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Acute gastrointestinal illness following a prolonged community-wide water emergency

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SUMMARY

The drinking water infrastructure in the United States is ageing; extreme weather events place additional stress on water systems that can lead to interruptions in the delivery of safe drinking water. We investigated the association between household exposures to water service problems and acute gastrointestinal illness (AGI) and acute respiratory illness (ARI) in Alabama communities that experienced a freeze-related community-wide water emergency. Following the water emergency, investigators conducted a household survey. Logistic regression models were used to estimate adjusted prevalence ratios (aPR) and 95% confidence intervals (CI) for self-reported AGI and ARI by water exposures. AGI was higher in households that lost water service for ⩾7 days (aPR 2·4, 95% CI 1·1–5·2) and experienced low water pressure for ⩾7 days (aPR 3·6, 95% CI 1·4–9·0) compared to households that experienced normal service and pressure; prevalence of AGI increased with increasing duration of water service interruptions. Investments in the ageing drinking water infrastructure are needed to prevent future low-pressure events and to maintain uninterrupted access to the fundamental public health protection provided by safe water supplies. Households and communities need to increase their awareness of and preparedness for water emergencies to mitigate adverse health impacts.

Key words: Infectious disease epidemiology, investigation, public health, water-borne infections.

INTRODUCTION

Access to safe water is essential to good health [1, 2]. In the United States, the public drinking water infrastructure supplies drinking water to approximately 87% of US households [3]; most of the time, this regulated drinking water is safe [4]. However, the US water infrastructure is ageing, and climate change, extreme weather events, and other natural disasters place additional strain on these systems that can lead to failures in utilities' ability to deliver safe, clean water [5–10].

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About 240 000 water mains breaks occur in the United States each year [11]; these present opportunities for pathogens to contaminate water in depressurized distribution systems. Several studies have implicated the distribution system as a source of contamination or a cause of increased risk of gastroenteritis without specifically linking low-pressure events to health outcomes [12–15]. Other studies have identified increased incidence of gastroenteritis in people exposed to low water pressure events [16, 17]. A recent meta-analysis conducted across studies of varying design and including data collected in low-income and high-income countries concluded that consuming tap water affected by distribution system problems was associated with gastrointestinal illnesses [18]. Many low-pressure events are isolated and affect a limited portion of a system, and these are routinely managed by water utilities without the involvement of public health agencies. Boil water advisories are frequently issued to address low-pressure events. A search of the Google news database for the term 'boil water advisory' yielded about 3000 results in the United States in the year 2013 alone. When events occur in large supply lines or multiple water mains and affect the water supply to entire communities, large numbers of residents may lose access to a potable public water supply, resulting in a public health emergency. Systematic investigations of health impacts from such community-wide water emergencies have seldom been undertaken.

During 8–19 January 2010 two counties in southwestern Alabama experienced drinking water shortages or complete loss of public drinking water service. The two counties are predominantly rural and characterized by extreme poverty. According to US Census data, there were 20·9 and 13·1 persons/square mile (8·0 and 5·0 persons/km^2) and 22·6% and 39·9% of individuals with incomes below the federal poverty level in 2000, compared to a US population density of 79·6/square mile (30·6/km^2) and 14·9% below the poverty level [19]. As this area does not typically experience extended periods of freezing temperatures, local building codes do not require the level of protection against freezing pipes often required in areas with colder climates. The service interruptions occurred following several days of atypical cold temperatures [lows of 12–21 °F (−11 to −6 °C) for 8 days] which contributed to water mains breaks and residential pipe failures throughout the water systems leading to low pressure, including breaks in many unoccupied weekend residences that went undetected for some time. Breakdowns of mechanical components, including an ageing well pump scheduled for replacement, low water storage levels prior to the freeze, and inability of neighbouring communities to supply a back-up water supply, contributed to the scale of the emergency. About 18 000 residents were affected, including several communities who were without drinking water for more than a week. The water interruption events prompted emergency response efforts from the Alabama Department of Public Health (ADPH); water boards, and Emergency Management Agencies (EMA) from each county. The ADPH and the Centers for Disease Control and Prevention (CDC) investigated potential health impacts related to the loss of water service and disseminated preliminary findings and recommendations [20]. The objective of this epidemiological study is to evaluate the association between a range of household water exposures and acute gastrointestinal illness (AGI) and acute respiratory illness (ARI) in a survey of residents of Alabama communities that experienced a community-wide water emergency.

