Published in final edited form as:
J Expo Sci Environ Epidemiol. 2023 January ; 33(1): 102–110. doi:10.1038/s41370-022-00498-7.

SANITARY SEWAGE OVERFLOWS, BOIL WATER ADVISORIES, AND EMERGENCY ROOM AND URGENT CARE VISITS FOR GASTROINTESTINAL ILLNESS: A CASE-CROSSOVER STUDY IN SOUTH CAROLINA, USA, 2013–2017

Sarah E. Rothenberg[1,*], **Jessica M. Furrer**[2], **Lucy A. Ingram**[3], **Tami S. Ashford-Carroll**[4], **Stephanie A. Foster**[1], **Perry Hystad**[1], **Denise M. Hynes**[1,5,6], **Tala Navab-Daneshmand**[7], **Adam J. Branscum**[1], **Pemika Kruearat**[1]

[1]Oregon State University, College of Public Health and Human Sciences, Corvallis, OR, 97331, USA

[2]Benedict College, Department of Computer Science, Physics, and Engineering, Columbia, SC, 29204, USA

[3]University of South Carolina, Arnold School of Public Health, Columbia, SC, 29208, USA

[4]Benedict College, Department of Health and Sport Management, Columbia SC, 29204, USA

[5]Oregon State University, Center for Quantitative Life Sciences, Corvallis, OR, 97331, USA

[6]US Department of Veterans Affairs, VA Portland Health Care System, Center to Improve Veteran Involvement in Care, Portland, OR, 97239, USA

[7]Oregon State University, College of Engineering, Corvallis, OR, 97331, USA

Abstract

Background: Sanitary sewage overflows (SSOs) release raw sewage, which may contaminate the drinking water supply. Boil water advisories (BWAs) are issued during low or negative pressure events, alerting customers to potential contamination in the drinking water distribution system.

Objective: We evaluated the associations between SSOs and BWAs and diagnoses of gastrointestinal (GI) illness in Columbia, South Carolina, and neighboring communities, 2013–2017.

*Corresponding author: Sarah E. Rothenberg, D.Env., Oregon State University, College of Public Health and Human Sciences, Environmental and Occupational Health Program, 103 Milam Hall, Corvallis, Oregon, 97331, USA, sarah.rothenberg@oregonstate.edu, Office: +1 541-737-3732.

AUTHOR CONTRIBUTIONS

SR designed the study, acquired and analyzed the data, and wrote the manuscript; JF, LI, TA-C, PH, DH, and TN-D helped design the research; and SF, AB, and PK contributed to data analyses. All authors read and approved the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests

ETHICAL APPROVAL

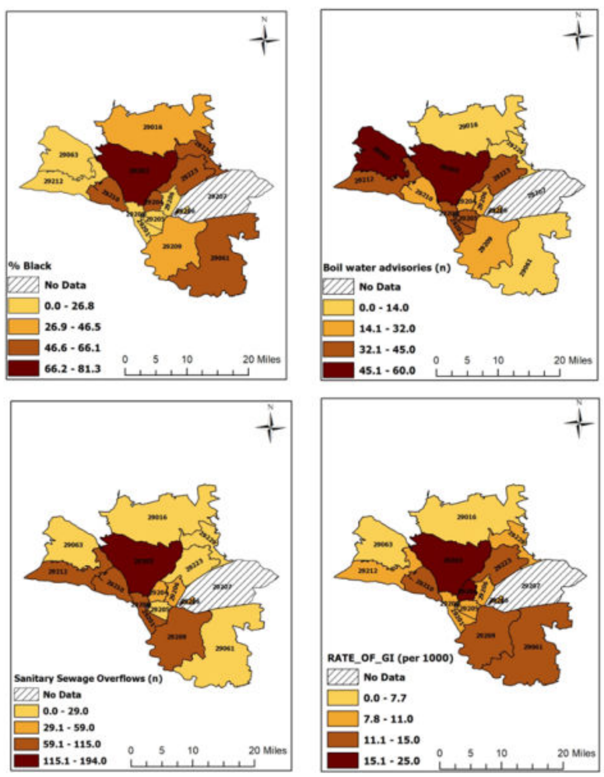
The Oregon State University Institutional Review Board reviewed and approved the protocols for this study.

Methods: A symmetric bi-directional case-crossover study design was used to assess the role of SSOs and BWAs on Emergency Room and Urgent Care visits with a primary diagnosis of GI illness. Cases were considered exposed if an SSO or BWA occurred 0–4 days, 5–9 days, or 10–14 days prior to the diagnosis, within the same residential zip code. Effect modification was explored via stratification on participant-level factors (e.g., sex, race, age) and season (January-March versus April-December).

Results: There were 830 SSOs, 423 BWAs, and 25,969 cases of GI illness. Highest numbers of SSOs, BWAs and GI cases were observed in a zip code where >80% of residents identified as Black or African-American. SSOs were associated with a 13% increase in the odds of a diagnosis for GI illness during the 0–4 day hazard period, compared to control periods (Odds Ratio: 1.13, 95% Confidence Interval: 1.09, 1.18), while no associations were observed during the other hazard periods. BWAs were not associated with increased or decreased odds of GI illness during all three hazard periods. However, in stratified analyses BWAs issued between January-March were associated with higher odds of GI illness, compared to advisories issued between April-December, in all three hazard periods.

Significance: SSOs (all months) and BWAs (January-March) were associated with increased odds of a diagnosis of GI illness. Future research should examine sewage contamination of the drinking water distribution system, and mechanisms of sewage intrusion from SSOs.

