A request was considered relevant to the service and data synthesis if it was: (1) directed by a leader of a water supplier and/or in collaboration with a municipal doctor, (2) of an acute nature and (3) severe enough to be referred to the leadership in the water supplier. Requests that originated from private individuals, private building owners, lawyers seeking expert opinions, municipal doctors who sought general advice on how to answer water-related questions, and water suppliers that sought advice on general questions regarding non-acute water hygiene in the offshore oil industry were filtered out and excluded from the data set, to ensure that only organisational capacities were monitored.

Data from the CIM log were imported to Excel for data management and analysis.

### Ethical considerations

Data from the crisis advisory service did not include individual health data or sensitive personal data; thus, ethical approval for this study was not required.

According to the Norwegian drinking water regulations enforced in 2017 (Lovdata 2018), the water suppliers have an obligation to notify customers and the Norwegian Food Safety Authority about events that may have implications for human health. Most notifications also have to be copied to the municipal medical officer responsible for infectious disease control measures.

Such events were few in number and could easily be traced back to specific water suppliers; hence, we simplified the descriptions of the events to avoid identification of the organisations and maintain credibility and trust in the advisory service.

## RESULTS

### Background for the establishment of the crisis advisory service

The inability of water suppliers in Norway to manage water emergencies, particularly for small-scale systems, has raised concerns. There are approximately 1,500 geographically widespread individual water supply systems, both public and privately owned, regulated and inspected by the Norwegian Food Safety Authority in Norway (Hyllestad *et al.* 2019). Many water supplies are managed by small organisations with limited training and competence. Reports on interruptions in the water supply caused by breakdowns in the distribution systems, and audits of the water distribution systems themselves, revealed non-compliances at 81% of the inspected waterworks (Norwegian Food Safety Authority

2013). All of the registered water suppliers in Norway must have an emergency preparedness plan, which is mandatory according to the Norwegian drinking water regulations enforced in 2017 (Lovdata 2018); however, a recent national audit revealed that two-thirds of the water suppliers did not conduct exercises, creating uncertainty with respect to the water suppliers' capacity to deliver safe drinking water during major events (Norwegian Food Safety Authority 2017). Against this backdrop, a decision to explore the opportunities and prerequisites for establishing a crisis advisory service for water supplies was made in 2016, following a discussion about the drinking water sector in Norway that had been ongoing since the middle of 2000.

### Expectations and need for advice: outcome of interviews with water suppliers

Based on input from the Norwegian Water Association which was collected in workshops with a group of water suppliers, the feedback and expectations differed between the large and small water suppliers. We expected that the large water suppliers would have the competence to manage operational breakdowns; however, they would expect advice on concerns such as outbreak investigations and the outcomes of microbiological analyses on which they would not necessarily be up to date. Experience revealed that advice in these areas was not fully provided by the municipal doctor. For the smaller water suppliers, there was a need for advice on troubleshooting breakdowns in daily operations and the distribution network. Both groups, however, expressed the advantage of having 24-hour advice available if needed.

### Purpose of the advisory service

The Norwegian NWG service is a 24-hour service for suppliers that need advice and support during events that can affect the water supply and have health consequences for the population. The idea behind the NWG was to use existing expertise in the drinking water sector and public health agencies to support other water suppliers in severe situations when needed. It was expected that the advice would enable water suppliers to implement appropriate measures in the early stages of a crisis, when drinking water safety was under siege. In the introductory phase, the crisis advisory service was named the National Water Guard (translated from Norwegian) after input from the people volunteering to the crisis service.

### Enabling factors

A prerequisite for the NWG was that it should rely on the existing structure to avoid extra costs relating to compensation for service provision for personnel. The participation of unpaid, experienced personnel from other water suppliers was one of the most important factors in the establishment of the NWG. To ensure 24-hour a day operations, the responsibility for running the service is shared by experienced personnel from various water suppliers that provide unpaid volunteers, and employees at the Norwegian Institute of Public Health who contribute as a part of their daily work routines. The network has remained stable since its formation, consisting of eight regular volunteers, who meet regularly to conduct preparedness training, discuss matters of common interest, and facilitate team building under the aegis of the Norwegian Institute of Public Health. Another prerequisite was to establish the NWG within existing public health structures in Norway, via the Norwegian Institute of Public Health, which comprises personnel with epidemiology, microbiology, toxicology and water hygiene expertise, with additional 24-hour health advice services provided by the Norwegian Poison Center and a duty officer on call for infectious disease control.