METHODS

The public health investigation included a household survey in four communities (A–D) in the two affected counties; focus group meetings; a survey of businesses, schools and healthcare facilities; and meetings with emergency responders. The investigation was a public health response and, therefore, determined to be 'non-research'. Two 'affected' communities, A (a town) and B (a named area of the county that does not have a separate municipal government), were heavily impacted by the water shortage and had been under boil water advisories. 'Unaffected' communities C and D were selected by the local ADPH staff because they were located in the same counties as A and B, respectively, and were regarded as the most similar nearby communities to A and B with respect to population size and demographics, but did not shut down their water supplies or issue boil water advisories. We refer to communities A and B as 'affected' and communities C and D as 'unaffected' based on knowledge available at the time the areas were selected, although the investigation subsequently revealed that some households in all surveyed communities experienced water service interruption or loss of pressure. All public water utilities serving the four communities used surface water sources disinfected with chlorine.

The household survey collected information on each household's water pressure and service during the emergency, water sources and uses, and acute illnesses experienced by household members. Residential addresses were randomly sampled from comprehensive lists of addresses and other locations in each county maintained for the purpose of enabling county emergency responders to locate reported emergencies. The sample included 300 addresses from each 'affected' community and 150 addresses from each 'unaffected' community to provide 80% power to detect a relative risk of 2·0, assuming a 5% illness prevalence in unexposed areas [21], 2·5 individuals per household, a 25% non-response rate, and 30% invalid addresses (i.e. vacant lot or vacant house). Interviewers visited each household multiple times until respondents were contacted or the survey period ended (26 February–9 March 2010). Eligible respondents had municipal water service, were aged $\geqslant 18$ years, and residing in the household from 1 to 31 January 2010. One household member completed the interview for each household and provided oral consent.

Respondents were asked about the number of days the home experienced low water pressure and complete loss of water service, the household's normal tap water consumption before the emergency, burst pipes on their property, and emergency water sources obtained during the shortage. For each source, residents were asked about uses, and whether they boiled the water before using it. Water exposure data were analysed by type of interruption, duration, sampling area, and potable use, defined as drinking, cooking, or brushing teeth. The interviewer asked questions about illnesses experienced by each household member from 4 to 31 January 2010. AGI was defined as 'stomach problems, such as diarrhoea or vomiting'; diarrhoea was defined as $\geqslant 3$ loose stools in a 24-h period [22]. ARI was defined as 'cold or flu symptoms like cough, runny or stuffy nose, headaches, or muscle or body aches'. Respondents were also asked about new onset of skin problems (rash, infection) and eye infections. Other information gathered about each resident included age, sex, school attendance (for residents aged 3–21 years), employment outside the home (for residents aged $\geqslant 15$ years), chronic health conditions that caused chronic diarrhoea (e.g. Crohn's disease, irritable bowel syndrome, coeliac disease), chronic respiratory problems (e.g. asthma, chronic obstructive pulmonary disease), and diabetes. Information on respondent-identified race/ethnicity (American Indian/Alaska Native, Asian, Black or African-American, Native Hawaiian/Pacific Islander, White, Hispanic or Latino, Other, or refused) was collected to enable a demographic characterization of survey participants; due to the low prevalence of races other than White and Black, all other categories are presented as 'Other.' Because of the small number of other races, for statistical analyses, we compared Blacks to all others.