Graphical Abstract



Keywords

environmental justice; population based studies; epidemiology; empirical/statistical models

INTRODUCTION

The U.S. Environmental Protection Agency (USEPA) estimates between 23,000 and 75,000 sanitary sewage overflows (SSOs) occur annually in the US, releasing raw sewage before it reaches the wastewater treatment plant.[1] Sewage contains microbial pathogens, including bacteria, viruses, protozoa (parasitic organisms), and helminths (intestinal worms), which cause gastrointestinal (GI) illness, characterized by diarrhea, vomiting, nausea, and abdominal cramps.[1] Few studies have investigated the impacts of sewage spills on the drinking water supply, which have the potential to broadly affect communities.[2–3]

SSOs can occur anywhere in the sanitary sewer system, releasing undiluted sewage into receiving waters, and onto public and private property.[1,4] In water bodies and on land, pathogens from sewage seep into the sediment, where microbial decay rates are lower, compared to the overlying water column.[5–7] Depending on the proximity between sewage pipes and water pipes, fecal microorganisms from sewage may intrude into the drinking water distribution system when hydraulic integrity (positive pressure) is compromised.[8–13] Briefly, there is positive pressure in water pipes while water is flowing, and water only flows out of the system.[13] However, during negative pressure events in the drinking water system (e.g., during water main breaks or repairs), the flow of water is reversed, allowing non-potable water to intrude into the potable water supply, either at the site of the break or through leaks elsewhere in the distribution system.[10, 13]

Intermittent water supply and water outages in the drinking water distribution system have been associated with higher rates of GI illness.[8, 14–16] In Norway, one week after water main breaks or maintenance, 13% of households in the exposure areas reported at least one case of GI illness within 0–7 days, compared to 8% of households in the unexposed areas.[16] In the United Kingdom, loss of water pressure was associated with higher rates of self-reported GI illness.[14] In Massachusetts, a water main break was associated with a 1.3-fold increased odds [95% confidence interval (CI): 1.1, 1.4] of Emergency Department visits for GI illness within 0–3 days, compared to control periods.[15] Results from these studies suggest that sewage from SSOs may increase the risk of GI illness following hydraulic disruptions in the water distribution system; however, this combination of events has not been previously investigated.

This study is based in Columbia, SC, and neighboring communities, where SSOs frequently occur due to aging infrastructure.[17] In 2013, the USEPA reached a settlement with the City of Columbia to resolve violations of the Clean Water Act, including unauthorized overflows of untreated raw sewage from SSOs[18]; however, SSOs continue to occur.[17] Boil water advisories (BWAs) are issued when there is a significant drop in water pressure (i.e., negative pressure events), and bacterial contamination of the drinking water system is possible (https://local.nixle.com/city/sc/columbia/). During this time, customers are advised to boil their water (https://local.nixle.com/city/sc/columbia/). Significant drops in water pressure in the same areas where SSOs occur may result in sewage intrusion into the drinking water system. Thus, we hypothesize that the rate of diagnoses for GI illness will increase after an SSO or a BWA. Further, we hypothesize the co-occurrence of an SSO and BWA will lead to a greater increase in diagnoses of GI illness, compared to exposure following just one event. To the best of our knowledge, this is the first study to investigate both SSOs and BWAs, and their impacts on diagnoses of GI illness.

METHODS

Site description.

Data were analyzed for hospitals and urgent care facilities in Columbia, SC, located in Richland County. All participants lived in Richland County, in one of 14 zip codes: 29016, 29061, 29063, 29201, 29203, 29204, 29205, 29206, 29208, 29209, 29210, 29212, 29223, and 29229 (Figure S1). The zip code 29208 (University of South Carolina) is enveloped in the zip code 29201; therefore SSO and BWA data were combined for both zip codes. The zip code 29207 (Fort Jackson) was excluded because hospital and urgent care data were not available for the military base. A majority of homes are served by Columbia Water or another public water system, while ~five percent of households have private wells (J. Martinez, personal communication, Columbia Water). Some homes have septic systems, although the total number is unknown because the South Carolina Department of Health and Environmental Control (SCDHEC) does not maintain records for more than five years (T. Stanley, personal communication, SCDHEC). All zip codes matched Zip Code Tabulation Areas, which were used to obtain demographic data from the American Community Survey.[19] Between 2015–2019, the total population in these 14 zip codes was 406,574, including 46% Black or African-American, 45% White, 4.6% Hispanic or Latino, 2.8% Asian and <1% American Indian (Table 1).[19]

Emergency Room and Urgent Care Visits.

Emergency Room (ER) and Urgent Care (UC) visits in Columbia, SC, from January 1, 2013 through December 31, 2017, were obtained from the SC Revenue and Fiscal Affairs Office in 2018. Patient-level data included age, race, sex, residential zip code, primary diagnostic code, admission date, discharge date, and admission type (ER or UC). The variable for race included the following categories: White, African-American, Asian, American Indian, Hispanic, and other races.

The diagnoses were coded according to the International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM). After October 1, 2015, ICD-9-CM codes were replaced by ICD-10-CM diagnostic codes; however, ICD-9-CM codes continued to be recorded and were used to identify cases for this study until Dec. 31, 2017. GI cases were limited to those with a primary diagnosis of ICD-9-CM 001–009, 558.9, 787.0, 787.01, 787.02, 787.03, 787.4, 787.9, or 787.91, as previously described[2, 20–22] This list includes bacterial, viral, and protozoal pathogens that have incubation periods ranging from <1 d to 14 d,[21] as well as general GI symptoms that are not associated with any specific pathogen. We excluded *a priori* ER or UC visits with a diagnosis of *Clostridium difficile* (008.45) because it is primarily considered a hospital-acquired infection.[22–23] Cases were excluded for newborns, elective admissions, and if the length of stay was >1 day (median: 3 days; range: 2–77 days). Longer length of stays were excluded to minimize potential bias due to differences in illness severity (n=1,056 cases excluded). A sensitivity analysis was conducted including cases with longer stays (see below).

The Oregon State University Institutional Review Board reviewed and approved the protocols for this study.

Sanitary sewage overflows (SSOs).