Although the discussions regarding establishment of a crisis advisory service had been ongoing since the middle of 2000 in Norway, it was only when developing the national goals for water and sanitation under the auspices of WHO/UNECE's Protocol on Water and Health (Norwegian Food Safety Authority 2014) that the establishment of such a service became a political commitment. When the scope of the advisory service had been defined and the costs estimated, the Ministry of Health and Care Services provided funding to launch the NWG. The funding was intended to cover a dedicated position to the crisis advice service and expenditure for meetings, travel and technical tools, such as computer software.

### Roles and responsibilities

In Norway, an important principle in crisis management is that those closest to the crisis are the most suitable people to deal with the situation ('the subsidiarity principle') (The Norwegian Government (Regjeringen) 2019). The subsidiarity principle has also been a guiding premise for the establishment of the NWG. The personnel associated with the NWG do not directly manage and control the incident; thus, the established roles and responsibilities for the emergency services in Norway have not changed.

### Technical assistance and tools

The technical tool used to manage the incoming requests for advice is a web-based CIM application, accessible from a PC or mobile, and the programme is used to record enquiries and to maintain communication about an enquiry while it is in progress. In addition, the programme is used to extract statistics and produce reports about the enquiries. The water supplier may contact the crisis advisory service by calling one number that is operational 24 hours a day. The day is divided between the Norwegian Institute of Public Health and the group of volunteers from the water suppliers, with the Institute covering normal office hours and the volunteer group serving after office hours and during weekends. The assistance mainly consists of providing telephone support, but the members are prepared to assist at the event in person locally if necessary.

### Registered requests submitted to the advisory service from 2017 to 2019

In the period 2017–2019, 50 (41%) of 122 requests were considered relevant to the NWG. The requests were referred to other organisations or, if considered to be non-acute requests, managed by the Norwegian Institute of Health as general public health advice. Fourteen of the 50 requests came to the service outside office work hours. All the requests were managed using telephone support only, except one that was managed by several telephone calls and mail counselling. Most callers were from small to medium water suppliers (serving less than 5,000 inhabitants).

The number of requests per year were 10 (2017), 22 (2018) and 18 (2019), respectively, with no clear trend (Figure 1), but the summer months produced the greatest number of requests.

Questions relating to possible microbiological contamination made up 72% of the requests (Table 1).

Usually, the callers sought advice on proper measures to take, such as whether to issue a boil water advisory or not, or whether to flush the pipe distribution system or use emergency chlorination. There were specific questions about the issuing of a boil water advisory, based on the findings of a coliform bacteria test, which did not detect *E. coli* in the water samples (Table 2). The reason for the request was uncertainty about the health consequences if the number of coliform bacteria was high and the significance of measuring coliform bacteria in the absence of clear action points for this parameter. Typical requests for advice regarding chemical spills concerned the risk to human health due to the possible consumption of the pollutants by residents.

The requests categorised as 'operational' were diverse. One common theme was failure of, or concerns relating to, the water treatment process. One request was of a more precautionary nature: due to an extremely warm period in early summer 2018, there was a shortage of the carbon dioxide needed for the coagulation process. This request came from the Norwegian Food Safety Authority on behalf of several water suppliers.

## DISCUSSION

Based on ongoing discussions and the expressed need for a 24-hour crisis advisory service for water supplies in Norway, the NWG was established in 2017. After its launch, the NWG received 50 relevant requests in its first three years of operation (2017–2019). All requests except one, mainly coming from small water suppliers, resulted in one-time support with no follow-up action. Almost three-quarters of the requests concerned microbial contamination.

