Precipitation, Raw Water Quality, Drinking Water Treatment and Gastrointestinal Illness

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“ Sometimes the road less traveled is less traveled for a reason”

~ Jerry Seinfeld

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Abstract

Background

On numerous occasions, outbreaks of acute gastrointestinal illnesses (AGI) have been linked to municipal drinking water in the industrialised world. Many of the reported outbreaks were observed after heavy rainfall events, which suggests that such events could result in a deterioration in the quality of drinking water. The observed drinking water-related outbreaks are, however, probably just the tip of the iceberg, and the extent to which public drinking water also influences the endemic level of gastroenteritis during non-outbreak periods is largely unknown. With climate change projected to increase the frequency of extreme weather events, data for preventive actions are needed now, to ensure safe drinking water today and in the future.

The primary aim of this thesis is to increase the knowledge of the extent to which rainfall can still be a risk for insufficient drinking water quality, even with modern drinking water production methods. We aim to study if the incidence of gastroenteritis during normal endemic levels can be associated with water quality and the efficacy of pathogen elimination in different treatment processes. The thesis focuses first on AGI in the Gothenburg population and how precipitation affects its main fresh water supply (papers I-III); this is followed by a broader comparison of AGI in 20 cities across Sweden (Paper IV).

Methods

Observational time series data was used for all papers to construct generalized additive regression models, using smooth functions to adjust for long-term trends. Delayed effects on the outcome were evaluated using distributed lag non-linear models.
In Paper I, the raw water-quality data for the river Göta älv were analysed – this water is used to produce drinking water for the population living in the north part of City of Gothenburg. The short-term variation of daily mean turbidity measurements and samples of three different types of indicator bacteria were modelled with daily precipitation using seven years of data. In papers II and III, the analyses aimed to determine whether the daily incidence of AGI in the population which households received drinking water produced from the river water could be associated with precipitation. As a measure of AGI, we used four years of data on the daily number of phone calls to the nurse advice line about vomiting, diarrhoea or abdominal pain (Paper II), and six years of data of the daily number of visits to health

care clinics, when individuals were diagnosed with gastrointestinal infections (Paper III). Paper III also evaluates the similarities and differences between the frequency of nurse advice calls and primary health care visits.
Paper IV analyses and compares the occurrence and seasonal patterns of nurse advice calls in twenty cities in Sweden, using seven years of data. The water treatment technique used by the public drinking water plants was obtained, and the processes theoretical efficacy of pathogen elimination was determined. The extent of AGI calls in relation to the pathogen elimination efficacy was analysed using a binomial regression design, adjusting for population size, age distribution and geographical area.

Results

We observed a strong relation between precipitation and the water quality in the Göta älv. A heavy rainfall event was related to increased concentrations of E. coli bacteria for several days, with the peak increase two days after the event. Precipitation was found to affect raw water quality parameters across all seasons.
Heavy precipitation was also associated with a significant increase in the daily number of nurse advice calls due to AGI symptoms, with the number of calls peaking five days later. Consecutive wet weather periods were associated with both an increased number of AGI calls, as well as visits to clinics that led to diagnoses of AGI.
Finally, we observed in Paper IV that cities with a higher pathogen elimination efficacy in their drinking water utility had a lower amount of AGI calls. The relations applied both to surface water and groundwater utilities, although the protective effect of a more advanced drinking water treatment on AGI was observed to be most significant in cities with surface water plants during the winter season.

Conclusions

The results suggest it is possible to reduce the occurrence of endemic gastroenteritis with a more advanced treatment process for drinking water. The delay between a heavy rainfall event (and the resulting decrease in raw water quality) and the increased number of nurse advice calls suggests viruses are the main cause, as the timing is consistent with viral incubation times. A viral transmission was also proposed when comparing different cities, as a more advanced water treatment process seems to be most beneficial during seasons where viruses are acknowledged as the main cause of AGI. Our research suggests that upgrades to drinking water treatment techniques, especially those aiming to better eliminate viruses, are warranted.

Svensk sammanfattning

Bakgrund

Vid ett flertal tillfällen har utbrott av magsjuka kopplats till kommunalt dricksvatten. Många av de rapporterade utbrotten observerades efter kraftiga regn, vilket pekar på att nederbörd utgör en risk för otillräcklig dricksvattenkvalitet. Det är dock svårt att uppskatta i vilken omfattning icke-uppmärksammade dricksvattenrelaterade utbrott sker, eller om dricksvatten påverkar den endemiska nivån av magsjuka även under icke-utbrottsperioder. Med klimatförändringarna förväntas frekvensen av extrema väderhändelser att öka, och det behöver utredas om förebyggande åtgärder behövs för att säkerställa rent dricksvatten i dag och i framtiden.

Syfte

Det primära syftet med detta arbete har varit att undersöka i vilken omfattning nederbörd kan utgöra en risk för otillräcklig dricksvattenkvalitet, genom att studera samband mellan nederbörd, råvattenkvalitet, beredningsteknik för dricksvatten och magsjuka. Detta har resulterat i 4 delstudier. Tre studier fokuserade på befolkningen i Göteborg och deras huvudsakliga råvattenkälla Göta älv. Valet föll på Göteborg eftersom dess populationsstorlek och tillgängligheten på data var gynnsamma för dessa typer av studier. Slutligen studerades ett flertal städer i Sverige (20 st.) där den genomsnittliga nivån av magsjuka ställdes i relation till den beredningsteknik som använts i det kommunala dricksvattenverket.

Metod

I den första studien analyserade sju års data av råvattenkvaliteten i Göta älv. Variationer i turbiditet (grumlighet) och tre typer av indikatorbakterier analyserades i relation med dygnsnederbörd. I studie II och III undersöktes om nederbörd samvarierat med den dagliga förekomsten av magsjuka i populationen med hemadress där dricksvatten härstammar från Göta Älv. Som ett mått på magsjuka analyserades fyra års data om dagligt antal telefonsamtal till 1177 Vårdguiden gällande kräkningar, diarré eller magsmärtor (studie II), och sex års data om dagligt antal besök till vårdcentraler där individer har diagnostiserats med gastrointestinella infektioner (studie III). I studie IV inhämtades information över vilka mikrobiologiska barriärer som använts i 21 olika vattenverk från 20 kommuner mellan åren 2007-2013. Den teoretiska effektiviteten att avlägsna patogener i vattenverken analyserades med mängden samtal till 1177 Vårdguiden angående symtom gällande magsjuka.

Resultat

Det observerades starka samband mellan nederbörd och vattenkvaliteten i Göta älv. Kraftigt regn relaterades till ökade koncentrationer av E. coli bakterier upp till en vecka, men med högsta koncentrationerna två dagar efter nederbörd. Nederbörd konstaterades vara den huvudsakliga orsaken för korttidsvariationer av råvattenparametrar. Kraftig nederbörd visade sig också ha signifikant samband med en ökning av antalet magsjukesamtal, med en fördröjning på 5-6 dagar. Ihållande regnigt väder samvarierande både med ökat antal samtal till 1177 Vårdguiden samt med antalet besök till vårdcentraler gällande magsjukeliknande besvär. Slutligen påvisades en skyddande effekt mot magsjuka med en mer avancerad beredning i dricksvattenproduktionen, där de tydligaste sambanden återfanns vintertid och bland kommuner med ytvattentäkter. Skyddande effekter mot magsjuka med en mer avancerad rening konstaterades även hos grundvatten-kommuner.

Slutsatser

Resultaten pekar på att den endemiska nivån av magsjuka kan minskas med hög avancerad beredning i dricksvattenverken.
Den tidsmässiga skillnaden mellan kraftigt regn, försämrad råvattenkvalitet och det ökade antalet samtal till 1177 Vårdguiden pekar på att det troligen är virus som är orsaken till fler fall av magsjuka eftersom fördröjningen stämmer överens med inkubationstider gällande virus. Resultaten motiverar bättre skydd mot förorening av Göta älv och förbättrade barriärer i dricksvattenproduktionen, särskilt de barriärer som är effektiva på att eliminera virus. Att det troligen är virus som sprids i rent dricksvatten styrks även i den sista delstudien då den mest skyddande effekten av effektiva barriärer mot patogener observerades vintertid, den period då förekomsten av magsjukevirus är dominerande.

Original papers

I. Precipitation effects on microbial pollution in a river: lag structures and seasonal effect modification.
PLoS One 9: e98546.

Tornevi A, Bergstedt O and Forsberg B.

II. Association between precipitation upstream of a drinking water utility and nurse advice calls relating to acute gastrointestinal illnesses. *PLoS One* 8: e69918.

Tornevi A, Axelsson G and Forsberg B.