Under the 2013 settlement with the USEPA, the City of Columbia is required to report all SSOs regardless of the volume, including the date, time, location, source, duration, estimated volume, receiving water (if any), cause, and actions taken to resolve the cause.[18] Although SSO events are published online, the addresses are withheld.[17] In 2021, we obtained the statewide SSO database (1998–2021), including SSO addresses (D. Stoudemire, personal communication, SCDHEC). Zip codes were determined for all SSOs in Richland County from Dec. 1, 2012 - Jan. 31, 2018, covering both hazard and control periods (described below). The duration of each SSO was assumed to be ≤1 day. During Hurricane Joaquin, Oct. 1–5, 2015, there were scores of SSOs throughout Columbia, SC[24]; however, SSOs were not monitored by the City of Columbia, and thus not recorded in the SSO database.[17] As a sensitivity analysis, we imputed SSOs during Hurricane Joaquin for all zip codes (n=14 SSOs) (described below). Excluding Hurricane Joaquin, there were 830 SSOs within 14 zip codes (Table 1). There were an additional ten SSOs without complete addresses for which zip codes could not be found, and these SSOs were excluded.

Boil water advisories (BWAs).

BWAs for the City of Columbia were obtained from Columbia Water, including date of issue, data of repeal, reason for the advisory, and area of effect (i.e., location) (J. Martinez, personal communication, Columbia Water). Reasons for advisories included breaks (91%), system maintenance (4.7%), and Hurricane Joaquin (4.7%). During Hurricane Joaquin, a system-wide BWA was issued (Oct. 4–14, 2015) in all zip codes due to multiple causes, including massive line breaks, loss of source water, and increased turbidity in the availability of source water (J. Martinez, personal communication, Columbia Water). All BWAs in this analysis were associated with low pressure events (J. Martinez, personal communication, Columbia Water). Zip codes were determined for locations of all BWAs issued from Dec. 1, 2012 - Jan. 31, 2018, which included both hazard and control periods. Including the hurricane, there were 423 BWAs within 14 zip codes (Table 1), and their duration ranged from 2–13 days (median: 3 days), by counting the first day of the advisory as Day 1.

Study design and statistics.

We used a symmetric bi-directional case-crossover study design to investigate SSOs and BWAs and their associations with diagnoses of GI illness, within zip codes in Columbia, SC, and neighboring communities. Briefly, case-crossover study design is appropriate when exposures are transient, and acute health effects are observed.[25] Using this approach, each case serves as its own control, thereby controlling for individual-level factors that may confound the association of interest. Moreover, selecting control days before and after the case admission eliminates most of the bias from trends in exposure over time.[26]

We hypothesized that SSOs or BWAs increased the risk of a diagnosis of ER- or UC-GI illness within 0–14 days following exposure. This 14-day hazard period prior to a diagnosis of ER- or UC-GI illness was divided into three mutually exclusive time windows of 0–4 days, 5–9 days, and 10–14 days, as previously described.[21–22] The 0–4 day window potentially reflected direct contact with flood waters and/or infections with short incubation periods (e.g., enteric viruses), while the 5–9 day window and the 10–14 day window potentially reflected indirect exposure or infections with longer incubation periods.[21–22, 27] Two symmetric control periods were selected, beginning two weeks prior to the 0–14 day hazard period, and two weeks following a 14-day washout period after the ER- or UC-GI case (Figure S2). To cover both hazard and control periods, the date ranges for SSOs and BWAs were extended by one month at the beginning and end of the date range for ER- and UC-GI cases, including Dec. 1–31, 2012 and Jan. 1–31, 2018.

We applied a fixed-effects conditional logistic regression, which is standard for case-crossover studies[25–26], to estimate the risk of a diagnosis of ER- or UC-GI illness (dependent variable) following SSOs and/or BWAs (independent variables). For each hazard period (i.e., 0–4 days, 5–9 days, or 10–14 days), we analyzed the risk of a diagnosis of ER- or UC-GI illness following 1) an SSO; or 2) a BWA; or 3) the co-occurrence of at least one SSO and at least one BWA. Because of their frequency and duration, SSOs and BWAs were evaluated first as categorical variables (0 or 1), and then as continuous variables. The co-occurrence of an SSO and a BWA was evaluated as a categorical variable (0 or 1).

Treating SSOs and BWAs as categorical variables, stratified analyses were conducted by sex (2 categories: male versus female), age (5 categories: <5 years of age, 5–17 years of age, 18–34 years of age, 35–64 years of age, and ≥65 years of age), race (3 categories: African-American, White, and all others), and season (2 categories: January-March and April-December). Categories for stratified analyses were based on previous studies concerning sewage, including analyses of different age groups[21], and winter season versus other seasons.[3, 28] Higher exposure to sewage has been observed in racial and ethnic minority communities compared to predominantly White communities, in part due to failing infrastructure, such as sewer and water services, and policy-driven inequities in jurisdiction and annexation statutes.[4, 29] There were five cases (0.02%) with missing data for race, and these observations were excluded in the stratified analyses for race. Evidence of significant effect modification was assessed by estimating the degree of heterogeneity between stratum-specific odds ratios (ORs) in pairwise comparisons using Breslow-Day and Tarone's homogeneity tests.[30]

As noted above, SSOs were not recorded between October 1–5, 2015, during Hurricane Joaquin. As a sensitivity analysis, models were re-evaluated by imputing SSOs (i.e., recoding 0s to 1s) in each zip code between October 1–5, 2015. Additionally, models were re-evaluated as a sensitivity analysis, which included all cases, regardless of the length of stay. Lastly, stratified analyses were conducted by zip code as a sensitivity analysis.

Results are reported as ORs (95% CI), which are interpreted as the relative increase in the odds of a diagnosis of ER- or UC-GI illness, within 0–4 days, 5–9 days, or 10–14 days following a SSO and/or BWA, compared to control periods. The attributable fractions for the exposed and total population were calculated based on Hanley.[31] Data were analyzed using Stata (v. 17.0) (College Station, TX) and the R-platform (v. 4.1.2, November 1, 2021).

RESULTS

Summary of GI cases.

