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Gastrointestinal illness linked to incidents in drinking water distribution networks in Sweden

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ABSTRACT

During recent years, knowledge gaps on drinking water-related gastrointestinal illness have been identified, especially for non-epidemic cases. Pathogen contamination of drinking water during distribution has been suggested to contribute to these cases, but the risk factors are not yet fully understood.

During 2014–2015, we conducted an epidemiological study in five municipalities in Sweden, to assess whether incidents in the drinking water distribution system influence the risk of gastrointestinal illness. Telephone interviews were conducted in the affected areas and in reference areas 7–14 days after a reported incident. Symptoms of gastrointestinal illness occurring during the period were documented for each household member.

The results showed a significantly elevated risk of vomiting and acute gastrointestinal illness (AGI) in the affected areas, compared to the reference areas ($OR_{vom.} = 2.0$, 95% CI: 1.2–3.3; $OR_{AGI} = 1.9$, 95% CI: 1.2–3.0). Certain conditions, or risk factors, during the incidents, such as sewage and drinking water pipelines at the same level in the trench, were associated with an elevated risk of AGI and vomiting. Safety measures taken during repair work, like flushing, were also associated with an elevated risk of AGI and vomiting.

These results show that incidents in the drinking water distribution network contribute to endemic gastrointestinal illness, especially AGI and vomiting, and that external pathogen contamination of the drinking water is a likely cause of these cases of gastrointestinal illness. The results also indicate that safety measures used today may not be sufficient for eliminating the risk of gastrointestinal illness.

1. Introduction

Large drinking water-related outbreaks in the Nordic countries in recent years (Jakopanec et al., 2008; Laine et al., 2011; Widerstrom et al., 2014) have increased awareness of risks associated with drinking water. In particular, the risk factors that may contribute to endemic gastrointestinal illness are poorly understood. This is alarming, since these cases are believed to account for the majority of all drinking water-related infections (Westrell et al., 2003; Lambertini et al., 2012). Previous studies indicate that 0–35% of all cases of endemic gastrointestinal illness may be drinking water-related (Payment et al., 1991, 1997; Hellard et al., 2001), but the cause of these infections is often unknown. Contamination of drinking water during distribution has been suggested as one pathway, and certain studies indicate that up to 37% of the total drinking water-related cases of gastrointestinal illness may originate from contamination during drinking water distribution (Nygard et al., 2004, 2007; Hunter et al., 2005; Tinker et al., 2009; Shortridge and Guikema, 2014; Murphy et al., 2015).

High water pressure, together with physical integrity of the distribution system, makes it possible to deliver drinking water to consumers. Physical integrity is the barrier that prevents the water from leaking out and external contamination from entering the distribution system (NRC, 2007). Insufficient physical integrity is either due to man-made mistakes (cross-connection, etc.) or

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normal wear resulting in e.g. leaking joints or cracks (Kirmeyer et al., 2001). In the event of a water pressure drop, even a small crack can lead to potentially pathogen-contaminated water entering the system (Kirmeyer et al., 2001; Besner et al., 2011), as pathogens can be present in soil and water surrounding drinking water pipelines (Karim et al., 2003; Besner et al., 2008). In epidemiological studies, the loss of water pressure and inadequate physical integrity of the distribution system have been shown to result in an increased risk of gastrointestinal illness (Ercumen et al., 2014), suggesting that the pathogen contamination originates from an external source. During recent years, knowledge on potential internal sources of pathogens within the drinking water distribution system have also come to light, as studies have shown that pathogens may persist within the biofilm and may be present in quantities exceeding the infectious dose (Storey and Ashbolt, 2003).

In Sweden, distribution systems have been identified as the source of contamination in a large proportion of drinking water-related outbreaks (Lindberg and Lindqvist, 2005). For endemic gastrointestinal illness related to the distribution system in Sweden, no significant increase in risk has yet been identified, although indications of an increased risk during pipe breaks have been reported (Malm et al., 2013). The purpose of the present study was to investigate these indications further. This was done by carrying out an observational study, using a study design different from that used in Malm et al.. In the present study we collected more detailed information on the incidents on the distribution network, detailed data on symptoms of gastrointestinal illness, as well as potential confounders.

2. Methods

2.1. General description of the study design

An epidemiological study was conducted during 2014–2015, in which the aim was to assess whether incidents (temporary changes in the hydraulic pressure and physical integrity) in the drinking water distribution system affect the risk of gastrointestinal illness. When an incident occurred in one of the study areas, information on the incident was documented and telephone interviews were conducted among households in the affected area and in a reference area.

2.2. Study areas and population

Five municipal water utilities were selected to participate in the study (Table 1). The inclusion criteria for the water utilities were: 1) the municipality should be average to large-sized by Swedish standards (15,000–100,000 inhabitants), 2) the distribution system should only be looped in a minor part of the network, avoiding unpredictable mixing of water in the network, and 3) the drinking water production should be centralized to one or two water works. Prior to the study, a list of addresses of households connected to the municipal distribution network was obtained from the five municipalities and information on the study was advertised in local newspapers. The study was approved by the Regional Ethics Review Board in Uppsala, Sweden.