Sampling weights were calculated as the inverse of the sampling probability in each community with adjustments for non-response. Data analyses were conducted using 'survey' procedures in SAS v. 9.3 (SAS Institute Inc., USA) to account for the stratified cluster sampling design and clustering within households, with finite population corrections applied. Descriptive analyses included frequency distributions (including period prevalence of illness), means, and medians. Within each county, we compared the *a priori* exposed and unexposed communities with respect to race (Black *vs.* others), dwelling type (house, mobile home, apartment), household size (1–3, 4–5, $\geqslant 6$), school attendance, employment status, age group, and chronic health conditions. Weighted logistic regression was used to model the association between water exposures and AGI and ARI. Odds ratios from these analyses approximate prevalence ratios (PR) because the outcomes are relatively rare [23]. Tests for linear trend were performed to assess the significance of 'dose-response' associations between duration of water service problems and the outcomes. Models were adjusted for age, county, and variables associated with the outcome at $P < 0{\cdot}2$ in univariate analyses; given the relatively small sample size, this P value was chosen in case some variables that were not significantly associated with the outcome might still be confounders of the association between water exposures and illness.

Local health department employees facilitated six focus group discussions. Participants were eligible if their home was connected to a city water system that experienced water service interruptions during January 2010. Topics included household impact of the water interruption, household emergency preparedness, and health communication messaging. Audio-recorded transcripts were analysed using ATLAS-ti software (Scientific Software Development, Germany).

Twenty-five healthcare-related institutions in the affected areas were invited to participate in structured interviews in person or by telephone. Facilities included six outpatient medical clinics, four dental clinics, five pharmacies, six home health agencies, a dialysis centre, a hospital, an assisted living facility, and a nursing home. The hospital provided de-identified discharge data for January 2010 and January 2009 for comparison to determine if there was an increase in visits for AGI and ARI during the water emergency.

RESULTS

Of 898 sampled addresses, 610 (67·9%) included an eligible respondent; of these, 470 (77%) participated in the household survey. Participation was higher in communities A and B (80·6%), where area-wide water interruptions occurred, than in 'unaffected' communities C and D (70·2%) ($P = 0{\cdot}004$). Communities A and C differed by race (88% *vs.* 70% Black, $P = 0{\cdot}01$) and housing (42% *vs.* 57% house, 55% *vs.* 34% mobile home, 3% *vs.* 9% apartment, $P = 0{\cdot}04$); communities B and D did not differ significantly by any of the demographic characteristics assessed. Residents in all surveyed communities reported experiencing problems with water pressure or service: 91% in community A, 96% in community B, 26% in 'unaffected' community C, and 55% in 'unaffected' community D. Overall, 31·1% of households reported both low water pressure and loss of service, 10·4% lost service only, and 22·7% experienced low water pressure only; the remaining 35·9% were unaffected (Table 1). Overall, 17·7% of respondents had no water for ⩾7 days, and 8·9% had low water pressure for ⩾7 days. A total of 23% of all households reported water service problems and used unboiled tap water for potable purposes. In communities A and B, where residents had been advised to boil their water, 23% of household respondents used unboiled tap water for potable purposes; in C and D, where no boil water advisory was issued, one household reported boiling tap water (data not shown).

Of the 1283 residents of the 470 surveyed households, 108 (7·6%) reported symptoms of AGI, 194 (14·8%) reported symptoms of ARI, 25 (1·6%) reported skin rash or infection, and 15 (1·0%) reported having an eye infection during January 2010 (Table 2). AGI and ARI prevalence varied by several demographic characteristics and chronic health conditions.

AGI prevalence did not differ significantly between 'affected' communities (A and B) and 'unaffected' communities (C and D) [PR 1·2, 95% confidence interval (CI) 0·7–2·1] (Table 3). However, households that reported low water pressure or a complete loss of water service experienced a higher prevalence of AGI than households that were not affected by service problems (9·3% *vs.* 4·3%, PR 2·3, 95% CI 1·0–5·2, $P = 0{\cdot}045$). After multivariable adjustment, the magnitude of this association was slightly attenuated and no longer statistically significant [adjusted prevalence ratio (aPR) 2·0, 95% CI 0·9–4·8].