Between Jan. 1, 2013-Dec. 31, 2017, there were 25,969 ER- and UC-cases with a diagnosis of GI illness, listed as the primary diagnostic code (Table 2 and S1). The median age was 26 years (range: 0–101 years), and adults 18–34 years of age comprised the largest proportion of cases (32%), compared to the other age categories (range: 9–27%). There were more female than male cases (59% versus 41%). Although African-American and White residents comprised 46% and 45% of the total population, respectively (Table 1), the proportion of GI cases was far higher among African-American residents, compared to White residents (71% versus 23%) (Table 2, Figure S1). The median number of GI cases per day was 13 (range: 2–59 cases). A cyclical trend was observed in the number of GI cases, peaking in the winter, which was reported in prior studies[28]; however, the same trends were not observed for SSOs or BWAs (Figure S3, Table 2).

Summary of SSOs and BWAs.

Between Dec. 1, 2012, and Jan. 31, 2018, there were 830 SSOs and 423 BWAs (Table 1). Sewage from 440 SSOs (of 830=53%) entered a stream or body of water, suggesting sewage from the remaining SSOs was deposited solely on public or private property. Annually, the total number of SSOs between 2013–2017 (excluding December 2012 and January 2018) was 152, 143, 165, 165, and 182, respectively, while the total number of BWAs for the same timeframe was 45, 73, 83, 97, and 93, respectively. The proportions of SSOs and BWAs were highest in zip code 29203 (23% and 14%, respectively), which had the highest average annual rate of GI admissions (25 per 1000), and the highest proportion of residents who identified as Black or African-American (81.3%) (Table 1, Figure S1). Within each hazard period (0–4 days, 5–9 days, or 10–14 days), 17% of the cases experienced at least one SSO (range: 1–6 SSOs), while 11–12% of cases experienced at least one BWA (range: 1–9 BWAs) (Table S2). Just 2% of cases experienced both, i.e., at least one SSO and at least one BWA, within the same hazard period. Between Jan. 1, 2013-Dec. 31, 2017, and excluding Hurricane Joaquin (October 1–5, 2015), the proportions of SSOs and BWAs were highest between January-March, comprising 33% and 30%, respectively. Between April-June, the proportions of SSOs and BWAs were 20% and 19%, respectively; between July-September, the proportions were 21% and 25%, respectively; and between October-December, the proportions were 27% and 26%, respectively.

Associations between diagnoses of GI cases and SSOs and/or BWAs.

Associations between diagnoses of GI illness and SSOs were observed after 0–4 days, while there were no associations between diagnoses of GI illness and SSOs 5–9 days or 10–14 days later (Table 3; Figure S4). In the hazard period 0–4 days following an SSO (categorical), there was a 13% increase (95% CI: 9%, 18%) in the odds of a diagnosis of GI illness 0–4 days following an SSO, compared to control periods. Similarly, when SSOs were analyzed as a continuous variable, the odds of a diagnosis for GI illness increased by

8% (95% CI: 6%, 11%) for each additional SSO occurring within 0–4 days, compared to control periods. Within the 0–4-day hazard period, the co-occurrence of at least one SSO and at least one BWA was associated with elevated diagnoses of GI illness (OR: 1.13, 95% CI: 1.02, 1.25). BWAs alone (categorical or continuous) were not associated with increased or decreased diagnoses of GI illness within all three hazard periods; i.e., 0–4 days, 5–9 days, and 10–14 days (Table 3; Figure S4).

Stratified analyses.

In stratified analyses, in all three hazard periods, there were no differences in the odds of diagnoses of GI illness following an SSO or BWA due to sex, age, or race (Tables 4–6), with one exception. In the 10–14 day period following an SSO, the odds of diagnoses for GI illness were higher among White cases, compared to cases among African-Americans and other races. Consistently, in all three hazard periods, differences were noted due to season for BWAs. The odds of diagnoses of GI illness were higher following BWAs issued between January-March, compared to advisories issued between April-December, for all three hazard periods (0–4 days, 5–9 days, and 10–14 days).

Sensitivity analyses.

Models were re-evaluated after imputing SSOs in each zip code during the 2015 hurricane (October 1–5, 2015), and the same trends were observed as in the main analyses (Tables S3–S6). SSOs (categorical and continuous) were associated with an increase in the odds of diagnoses for GI illness 0–4 days later, compared to control periods (categorical: OR: 1.12, 95% CI: 1.08, 1.17; continuous: OR: 1.07, 95% CI 1.05, 1.10), while associations between SSOs and GI illness diagnoses were not observed during the other hazard periods (5–9 days and 10–14 days) (Table S3). The co-occurrence of an SSO and BWA was also associated with increased odds of GI illness diagnoses, compared to control periods, although the confidence interval was wide (OR: 1.09, 95% CI: 0.995, 1.20) (Table S3). In stratified analyses, the same trends were observed after imputing SSOs in each zip code during the 2015 hurricane, as in the main analyses (Tables S4–S6). Additionally, when all cases were included regardless of the length of stay, no differences were observed, compared to cases with lengths of stay ≤1 day (Tables S7–S10). Lastly, no differences were observed between zip codes in the odds of GI illness diagnoses following an SSO or a BWA in all three hazard periods (Tables S11–S13).

Attributable fraction due to SSOs.

As many as 11.5% (95% CI: 8.3%, 15%) of ER- or UC-diagnoses for GI illness following at least one SSO within 0–4 days could be attributed to SSOs [attributable fraction = (1.13−1)/1.13]. The population attributable fraction is defined as the fraction of all cases (exposed and unexposed) that would not have occurred if exposure had not occurred.[31] The fraction of exposed cases in the 0–4 day period was 17.3% (=4,489/25,969) (Table S2), and thus, the population attributable fraction following at least one SSO was 20 per 1000 (0.115 × 0.173=0.020).

DISCUSSION

Between 2013–2017, in Columbia, SC, and neighboring communities, a statistically significant increase in the odds of ER- and UC-diagnoses for GI illness was observed 0–4 days after an SSO, compared to control periods. In this hazard period, higher odds of diagnoses for GI illness did not differ by race, gender, or age. BWAs were not associated with a significant increase or decrease in the odds of ER and UC diagnoses for GI illness in all hazard periods (0–4 days, 5–9 days, and 10–14 days). However, in stratified analyses, BWAs issued between January-March were associated with higher rates of GI illness diagnoses in all three hazard periods, compared to those issued April-December.