2.3. Questionnaires to water utilities

The water utilities were encouraged to report as many incidents as possible in which at least 20 households were affected. The questionnaire contained questions about: time of the incident, type of incident, affected area, safety measures, suggestion of reference area, duration of low pressure and valve closure (in hours), water levels in the pipe trench, location of sewage water pipelines in relation to drinking water pipelines, and whether information about the incident had been communicated to the public. For each incident that was followed up, a new reference area was selected by the receiver of the questionnaire at the National Food Agency. The reference area had to be geographically close to the affected area (but not affected by the incident) and cover a similar number of households. To ensure that the reference area was representative, statistics from Statistics Sweden on postcode level for 2010 on property composition, demographics, and education level in the relevant areas were used. When a reference area was suggested by the municipality, this area was primarily evaluated as a potential reference area according to the criteria.

2.4. Questionnaire to households

Addresses for the affected and reference areas were tagged with a randomly chosen identification key before being sent to an independent survey company. Contact information for households at the selected addresses was obtained from a national consumer register. Computer-assisted telephone interviews were carried out by professional interviewers, with as many households as possible in both areas in parallel, but with 100 interviews (randomly chosen) as a limit from each area, and only one interview per household. Interviews were held 7–14 days after the reported incident. Information collected during the interviews included: age of all household members (0–1, 2–5, 6–10, 11–17 years and adults); self-reported tap water consumption (for the respondent and children up to 5 years old only); any episodes of gastrointestinal illness within the household during the last 7 days and, in the event of illness, self-reported symptoms for household members with illness (vomiting, diarrhoea, stomach ache, fever, duration of illness); chronic intestinal illness among household members; travel abroad (28 days) by household members; pets or domestic animals; any risk professions within the household (day-care, kindergarten, school, youth recreation centre, medical care, retirement home, or sewage-related work); observed changes in

Table 1
Description of the five study areas.

Municipal area	Municipal population (Statistics Sweden, 2010)	Raw water	Terrain	Chlorine in production	Incidents included	Households interviews	
						Affected	Reference
1	50000	Groundwater	hilly	no	13	403	298
2	71000	Groundwater	flat	yes	20	385	339
3a	89000	Surface water	hilly	yes	6	173	170
3b[a]	800	Groundwater	hilly	yes	1	52	66
4[b]	30000	Surface water	flat	yes	15	278	283
5a	35000	Surface water	flat	yes	11	339	354
5b[a]	600	Groundwater	hilly	no	3	57	42

[a] Independent distribution system for settlement with 600–800 inhabitants.
[b] Area receives drinking water from a facility that produces water for 400,000 inhabitants.

water pressure or water quality; and information received by the municipality about an incident. To reduce recall bias, all questions regarding gastrointestinal illness were asked at an early stage of the interviews. The Swedish language was used exclusively throughout the study.

2.5. Statistical analysis

Statistical analysis was performed using R version 3.2.3 (R Core Team, 2015, R Foundation for Statistical Computing, Vienna, Austria). Odds ratios were calculated in both univariate and multivariate models with mixed logistic linear models using lme4 package (Bates et al., 2015). The incidence was estimated using epi-conf in epiR (Stevenson et al., 2015). In all regression analyses, household, incident and municipal area were included as random factors (in order to take cluster variation into account), while conditions, safety measures and risk factors, during the incidents and affected/reference areas were included as fixed factors. Univariate analysis and multivariate analyses were performed to compare risk between the affected areas and the reference areas. Univariate analyses were also performed for affected areas and the reference areas separately, analysing exposure or non-exposure within these two areas. The univariate analyses were performed on individual level for each household member. In the multivariate analyses, only the respondents were included and point estimates of self-reported daily consumption for each respondent (adults only) were used. The hypothesis of the study was to test if there is an elevated risk of gastrointestinal illness due to incidents on the drinking water distribution system. All analyses to compare circumstances, risk factors and safety measures are therefore explanatory to the primary analyses.

Gastrointestinal illness with undefined symptoms (GI), vomiting, and acute gastrointestinal illness (AGI; vomiting and/or at least three loose stools during a 24-h period) were used as symptom definitions in all analyses. Information about duration of symptoms and number of diarrhoea episodes was only collected for 62% of the incidents studied, as it was added into the questionnaire after the start of the study and was not compulsory to answer. All analyses using AGI as the endpoint are therefore based on fewer data than analysis of other symptoms and therefore data on vomiting are also presented. The difference between affected areas and the reference areas with regard to descriptive household information and descriptive attack rates for age groups and symptoms was analysed using *t*-test (numerical values) or chi square test (categorical values). As the study areas were distributed over a large part of Sweden, climate differences were overcome by using the meteorological definition of seasons: daily mean temperature less than 0 °C for more than five consecutive days for winter, daily mean temperature between 0.1 and 9.9 °C for more than seven consecutive days for start of spring, daily mean temperature more than 10 °C for more than five consecutive days for summer, and daily mean temperature between 0.1 and 9.9 °C for more than five consecutive days for start of fall.

3. Results

3.1. Incidents included in the study

A total of 69 incidents were included in the study. These were either pipe breaks or pre-scheduled maintenance work, all resulting in short or long term pressure drops (due to leakage or shutdown of water). The median duration for reported pressure drops was 4 h (min <1 h and max 26 h). In all, 70% of the incidents occurred in the urban parts of the municipalities (defined as coherent urban area with at least 200 inhabitants), while the remaining incidents occurred in rural parts of the distribution network. Some 74% of the incidents affected 20–100 households, while the rest affected more than 100 households. In 22% of the incidents, the water level in the trench was high, for four of the incidents even covering the drinking water pipeline. In 4% of the incidents there was visible leakage from sewage pipes and in 16% of the incidents there were sewage water pipelines on the same level as water pipelines in the trench. Most incidents occurred during summer (35%) and spring (29%). Risk factors during the incidents were evenly distributed between seasons. The most commonly used safety measures were hydrant flushing (86%), followed by sampling of the water (35%), and providing a temporary water supply (30%). In five of the incidents, no safety measures were taken. No chlorination was used in any of the incidents and no recommendation on boiling drinking water was issued during any of the incidents.