Table 1. *Household characteristics and water-related exposures of persons in counties affected by water service interruptions, Alabama, 2010 (N = 470)*

	N (%)*
Household size, mean (95% CI)	2·8 (2·6–2·9)
Household includes children aged <5 yr	67 (13·4)
Household includes seniors aged ⩾65 yr	136 (29·2)
Dwelling type	
House	294 (65·9)
Mobile home	130 (22·6)
Apartment	46 (11·6)
Normally drink tap water	340 (70·2)
Household has a private well	18 (3·3)
Water service during emergency of January, 2010	
Water service interruption	
Loss of service and loss of pressure	185 (31·1)
Loss of service only	57 (10·4)
Loss of pressure only	102 (22·7)
No loss of service or pressure	126 (35·9)
Loss of service	
Median, days (range)	1 (0–30)
None	229 (59·0)
<7 days	130 (23·4)
⩾7 days	111 (17·7)
Loss of pressure	
Median, days (range)	1 (0–45)
None	183 (47·0)
1–2 days	146 (28·7)
3–6 days	83 (15·3)
⩾7 days	53 (8·9)
Experienced burst pipes	124 (23·3)
Tap water access and use	
Unaffected household (did not report low pressure or service interruption)	126 (35·9)
Affected household, non-potable use of tap water only	49 (9·3)
Affected household, used boiled tap water for potable purposes†	25 (4·4)
Affected household, use unboiled tap water for potable purposes†	109 (23·2)
Did not report obtaining tap water	161 (27·2)

CI, Confidence interval.

* Estimates are weighted by inverse of sampling probability, adjusted for non-response.

† Potable purposes defined as drinking, cooking, brushing teeth, or preparing infant formula; regardless of treatment. Some category totals do not equal 100% due to rounding.

Table 2. *Description of individual residents in households in counties affected by water-service interruptions, and estimated prevalence of acute gastrointestinal illness (AGI) and acute respiratory illness (ARI) by residents' characteristics, Alabama, 2010 (N = 1283)*

	N (%)*	AGI (%)*	*P* value†	ARI (%)*	*P* value†
Age, years					
Median (min–max)	37 (0–94)				
0–4	90 (7·0)	20·4	<0·0001	33·3	<0·0001
5–17	285 (21·7)	10·9		24·0	
18–64	721 (56·5)	5·5		10·4	
65–74	101 (7·9)	6·2		8·0	
⩾75	85 (6·8)	2·6		10·7	
Race					
Black	771 (55·1)	10·3	0·02‡	18·9	0·0031‡
White	499 (43·7)	4·4		9·6	
Other	13 (1·2)	0·0		14·9	
Sex					
Male	584 (45·6)	7·3	0·72	15·1	0·75
Female	699 (54·4)	7·8		14·5	
Employed					
Not applicable§	317 (23·9)	12·8	0·02	26·4	0·10
Yes	400 (32·8)	3·9		9·1	
No	566 (43·6)	7·5		12·7	
Attends school					
Not applicable§	894 (70·0)	6·0	0·44	10·6	0·55
Yes	322 (24·4)	11·9		25·3	
No	67 (5·6)	8·9		21·0	
Dwelling type					
House	797 (66·6)	5·8	0·01	11·5	0·02
Mobile home	389 (24·3)	10·3		22·3	
Apartment	97 (9·1)	13·6		18·6	
County of residence					
Community A county	750 (73·2)	6·2	0·02	13·5	0·11
Community B county	533 (26·8)	11·2		18·7	
Chronic diarrhoea					
No	1273 (99·3)	7·5	0·23	14·9	0·35
Yes	10 (0·7)	17·7		6·4	
Chronic respiratory problem					
No	1175 (91·5)	7·0	0·01	12·7	<0·0001
Yes	108 (8·5)	17·7		37·8	
Diabetes					
No	1170 (91·9)	7·0	0·01	14·2	0·07
Yes	113 (8·1)	14·5		21·5	
Acute illnesses					
AGI	108 (7·6)				
ARI	194 (14·8)				
Skin problem	25 (1·6)				
Eye problem	15 (1·0)				

* Percentage estimates are weighted by inverse of sampling probability, adjusted for non-response.
† P value from Rao–Scott χ^2 test.
‡ P value calculated with Whites and others combined.
§ Information on employment elicited for residents aged ⩾15 years. Information on school attendance (including preschool) elicited for residents aged 3–21 years. P values calculated after excluding residents outside the relevant age category using a domain analysis.
Some category totals do not equal 100% due to rounding.