III. Precipitation and primary health care visits for gastrointestinal illness in Gothenburg, Sweden.
PLoS One 10: e0128487.

Tornevi A, Barregård L and Forsberg B.

IV. An Association between the Efficacy of Water Treatment Processes and Endemic Gastrointestinal Illness - A Multi-City Study of Telephone Triage Data in Sweden. (Submitted)

Tornevi A, Säve-Söderbergh M, Forsberg B, Simonsson M and Toljander J.

Abbreviations

AGI – Acute gastrointestinal illnesses, gastroenteritis

AGI calls – Calls to the nurse advice line issuing symptoms of gastroenteritis

AGI visits – Visits to primary health centres diagnosed with ICD-10: A00-A09

AIC – Akaike's information criterion

AWU – Alelyckan drinking water plant (utility)

CFU – Colony forming unit

CI – Confidence interval

DLNM – Distributed lags non-linear models

df – Degrees of freedom

FNU – Formazine nephelometric units

GAM – Generalized additive models

ICD-10 – International Classification of Disease, 10th revision

LWU – Lackarbäck drinking water plant (utility)

MPN – Most probable number

MGCV – Mixed GAM Computation Vehicle

OR – Odds ratio

RR – Relative risk

UV – Ultraviolet

WLR – Weighted log reduction

Introduction

Background

Water is one of nature's most precious resources, and a prerequisite for life, but it is also an element for transmitting disease. An association between drinking water and gastrointestinal illness was probably first scientifically reported by John Snow about 150 years ago [1]. Snow linked an increased number of cholera deaths in London to a particular source of freshwater by mapping the location of the cases and their proximity to a specific well. His methodology is today often referred to as the origin of the science of modern epidemiology. Snow's theory – that water transmits disease – was however not acknowledged until Robert Koch in 1883 isolated the bacterium (Vibrio cholerae) and explained its mode of transmission [2]. Thereafter, an increasing knowledge of the risks with poor drinking water on public health developed, and protective actions of freshwater sources, water filtration through sand, and chlorine disinfection (which drastically decreased the exposure to waterborne pathogens) became common practice. The first continuous use of chlorine disinfection in public water probably occurred in Jersey City (New Jersey, U.S.) in 1908 [3]. However, waterborne diseases are still a major health concern worldwide, especially in low- and middle-income countries, where diarrhoeal diseases due to poor sanitation still continue to be one of the main causes of mortality among children [4]. This thesis, however, focuses on drinking water treatment in the industrialised world – specifically on Sweden's modern utilities and the possible risks of gastrointestinal illness.

Drinking water and acute gastrointestinal illness

Clean drinking water and good sanitation has become almost taken for granted in high-income countries. However, public drinking water still continues to be confirmed as a risk factor for acute gastrointestinal illness (AGI). For example, populations in Sweden have recently experienced the two largest drinking water-related outbreaks of AGI in modern European history; in the city of Östersund it was estimated that around 45% (27,000) of the inhabitants were infected with the protozoa Cryptosporidium during the autumn of 2010 [5], and the same microbial agent infected a comparable number of individuals in the city Skellefteå the following year [6]. In recent times, 59 outbreaks have been documented in Sweden for the period 1998-2011. The numbers are comparable in the neighbouring countries of Norway and Finland, resulting in an average of about one documented drinking water-related outbreak each month in Scandinavia [7]. Regarding other industrialised countries, the outbreak in Milwaukee (Wisconsin, U.S.) in 1993 was probably the most severe ever in the Western world, with over 400,000 infected people, and around 50 deaths [8,9]. In the Milwaukee outbreak, Cryptosporidium was also determined to be the infecting agent [10]. Agencies in North America have, in total, reported 833 outbreaks associated with drinking water in the United States between 1971 – 2006 [11], and 288 drinking water-caused outbreaks between the years 1971 – 2002 in Canada [12]. In England and Wales, 49 outbreaks of AGI were related to drinking water between 1992 – 2003 [13].

However, the reported outbreaks are probably just a fraction of the true scale of AGI due to poor drinking water quality in the industrialised world. For an outbreak to be recognised, it may require health authorities to notice an unusual localised increase of cases, which depends on the sensitivity of the monitoring systems in place. There is, however, no definition of how many cases are required, or what percentage increase must occur, for an event to be defined as an 'outbreak'. In theory, one single case could be defined as an outbreak, but sporadic cases of AGI are very difficult to link to drinking water. The treatment of AGI usually doesn't need prescription medicine or medical care; therefore, an outbreak of AGI may have to increase significantly before it is officially acknowledged. The number of observed outbreaks of AGI is, therefore, likely to be under-reported [14], and the extent to which pathogens are regularly present in our tap water is difficult to estimate, and is today largely unknown [15].
In contrast to outbreak situations, the endemic level refers to the usual level of ongoing persistent incidences, which, regarding AGI, also have been observed according to seasonality patterns [16,17]. The level of occurrence may also depend on the population or geographical area, and there is no generally accepted 'normal' level of incidence for AGI.

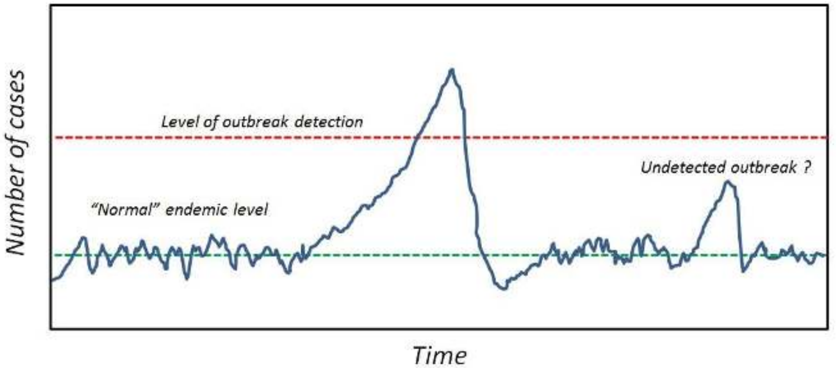

Figure 1. AGI cases over time. A sketch of sporadic fluctuations around an endemic level, showing a detected outbreak and an increase in cases that might be considered as 'non-normal' (if detected).

Besides the number of outbreaks of AGI that have been linked to public drinking water, there are also studies that have shown an association between different varying water quality parameters, such as water turbidity, and the incidence of AGI during periods when the endemic rate was considered normal [18-28]. In the literature there are also some studies testing for such associations that did not find any relation between drinking water quality and AGI [29,30]. Neither did Colford et al., who performed a randomised controlled intervention study in 2005 (Iowa, U.S.) [31]. However, the following year, Colford et al. also performed a review study on drinking water intervention trials conducted in industrialised countries, and cautiously estimated that between 4.3-11.7 million cases of AGI in the U.S. are attributable each year to public drinking water [32].

Waterborne pathogens and drinking water treatment

The microorganisms that can cause infections or create health problems in humans are referred to as pathogens. The pathogens that can potentially transmit AGI through drinking water are, in the broadest definition, viruses, bacteria and protozoans, and are often of faecal origin. They have different characteristics in their structure and the different symptoms of an infection are more or less dependent on the pathogen. Viruses are the smallest of these pathogen groups and are unable to move, have no metabolism and cannot reproduce on their own – they must first infect a living cell. Examples of viruses that can cause gastroenteritis are rotavirus and calicivirus (Caliciviridae); the latter is the virus family to which the various types of norovirus belong. AGI due to virus infections often causes vomiting and diarrhoea, is highly contagious and has a relatively short incubation period. AGI caused by bacteria can also have a short incubation period, and the condition that is often called “travellers’ diarrhoea” is often of bacterial cause [33]. Campylobacter is perhaps the most common agent for bacterial AGI in Sweden, mainly causing diarrhoea, but also fevers. Caliciviruses, followed by campylobacter, have been reported as the most common agents for waterborne outbreaks in Scandinavia [7]. Protozoans have, as mentioned above, caused large drinking water-related AGI outbreaks and can cause long-lasting symptoms [6]. In the industrialised world, it is primarily Giardia and Cryptosporidium that have been detected in treated drinking water. Common symptoms in infections caused by protozoans are diarrhoea and abdominal pain, but the incubation time is generally longer than that of AGI caused by viruses or bacteria [34].

Incubation times can also depend on the intake dose, and how large a dose it takes for an infection to develop varies between different pathogens. In general, viruses and protozoans can cause symptoms of illnesses after very small doses (1-100 particles), while the infectious dose for some bacteria can be very high [35].