### Timeliness and added value of the Norwegian crisis advisory service

On average, one to two requests per month were considered relevant to the NWG. However, it is not the

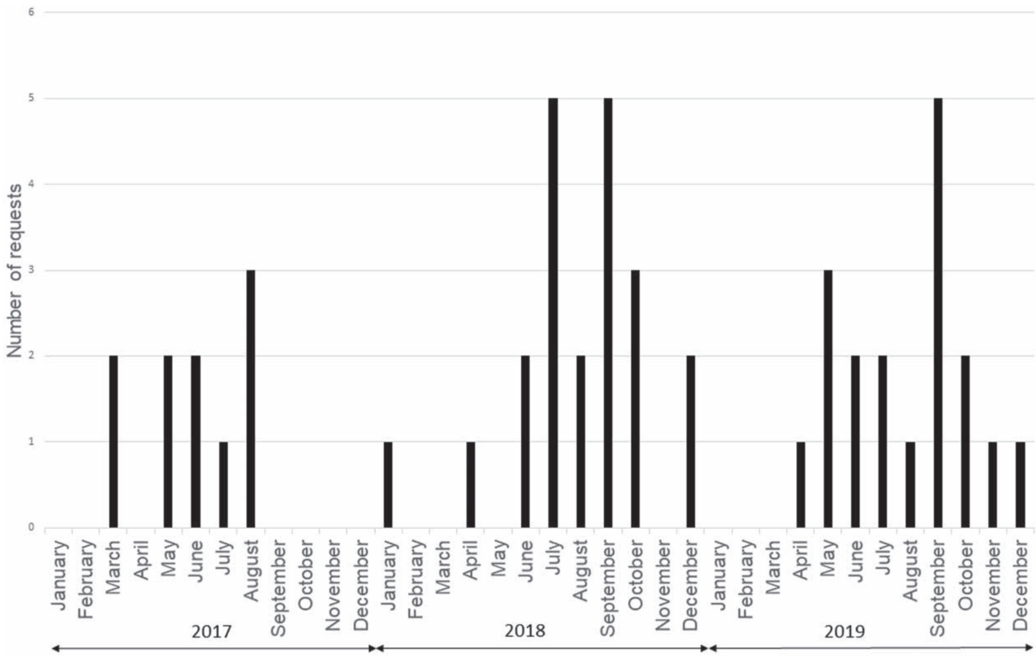


**Figure 1** | Requests per month submitted to the Norwegian crisis advice service for water supplies, in the period 2017–2019.

**Table 1** | The main topics of the requests submitted to the Norwegian crisis advice service for water supplies 2017–2019 ($N = 50$)

| Topic | Number (%) | Main topic of the request (with the number of such requests) |
|---|---|---|
| Microbiological | 36 (72) | Detection of faecal indicator bacteria[a] in routine samples (27)<br>Suspected contamination (due to pipe break) (4)<br>Suspected contamination due to increased number of consultations at a doctor's office (2)<br>Problems with cyanobacteria (1)<br>Problems with mould in reservoirs (1)<br>Provision to a dentist of a water-boiling advisory (1) |
| Chemical | 6 (12) | Spill of petroleum products near a water source (3)<br>Spill of pesticides after a fire in a storage shed (1)<br>Spill of sodium hydroxide (1)<br>Suspected chemical pollution in a reservoir after sabotage (1) |
| Operational | 8 (16) | Unusual taste and smell of the drinking water (2)<br>Failure of the UV-radiation process (2)<br>Failure of the pH adjustment (1)<br>Sub-optimal coagulation process (1)<br>Precautionary mobilisation due to shortage of carbon dioxide needed for water treatment (1)<br>Shift to emergency water source (1) |

[a]*Escherichia. coli,* coliform bacteria, heterotrophic plate count, intestinal enterococci, or *Clostridium perfringens* according to standard methods for analysing faecal indicator bacteria (Lovdata 2018).

number of requests that determined the usefulness of the NWG, but rather whether the water supplier received advice that was both timely and useful in the given situation. Since most of these requests came from small to medium organisations, it may indicate that the large water suppliers were able to manage serious problems