Table 3. *Unadjusted and adjusted prevalence ratios* for acute gastrointestinal illness (AGI) in persons in counties affected by water service interruptions, Alabama, 2010 (N = 1283)*

	Persons with AGI, *N* (%)*	Unadjusted*†		Adjusted*†‡	
		PR	95% CI	PR	95% CI
Sampling area					
Area under boil water advisory	77 (8·2)	1·2	0·7–2·1	1·2	0·6–2·2
Area not under boil water advisory	31 (6·9)	1·0		1·0	
Household water service interruption					
No loss of service or pressure	13 (4·3)	1·0		1·0	
Yes, low pressure and/or loss of service	95 (9·3)	2·3	1·0–5·2	2·0	0·9–4·8
Loss of service and loss of pressure	67 (12·4)	3·2	1·4–7·4	2·7	1·1–6·8
Loss of service only	10 (6·1)	1·5	0·5–4·1	1·2	0·4–3·4
Loss of pressure only	18 (6·6)	1·6	0·6–4·1	1·7	0·6–4·4
Loss of service					
None	31 (5·2)	1·0		1·0	
<7 days	31 (8·8)	1·8	0·9–3·4	1·4	0·7–2·7
≥7 days	46 (13·2)	2·8	1·5–5·4	2·4	1·1–5·2
P_{trend}			0·001		0·03
Loss of pressure					
None	23 (4·7)	1·0		1·0	
1–2 days	32 (7·1)	1·6	0·7–3·2	1·5	0·7–3·2
3–6 days	30 (12·7)	2·9	1·4–6·2	3·0	1·4–6·4
≥7 days	23 (15·6)	3·8	1·6–8·7	3·6	1·4–9·0
P_{trend}			0·0002		0·002
Tap water access and use					
Unaffected household	13 (4·3)	1·0		1·0	
Affected household, non-potable use of tap water only	6 (3·9)	0·9	0·3–3·2	1·0	0·3–3·7
Affected household, used boiled tap water for potable purposes§	8 (10·6)	2·6	0·7–9·5	2·1	0·5–8·3
Affected household, use unboiled tap water for potable purposes§	32 (10·0)	2·5	1·0–6·0	2·3	0·9–5·5
Did not report obtaining tap water	49 (10·3)	2·6	1·1–6·2	2·2	0·8–5·6
Burst pipes					
No	67 (6·8)	1·0		1·0	
Yes	41 (9·8)	1·5	0·8–2·6	1·4	0·7–2·7

* Percentage estimates are weighted by inverse of sampling probability, adjusted for non-response.
† Prevalence ratios (PR) and 95% confidence intervals (CI) estimated from weighted logistic regression models.
‡ All results shown are from separate models, each adjusted for age, race, employment, dwelling type, county of residence, and chronic health problems (respiratory or diabetes).
§ Potable purposes defined as drinking, cooking, brushing teeth, or preparing infant formula; regardless of treatment.

Residents of households who experienced both loss of service and low-pressure episodes had significantly higher prevalence of AGI than residents of households that did not experience these problems (aPR 2·7, 95% CI 1·1–6·8). Prevalence of AGI also showed a graded increase with increasing duration of loss of service ($P_{trend} = 0·03$); residents who lost service for ⩾7 days were more than twice as likely to experience AGI than residents who did not lose service (aPR 2·4, 95% CI 1·1–5·2). Likewise, there was a graded increase in prevalence of AGI with duration of low water pressure ($P_{trend} = 0·002$), and residents who experienced low pressure for ⩾7 days were more than three times as likely to have AGI than residents who did not experience low pressure (aPR 3·6, 95% CI 1·4–9·0). Compared to residents of households that maintained normal water service, residents of households with low pressure or loss of service who used tap water exclusively for non-potable purposes had a similar prevalence of AGI (aPR 1·0, 95% CI 0·3–3·7). Other residents of the impacted households, including those who reported using only boiled or unboiled tap water for potable purposes and those who did not specify whether they used tap water all had elevated prevalence of AGI (ranging from 10·0% to 10·6%).