3.2. Response rate

The average response rate for the telephone interviews was 30% (8–72%) in the affected areas and 31% (7–67%) in the reference areas. The most common (ca. 80%) reason for non-participation was refusal to participate, not answering the phone, or not having time to participate. Only 1% of the respondents were unable to participate due to language difficulties (interviews were carried out in Swedish) or other communication difficulties. A total of 3238 households were interviewed, resulting in a total of 7431 individuals being included in the analyses. On average, 40% of the interviews were completed during the first day of interviews, and within four days 80% of the interviews had been completed. The affected areas and the reference areas were similar with regard to sex, age, number of household members, travel habits, chronic gastrointestinal illness (due to illness, pregnancy, etc.), and having a risk profession in the household (Table 2). The exception was children aged 0–1 year, which constituted a significantly higher proportion in the affected areas (Table 2). Of all households surveyed in the affected areas, 40% reported changes in water quality or pressure. The corresponding percentage for reference areas was 9% (Table 2). About 33% of the households in the affected area responded to having received information of the incident from the drinking water supplier and the corresponding percentage was 5% in the reference area (Table 2).

3.3. Study population and gastrointestinal illness

The attack rate of GI was 3.0% in the affected areas and 2.8% in the reference areas (Table 3). Although there was no significant difference in the incidence of GI between the areas, there was a significantly elevated risk of vomiting ($p = 0.04$) in the affected areas (attack rate 1.3%) in comparison to the reference areas (attack rate 0.8%). Although based on fewer individuals, there was also a significant difference for AGI ($p = 0.02$), with an attack rate of 1.6% in the affected areas and 1.0% in reference areas. The attack rate of GI, vomiting, and AGI was highest in the age groups 0–1 year and 2–5 years in both the reference areas and the affected areas (Table 4). The highest attributable fraction of AGI between affected areas and the reference areas was seen for 2–5 year-olds (Table 4).

Each additional self-reported glass of tap water consumed among the respondents in affected areas and reference areas, resulted in a significantly elevated risk of vomiting and AGI ($OR_{vom.} = 1.1$, 95% CI: 1.0–1.2; $OR_{AGI} = 1.1$, 95% CI: 1.0–1.2), when drinking water consumption, children, and exposure/non-exposure were included as co-variables in the multivariate analyses. When the affected area and the reference areas were analysed separately, an elevated risk was seen in both areas with an OR of 1.1, although

Table 2
Description of households interviewed.

	Affected	Reference	P-value
	n (%)	n (%)	
Sex, respondents			
Male	753 (46%)	761 (48%)	0.3
Female	867 (54%)	816 (51%)	
Age, individuals			
0–1 years	57 (1.5%)	35 (1.0%)	0.03
2–5 years	193 (5.1%)	145 (4.0%)	0.05
6–10 years	274 (7.2%)	289 (8.0%)	0.5
11–17 years	348 (9.2%)	324 (8.9%)	0.6
Adult	2929 (77%)	2829 (78%)	0.7
Reoccurring abdominal discomfort	18 (1.0%)	16 (0.4%)	0.9
Travel abroad by household member (last 28 days)	365 (11%)	335 (11%)	0.7
Risk profession in household[a]	396 (24%)	346 (22%)	0.1
Experienced changes during incident			
Quality	77 (5%)	44 (3%)	0.04
Pressure	143 (9%)	54 (3%)	<0.01
Quality & pressure	20 (1%)	2 (0.1%)	<0.01
Water shutdown	378 (23%)	16 (1%)	<0.01
Other	30 (2%)	17 (1%)	0.07
Received information from water supplier	535 (33%)	83 (5%)	<0.01

[a] Daycare, kindergarten, school, youth recreation center, medical care, retirement homes or sewage-related work.

Table 3
Attack rate and duration of self-defined symptoms of gastrointestinal illness in the reference areas and the affected areas.

	Reference (n = 3622)	Affected (n = 3801)	
	n (%)	n (%)	P-value
GI	100 (2.8%)	114 (3.0%)	0.6
Vomiting	28 (0.8%)	49 (1.3%)	0.04
Diarrhea	54 (1.5%)	61 (1.6%)	0.8
Nausea	33 (0.9%)	38 (1.0%)	0.8
Stomach pain	53 (1.5%)	45 (1.2%)	0.3
Fever	12 (0.3%)	15 (0.4%)	0.8
AGI	35 (1.0%)	61 (1.6%)	0.02
	Reference (n = 1574)	Affected (n = 1639)	
	n (mean ± 95% CI)	n (mean ± 95% CI)	P-value
GI			
Days of duration	46 (2.4 ± 1.7–3.1)	51 (1.9 ± 1.4–2.3)	0.2
Vomiting			
Days of duration	19 (1.0 ± 0.6–1.4)	18 (0.6 ± 0.3–0.9)	0.1
Diarrhea			
Days of duration	21 (2.4 ± 1.4–3.5)	20 (2.0 ± 1.2–2.9)	0.5
Number of episodes	22 (2.8 ± 1.3–4.3)	20 (3.2 ± 1.9–4.4)	0.7

GI: gastrointestinal illness (all symptoms).
AGI: acute gastrointestinal illness (vomiting and/or three episodes of diarrhea during 24 h).