**Table 2** | Examples of requests for advice and the advice given by the Norwegian crisis advisory service for water suppliers

| | Caller | Event | Question(s) asked | Brief summary of the advice provided by the National Water Guard |
|---|---|---|---|---|
| Example 1 | Representative of a medium-sized water supply | Leakage on the distribution system was repaired and flushed, however, the control samples tested positive for intestinal enterococci (no *E. coli*) | Should they issue a boil water advisory? | Advice to issue a boil water advisory, in conjunction with the municipal doctor, was given until negative results for the tests were obtained |
| Example 2 | Representative of a small water supply | Spill of 2–300 litres of petroleum after a truck fell into a river that was used as a raw water source for the water supply to the municipality | What could they do to limit the spillage, which could affect the wells in the water supply system? | Inspect the river on the same side as the wells, consider suctioning visible petroleum spills, assign a person to test for the smell/taste of petroleum at the intake, and consider closing the supply in case of the smell/taste of petroleum. If so, notify the customers and use a reserve water source |
| Example 3 | Representative of a small water supply | Shortage of water resulting in the use of a reserve water source, which included pumping water from an undocumented water source (without water testing) to the intake of the existing water supply | Was there any risk from using this 'unknown' water source, even if they treated the water? | Since the quality of the water source was not documented, there was a risk that the existing treatment would not have the capacity to act as an adequate hygiene barrier for this particular reserve water source; therefore, a boil water advisory should be issued until water testing had been conducted |
| Example 4 | Representative of a large water supply | A landslide had cut the main supply pipe to the water treatment plant, resulting in a water-boiling advisory affecting 15,000 inhabitants. A series of water sample tests revealed coliform bacteria, but not *E. coli* and intestinal enterococci | Since they did not detect faecal indicators such as *E. coli* and intestinal enterococci, could they rescind the boil water advisory? | This event was of a rather serious character and it was assumed that the detected coliform bacteria resulted from the event. Despite no faecal indicators being detected, it was reasonable to assume that the drinking water had been affected by the event and that the situation remained unstable. In this situation, it might be advisable to take precautionary measures and await further information before rescinding the boil water advisory |

themselves, or that severe situations occurred relatively rarely for them.

The value of the advice given for each of the requests submitted to the NWG was a challenge to evaluate. The purpose of the NWG is to contribute in situations that the water suppliers experience difficulty in managing. In response to some of their requests, the water suppliers found support in merely seeking a second opinion regarding their already-planned actions, which may have facilitated timely action. It was difficult to evaluate the added value of preventive measures for water suppliers; however, the societal costs relating to severe outbreaks of waterborne diseases are high (Halonen *et al.* 2012; Larsson *et al.* 2014), so the benefits of early action, even regarding less severe events, should not be underestimated.

An important function of the NWG is to be available 24 hours a day to ensure immediate action and prevent developments that could have major consequences. Most of the requests to the crisis advisory service came during daytime in the assessed period; however, 14 requests after normal working hours demonstrated the need for round-the-clock availability. Due to the low number of requests, it was not possible to evaluate the timeliness of the advisory service overall; however, in one of the cases, relating to the spillage of petroleum into a river serving as a raw water source for a municipal water supply, the timeliness was clearly demonstrated: since the event occurred during the evening, contact with the crisis advisory service was made and the situation was managed during the night. By the following morning, the situation was under control and the case could then be closed, with the conclusion that any harm to the water supply had been avoided (Table 2).

### Reaching the target audience: The water suppliers

The rather low rate of contact from what is considered to be the target group of the NWG (41% of all initial contacts) indicated that either awareness of the purpose of the service remains unclear among the water suppliers and/or that the public misunderstands who the target audience for the service is. This may be explained by the fact that the NWG is still a new facility within the context of the Norwegian water sector, despite its three years of operation. Continuous efforts to raise awareness of the NWG will therefore be important. However, occasional telephone contact from private individuals will be inevitable, since information about the service and the phone number are available online to create easy access to information about water supplies.

### Introducing a new actor for the management of crises

The uncertainty of roles and responsibilities during an emergency is likely to interfere with an effective response (Hrudey & Hrudey 2014). A concern in the early discussions regarding the NWG was whether such a service would interfere with established roles and responsibilities according to the 'subsidiarity principle' in Norway. When managing a request from a water supplier, the experienced volunteers of the NWG do not, with few exceptions, have first-hand knowledge of the water supplier seeking advice. The advice must then be based on information provided by telephone about the incident and the water supplier's capabilities, meaning that the advisor will experience limitations. Nevertheless, a detailed description of the situation, and in some cases, maps and other additional information, contributed to effective and targeted counselling. This underlines the importance of the water supplier (the 'event owner') contacting NWG, rather than other actors, outside the crisis management arena, that do not have current information to hand. Telephone counselling, as the NWG delivers their advice at present, requires the water supplier to understand and describe its problem relatively accurately, which may improve the supplier's own crisis management ability.