None of the water exposures were significantly associated with ARI, except that there was a marginally significant trend of increasing odds of ARI with increasing duration of low water pressure (P_{trend} = 0·06) (Table 4). Skin rash/infection and eye infections were not significantly associated with the water service interruptions (not shown).

Examination of hospital discharge data did not reveal any elevation in emergency department visits or in-patient admissions for gastrointestinal or respiratory illnesses compared to January 2009 (not shown). The six outpatient healthcare providers from community A did not notice any increases in office visits for AGI during January 2010; however, these were probably subjective assessments because clinics were not asked to quantify number of visits and reasons for visits. During the focus group meetings, some community B residents mentioned being ill with nausea, diarrhoea, and upset stomach during the water emergency, but none attributed the illnesses to the water problems or indicated any perception or awareness of a widespread illness outbreak. However, several residents of community B did express longstanding mistrust of the quality and safety of their water based on its aesthetic characteristics, and some stated they had quit drinking the water at some time in the past because they perceived that it caused gastrointestinal distress. One community B resident recalled experiencing itchy skin following contact with tap water after the outage, and an eye infection in a family member, but no other focus group participants reported these problems. Focus group participants in both communities agreed that inability to bathe, clean their homes and dishes, or use the commode were major concerns during the water emergency.

DISCUSSION

The events of January 2010 in southwestern Alabama provided an opportunity to identify excess AGI following a water emergency that resulted from extreme weather and shortcomings of the water system infrastructure. The number of community-wide water emergencies occurring every year in the United States is unknown, and these events are not routinely the subject of extensive public health investigations. To our knowledge, health effects from similar water emergencies in the United States have not previously been documented in the literature. Preliminary findings from the Alabama investigation were published along with recommendations for public health agency preparedness measures; the current report includes a more comprehensive analysis of a range of relevant water exposures, including consumption of potentially contaminated tap water during the boil water advisories [20]. A small number of studies, primarily conducted in other countries, have identified an increased risk of AGI associated with low-pressure events in water distribution systems [16, 17]. A prospective study in Norway identified a 58% increased risk of AGI associated with breaks and maintenance in water systems [17]. In the UK, a study in the control arm of a trial identified 12-fold greater odds of AGI in residents who reported experiencing low water pressure [16]. In Canada, an intervention study identified excess AGI attributable to water that had been transported through the distribution system compared to water that had been bottled at the treatment plant, suggesting that contamination through cracks in distribution pipes had led to some of the illnesses [24]; notably, these effects occurred during normal system operation rather than during widespread service interruptions. Intervention studies in the United States and Australia, also conducted during normal operations, have not identified significantly increased risk of illness from water that passed through the distribution system [25, 26]. A recent study conducted in Wisconsin found that enteric viruses entered the drinking water through the distribution system [14]. As the communities involved were served by groundwater that was not required to be treated with a disinfectant per US regulations, there was no disinfectant residual to prevent the viruses from reaching residents [14]. Increased AGI from the prolonged water shortage in Alabama is plausible in light of the many studies that show health effects for shorter exposures to low-pressure events.

We believe our findings are consistent with residents becoming ill with AGI following ingestion of water that became contaminated while travelling through a depressurized distribution system. Illness prevalence was about twofold higher in households where residents reportedly drank or otherwise potentially consumed tap water compared to households where residents did not consume tap water (see Table 3). Although both complete loss of service and low water pressure were associated with increased prevalence of AGI, particularly if these interruptions were prolonged, the association was strongest for low

Table 4. *Unadjusted and adjusted prevalence ratios for acute respiratory illness (ARI) in persons in counties affected by water service interruptions, Alabama, 2010 (N = 1283)*