The barriers used in the treatment of drinking water used in drinking water utilities either remove or kill pathogens. Chemical coagulation, flocculation and different types of membrane filtrations are barriers designed for the removal of pathogens, while disinfections in the form of ultraviolet (UV) light, ozone and chlorination are used to kill pathogens. Different types of barriers are more or less effective in reducing pathogens in general, and have different capacities in reducing specific pathogen groups [36,37]. For example, protozoans are very resistant to disinfection by chlorination, while ozone is usually very effective in eliminating bacteria. Drinking water plants often use multiple barriers in their treatment, and the number of barriers often depends on the expected microbial load in the incoming raw water. Surface water sources are generally considered to be more susceptible to microbial contamination than groundwater sources, and thus surface water plants often have a more advanced treatment technique.

Pathogens are either difficult to detect or impossible to quantify at low levels, and other parameters are often used to estimate their prevalence. A quick method of estimating the possible presence of pathogens is to measure the water's turbidity, which is a measure of the amount of suspended particulates, and can be interpreted as how transparent or cloudy the water is. Turbidity is a key test of water quality and is determined by optical instruments in real time (i.e., every second) how much light is scattered, broken and absorbed by the particles in the water. To more precisely assess the degree of faecal impact in the water, the amount of indicator bacteria is commonly analysed, which is faster and less expensive than trying to analyse the extent of the actual pathogens. The concentrations of different types of indicator bacteria, such as coliforms (or Escherichia coli (E. coli)), have been shown to correlate with concentrations of actual pathogens [38-41]. The levels of indicator bacteria are usually determined in a laboratory and therefore the information is delayed, which is why drinking water treatment plants often combine monitoring of turbidity and tests for indicator bacteria to estimate the water's quality.

There are three main explanations as to why consuming drinking water produced in modern drinking water plants can be a risk for AGI: (i) the barriers used in the treatment system do not have the potential to eliminate the pathogen concentrations that exist in the incoming raw water, (ii) temporal malfunctions in the treatment system cause insufficient water treatment, or (iii) intrusions of pathogens occur directly on the drinking water distribution system (after the drinking water plant) [42].

Precipitation increases risks of poor drinking water

According to the Swedish Climate and Vulnerability Assessment Report (2007), climate change will cause major challenges for the various infrastructure systems in Sweden [43]. In many parts of Sweden, precipitation is expected to increase during both summer and winter, and heavy rainfall events are expected to increase in frequency and intensity throughout the entire country [44]. Heavy rain and the risk of high flows may cause stress to systems that are generally not suited for anything other than ‘normal conditions’.

Heavy rainfall or episodes of drought can thus provide challenges for drinking water producers and have consequences for the drinking water supply. Extreme weather affects both surface water and groundwater sources, but distribution systems and wastewater treatment plants are also, to varying degrees not designed to cope with extreme weather. With excessive rainfall, runoff causes the water in many surface water sources to become more turbid with higher content of humus, but it may also contain more pathogens. Groundwater sources may also be affected by an increased amount of precipitation as the levels may be increased, which limits the filtration capacity and thus the ability to purify the water. Climate change is believed, therefore, to affect both groundwater and surface water sources, but surface water sources are particularly vulnerable to extreme weather events because surface water sources exhibit greater and quicker variations in quality than groundwater sources [45].

In Sweden, several storm water systems are combined with sewer water systems; thus, they are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. These systems transport the wastewater to a sewage treatment plant to be cleaned and then discharged into a recipient, such as a lake or a river. In events of heavy rainfall, or events leading to severe flooding (e.g., snowmelt), the water volume can exceed the capacity of the treatment plant and/or the sewer system. For this reason, combined sewer systems are designed to be able to overflow and discharge excess wastewater directly into nature. Separate systems are designed to distribute wastewater and storm water in separate pipes. However, these systems also have capacity limitations, and may be designed so that storm water is sent directly to a water body or a ditch without passing through a treatment plant. Besides these contamination sources, which could be regarded as point sources of contamination, runoff from the general environment can affect the microbial levels in water supplies used for drinking water production [46-48]. These diffuse sources for elevated risks for microbial contamination in raw water supplies are, theoretically, particularly relevant regarding runoff from farmland or agricultural areas [49].

Thus, precipitation that causes runoff, or events that cause untreated sewage water to enter directly into surface water sources, can greatly affect the microbiological level. Many drinking water treatment plants are equipped to clean the raw water only to a specific microbiological concentration and they can thus be vulnerable to such events that greatly affect the raw water quality. Drinking water treatment plants supplied with groundwater are often equipped with a less advanced treatment technique, and therefore could be even more sensitive to smaller variations in microbiological levels. For groundwater sources, the throughput of water can be slower and a microbiological impact may therefore be more persistent than, for example, a river.

In the literature, precipitation has also been associated with an increased risk of AGI in industrialised countries. The majority of the registered drinking water-related outbreaks in U.S. between 1948–1994 were linked to events of heavy rainfall [50]. Cumulated rainfall over five days was also associated with an elevated risk of outbreaks (1975–2001) in Canada [51], and cumulated rainfall over a week was associated with increased outbreaks in England and Wales throughout the last century (1910–1999) [52]. A limited number of studies has also linked rainfall to cases of AGI during non-outbreak situations; a time series study from Milwaukee saw an increase of AGI cases among children four days after rainfall [53], and in North West of England confirmed cases of cryptosporidium increased with weekly cumulative rainfall [54]. In Canada, rainfall, together with snowmelt, was associated with increased cases of AGI two and four weeks later [55]. In New Zealand, annual precipitation was related to AGI caused by protozoans [56]. There are, however, also studies that did not relate precipitation to increased AGI, particularly when studying AGI caused by Campylobacter [57-60].

To summarise, precipitation has been associated with outbreaks of AGI many times in the Western world, and a few studies have related rainfall to AGI also during episodes when the endemic level was considered ‘normal’. However, improved understanding about risks of AGI due to insufficient drinking water quality should be an important step to find ways to limit the burden on public health, especially when increasing events of extreme weather are predicted with climate change.

Objectives

Overall aim

The overall aim of this thesis is to determine whether cases of acute gastrointestinal illnesses can be associated with drinking water quality during periods when the drinking water is presumed to be clean. The first three studies focus on the population in Gothenburg (Sweden) and its main fresh water supply. The last study is a multi-city study and analyses if a more advanced drinking water treatment technique associates with a lower occurrence of AGI.

Specific aims

In Paper I, the aim was to determine how precipitation affects water quality in the river Göta älv, which is used to produce drinking water for the population of Gothenburg. Daily data of indicator bacteria and water turbidity were analysed, and the main motivation was to identify how the varying quality is distributed over time after precipitation events, and if seasonal modifications of precipitation effects are present.

In Paper II, the aim was to identify whether the incidence of AGI within the population in Gothenburg (receiving drinking water produced from the Göta älv) is associated with prior rainfall. As a measure of AGI, we used the daily number of calls to the national nurse advice line relating to vomiting, diarrhoeal or abdominal pain.

In Paper III, a similar hypothesis as in Paper II was tested, but with the number of visits to primary health centres diagnosed with gastrointestinal infections as the measure of AGI. Another aim was to evaluate the similarities and differences between the frequency of nurse advice calls and primary health care visits relating to AGI.

The aim in Paper IV was to analyse whether different drinking water treatment techniques were related to the occurrence of AGI by comparing the frequency of nurse advice calls in 20 Swedish cities. Seasonal patterns of AGI were evaluated in relation to different efficacies of pathogen elimination in the treatment processes.

Materials and Methods

This section describes details about the data, locations and the statistical methods used. However, a short summary would be; for all papers, time series data covering several years was obtained, and with time series regression investigate associations between outcome variables and possible explanatory variables.

Papers I – III

Study area

In papers I–III, the population of Gothenburg and its main water supply were studied. Five drinking water plants use the Göta älv as their raw water source, and the total distribution of drinking water is to approximately 700,000 people. Two of these drinking water plants, Alelyckan (AWU) and Lackarebäck (LWU), supply drinking water to the population of Gothenburg. LWU, however, takes its raw water from a lake system (Delsjörna), which under normal conditions is constantly supplied with river water through a 9 km-long tunnel that is designed to avoid dry-out and use the lakes as a raw water reservoir. The raw water intake at AWU takes approximately two cubic meters of water per second, with about half of the volume being for drinking water production – the other half being pumped to the reservoir. This raw water intake can, though, be closed when information suggests that water from the tunnel/lakes is a preferable choice for drinking water production. Closure of the raw water intake is for example determined by high-turbidity data, analyses of indicator bacteria concentrations, information about heavy rainfall upstream or releases of untreated sewage water. The Göta älv is a recipient of the effluent from eight wastewater treatment plants upstream of the raw water intake to AWU. The distribution systems of the two drinking water plants (AWU and LWU) are interconnected, but the northern part of the city receives drinking water from AWU alone and the southern part from LWU alone, and thus the central parts of the city receive a blend of water from the two plants. In total, the two drinking water plants supply drinking water to half a million people.
Considering the northern latitude of the study area, the climate is very mild. February is usually the coldest month, with a daily mean temperature a few degrees Celsius below zero, but the river usually doesn't freeze during winter. Precipitation is fairly constant, but events of heavy rainfall are more likely during the second half of the year.