Table 4
Attack rate of self-defined symptoms of gastrointestinal illness in the reference areas and the affected areas by age group.

	Total	GI	Vomiting	Diarrhea	AGI
	n	n (%)	n (%)	n (%)	n (%)
Affected					
Adult	2929	69 (2.4%)	18 (0.6%)	41 (1.4%)	26 (0.9%)
11–17 years	348	12 (3.4%)	9 (2.6%)	5 (1.4%)	10 (2.9%)
6–10 years	274	6 (2.2%)	1 (0.4%)	5 (1.8%)	1 (0.4%)
2–5 years	193	25 (13%)	19 (9.8%)	10 (5.2%)	22 (11%)
0–1 years	57	2 (3.5%)	2 (3.5%)	0 (0%)	2 (3.5%)
Reference					
Adult	2829	78 (2.8%)	17 (0.6%)	42 (1.5%)	22 (0.8%)
11–17 years	324	7 (2.2%)	3 (0.9%)	4 (1.2%)	3 (0.9%)
6–10 years	289	7 (2.4%)	2 (0.7%)	4 (1.4%)	2 (0.7%)
2–5 years	145	6 (4.1%)	5 (3.4%)	2 (1.4%)	6 (4.1%)
0–1 years	35	2 (5.7%)	1 (2.9%)	2 (5.7%)	2 (5.7%)
P-value		<0.001	<0.001	0.007	<0.001

GI: gastrointestinal illness (all symptoms).
AGI: acute gastrointestinal illness (vomiting and/or three episodes of diarrhea during a 24-h period).

non-significant in the reference area.

A significantly elevated risk of GI was seen in both the affected areas and reference areas when the household had experienced changes in water quality ($OR_{GI} = 2.6$, 95% CI: 1.0–6.8 and $OR_{GI} = 5.6$ 95% CI: 2.1–15, respectively). For changes in water pressure, a significantly elevated risk was seen for GI and AGI in the affected areas ($OR_{GI} = 2.6$, 95% CI: 1.2–5.6; $OR_{AGI} = 3.1$, 95% CI: 1.2–8.3) and for gastrointestinal illness, regardless of the symptom definition, in the reference areas ($OR_{GI} = 3.6$, 95% CI: 1.2–11; $OR_{vom.} = 10$, 95% CI: 2.6–38; $OR_{AGI} = 6.4$, 95% CI: 1.8–23). There was a non-significant reduction in the risk of GI, vomiting and AGI in the affected area when having received information from the drinking water supplier, compared to not having received information (self-reported) and the opposite was seen in the reference area for vomiting and AGI (Table 5). Inclusion or exclusion of households who reports/experience no water, changes in quality/pressure, or reports having received information will not affect the primary hypothesis, as the analyses where these households are excluded results in an OR similar to the total dataset (Table 5, Table 6).

3.4. *Circumstances, risk factors and safety measures during incidents*

The results show an elevated risk of vomiting and AGI in the area affected by an incident, compared to the reference area ($OR_{vom.} = 2.0$, 95% CI: 1.2–3.3; $OR_{AGI} = 1.9$, 95% CI:1.2–3.0) (Table 6). For most explanatory circumstances in the study areas, there was an elevated risk of gastrointestinal illness in the affected areas compared with the reference areas, especially for vomiting and AGI (Table 6). Although they were sometimes significant, the elevated risks could not be explained by the presence or absence of certain circumstances in the study areas during the incidents in the affected areas (Table 6). The only exception was chlorination in drinking water production, for which analyses in the affected areas indicated a significantly elevated risk of vomiting and AGI in areas with chlorinated drinking water compared with affected areas where chlorination was not used ($OR_{vom.} = 10$, 95% CI: 1.2–83.3;

Table 5
Odds ratio (OR) of gastrointestinal illness in households that perceived recent changes or received information relative to households that did not.

Included in analyses	Water quality	Water pressure	No water	Information[a]
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Affected areas (n = 3803)				
Changes/info.: yes vs. no (ref)				
GI	2.6 (1.0–6.8)	2.6 (1.2–5.6)	1.2 (0.6–2.4)	0.6 (0.3–1.2)
Vomiting	2.8 (0.7–11)	1.7 (0.5–5.9)	1.1 (0.4–2.9)	0.7 (0.3–1.8)
AGI	2.3 (0.6–2.6)	3.1 (1.2–8.3)	1.2 (0.5–3.0)	0.7 (0.3–1.5)
Reference areas (n = 3628)				
Changes/info.: yes vs. no (ref)				
GI	5.6 (2.1–15)	3.6 (1.2–11)	2.9 (0.4–23)	0.5 (0.1–3.4)
Vomiting	3.9 (0.5–34)	10 (2.6–38)	-	1.6 (0.2–13)
AGI	4.9 (1.0–24)	6.4 (1.8–23)	-	1.2 (0.2–8.6)
Affected vs reference	(n = 324)	(n = 467)	(n = 955)	(n = 1394)
Changes/info.: yes				
GI	0.8 (0.2–2.7)	0.8 (0.3–2.1)	0.7 (0.1–6.9)	1.2 (0.3–4.2)
Vomiting	0.4 (0.02–9.8)	0.5 (0.1–2.7)	-	1.6 (0.2–14)
AGI	1.2 (0.1–11)	0.7 (0.2–2.6)	-	1.8 (0.2–15)
Affected vs reference	(n = 7107)	(n = 6964)	(n = 6476)	(n = 6037)
Changes/info.: no				
GI	1.1 (0.8–1.5)	1.2 (0.9–1.6)	1.1 (0.8–1.5)	1.2 (0.9–1.7)
Vomiting	2.0 (1.2–3.3)	2.2 (1.3–3.8)	1.8 (1.0–3.0)	2.3 (1.3–3.9)
AGI	1.9 (1.2–3.0)	2.1 (1.3–3.3)	1.7 (1.1–2.8)	2.2 (1.3–3.5)