Although SSOs occurred throughout Columbia, SC, and neighboring communities, the zip code with the highest numbers of SSOs and BWAs and the highest rate of GI illness, also had the highest proportion of residents who identified as Black as African-American (>80%) (Table 1, Figure S1). In stratified analyses from the 0–4 day hazard period, significant differences were not observed between races in models relating SSOs, BWAs, and diagnoses of GI illness (Table 4), suggesting a common exposure pathway for sewage. Infrastructure disparities have been reported in underserved minority neighborhoods, which lack up-to-code sewage and drinking water systems, causing higher exposure to pathogens.[29, 32] For example, in Greenville, Mississippi, where residents are approximately 80% Black, SSOs occur frequently.[4] Likewise, in Concordia Parish, Louisiana, the population is over 80% Black, and neglect and disrepair of the sewage treatment plants has resulted in the frequent overflow of sewage into streets, homes, and neighborhoods.[4] Similarly, in Columbia, SC, and neighboring communities, higher numbers of SSOs and BWAs occurred in a zip code where >80% of residents identified as Black or African-American, which reflected a disproportionate burden of exposure to sewage, and likely contributed to a higher number of diagnoses of GI illness.

Although raw sewage contains a myriad of pathogens, just one study investigated associations between SSOs and GI illness in four counties in eastern Massachusetts.[21] Using case-crossover study design with the same hazard periods (0–4 days, 5–9 days, and 10–14 days), the authors reported an increase in ER visits for GI illness 10–14 days after an SSO (OR: 1.09, 95% CI: 1.03, 1.16); however, there were no associations 0–4 days or 5–9 days after an SSO.[21] This timeframe differed from our study, where associations between SSOs and diagnoses of GI illness were observed within 0–4 days, which possibly reflected differences in geographic scale. In Massachusetts, GI cases were considered exposed if an SSO occurred within the same county[21], whereas in Columbia, SC, and neighboring communities, cases were considered exposed if an SSO occurred within the same zip code. Using a finer spatial scale, it was possible that exposure to SSOs occurred more rapidly, especially if sewage intruded into the drinking water distribution system. This explanation was consistent with a recent study concerning the impact of a water main break on GI illness in Massachusetts.[15] Residents living closer to the break (≤12 miles) experienced a higher rate of GI illness within 0–3 days, while the rate of GI illness was higher within 4–7 days among those living further away (>12 miles), compared to control periods.[15] The authors suggested the differences were due to the additional time it took for distributed water to reach areas further away.[15]

Results in Columbia, SC, and neighboring communities supported the notion that drinking water was an important exposure route for pathogens from SSOs within 0–4 days. For example, in stratified analyses, there were no differences in the odds ratios based on season or age categories, which would have suggested other exposure pathways were more important, such as recreational water sports (Tables 4–6). Importantly, several studies have implicated drinking water as an exposure source due to sewage contamination.[2–3, 28] For example, sewage bypass events were associated with an increase of 2.5 to 2.7 visits in pediatric ER visits for GI within 3–7 days, for communities that relied on Lake Michigan as a drinking water source, compared to communities that did not.[3] In Massachusetts, eight days following extreme rainfall events, GI cases for all age groups increased by 13% in an area exposed to sewage through drinking water, while associations were not observed in an area where exposure to sewage occurred through recreational water activities, nor in an area without sewage spills.[2] In Wauwatosa, WI, a sewage release event was associated with increased GI illness in children, thus implicating sewage contamination of the drinking water system, potentially through infiltration and inflow of drinking water pipes due to aging infrastructure.[28] Conversely, following flooding along the Mississippi River in 2001, contact with floodwater was more strongly associated with self-reported GI illness, compared to drinking water.[33]

We hypothesized that BWAs would be associated with higher rates of diagnoses of GI illness, due to frequent negative pressure events.[8, 14–16] The co-occurrence of at least one SSO and at least one BWA was associated with higher odds of diagnoses for GI illness; however, the OR did not differ from SSOs alone (Table 3), suggesting the effects on diagnoses of GI illness from co-occurrences were not additive. Moreover, BWAs co-occurring with SSOs did not reduce diagnoses of GI illness, and thus were not considered protective. There were potentially other mechanisms by which sewage from SSOs intruded into the drinking water supply. For example, sewage intrusion possibly occurred through leaks and cracks in the water pipes, following pressure transients.[10] Pressure transients (sometimes termed “surge” or “water hammer”) are caused by an abrupt change in the velocity of water, creating waves that travel through the water distribution system, resulting in low or negative pressures in many different locations (i.e., nodes).[10, 13, 34–36] The duration of negative pressure events due to pressure transients are typically brief (<1 s to 165 s); however, the drop in pressure is sufficient to increase viral and bacterial pathogen intrusion into the drinking water system through leaks.[13, 34, 36–37] Pressure transients differ from those BWAs included in this study, which had a duration of 2–13 days, and the public was alerted to potential contamination (https://local.nixle.com/city/sc/columbia/). Conversely, pressure transients are rarely monitored or alarmed due to the short timeframe; however, they carry the same potential risk of sewage contamination of the drinking water supply.[10, 34, 36] Associations between SSOs, GI illness, and the timing of pressure transients should be further studied.