Data – precipitation, raw water quality and AGI

Precipitation data from three meteorological stations along the Göta älv were obtained from the Swedish Meteorological and Hydrological Institute. The stations where daily measurements had been recorded were located in Gothenburg, the village of Alvhem and in Vänersborg, located approximately 35 km and 90 km upstream of the AWU's raw water intake (Figure 2).

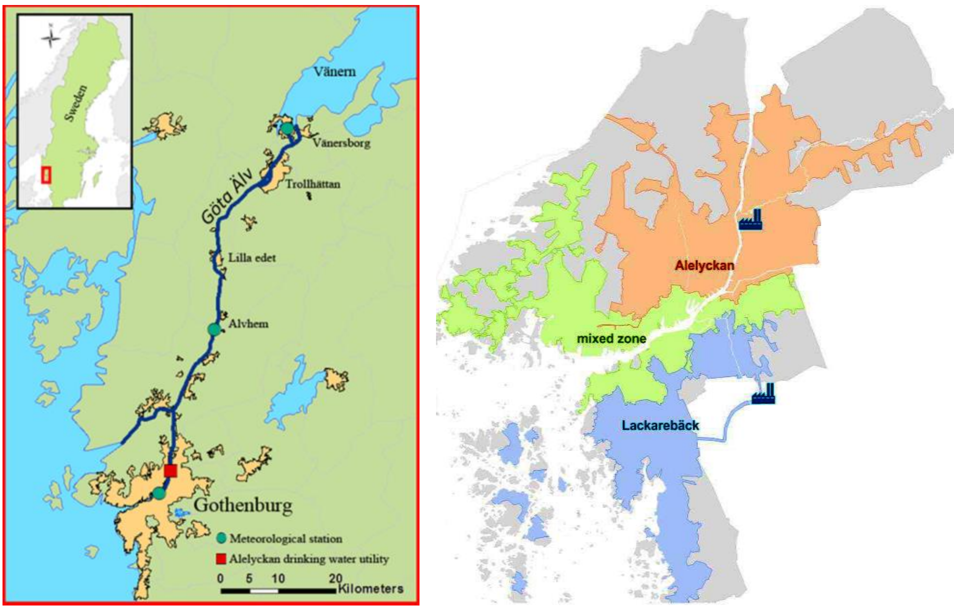

Figure 2. Map. Left: a map of the Göta älv and Gothenburg. Right: Gothenburg's drinking water plants distribution zones. Red and blue areas are distributed water from AWU (Alelyckan) and LWU (Lackarbäck) exclusively at least 95 % of the time.

In Paper I, daily mean values of turbidity, along with samples of three types of indicator bacteria, were used as outcomes. AWU continuously measures turbidity near of raw water intake, and daily mean values between 2004 – 2010 were provided to us by Gothenburg's water department (Department of Sustainable Waste and Water). Turbidity was expressed in units of FNU (Formazine Nephelometric Units, a relative unit to the reference solution Formazine). Over the same time period, Gothenburg's water department provided laboratory results for the level of total coliforms, E. coli (reported in units of Most Probable Number (MPN) per 100 ml) and Clostridium concentrations (reported in Colony Forming Unit (CFU) per 100 ml). These indicator bacteria had been measured three times a week, but sometimes more often if high values could be expected to be present, for example if upstream sewer system overflows have been reported.

In Sweden, a relatively new database that can be used to study morbidity is the nurse advice line (formally named Swedish National Healthcare Guide 1177). In 2003, the project started creating a public health service with a national phone number (1177) intended for triage of non-emergency concerns [61]. The service is available 24 hours a day, and nurses give treatment advice or recommend visits to clinics for medical examination. The subjects of the calls are recorded in predefined classifications.

For Paper II, all telephone calls to the nurse advice line from individuals with a registered address in Gothenburg were provided (anonymised) for about a four year period (November 2007–December 2011). Hydraulic modelling, performed by Gothenburg's water department, made it possible for calls to be isolated for Alelyckan's distribution area with 95 % accuracy, which means that these areas receive drinking water only from AWU at least 95 % of the time (Figure 2). All calls to the nurse advice line during the time period were provided, but only recordings of AGI related symptoms (vomiting and nausea, diarrhoea or abdominal pain (three classifications)) were specified. Thus, we could compare nurse advice line calls relating to AGI (AGI calls) with other nurse advice line calls (non-AGI calls).

For Paper III, the number of daily visits to primary health care centres regarding gastrointestinal diagnoses (diagnose codes A00-A09 according to International Classification of Disease, 10th revision (ICD-10)) (AGI visits) was obtained for the period 2007– 2012 (6 years). The data was anonymised and categorised with an area code. This, however, meant that cases' home addresses could, with 75 % accuracy, be located to the AWU distribution area (75 % of the time the cases received drinking water only from AWU). The remaining area was defined as LWU area. The majority of cases (95 %) were diagnosed to A09 (*infectious gastroenteritis and colitis, unspecified*). When analysing potential relations with precipitation, some of the ICD codes were excluded, for example cholera and salmonella, since their presence in drinking water in Sweden are very unlikely. The data of AGI visits and AGI calls are shown in figure 3.

Paper IV

Data –Drinking water treatment and AGI

In the last study of this thesis (Paper IV), all calls to the nurse advice line from November 2007 to February 2014 were obtained from 20 municipalities in Sweden. AGI calls (symptoms of vomiting, diarrhoea or abdominal pain) were separated out from the rest. Calls from citizens with postcodes not belonging to the municipalities' locality were excluded, to

ensure that only citizens with public drinking water at their home address to be included (i.e. excluding private wells). Data from Gothenburg were also included in this study, with calls being separated by AWU and LWU distribution areas, resulting in a total of 21 study sites.
For each study site, the raw water source was identified (groundwater or surface water) along with the water treatment technique the plant was using during this time period. The theoretical efficacy of pathogen elimination in the treatment was calculated for viruses, bacteria and protozoa for each drinking water plant. These efficacies are expressed as log reductions, where one unit of log reduction corresponds to a ten-fold (90%) reduction of microorganisms. Thus, three different log reductions were derived from each plant and, thereafter, a weighted mean value was calculated based on the relative rate of which viruses, bacteria, and protozoa cause AGI in the general population. Viruses are reported to be the most common cause of AGI and, thus, barriers with good efficacy in eliminating viruses were given a higher weight. The weights were based on estimates from community cases of AGI in a study from the Netherlands [62], and pretty similar numbers have been reported in the U.S., with around 80 % of all cases of AGI being of viral cause [63].

Further, we hypothesised that population size, age distribution and climatic conditions could possibly be related to the occurrence of AGI. Total population, along with the number of children (<15 years) and elderly (>65 years) for each study site were provided by Statistics Sweden (SCB), and categorisations data from The Swedish Horticultural Society were used to define climate zones. The study sites were collapsed into three different climate zones.

Statistical methods

In all the included studies (papers I-IV), generalized additive regression models (GAM) [64] (or generalized linear models) were fitted to investigate the associations between exposure variables and an outcome. GAM's is a combination of the parametric *generalized linear models* and the non-parametric *additive models* [65,66].

Control for long-term trends

In time series regression models applied to study environmental health risks GAM´s has been primarily been used for adjusting for unmeasured confounding over time, and to fit non-linear exposure-response relationships. With time-dependent data, in order to draw conclusions about possible short-term associations between an exposure variable and an outcome variable, it is essential to adjust for long-term trends to avoid possible confounding by unmeasured time varying variables. A hypothetical example of time-confounding could be (if seasonal patterns are not adjusted for in regression models) that a higher incidence of AGI during winter, combined with low levels of seasonal precipitation, would result in an interpretation that low rainfall is a risk factor for AGI, while its actually non-rainfall factors causing higher rates in winter. Seasonal patterns could be adjusted for in many ways. Seasonality could, for example, be addressed by incorporating weather variables, such as temperature and humidity, if seasonal changes are believed to be fully explained by meteorological conditions. If it could be assumed that the outcome follows very regular seasonal patterns, a factor for *calendar month,* or more smoothly by using Fourier terms, could be incorporated in the model [67]. However, regarding data on the number of AGI cases (or other data relating to infectious diseases), trends could be due to a number of different causes, and data may not only be a reflection of the presence of infectious agents in the population, and thereby the number of infected people. Trends could be a result of changes in the host susceptibility or immunity in the population [68]. The populations' inclination to seek medical contact, or the registrations of cases by health authorities, could also be the cause of trends in the data. By letting a spline function adjust for *time* (i.e., the consecutive order of the data) we control for all possible reasons for slowly varying time patterns, and the short-term fluctuations are left to be tested for association with specific factors of interest. Thin-plate regression splines were used to adjust for long-term trends [69]. Sensibility analyses with respect to the long-term component were, however, always performed by studying changes of effect estimates when altering the splines' smoothness. For papers I-III one spline function in each model was included to adjust for long-term trends and seasonal patterns simultaneously. Thus, seasonal patterns were not assumed to be similar between years. For Paper IV, the seasonal pattern was of interest to compare between cities and, therefore, cyclic spline functions were included in the models together with penalized thin-plate regression splines to adjust for yearly trends within each city.