GI: gastrointestinal illness (all symptoms).
AGI: acute gastrointestinal illness (vomiting and/or three episodes of diarrhea during 24 h).
[a] Received information from water supplier (self-reported).

Table 6
Odds ratio (OR) of gastrointestinal illness in the affected areas compared to the reference areas, limited to different circumstances, risk factors and safety measures during the incident.

Included in analyses	Incidents	Persons	GI	Vomiting	AGI
			OR (95% CI)	OR (95% CI)	OR (95% CI)
Affected vs. reference area*	69	7431	1.1 (0.9–1.5)	2.0 (1.2–3.3)	1.9 (1.2–3.0)
Study area					
Raw water: Surface water	32	3761	1.4 (1.0–2.1)	3.2 (1.5–6.8)	3.2 (1.6–6.3)
Raw water: Groundwater	37	3670	0.9 (0.6–1.3)	1.2 (0.6–2.5)	1.1 (0.6–2.1)
Production: no chlor.	16	1856	0.6 (0.4–1.1)	0.5 (0.2–1.3)	0.6 (0.3–1.4)
Production: chlor.	53	5575	1.3 (1.0–1.9)	2.9 (1.6–5.3)	2.7 (1.5–4.6)
Terrain: hilly	46	3075	0.8 (0.5–1.3)	1.2 (0.5–2.8)	1.1 (0.6–2.3)
Terrain: flat	23	4356	1.4 (1.0–2.0)	2.6 (1.4–5.0)	2.6 (1.4–4.7)
Season					
Winter	12	1409	0.6 (0.4–1.2)	0.9 (0.3–2.7)	0.8 (0.3–2.3)
Spring	20	2357	0.8 (0.5–1.5)	3.0 (1.1–8.5)	2.8 (1.1–7.1)
Summer	24	3078	2.4 (1.5–4.0)	7.3 (2.2–24)	4.1 (1.8–9.4)
Fall	13	587	0.7 (0.3–1.5)	0.3 (0.1–1.2)	0.6 (0.2–1.6)
Incidents					
Urban area (locality)	48	3730	1.3 (1.9–1.9)	1.8 (1.0–3.2)	1.8 (1.1–3.1)
Rural area	21	3701	0.9 (0.6–1.4)	2.8 (1.0–7.7)	2.1 (0.9–5.0)
>100 households	21	4708	1.1 (0.8–1.5)	2.2 (1.0–4.8)	1.7 (0.9–3.1)
≤100 households	48	2723	1.3 (0.8–2.0)	1.9 (1.0–3.7)	2.2 (1.2–4.1)
No water pressure >6 h	12	1685	1.2 (0.6–2.2)	2.0 (0.6–6.7)	1.7 (0.6–5.0)
Water pressure intact [a]	7	4200	1.1 (0.8–1.6)	2.2 (1.2–4.2)	2.4 (1.3–4.3)
Pipelines on same level [b]	11	1640	2.0 (1.0–4.1)	12 (1.5–91)	13 (1.6–99)
No sewage pipelines [c]	8	567	1.3 (0.3–4.8)	1.1 (0.1–18)	0.7 (0.1–4.0)
High water in trench	15	1050	0.9 (0.4–1.9)	1.8 (0.6–5.7)	1.6 (0.6–4.7)
Leaking sewage [d]	3	355	2.1 (0.2–24)	–	1.1 (0.07–17)
Safety Measures					
No safety measures	5	775	0.8 (0.4–1.7)	2.1 (0.4–11)	2.1 (0.4–11)
Hydrant flushing	54	5117	1.4 (1.0–2.9)	3.2 (1.7–6.1)	2.9 (1.6–5.1)
Temporary water	21	2260	1.7 (1.0–2.9)	6.8 (2.0–24)	6.3 (2.1–19)
Sampling of water	12	2940	1.1 (0.7–1.7)	1.6 (0.8–3.3)	1.4 (0.7–2.8)

GI: gastrointestinal illness (all symptoms).
AGI: acute gastrointestinal illness (vomiting and/or three episodes of diarrhea during a 24-h period).
* Primary hypothesis, all other analyses are to be considered explanatory.
[a] Intact water pressure, until shutdown for work on the distribution system.
[b] Sewage water pipelines on the same level as drinking water pipelines in trench.
[c] No sewage water pipelines in the trench.
[d] Leaking sewage water pipeline in the trench.