### Information used to give guidance and facilitate precautionary actions

Based on the assessed requests, it was difficult to spot trends, since the request topics varied greatly and were rarely repeated. Microbiological questions can be expected to recur, as they are of obvious health significance and the value of guidance (zero occurrence of *E. coli*) is attested by the Norwegian drinking water regulations enforced in 2017 (Lovdata 2018). However, regarding microbiological contamination, one recurring type of request related to uncertainty about positive test results for coliform bacteria and, based on this, the desirability of issuing a water-boiling advisory (despite no *E. coli* being detected in the water samples). In Norway, no official guidance exists regarding the presence of coliform bacteria and potential remedial actions, such as boiling water; however, an assessment of the situation to determine possible health consequences is vital. Guidance on safe levels of coliform bacteria does, however, exist in Denmark (Ministry of Environment & Food of Denmark – Natur Agency (Naturstyrelsen) 2013) and Sweden (Swedish Food Agency (Livsmedelsverket) 2017), where specific levels of coliform bacteria are indicated to necessitate a boil water advisory (along with an assessment of the situation) as a precautionary measure. The information obtained from the NWG supports the development of similar national guidance for Norway, to make the evaluation of test results and the planning of action easier or to provide guidance for both water supplies and the municipal doctors for questions linked to infectious disease control.

### Limitations of the data

Our results are only valid for the requests recorded by the NWG and should not be generalised to all water supply-related events. According to the Norwegian drinking water regulations, failure to meet drinking water quality standards and breaches of significance must be reported to the Norwegian Food Safety Authority (Lovdata 2018). This implies that there may have been several adverse events relating to water suppliers during the period assessed, but advice on how to manage the situation was not sought from the NWG, either due to lack of awareness or the event requiring no assistance to manage.

In some cases, it was difficult to classify the events we examined as microbiological, chemical or operational; for example, an operational failure of disinfection would ultimately result in a suspected microbiological contamination and it was debatable whether this request should be classified as a microbiological contamination event or/and an operational failure event. Similarly, accounts of a water treatment failure resulting in excess sodium hydroxide could be classified as an operational failure or a chemical spill event. The results may therefore be prone to classification bias that could affect the aggregated data over time, thus leading to a failure to provide accurate information when a breakdown of the water supply system occurs. A more nuanced manner of classifying requests could prevent this classification bias over time. A means of spotting trends more accurately or identifying common issues among the water suppliers would provide useful information to enhance their preparedness; however, a descriptive synthesis of data would, to a large degree, be heterogeneous and not suitable for detailed assessment.

Assessing whether incidents were severe enough to be considered relevant to the NWG was another challenge for the screening of the requests. Among the approximately 1,500 individual water supply systems in Norway, estimations of an acute situation will vary depending on the experience and competence of the organisation. An event that may be considered routine for a large water supplier could be a challenging event for a small water supplier, but this did not imply that the advice given was of less value than in complicated situations. By contrast, it may confirm that competence, or access to information, is limited and more challenging for small water suppliers.

### Recommendations to the Norwegian crisis service on the way forward

Based on the three years of experience, it is recommended to continue to promote the existence and usefulness of the NWG among the water suppliers in Norway to ensure awareness and most possible use, in case of events and to avoid consequences of near misses. Future improvements should also include a more accurate synthesis of data on events, to inform national guidance and capacity building in the drinking water sector from experience from local events. A more in-depth evaluation should also be conducted to inform future decisions related to the development of the NWG.

## CONCLUSION

Water supply systems are vulnerable to a number of adverse events that may have health consequences. In Norway, the NWG for water suppliers has, since it was launched in 2017, been approached for advice in different situations by various water suppliers, mainly by managers of small-scale water supply systems. The personnel operating water supplies in Norway have benefited from the NWG when evaluating situations and prioritising timely and effective actions. The NWG is one example of how expertise can be used effectively across water suppliers nationally to prevent the consequences of unwanted water supply events in countries like Norway, where the water supply sector comprises many small water suppliers. The requests elicit information that is useful for improving guidance on water hygiene questions at the national level.

## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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