Time distributed effects

Associations between weather variability and an outcome should not be assumed to be linear, and possible effects should be considered to be delayed in time. In papers I-III, the delayed effects of the exposure variable on the outcome is evaluated with distributed lag non-linear models (DLNM) [70]. DLNM is a modelling framework used with the statistical software R, and simultaneously allows associations to be modelled smoothly along dimensions of exposure and a predefined lag period. A purpose of DLNM is to *constrain* the effects over the lag space, compared to an unconstrained approach where the effect in each lag is assumed to be independent. DLNM can be regarded as a bi-dimensional exposure function that is included in the regression model, and non-linear associations with the outcome can be designed in many ways, for example with splines or polynomial functions, step functions or 'hockey stick' relationships. DLNM is parameter-efficient and has today being used for a wide range of research topics where the effect of an exposure can be assumed to be delayed in time [71-74]. Exposure of precipitation and flooding on different outcomes – for example, cases of cholera – has also been modelled using DLNM [75-77]. DLNM doesn't consider, however, the effects of consecutive exposure on the outcome. Therefore, to analyse the effects of consecutive events of precipitation, an alternative precipitation variable was employed: consecutive days of wet or dry weather, where a wet day was defined as a day with any precipitation at all (> 0 mm). So, the time-distributed effects of precipitation due to daily events (mm/24-h) were analysed with DLNM, and the effects of prolonged wet or dry weather were analysed with a variable counting consecutive wet or dry days (which was primarily treated as a factor variable and truncated at end points). These two precipitation variables were included both separately and simultaneously in the models to study sensitivity of estimates that were possibly attributable to collinearity.

Summary of the regression models and covariates

For Paper I, the outcomes (turbidity and the three types of indicator bacteria) were assumed to be log-normal distributed (the outcomes were log-transformed with the natural logarithm). The spline controlling for long-term trends was relaxed to 7 degrees of freedom (df) per year (10 df/year modelling turbidity). The precipitation DLNM function was limited to model relationships with the outcome 15 days after a rainfall event, with natural cubic spline associations in both exposure space and lag space. Unconstrained distributed lag models were also fitted to compare and validate the two methods. Short-term effects of temperature and changes in upstream snow depth was analysed using DLNM designs. An indicator variable for *day of week* was included in models to study eventual weekday patterns. Seasonal effect modifications of precipitation were evaluated by stepwise analysing segments of 90 days within seasons.

The regression models analysing effects of precipitation on AGI in Paper II and Paper III had many similarities. The daily count of AGI cases was assumed to be Poisson-distributed. Besides adjusting for long-term trends with thin-plate splines (using 7 df/ year), indicator variables for day of week, national holidays and days in connection to national holidays were adjusted

for. Again, the precipitation effects were primarily evaluated with DLNM functions using natural cubic splines for both dimensions, considering possible delayed associations up to three weeks.
Short-term and long-term similarities between the two AGI data sets were analysed in different models. Possible delayed effects on AGI visits due to a varying number of AGI calls were analysed in a two-step modelling approach; the first step adjusted for long-term variations, and weekday patterns, of AGI calls. The residuals from the first step were tested for associations with AGI visits over a lag period of seven days, using an unconstrained distributed lag model. Long-term similarities (or differences) were assessed by considering AGI visits as 'successes' from the total counts of the two AGI data sets (a binomial distribution), and effects of *day of week*, *month of year* and *year* was studied. The effect of precipitation (lag 0) on AGI visits relative to AGI calls was also studied.

For all DLNM models, a 'best' design of the DLNM function (for example, with respect to the flexibility in lag space or the degree of non-linearity in exposure space) was evaluated according to Akaike's information criterion scores (AIC) [78].

For Paper IV (the multi-city study), the daily number of AGI-related nurse advice line calls was analysed in relation to all other concerns. For each study site, the daily number of AGI calls was considered as 'successes' from the total number of nurse advice calls, which resulted in an outcome of binomial distributed data. The purpose of studying proportions was to adjust for different frequency of using the nurse advice line between cities. Thus, we did not assume that the total number of nurse advice calls depended solely on the population size within cities – there could simply be different inclinations between populations to use this service.
The weighted log reductions (WLR) were considered as a linear continuous exposure variable or, to account for possible non-linear associations with AGI, WLR was categorised into three levels (low, medium or high). Additionally, as groundwater and surface waters cannot be assumed to have a similar microbiological level, the interaction effects between WLR and the type of raw water was a primary consideration. Seasonal patterns of AGI were studied in relation to WLR, using cyclic spline functions and, alternatively, by studying the interaction effects between WLR and *quarter of year*. Different types of AGI outcome were analysed (children, adults, vomiting, diarrhoea and abdominal pain). A complete sensitivity analysis of how the covariates (population size, age distribution and climate zone) might have influenced the results was performed by stepwise excluding or including or the covariates to the model. AIC were used in decisions of whether to include covariates in models.

The statistical software R, together with MGCV and DLNM packages, was used throughout all analyses [70,79,80].

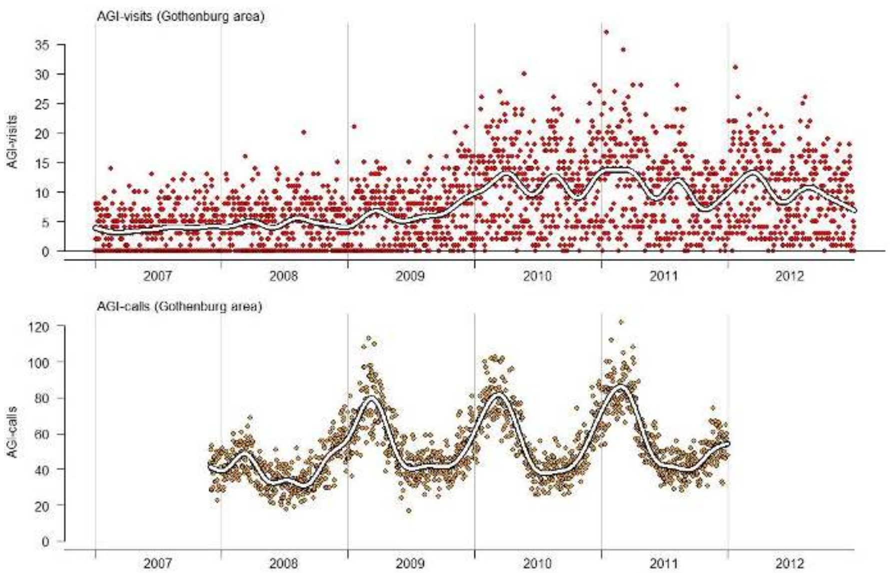

Figure 3. AGI time series data from Gothenburg. Top: daily numbers of visits to primary health care centres diagnosed with gastrointestinal infections (ICD-10: A00-A09). Bottom: daily numbers of nurse advice line calls registered with symptoms of vomiting, diarrhoea, or abdominal pain. Smooth curves are generated by spline functions, using 7 degrees of freedom per year.