$OR_{AGI} = 6.3$, 95% CI:1.3–29.4) (Table 7). The opposite was observed in analyses of the reference areas, in which there was a significantly elevated risk of gastrointestinal illness, regardless of symptoms, when the drinking water was not chlorinated compared to chlorinated water (OR_{GI} = 3.2, 95% CI: 1.7–5.9; $OR_{vom.}$ = 3.5, 95% CI: 1.2–10; OR_{AGI} = 3.7, 95% CI: 1.5–9.1) (Table 8). In municipalities where chlorination was used during production of drinking water, there was a non-significant trend for a reduced risk of GI and AGI in the affected areas compared with the reference areas (OR_{GI} = 0.6, 95% CI: 0.4–1.1; OR_{AGI} = 0.6, 95% CI: 0.3–1.4) (Table 6).

There was an elevated risk of gastrointestinal illness, regardless of symptoms, in the affected areas compared with the reference areas during summer (OR_{GI} = 2.4, 95% CI: 1.5–4.0; $OR_{vom.}$ = 7.3, 95% CI: 2.2–24; OR_{AGI} = 4.1, 95% CI: 1.8–9.4) (Table 6). This was also observed within the affected areas only, although not significant (Table 7). When analysing only the reference areas, there was tendency for an elevated risk of gastrointestinal illness during fall compared with other seasons (Table 8).

Generally, the presence of most risk factors during incidents was associated with an elevated risk (Table 6). Sewage water pipelines on the same level as drinking water pipelines in the trench resulted in a significantly elevated risk of vomiting and AGI when the affected areas were compared with the reference areas ($OR_{vom.}$ = 12, 95% CI: 1.5–91; OR_{AGI} = 13, 95% CI: 1.3–99) (Table 6). Leaking sewage water pipelines in the trench did not significantly affect the risk of gastrointestinal illness, but this risk factor was only present during three incidents (Table 6). The shutdown of water for more than 6 h (highest quartile) did not indicate a significantly elevated risk when compared to shutdown for less than 6 h (OR_{GI} = 1.2, 95% CI: 0.6–2.2; OR_{AGI} = 1.7, 95% CI: 0.6–5.0) (Table 6).

Flushing as a safety measure was associated with a significantly elevated risk of vomiting and AGI in the affected areas compared with the reference areas ($OR_{vom.}$ = 3.2, 95% CI: 1.7–6.1; OR_{AGI} = 2.9, 95% CI: 1.6–5.1) (Table 5). In the analyses of the affected areas only, the use of flushing was also associated with an elevated risk compared with no flushing ($OR_{vom.}$ = 6.5, 95% CI: 1.3–32; OR_{AGI} = 5.3, 95% CI: 1.4–20) (Table 6). Presence of a temporary water supply during an incident was also associated with a significantly elevated risk of vomiting and AGI in the affected areas compared with the reference areas ($OR_{vom.}$ = 6.8, 95% CI: 2.0–24; OR_{AGI} = 6.3, 95% CI: 2.1–19) (Table 6). However, this effect was not significant when looking at only the affected areas (OR_{GI} = 1.4, 95% CI: 0.7–2.9; OR_{AGI} = 1.8, 95% CI: 0.5–5.8) (Table 7).

4. Discussion

4.1. Study population and gastrointestinal illness

As reported in previous studies (Nygard et al., 2007; Ercumen et al., 2014), the results from this study show that incidents in the drinking water distribution network may increase the risk of vomiting and AGI among connected households. The relative risk increase for AGI was 38%, which was similar to the increase reported by Nygard et al. (2007), although the attack rate was several times lower in the present study. The total incidence of AGI in the reference areas in the present study is in line with recently reported incidents of AGI in Sweden (Hansdotter et al., 2015).

In the present study, the incidence of gastrointestinal illness was highest among children aged 0–5 years. The incidence for this age group was 1.2 episodes of AGI per person and year in the reference areas (recall 7 days). A yearly incidence of 0.84 episodes of AGI per person and year for children aged 0–4 years has previously been reported in Sweden (Hansdotter et al., 2015). The difference in incidence is likely due to differences in the data collection method, as the previous Swedish study used a recall time of one year (Hansdotter et al., 2015). In the present study, the age group 2–5 year olds had the highest attributable fraction of AGI for the affected areas and the reference areas. This may be explained by the fact that small children are more susceptible to pathogens compared with adults (Nwachuku and Gerba, 2004; Alexeeff and Marty, 2007). Children also generally consume more water per unit body weight compared with adults and previous studies have shown that there is

Table 7
Odds ratio (OR) of gastrointestinal illness relative to circumstances, risk factors and safety measures within the affected areas during an incident (n = 3803).