	Persons with ARI, *N* (%)*	Unadjusted*†		Adjusted*†‡	
		PR	95% CI	PR	95% CI
Sampling area					
Area under boil water advisory	122 (13·7)	0·8	0·5–1·3	0·7	0·4–1·2
Area not under boil water advisory	72 (16·2)	1·0		1·0	
Household water service interruption					
No loss of service or pressure	40 (13·9)	1·0		1·0	
Yes, low pressure and/or loss of service	154 (15·3)	1·1	0·6–2·0	0·9	0·5–1·7
Loss of service and loss of pressure	40 (13·9)	1·4	0·8–2·6	1·1	0·6–2·2
Loss of service only	18 (9·3)	0·6	0·2–1·6	0·5	0·2–1·4
Loss of pressure only	40 (13·9)	1·0	0·5–2·0	1·0	0·5–1·9
No loss of service or pressure	96 (18·5)	1·0		1·0	
Loss of service					
None	80 (13·8)	1·0		1·0	
<7 days	50 (13·7)	1·0	0·6–1·8	0·8	0·4–1·5
≥7 days	64 (19·0)	1·5	0·9–2·5	1·2	0·6–2·4
P_{trend}			0·16		0·49
Loss of pressure					
None	59 (12·7)	1·0		1·0	
1–2 days	53 (12·8)	1·0	0·6–1·9	0·9	0·5–1·7
3–6 days	47 (20·5)	1·8	1·0–3·3	1·8	0·9–3·3
≥7 days	35 (22·8)	2·0	1·0–4·2	1·9	0·8–4·4
P_{trend}			0·02		0·06
Tap water access and use					
Unaffected household	40 (13·9)	1·0		1·0	
Affected household, non-potable use of tap water only	16 (12·5)	0·9	0·3–2·4	1·0	0·3–2·9
Affected household, used boiled tap water for potable purposes§	10 (12·5)	0·9	0·3–2·3	0·6	0·2–1·8
Affected household, use unboiled tap water for potable purposes§	50 (14·8)	1·1	0·6–2·1	0·9	0·5–1·8
Did not report obtaining tap water	78 (17·2)	1·3	0·7–2·4	1·0	0·5–1·9
Burst pipes					
No	121 (13·1)	1·0		1·0	
Yes	73 (19·7)	1·6	1·0–2·6	1·5	0·9–2·6

* Estimates are weighted by inverse of sampling probability, adjusted for non-response.
† Prevalence ratios (PR) and 95% confidence intervals (CI) estimated from weighted logistic regression models.
‡ All results shown are from separate models, each adjusted for age, race, employment, dwelling type, county of residence, and chronic health problems (respiratory or diabetes).
§ Potable purposes defined as drinking, cooking, brushing teeth, or preparing infant formula; regardless of treatment.

water pressure. The increasing association of illness with increasing duration of low water pressure ($P_{trend} = 0·002$) is also consistent with distribution system contamination. Burst pipes on residents' property could be one cause of household water service interruptions, and while burst pipes were common during the freeze of January 2010, they were not significantly associated with AGI. Interestingly, a community-wide increase in illness was not noted by other agencies: the hospital logs did not reveal an increase in visits for gastrointestinal complaints compared to the same period during the previous year; the doctor's offices did not report an increase in visits; and the focus group participants did not relate any anecdotal awareness of a diarrhoeal disease outbreak. These null findings could be interpreted as a lack of corroboration of the epidemiological findings from the survey; however, we are not surprised that healthcare visits were not generally increased, since the majority of people do not seek medical care for AGI [21]. We considered the possibility that the publicity surrounding the water emergency might have induced concern about health effects related to the water service interruptions, which might have led residents who experienced shortages to over-report symptoms, or might have led residents who experienced illnesses to report a more extensive water service interruption; these recall biases could have led to spurious associations between water exposures and illness. However, because focus group attendees did not relate any anecdotal awareness of a diarrhoeal disease outbreak, it seems there was not a widespread belief that residents' health had been harmed by the emergency, thus the magnitude of the bias might have been small. Likewise, if residents who were more severely affected by the water crisis were inclined to over-report health events, we would expect them to report more skin, eye, and respiratory complaints as well, but this was not the case.