Results

Paper I - precipitation and raw water quality

Strong effects of rainfall on raw water quality were detected, regardless of which meteorological station was used for precipitation data in the analysis. Precipitation data from the different stations were highly correlated, but it was determined that the precipitation registered in Alvhem – located about 3.5 miles upstream the raw water intake – generally had the best predictive ability for short-term variations of both indicator bacteria and turbidity. Decreased raw water quality after rainfall was concluded over several days after rainfall events, but generally most affected two days later. Two days after an event with at least 15 mm of rainfall (around the 95th percentile for the area), turbidity was estimated to have increased by 30%, and concentrations of E. coli were estimated to have increased three-fold. Exponentially increasing concentrations of indicator bacteria with increased rainfall were observed, while turbidity was declined after extreme rain events (Figure 4). So precipitation, compared to turbidity, could be a better risk validation factor for high concentrations of indicator bacteria during events of heavy rainfall. This was also verified by comparing regression models of indicator bacteria with turbidity as an explanatory variable, with models using the amount of rainfall two days earlier as a predictor. Strong relations between cumulative days of precipitation and elevated levels of indicator bacteria and turbidity were also observed: a four-fold increase of E. coli concentrations was observed after at least a week of wet weather, compared to seven days of dry weather. The analyses also concluded that rainfall affected the raw water quality regardless of the season, but that the relationship between rainfall and turbidity weakened in the summer.

In summary, rainfall as a cumulative or single event profoundly affects raw water quality, where heavy rainfall multiplies the concentration of indicator bacteria many times. The time delay of the rain effect generally peaks two days later, and the effects should be expected all year round. Having established this clear relation, there was also a motivation to study the possible relation between precipitation and variations in AGI within the population receiving drinking water produced from this river water.

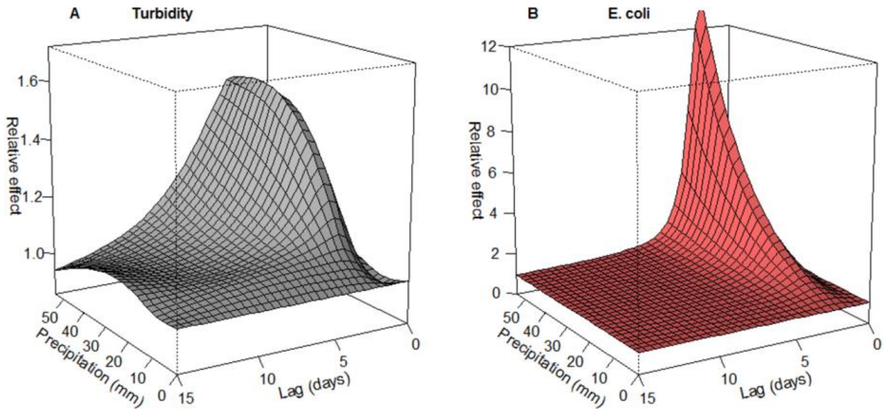

Figure 4. Precipitation effects on raw water quality. Short-term effects of the amount of daily precipitation on raw water turbidity and E. coli concentrations over the following 15 days.

Paper II and III - precipitation and gastrointestinal illness

Nurse advice line calls regarding AGI symptoms from individuals with home addresses within the AWU distribution area were found to be associated with precipitation. An increasing frequency of calls was observed in direct relation to precipitation on the same day, and there was also an increase with a delay around 5-6 days. It was estimated that a precipitation event of 30 mm/24-hour period related with an increase in AGI-related calls of about 13% 5-6 days later (Table 1). An increase in AGI calls was also observed after cumulative days of wet weather, where about 8% more AGI-related calls were observed after periods of at least five consecutive rainy days, compared with dry periods of more than 5 days. No such relationship was found in analyses regarding non-AGI-related calls.

Table 1. Estimated association between heavy rainfall and AGI-related calls to the nurse advice line. Changes in percent (95% confidence interval).

Precipitation (mm/24-h)	lag 0	lag 4	lag 5	lag 6	lag 7
25	11 (5-16)	2 (-0-5)	3 (0-6)	3 (0-6)	2 (-0-4)
30	15 (7-23)	4 (0-9)	7 (2-12)	6 (2-10)	4 (1-7)
35	19 (8-32)	7 (1-13)	11 (4-19)	10 (4-16)	7 (2-12)
40	24 (8-42)	10 (2-19)	17 (7-27)	15 (6-24)	10 (3-17)
45	29 (8-54)	13 (2-25)	22 (9-37)	20 (8-32)	13 (4-23)

Analysing the daily number of AGI diagnoses in health clinics, there was also an association with rainfall the same day, but in a reversed relation compared to nurse advice calls. Thus, a decrease was observed during days of heavy rainfall. Similarly as with AGI calls, an increased number of visits in relation to extended periods of rainy weather was observed. A 25% increase in AGI visits was estimated after cumulative rainy days for a week or more, compared to days counting one or two consecutive dry or wet weather (the most common weather scenario). The increased number of AGI visits after consecutive wet days was only concluded as being significant for the population consuming drinking water produced mostly of water from the river. In contrast to AGI calls, no delayed increase in AGI visits after an event of heavy rainfall was identified, and only weak relations were observed between AGI visits and AGI calls. AGI calls reflected a very clear seasonal pattern, with clear winter peaks. Data on AGI visits did not reflect these winter peaks to a similar extent, showing an almost equal increase in August as in February.

Figure 5 illustrates the estimated effect of a heavy daily precipitation event on the concentration of E. coli in river water, and the number of AGI-related calls for the following three weeks (combined results from Paper I and Paper II).

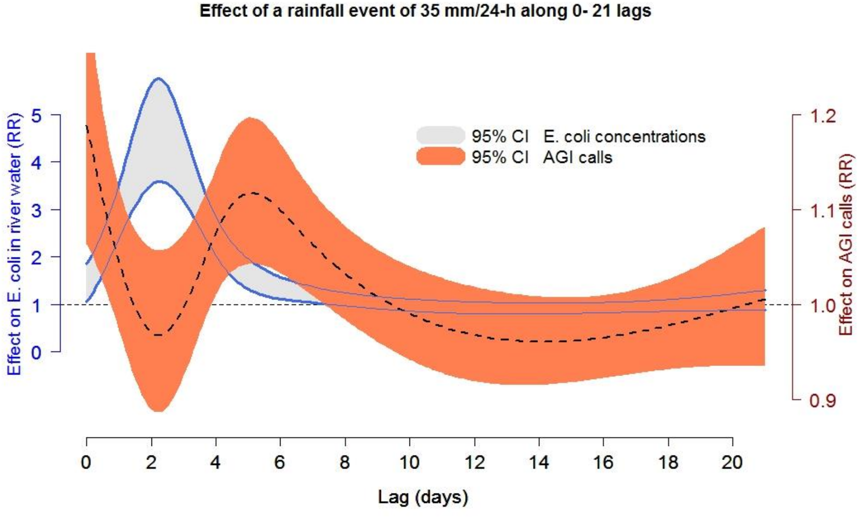

Figure 5. Precipitation effect on raw water quality and AGI. Short-term effects (relative risks) of the amount of a heavy rainfall event (35 mm/24-h) on E. coli concentrations in river water and the number of nurse advice line calls relating to AGI over the following 21 days**.**

Paper IV - pathogen elimination and gastrointestinal illness

There were more than half a million AGI-related nurse advice line calls (AGI calls) and nearly four million calls relating to other issues (non-AGI calls) included in the study. The weighted log reductions in the drinking water plants varied between 0 - 6.4 units in the 21 study sites. The occurrence of AGI, in terms of the proportion of AGI calls, was found to be associated with the treatment technique in the municipal drinking water plant for both groundwater and surface water study sites. In general, for every unit increase in weighted log reduction in the water treatment, there was a decrease of 4% in the proportion of AGI calls (odds ratio (OR) = 0.96). Populations receiving drinking water produced in plants exceeding four WLRs were particularly found to have the smallest probability that an AGI call had been made. The populations with a WLR >4 were only found in surface water municipalities. It was also within surface water study sites that the largest difference was found. An OR of 0.87 was estimated when comparing surface water study sites with a WLR below 4 units with those exceeding 4 WLR units. The protective effect of effective pathogen elimination (in terms of WLR) in the drinking water plants increased even more when studying children separately, or when studying vomiting as a separate outcome. The effect of high WLR was also found to be particularly relevant in the winter season. Figure 6 shows the seasonal patterns of the probability that a nurse advice call is recorded as AGI for different levels of WLR.

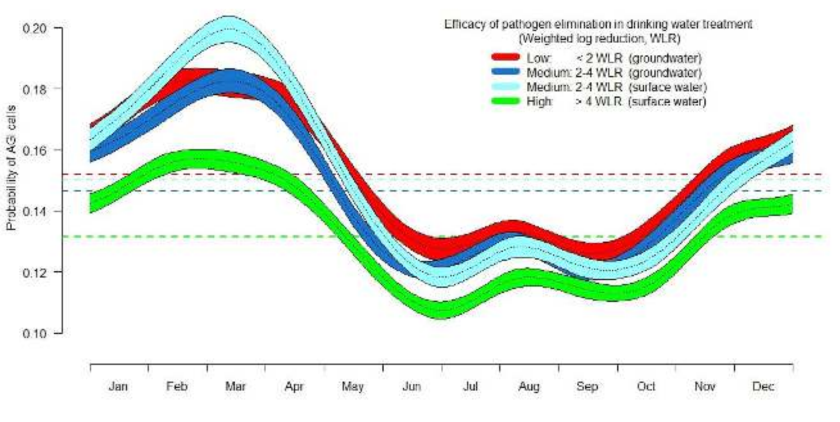

Figure 6. Seasonal patterns of AGI in relation to drinking water treatment. Estimated probability of that a nurse advice call is classified as vomiting, diarrheal, or abdominal pain within groundwater or surface water cities with different weighted pathogen log reduction (WLR) in the cities drinking water plant. Horizontal lines represent an average within each WLR group.