Included in analyses	GI	Vomiting	AGI
	OR (95% CI)	OR (95% CI)	OR (95% CI)
Study area			
Raw water: Surface vs. groundwater (ref)	1.8 (0.9–3.6)	2.0 (0.6–6.9)	2.0 (0.7–5.8)
Production: chlor vs. no chlor. (ref)	2.3 (0.9–6.0)	10.0 (1.2–83.3)	6.3 (1.3–29.4)
Terrain: flat vs. hilly terrain (ref)	1.7 (0.8–3.7)	2.5 (0.7–8.4)	2.2 (0.8–6.5)
Season			
Winter (ref)			
Spring	0.6 (0.2–1.5)	1.1 (0.2–5.5)	1.2 (0.3–5.2)
Summer	1.9 (0.8–4.2)	3.0 (0.6–16)	3.6 (0.8–16)
Fall	1.6 (0.6–4.4)	0.9 (0.1–8.9)	2.2 (0.4–12.8)
Circumstances			
Rural vs. urban area (ref)	0.7 (0.3–1.4)	0.4 (0.1–1.4)	0.4 (0.1–1.1)
>100 vs. ≤100 households (ref)	0.8 (0.4–1.5)	0.4 (0.2–1.0)	0.4 (0.2–0.8)
Water pressure: loss ≥6 h vs. <6 h (ref)	0.7 (0.3–1.6)	0.4 (0.1–1.6)	0.4 (0.1–1.3)
Water pressure: intact yes vs. no (ref) [a]	1.3 (0.6–2.5)	0.9 (0.3–2.8)	1.0 (0.4–2.8)
Pipelines on same level: yes vs. no (ref) [b]	0.8 (0.3–2.1)	1.6 (0.4–6.4)	1.2 (0.4–3.9)
Sewer pipelines: yes vs. no (ref) [c]	0.9 (0.2–3.5)	0.5 (0.04–5.6)	0.4 (0.04–3.5)
High water in trench: yes vs. no (ref)	0.9 (0.3–2.3)	1.1 (0.3–4.5)	1.0 (0.3–3.4)
Leaking sewage: yes vs. no (ref) [d]	0.2 (0.02–2.3)	–	–
Safety Measures			
Safety measures: no vs. yes (ref)	1.1 (0.3–3.7)	0.9 (0.1–6.6)	0.6 (0.1–3.8)
Hydrant flushing: yes vs. no (ref)	2.0 (0.9–4.5)	6.5 (1.3–32)	5.3 (1.4–20)
Temporary water: yes vs. no (ref)	1.4 (0.7–2.9)	2.1 (0.7–6.6)	1.8 (0.5–5.8)
Sampling of water: yes vs. no (ref)	0.8 (0.4–1.7)	0.8 (0.2–2.5)	0.6 (0.2–1.8)

GI: gastrointestinal illness (all symptoms).
AGI: acute gastrointestinal illness (vomiting and/or three episodes of diarrhea during 24 h).
[a] Intact water pressure, until shutdown for work on the distribution system.
[b] Sewage water pipelines on the same level as drinking water pipelines in the trench.
[c] No sewage water pipelines in the trench.
[d] Leaking sewage water pipeline in the trench.

Table 8
Odds ratio (OR) for incidence of gastrointestinal illness relative to different circumstances within the reference areas during an incident (n = 3628).

Included in analyses	GI	Vomiting	AGI
	OR (95% CI)	OR (95% CI)	OR (95% CI)
Study area			
Raw water: Surface vs. groundwater (ref)	0.7 (0.3–1.7)	0.4 (0.1–1.2)	0.4 (0.1–1.2)
Production: no chlor vs. chlor. (ref)	3.2 (1.7–5.9)	3.5 (1.2–10)	3.7 (1.5–9.1)
Terrain: flat vs. hilly terrain (ref)	0.4 (0.2–0.8)	0.5 (0.2–1.8)	0.4 (0.2–1.2)
Season			
Winter (ref)			
Spring	0.6 (0.2–1.4)	0.7 (0.2–3.3)	0.7 (0.2–2.7)
Summer	0.9 (0.4–2.2)	0.3 (0.1–2.0)	0.8 (0.2–3.1)
Fall	1.1 (0.3–3.6)	3.6 (0.7–17)	2.7 (0.6–12)
Circumstances			
Rural vs. urban area (ref)	1.2 (0.6–2.3)	0.5 (0.1–1.7)	0.6 (0.2–1.8)
>100 vs. ≤100 households (ref)	1.4 (0.7–2.7)	0.8 (0.3–2.4)	1.2 (0.5–3.1)

GI: gastrointestinal illness (all symptoms).
AGI: acute gastrointestinal illness (vomiting and/or three episodes of diarrhea during 24 h).

an increased risk of gastrointestinal illness in relation to amount of drinking water consumed, for adults as well as children (Payment et al., 1991, 1997; Gagnon et al., 2006; Nygard et al., 2007). An elevated risk of AGI in relation to increased drinking water consumption among adult respondents was seen in this study, but we were unable to conduct similar analyses for children as the consumption was aggregated for all children 0–10 years in the household. Poor hand hygiene, due to lack of running water during the incidents, may also be a potential contributor to the risk of exposure to pathogens. In connection to the study by Nygard et al. (2007), lack of hygiene was discussed even though this was not included in the published paper (Erik Wahl, Norwegian Food Safety Authority, personal communication, October 2015). Nevertheless, only 23% of households in the affected areas in the present study had experienced a shutdown of their water. In addition, in households reporting at least one member experiencing GI, only 14% also reported shutdown of water. Of the reported cases of GI among 2-5-year-old, only 10% lived in a household that had experienced water shutdown. We can therefore conclude that whether or not people had access to running water had a limited contribution to cases of gastrointestinal illness in this study.

4.2. Circumstances, risk factors and safety measures during incidents

Except for chlorination, potential risk factors in the areas did not appear to affect the risk of gastrointestinal illness during incidents in the distribution network. Previous studies have shown that chlorination of drinking water reduces the risk of gastrointestinal illness in settings similar to Sweden (Kapperud et al., 2003; Kuusi et al., 2004). Chlorination of drinking water was also associated with lower risk of gastrointestinal illness in the reference areas in this study. However, the opposite was found in the affected areas, where there was an elevated risk of gastrointestinal illness in areas with chlorinated drinking water compared to no chlorination. This may indicate that although drinking water chlorination is an important means of reducing risks in drinking water production, it does not protect against microbial contamination during incidents in the distribution network. Additionally, the difference in attack rate between the exposed areas and reference areas was higher for water utilities using monochloramine (aimed to reduce growth in the distribution network and not a microbial barrier) than in areas with water utilities using hypochlorite as primary chlorination (data not shown). Still, due to the design of the study we cannot draw any stronger conclusions and therefore further research is recommended.