In stratified analyses, we observed increased odds of diagnoses of GI illness following BWAs in January-March compared to April-December, in all three hazard periods (0–4 days, 5–9 days, and 10–14 days) (Tables 4–6). Additionally, between 10–14 days, BWAs issued between April-December had lower odds of diagnoses of GI illness, compared to advisories issued January-March (Table 6). These associations are suggestive of seasonal effects, although the reasons are uncertain. In Wauwatosa, WI, stronger associations were observed between rainfall and GI illness between December-March, compared to other months.[28] The authors suggested that contaminated runoff was greater when the ground was frozen, or the rapid freeze/thaw cycle potentially compromised the integrity of the water distribution system.[28] In this study, the proportion of BWAs was higher January-March compared to other months; however, BWAs were issued year-around, which would not likely explain seasonal trends (Figure S3). The ground was also less likely to freeze in Columbia, SC, compared to Wisconsin. An alternative explanation may be due to higher persistence of pathogens in colder temperatures in sediments.[6] Sediments are considered reservoirs for fecal microorganisms, compared to the overlying surface water, due to protection from ultraviolet radiation, decreased predation, and increased availability of nutrients.[5, 7, 38–41] Moreover, decay rates for sediment fecal microorganisms were 15 times lower at 4°C compared to 24°C, due to decreased predation.[6] One hypothesis is that higher odds of diagnoses of GI illness following BWAs issued between January-March compared to other months potentially reflected increased persistence of sewage-derived pathogens in colder temperatures, which contaminated the drinking water supply during negative pressure events. Alternatively, seasonal trends were due to some unconsidered bias or random variation, which were not measured in this study.

Unlike SSOs, which were associated with higher odds of diagnoses of GI illness within 0–4 days, seasonal trends for BWAs were observed during all three hazard periods (0–4 days, 5–7 days, and 10–14 days). The hazard period of 0–4 days was based on the median incubation period, mainly for enteric viruses[22, 27]; however, longer incubation periods have been reported. For example, noroviruses are spread through food, person-to-person, and through drinking water.[42] Although the median incubation period for noroviruses is 1.2 days[27], in Spain in a long term care facility, the incubation period for secondary infections ranged from 1–7 days.[43] Shiga-toxin producing *E. coli* (STEC) are bacterial pathogens that cause GI illness through foodborne and waterborne transmission.[44] In England and Wales, out of 41 outbreaks, the median incubation period for STEC was four days, although two outbreaks recorded longer incubation periods of 13.5 days.[45] *Salmonella* bacterial infection is caused by eating contaminated food or drinking contaminated water.[46] In Minnesota, USA[47] and Japan[48], the incubation periods for foodborne outbreaks of *Salmonella* were as long as 16 days. In Japan, the authors attributed longer incubation periods to a lower contaminating dose.[48] This suggests that the hazard periods for BWAs and SSOs were potentially related to specific pathogens (viral versus bacterial), and the dose of fecal microorganisms; however, further research is needed.

Although our study has several strengths, there are some limitations to report. First, the results of this study were based on diagnoses of ED- and UC-GI illness. However, GI illness is often under-reported, which is due in part to access to services.[49] Thus, associations between SSOs, BWAs, and diagnoses GI illness would likely differ, if all GI cases were included.[50] Second, minority communities have higher ED utilization, in part because these communities often lack a primary provider.[50] Therefore, our findings of racial disparities in rates of GI illness (Table 1) were potentially influenced by higher rates of ED- and UC-utilization by Black or African-American residents, and thus our findings should be interpreted with caution. Another limitation is that the variable for race did not include a

VA Author Manuscript

VA Author Manuscript

category for two or more races (Table 2). However, according to the American Community Survey, 2.9% of residents in these 14 zip codes identify as two or more races;[19] therefore, some cases were potentially misclassified by race. Our study utilized zip codes as the geographic unit of measure; however, a finer spatial scale (e.g., census blocks) may yield more precise results. Furthermore, we did not assess whether the SSO volume of sewage impacted diagnoses of GI illness, because SSO volume is crudely estimated, if at all.[24] Instead we focused on numbers of SSOs in each zip code, which were strongly positively correlated with estimated sewage volume (Spearman's rho: 0.82, n=14 zip codes). There were potentially other factors that influenced the associations between SSOs, BWAs and GI illness, such as pipe age and distribution system length, which were not accounted for in this study and could have influenced our results.

In conclusion, SSOs were associated with increased odds of diagnoses of GI illness within 0–4 days, while BWAs issued between January-March were associated with increased odds of diagnoses of GI compared to other months. Future research should examine potential sewage contamination of the drinking water distribution system, and mechanisms of sewage intrusion from SSOs.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Mark LeChevallier and Dr. Tyler Radniecki for providing critical advice on the manuscript. The authors also thank Dr. Kwadwo Adu Boakye for providing GIS maps.

FUNDING

DH was supported in part by a US Department of Veterans Affairs Research Career Scientist award RCS 21-136. The views expressed in this manuscript are those of the authors and do not necessarily reflect the position or policy of the Department of Veterans Affairs or the United States government.

DATA AVAILABILITY STATEMENT

SSO and BWA datasets are available from the corresponding author on reasonable request.

REFERENCES

1. U.S. Environmental Protection Agency (USEPA). Report to Congress on Impacts and Control of Combined Sewer Overflows and Sanitary Sewer Overflows, EPA 833-R-04–001. 2004. https://www.epa.gov/sites/default/files/2015-10/documents/csossortc2004_full.pdf (last accessed October 19, 2022)
2. Jagai JS, Li Q, Wang S, Messier KP, Wade TJ, Hilborn ED Extreme precipitation and emergency room visits for gastrointestinal illness in areas with and without combined sewer systems: an analysis of Massachusetts data, 2003–2007. Environ Health Perspect. 2015; 123:873–879. [PubMed: 25855939]
3. Redman RL, Nenn CA, Eastwood D, Gorelick MH Pediatric emergency department visits for diarrheal illness increased after release of undertreated sewage. Pediatrics. 2007; 10.1542/peds.2007-0283
4. Alabama Center for Rural Enterprise (ACRE), The Columbia Law School Human Rights Clinic, The Institute for the Study of Human Rights at Columbia University. Flushed

and Forgotten: Sanitation and Wastewater in Rural Communities in the United States. 2019. https://www.humanrightscolumbia.org/sites/default/files/Flushed%20and%20Forgotten%20-%20FINAL%20%281%29.pdf (last accessed October 19, 2022)