Although there was a marginally significant dose-response trend of increasing ARI with extended low water pressure, the magnitude of this association was much smaller than that for AGI, and no other water exposures were associated with ARI. Residents who reported no access to tap water had significantly increased AGI compared to residents who had tap water but did not consume it, raising the possibility that some illness may have been transmitted person-to-person in residents who were unable to use water to maintain hand hygiene or clean their homes. However, if that were a major factor, we would expect that ARI would also be significantly elevated in residents who did not have any tap water, contrary to our findings.

Pressure fluctuations within water distribution systems following mains breaks and repairs are complex [27]. We relied on self-reported information on household water pressure problems following a winter freeze. A recent study in different water systems in the same region of Alabama found that self-reported low water pressure was associated with measured water pressure [28]. Although we chose two communities that were strongly affected by the water service interruption and the two most comparable nearby communities that were relatively unaffected, in reality the impact of the freeze on water systems was widespread and heterogeneous. In the 'affected' communities (A and B), the duration of loss of service or pressure varied from many weeks to none at all, and in the 'unaffected' communities (C and D), service interruptions were actually quite common (26% in community C and 55% in community D). As a result, a straightforward comparison of illness prevalence by sampling area did not yield significant differences; however, a closer look by reported days of service interruptions revealed a duration-dependent association between gastrointestinal illness and loss of service and pressure, underscoring the importance of carefully measuring water exposures at the household level when investigating water service interruptions.

Several limitations of this investigation merit consideration. Because of the 6-week interval between the emergency and investigation, we did not collect detailed information on timing of water exposures and illness onset, thus their temporal order is uncertain. For the same reason, we did not collect any biological samples to corroborate illness or identify pathogens. Further, identifying specific environmental sources of faecal contamination of the water system was not a focus of this investigation. In the household survey, no specific time-frame was used for alternative water source questions, and residents might have answered differently depending on whether and how long they lost service; some residents who drank potentially contaminated tap water after the service was restored but before the boil water advisory was lifted might not have thought of this being water obtained 'during the emergency', thus some households who did not report obtaining tap water might have been exposed but misclassified as unexposed. Because of this ambiguity, we analysed residents who did not report obtaining tap water during the emergency as a separate category. Questions about water sources and uses were only asked of the household respondent and were assumed to apply to all household members equally; however, sources and uses likely differed in household members, and this probably resulted in some exposure misclassification. Because of the diversity of emergency water sources available in the communities, including bottled water, water filtered on-site by emergency responders, non-potable water provided for flushing toilets, and wells and springs in the area, we were also not able to adjust for confounding by all other water sources in our analysis of consumption of tap water. Finally, since we relied on self-report for both exposures and illnesses, recall bias could explain some of our findings. Concerns regarding bias are mitigated somewhat by the specificity of the associations with AGI and the dose-response relationships observed, and the fact that focus group discussants did not associate the water emergency with increased illness in their communities.

The results of this investigation highlight the critical importance of water systems to public health. In many parts of the world, provision of a continuous piped water supply has not yet been achieved, and intermittent supplies with interruptions in water service are a daily reality [18, 29]. The marked reduction in mortality from epidemics of waterborne diseases like cholera and typhoid fever that were accomplished with the advent of chlorinated public water systems was one of the greatest public health achievements of the 20th century in the United States [30]. However, our water systems are ageing and, in many cases, reaching the end of their useful life [31]. Extreme weather events, which might become more common with climate change, place additional stress on an ageing water infrastructure [5]. Failure of ageing water system components can make water systems vulnerable to low-pressure events. Safeguarding the water systems in these settings will require a considerable investment in infrastructure. Public health agencies can prepare for water emergencies and potentially mitigate health impacts by developing emergency response protocols, emergency water distribution plans, and community communication toolkits, and providing guidance for household and institutional preparedness [20]. Water utilities and public health agencies also need to be aware that the health impacts from such emergencies might not come to their attention through existing notifiable disease, active laboratory-based, or syndromic surveillance systems.

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DECLARATION OF INTEREST

None.

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