Discussion

Findings

Associations between municipal drinking water without known temporal disturbances and gastrointestinal illnesses have not been shown previously in Swedish populations. In particular, the first study exposed a solid relation between prior precipitation and variations in raw water quality to be used for drinking water production and thereafter (papers II-III) associations between heavy rainfall and an increased incidence of gastrointestinal illness. Additionally, in Paper IV, an association was found between higher pathogen elimination in drinking water and a lower occurrence of AGI, which, to the best of our knowledge, has not yet been reported elsewhere.

The findings of the studies on the Gothenburg population which are primarily consistent with the hypothesis that transmission of pathogens occurs through drinking water is the delay in the increase in the number of calls to the nurse advice line is around 5 days after heavy rainfall. With the results from Paper I in mind, where the analyses show that raw water quality in general was most affected two days after precipitation, and that the drinking water production time (including distribution) is generally within a few days, the peak effect on AGI calls occurring about 5 days later points to a gastrointestinal illness with an onset of 1-2 days. Viruses, such as norovirus, have this short incubation period, but also some of the bacteria causing AGI have been recognised as having a relatively fast onset. Gastroenteritis caused by waterborne protozoans, e.g., Giardia and Cryptosporidium, commonly has a longer incubation time [34]. That both viruses and protozoa can cause infections with only very low intake doses, added to the fact that viruses are more resistant to disinfection than bacteria and are more difficult to measure and detect at small quantities, suggest that the increases in AGI calls after heavy rainfalls was most likely due to viral agents. The results from Paper IV also suggest that especially viral AGI could be reduced with a high efficacy of pathogen elimination in the drinking water treatment. This conclusion is based on that the protective effect of high pathogen elimination was particularly clear during winter seasons when viruses are the dominant cause of AGI [16], and as calls to the nurse advice line concerning vomiting were estimated as having the largest protective effect as viral-caused AGI typically includes vomiting. Also, when only using the viral log reductions (not the WLR) in the treatment processes as a predictor of the occurrence of AGI, a protective effect with a high elimination capacity was shown, this was not observed when using only the bacterial log reduction as an exposure variable.

It was further determined that consecutive days of precipitation also clearly affected the raw water quality, together with an increase both in AGI-related calls to the nurse advice line and the number of visits to primary health care centres with a diagnosis of AGI. These observed increases of cases may have been due to insufficient drinking water quality, but it cannot be ruled out that there may have been other underlying reasons that contributed to this increases; for example, during periods of wet weather, it can safely be assumed that people spend more time indoors, or that public transport is used to a greater extent. Such behaviour patterns should increase the risk of infections being transmitted between people. However, there are other studies that have also shown a relationship between cumulative rainfall and an increased risk of drinking water-related AGI. Cumulative rainfall over five days has been associated with an increased risk of waterborne disease outbreaks in both Canada and the United States [50,51]. Cumulative rainfall over seven days has been shown to coincide with increases in the number of cases caused by Cryptosporidium in England [54]. What also indicates that the findings of increased AGI associated with rainy periods could be due to drinking water is that the associations were only observed within the population receiving drinking water from the Göta älv. The Göta älv is more directly affected by rainfall events than the lake system, as it has neighbouring farmlands and receives effluent from several wastewater treatment plants [81].

It should be noted that the epidemiological studies on the population receiving drinking water from AWU take no account of the fact that the raw water intake to AWU may have been closed after rainfall events, and the raw water could have been taken instead from the tunnel leading to the reservoir. Previous studies by Åström et al. on the effect of this action have indicated that this is an important method to ensure high quality of the raw water [82], although this water supply is otherwise filled with water from the river. We did, however, try to verify whether the intake closures after heavy rainfall affected the number of AGI calls by only analysing the episodes when the intake was open during the following days after heavy rainfall events. Those analyses indeed showed a larger effect of heavy rainfall on the delayed increase of calls, but an increase of calls was also observed when analysing events when the intake was closed for some time during the day after the heavy rainfall. However, the amount of data was too limited to draw any significant conclusions about how changes to the raw water intake had any consequences for public health (these data were obtained later and the analyses were not reported in Paper II). It should also be clarified that the effect of precipitation reported is based on averages from several years of data, and single events may not follow expected patterns. For example, some of the highest E. coli concentrations were observed the same day (lag 0) as the heaviest rainfall events; therefore a closure of the raw water intake the following day would have been too late to avoid high levels of E. coli in the water to be used for drinking water production.

A challenge that arises in epidemiological studies of AGI is that the illness can be of short duration and the individuals affected by it rarely seek medical care. This means that hospital data, or information from health care centres, only report a fraction of the actual number of cases. Studies have been done by the Swedish National Food Agency on how many people would seek a consultation with a nurse by phone (by dialling the nurse advice line) during episodes of AGI symptoms, and 9% reported that it was likely [83]. Although this number is probably even lower in reality (unpublished data from the same agency suggest that a more accurate number is around 4.5%), it points to the advantage of studying phone contacts when the focus is AGI, at least compared with data regarding visits to primary health care centres. Comparing these different data sources for AGI (calls and visits) revealed an approximately five times higher number of calls than clinic visits (Paper III). Other studies have tried to tackle this underreporting problem by, for example, studying variations in over-the-counter pharmacy sales of gastric medications [20], or by preforming panel studies [18,23]. Recently, it has been shown that telephone-triage data (the nurse advice line) are preferable for early detection of increases in cases of gastroenteritis compared to other data sources, for example purchases of anti-diarrheal medicine [84]. What also indicates that telephone data may be preferable when studying AGI compared to other health registers, is the large difference in seasonal patterns between AGI calls and AGI visits, where the winter peaks were more pronounced regarding calls (Paper III). Thus, data from the nurse advice line are likely to reflect more cases of viral gastroenteritis, which makes it easier to link variations among viral cases to possible causalities. One explanation as to why clinical data (AGI visits) do not reflect the winter peaks to a similar extent could be that viral gastroenteritis caused by Norwalk-like agents is often of short duration (a couple of days) [34], and the recommendation from health authorities when viral gastroenteritis is suspected is to wait a while for a recovery at home, to reduce the spread of infection.

In Paper IV, the large amount of data made it possible to study seasonal patterns in detail, and some components to seasonal variations were observed. Besides the large winter peaks, which mostly were created by children, the increase in the summer – peaking in early August – was observed only to be created by adults with symptoms of diarrhoea (Figure 7). An August peak was also observed in visits to primary health care centres and, if it was of bacterial cause, it could be due to August being the period of the year where bacterial growth in food is optimal. The increase could also have been created by people returning home from vacations abroad seeking advice for problems with diarrhoea. Bacteria account for 85% of the cases of 'travellers' diarrhoea', which peak in the summer season for the European population [33].

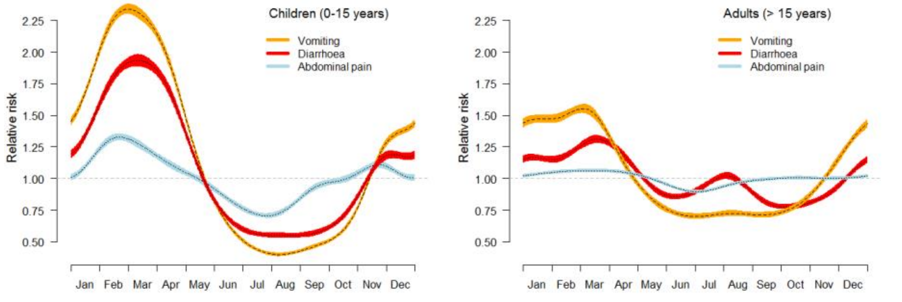

Figure 7. Seasonal patterns of AGI. Seasonal patterns in terms of relative risks of nurse advice calls issuing concerns registered as vomiting, diarrhoea or abdominal pain, separated by children and adults.