5. Craig DL, Fallowfield HJ, Cromar NJ Use of microcosms to determine persistence of *Escherichia coli* in recreational coastal water and sediment and validation with in situ measurements. J Appl Microbiol. 2004; 96:922–930. [PubMed: 15078507]
6. Garzio-Hadzik A, Shelton DR, Hill RL, Pachepsky YA, Guber AK, Rowland R Survival of manure-borne *E. coli* in streambed sediment: effects of temperature and sediment properties. Water Res. 2010; 44:2753–2762. [PubMed: 20219232]
7. Shelton DR, Pachepsky YA, Kiefer LA, Blaustein RA, McCarty GW, Dao TH Response of coliform populations in streambed sediment and water column to changes in nutrient concentrations in water. Water Res. 2014; 59:316–324. [PubMed: 24839925]
8. Ercumen A, Gruber JS, Colford JM Jr. Water distribution system deficiencies and gastrointestinal illness: a systematic review and meta-analysis. Environ Health Perspect. 2014. 122:651–660. [PubMed: 24659576]
9. Karim MR, Abbaszadegan M, LeChevallier M 2003. Potential for pathogen intrusion during pressure transients. J Am Water Work Assoc. 2003; 95:124–146.
10. LeChevallier MW, Gullick RW, Karim MR, Friedman M, Funk JE The potential for health risks from intrusion of contaminants into the distribution system from pressure transients. J Water Health. 2003; 1:3–14. [PubMed: 15384268]
11. National Research Council (NRC). Drinking Water Distribution Systems: Assessing and Reducing Risks. 2006. https://www.nap.edu/catalog/11728/drinking-water-distribution-systems-assessing-and-reducing-risks (last accessed October 19, 2022)
12. Reynolds KA, Mena KD, Gerba CP Risk of waterborne illness via drinking water in the United States. Rev Environ Contam Toxicol. 2008; 192:117–158. [PubMed: 18020305]
13. Teunis PFM, Xu M, Fleming KK, Yang J, Moe CL, LeChevallier MW Enteric virus infection risk from intrusion of sewage into a drinking water distribution network. Environ Sci Technol. 2010; 44:8561–8566. [PubMed: 20968297]
14. Hunter PR, Chalmers RM, Hughes S, Syed Q 2005. Self-reported diarrhea in a control group: a strong association with reporting of low-pressure events in tap water. Clin Infect Dis. 2005; 10.1086/427750
15. Lin GJ, Richardson DB, Hilborn ED, Weinberg H, Engel LS, Wade TJ Emergency Department visits for acute gastrointestinal illness after a major water pipe break in 2010. Epidemiology. 2019; 30:893–900. [PubMed: 31430266]
16. Nygård K, Wahl E, Krogh T, Tveit OA, Bøhleng E, Tverdal A, et al. Breaks and maintenance work in the water distribution systems and gastrointestinal illness: a cohort study. Int J Epidemiol. 2007; 36:873–880. [PubMed: 17389718]
17. South Carolina Department of Health and Environmental Control (SCDHEC). Wastewater (Sewer) Overflows. 2022. https://scdhec.gov/wastewater-sewer-overflows (last accessed October 19, 2022)
18. U.S. Environmental Protection Agency (USEPA). The United States of America and State of South Carolina v. The City of Columbia, 2013. https://www.epa.gov/sites/default/files/2013-09/documents/columbia-cd.pdf (last accessed October 19, 2022)
19. U.S. Census Bureau. American Community Survey, 5-Year Estimates, 2015–2019. 2022. https://data.census.gov/cedsci/ (last accessed October 19, 2022)
20. Brokamp C, Beck AF, Muglia L, Ryan P Combined sewer overflow events and childhood emergency department visits: A case-crossover study. Sci Total Environ. 2017; 607–608:1180–1187.
21. Jagai J,S, DeFlorio-Barker S, Lin CJ, Hilborn ED, Wade TJ Sanitary sewer overflows and emergency room visits for gastrointestinal illness: analysis of Massachusetts data, 2006–2007. Environ Health Perspect. 2017; 10.1289/EHP2048.
22. Wade TJ, Lin CJ, Jagai JS, Hilborn ED Flooding and emergency room visits for gastrointestinal illness in Massachusetts: a case-crossover study. PLoS One. 2014; 10.1371/journal.pone.0110474
23. Lin CJ, Wade TJ, Hilborn ED Flooding and *Clostridium difficile* infection: a case-crossover analysis. Int J Environ Res Public Health. 2015; 12:6948–6964. [PubMed: 26090609]