Viruses (rotavirus, norovirus and enteroviruses) and campylobacter have been suggested to be the most likely pathogens causing gastrointestinal illness associated with drinking water distribution (Westrell et al., 2003; Lambertini et al., 2011, 2012) and pathogens have also been detected in soil and water surrounding the distribution system (Karim et al., 2003; Besner et al., 2008). In simulations of low pressure incidents, the duration of the low pressure was one of the most important factors for the average risk of virus infection (Teunis et al., 2010) and longer duration of water shutdown during break repairs has been shown to increase the risk of infection (Nygard et al., 2007). In our study, the presence of sewage water pipelines on the same level as drinking water pipelines in the trench was associated with an elevated risk of gastrointestinal illness, but the risk was not affected by the duration of lack of water pressure. Our results therefore strengthen the theory of an external source of pathogen contamination, and indicate that the duration of low pressure may not be as important risk factor as the conditions in the surroundings of the water pipelines.

The drinking water producers participating in the study stated that they use hydrant flushing as a safety measure as often as possible, but too large diameter of the water pipes or badly placed fire hydrants were factors that sometimes made flushing difficult to perform. Flushing as a safety measure has been shown to reduce the number of microorganisms and the risk of gastrointestinal illness (Nygard et al., 2007; Besner et al., 2008; Lambertini et al., 2011). However, the results in this study indicate an elevated risk of gastrointestinal illness in the affected areas compared to the reference areas when flushing was used. Therefore we can conclude that additional safety measures besides hydrant flushing may be needed to reduce the risk of gastrointestinal illness during distribution network incidents.

An elevated risk in the affected areas was observed when a temporary water supply (water tank, hose, etc.) was supplied during incidents. The drinking water producers in the study stated that the use of a temporary water supply was dependent on the availability of equipment, the estimated time to repair the pipe break, and whether important public services were located in the affected areas. As we did not collect detailed information on the temporary water supply and how many households actually used a temporary water supply, we cannot draw any further conclusions on whether the elevated risk observed was due to the supply system or to the incident per se. Further research is therefore needed.

The results presented in this paper also indicated seasonal effects on the incidence of gastrointestinal illness, with incidents during spring and summer being associated with a significantly elevated risk of vomiting and AGI in the affected areas. Similar seasonal trends have been observed in a previous study (Nygard et al., 2007). The most likely reason for the higher odds ratio during summer is the high background incidence of gastrointestinal illness during the cold season in Sweden, due to peaks of viral infections. Possible reasons for seasonal differences may also be the turnover time of the water during distribution, the temperature of the drinking water or the surrounding soil, or the level of the shallow groundwater affecting saturation of the soil surrounding the water pipelines. During holidays, there is also less manpower available and regular staff working with drinking water pipelines may have been replaced with less experienced personnel, which may affect how safety measures are implemented.

Since the interviews were conducted 7–14 days after the incidents reported by municipalities in this study, there may have been cases of gastrointestinal illness that were not included, due to the long incubation period for some pathogens, such as parasites. Additionally, secondary cases of drinking water-related gastrointestinal illness may have been included in the results due to person-to-person transmission, e.g., within households. However, such secondary cases were taken into account in our statistical analyses, in which household and incidents were used as random factors.

The study was designed to be double-blinded, but drinking water producers are obliged to inform the public of incidents resulting in loss of water. Therefore the participants in the affected areas may have received information about the incident, or may have experienced loss of water first-hand, and therefore it was not possible to make the study double-blinded sensu stricto. Still, only one-third of the households in the affected areas stated that they had received information and therefore most participants did not know whether they were in the affected areas or not. To limit potential bias introduced by non-blinding in the future, we recommend confirming cases of gastrointestinal illness by additional pathogen analyses in stool samples from subjects.

Most participants in the reference areas had not experienced any changes in their water pressure or quality, or shutdown of water, but for some incidents a large percentage had experienced changes (data not shown). As this study focused only on the municipal drinking water distribution system, incidents or work on the privately owned parts of the distribution system were not included. Therefore, we cannot be certain whether the changes experienced by respondents were related to the incident concerned, or whether there had been an incident or shutdown in the private distribution system connected to properties. Nevertheless, in the study by Nygard et al. (2007), a similar proportion of households in the reference areas reported changes in water pressure or quality. Therefore we can conclude that drinking water consumers are regularly affected by quality changes or low pressure events, even when there are no major incidents in the municipal drinking water distribution system.

5. Conclusions

The results from this study show a significantly elevated risk of gastrointestinal illness, especially vomiting and AGI, linked to incidents in the drinking water distribution and that children in the age group 2–5 years are at the highest risk. These results also support the hypothesis that pathogens causing gastrointestinal illness originate from an external source, such as sewage, as an elevated risk of vomiting and AGI was associated with drinking water pipelines being on the same level as sewage pipes in pipe trenches.

In contrast to previous studies, this study indicates that there was still an elevated risk of gastrointestinal illness after flushing was used as a safety measure. This indicates that safety measures and routines used today may not be sufficient for reducing the risk of gastrointestinal illness and additional safety measures should therefore be considered.

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