In Paper II, an increase in AGI calls was also observed in direct relation to rainfall. This increase is difficult to attach to a possible drinking water-related cause. It would be too quick for rainfall-driven concentrations of pathogens to pass through the drinking water plant and be present in drinking water for any possible agent, especially when considering incubation times. Several other explanations were offered, including the idea that rainfall may have caused intrusions of pathogens directly into the distribution network. This phenomenon has been discussed elsewhere as a potential risk for AGI, especially if drinking water pipes run in close proximity to sewage pipes [85,86]. However, in Paper III, conversely to the direct increase in calls, a decrease in AGI visits to primary health care centres was observed, which led to the hypothesis that there was a change in behaviour due to the prevailing weather conditions. During rainy weather, it seems that medical contacts are moved from clinical visits to contact by phone. This change in behaviour should be taken into account in future epidemiological studies. A reduction in accident and emergency (A&E) visits in relation to wet weather has also been reported previously [87]. There were only small short-term effects observed when comparing AGI calls and AGI visits, which could also be explained by the nurse advice line always being open, 24 hours per day, while primary health care centres have limited opening hours at evenings and weekends. During these times, patients may be referred to A&E instead, or asked to wait until Monday for a medical examination. This also suggests that the data from nurse advice calls is preferable to data from the number of primary health care visits, when the analysis is aimed at studying the potential delayed effects of non-severe health outcomes.

The results regarding the population of Gothenburg and its raw water supply should not be directly generalised to other surface water sources and populations, because the delayed effects of rainfall cannot be assumed to be similar at other sites. Therefore, studies of how rainfall increases the risk of contaminated raw water in other water sources should be performed separately. It is important that drinking water providers understand the relationship between rainfall and water quality, in order to better realise and validate risks. Climate change projections show that annual rainfall will increase, with more incidents of heavy rain in large parts of Sweden [44]. It can, therefore, be assumed that in future the Göta älv will encounter more days per year with insufficient raw water quality, compared to the study period. Although AWU has the option to close the raw water intake, this creates problems because the volume of water in the reservoir cannot support the population in Gothenburg over longer time periods; the Göta älv is the only currently available source of raw water in the quantities required. The results from the studies have highlighted the fact that remedial action on pathogen contamination in the river is warranted, as are upgrades to drinking water treatment techniques with additional barriers, to limit the burden on public health resources and be more prepared for the future climate. Paper IV provides further evidence of the same, namely that the situation in Gothenburg is not unique, and that more advanced barriers are warranted at many drinking water plants to limit the burden of AGI in the population.

Actions taken

Today, the drinking water plants in Gothenburg have invested in an additional barrier for their treatment processes; LWU has been equipped with ultrafiltration during 2015, and AWU is now equipped with UV disinfection, but will also be equipped with ultrafiltration in the near future. The results of these studies have led to that rainfall, considered as a risk factor of poor raw water quality, has gained more weight in the determination of whether to close the raw water intake or not. In addition, a new precipitation monitoring station is planned near the village of Alvhem, to more quickly get information on rainfall events. The municipal water company in Gothenburg has become a leading force in the operational use of processed statistics from the nurse advice line; for example, the frequency of AGI calls in municipalities upstream Gothenburg are continuously monitored and an elevated number of AGI calls is considered a risk factor for elevated pathogen concentrations in the raw water. Investigation of possible additional raw water supplies from other lakes is also under consideration. All these actions can be an important step in ensuring drinking water quality and mitigating the effects of heavy rainfall on public health – also in an uncertain future climate.

Future research

This research has showed that analysing data from the nurse advice line is an effective way of measuring fluctuations in AGI. The data used in Paper IV demonstrate that the usefulness of barriers in the treatment of drinking water in terms of public health can be evaluated. The analyses in Paper IV should, however, be viewed as only a first cross-sectional analysis of this large dataset, because it has great potential for several additional analyses. For example, the analysis could be sharpened by taking into account data of raw water parameters for each study site, for example levels of indicator bacteria. Such data could be used to incorporate an additional factor for evaluating a barrier's efficacy. Precipitation effects or other possible water quality data could also be taken into consideration, and possible short-term associations with the incidence of AGI could be studied in a meta-analysis over several study sites. Other possibilities could be to study the effect of upgrades at the water treatment plants on the occurrence of AGI, because several drinking water plants have recently been upgraded, or are about to be upgraded. Thus, with time, there will be sufficient data on AGI rates after upgrades to analyse the effects on public health of these interventions.

Main conclusions

The results suggest it is possible to reduce the occurrence of endemic gastroenteritis with a more advanced treatment process for drinking water. The delay between heavy rainfall events, decreased raw water quality, and increased frequency of nurse advice calls relating to gastroenteritis, is consistent with viral incubation times. A viral transmission was also proposed when comparing different cities as a more advanced water treatment process appears most protective during seasons where viruses are acknowledged as the main cause of AGI illnesses. Our research suggests that upgrades of drinking water treatment techniques, especially aiming to better eliminate viruses, is warranted.

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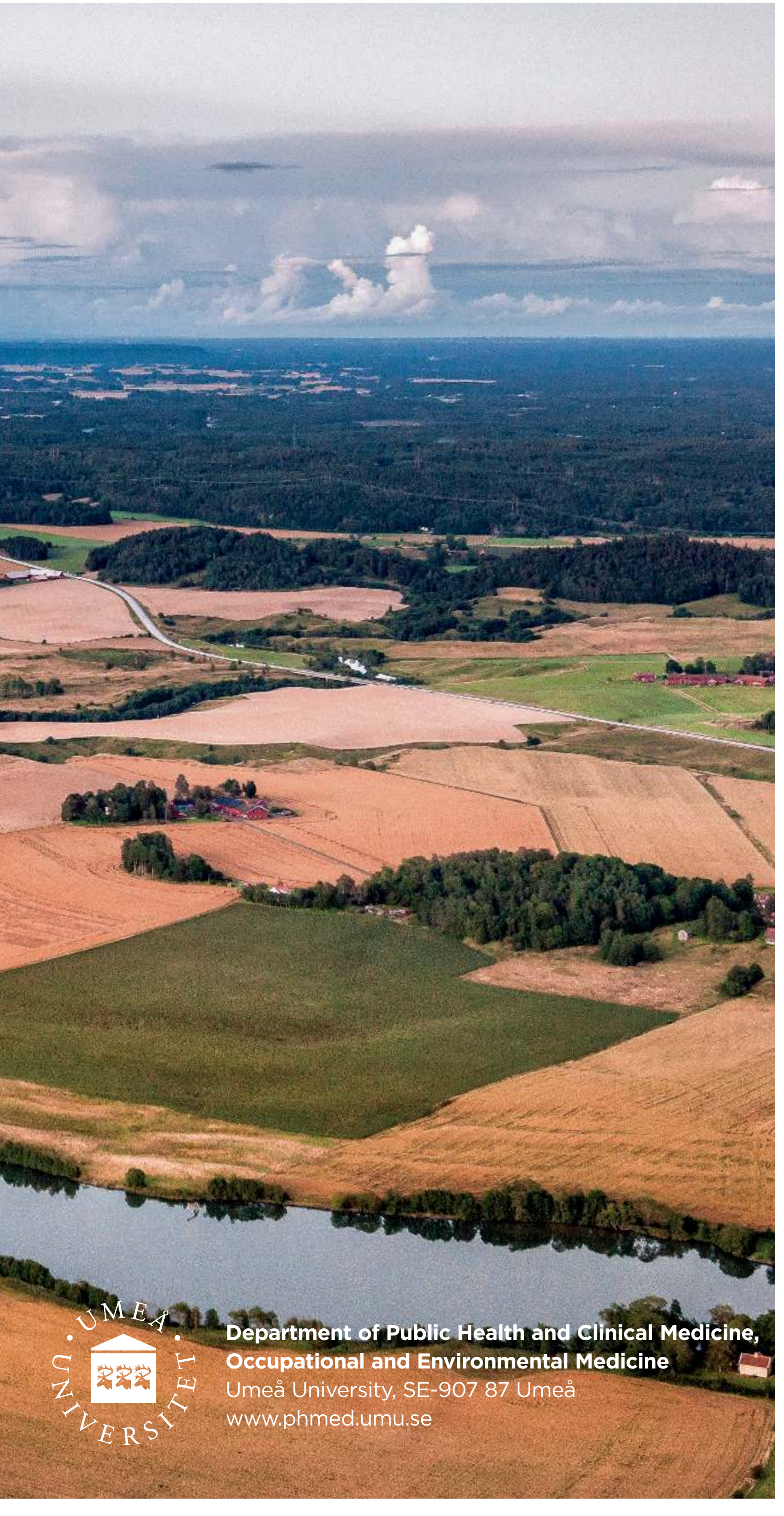

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