24. Emmons AM, Bizimis M, Lang SQ, Stangler W, Geidel G, Baalousha M, et al. Enrichments of metals, including methylmercury, in sewage spills in South Carolina, USA. J Environ Qual. 2018; 47:1258–1266. [PubMed: 30272795]
25. Maclure M 1991. The case-crossover design: a method for studying transient effects on the risk of acute events. Am J Epidemiol. 1991; 133:144–153. [PubMed: 1985444]
26. Maclure M, Mittleman MA Should we use a case-crossover design? Annu Rev Public Health. 2000; 21:193–221. [PubMed: 10884952]
27. Lee RM, Lessler J, Lee RA, Rudolph KE, Reich NG, Perl TM, et al. Incubation periods of viral gastroenteritis: a systematic review. BMC Infect Dis. 2013; 10.1186/1471-2334-13-446
28. Drayna P, McLellan SL, Simpson P, Li S-H, Gorelick MH Association between rainfall and pediatric emergency department visits for acute gastrointestinal illness. Environ Health Perspect. 2010; 118:1439–1443. [PubMed: 20515725]
29. Wilson SM, Heaney CD, Cooper J, Wilson O Built environment issues in unserved and underserved African-American neighborhoods in North Carolina. Environ Justice. 2008; 1:63–72.
30. Kaufman JS, MacLehose RF Which of these things is not like the other? Cancer. 2013; 119:4216–4222. [PubMed: 24022386]
31. Hanley JA A heuristic approach to the formulas for population attributable fraction. J Epidemiol Community Health. 2001; 55:508–514. [PubMed: 11413183]
32. Heaney C, Wilson S, Wilson O, Cooper J, Bumpass N, Snipes M Use of community-owned and -managed research to assess the vulnerability of water and sewer services in marginalized and underserved environmental justice communities. J Environ Health. 2011; 74:8–17.
33. Wade TJ, Sandhu SK, Levy D, Lee S, LeChevallier MW, Katz L, et al. Did a severe flood in the Midwest cause an increase in the incidence of gastrointestinal symptoms? Am J Epidemiol. 2004; 159:398–405. [PubMed: 14769644]
34. Gullick RW, LeChevallier MW, Svindland RC, Friedman MJ Occurrence of transient low and negative pressures in distribution systems. J Am Water Work Assoc. 2004; 96:52–66.
35. Marsili V, Meniconi S, Alvisi S, Brunone B, Franchini M Experimental analysis of the water consumption effect on the dynamic behavior of a real pipe network. J Hydraul Res. 2021; 59:477–487.
36. Yang J, LeChevallier MW, Teunis PFM, Xu M Managing risks from virus intrusion into water distribution systems due to pressure transients. J Water Health. 2011; 9:291–305. [PubMed: 21942194]
37. Gibson J, Karney B, Guo Y Predicting health risks from intrusion into drinking water pipes over time. J Water Resour Plann Manage. 2019; 10.1061/(ASCE)WR.1943-5452.0001039
38. Calderon JS, Verbyla ME, Gil M, Pinongcos F, Kinoshita A,M, Mladenov N Persistence of fecal indicators and microbial source tracking markers in water flushed from riverbank soils. Water Air Soil Pollut. 2022; 10.1007/s11270-022-05542-8.
39. Byappanahalli MN, Fujioka RS Evidence that tropical soil environment can support the growth of *Escherichia coli*. Water Sci Technol. 1998; 38:171–174.
40. Mika KB, Imamura G, Chang C, Conway V, Fernandez G, Griffith JF, et al. Pilot- and bench-scale testing of faecal indicator bacteria survival in marine beach sand near point sources. J Appl Microbiol. 2009; 107:72–84. [PubMed: 19302327]
41. Zimmer-Faust AG, Thulsiraj V, Marambio-Jones C, Cao Y, Griffith JF, Holden PA, et al. Effect of freshwater sediment characteristics on the persistence of fecal indicator bacteria and genetic markers within a Southern California watershed. Water Res. 2017; 119:1–11. [PubMed: 28433878]
42. Centers for Disease Control and Prevention (CDC). How Norovirus Spreads. 2021. https://www.cdc.gov/norovirus/about/transmission.html (last accessed October 19, 2022)
43. Navarro G, Sala RM, Segura F, Arias C, Anton E, Varela P, et al. An outbreak of norovirus infection in a long-term-care unit in Spain. Infect Control Hosp Epidemiol. 2005; 26:259–262. [PubMed: 15796277]
44. Centers for Disease Control and Prevention (CDC). E. coli (Escherichia coli) 2014. https://www.cdc.gov/ecoli/general/index.html (last accessed October 19, 2022)

VA Author Manuscript

VA Author Manuscript

45. Awofisayo-Okuyelu A, Hall I, Arnold E, Byrne L, McCarthy N 2019 Analysis of individual patient data to describe the incubation period distribution of Shiga-toxin producing *Escherichia coli*. Epidemiol Infect. 2019; 147:1–10.

46. Centers for Disease Control and Prevention (CDC). Salmonella. 2019. https://www.cdc.gov/salmonella/general/index.html (last accessed October 19, 2022)

47. Eikmeier D, Medus C, Smith K Incubation period for outbreak-associated, non-typhoidal salmonellosis cases, Minnesota, 2000–2015. Epidemiol Infect. 2018; 146:423–429. [PubMed: 29409557]

48. Matsui T, Suzuki S, Takahashi H, Ohyama T, Kobayashi J, Izumiya H, et al. *Salmonella* Enteritidis outbreak associated with a school-lunch dessert: cross-contamination and a long incubation period, Japan, 2001. Epidemiol Infect. 2004; 132:873–879. [PubMed: 15473150]

49. MacDougall L, Majowicz S, Dore K, Flint J, Thomas K, Kovacs S, et al. Under-reporting of infectious gastrointestinal illness in British Columbia, Canada: who is counted in Provincial communicable disease statistics? Epidemiol Infect. 2007; 136:248–256. [PubMed: 17433132]

50. Hong R, Baumann BM, Boudreaux ED The Emergency Department for routine healthcare: race/ethnicity, socioeconomic status, and perceptual factors. J Emerg Med. 2007; 32:149–158. [PubMed: 17307624]

VA Author Manuscript

VA Author Manuscript

IMPACT STATEMENT

Sewage contains pathogens, which cause gastrointestinal (GI) illness. In Columbia, South Carolina, USA, between 2013–2017, there were 830 sanitary sewage overflows (SSOs). There were also 423 boil water advisories, which were issued during negative pressure events. Using case-crossover design, SSOs (all months) and boil water advisories (January-March) were associated with increased odds of Emergency Room and Urgent Care diagnoses of GI illness, potentially due to contamination of the drinking water distribution system. Lastly, we identified a community where >80% of residents identified as Black or African-American, which experienced a disproportionate burden of sewage exposure, compared to the rest of Columbia.

Table 1.

Demographics, sanitary sewage overflows, boil water advisories, and rate of gastrointestinal illness in Columbia, South Carolina and neighboring communities.

Zip code	City	Area (km^2)[a]	Population[a]	%Black or African-American[a]	% White[a]	%Hispanic or Latino[a]	% Asian[a]	%American Indian[a]	SSO[b] n (%)	BWA[c] n (%)	2013–2017 No. of ED- and UC-GI cases	2013–2017 Avg. Annual Rate of GI (per 1000)
29016	Blythewood	225	21,389	35.7	59.0	3.9	1.4	0.2	14 (2)	11 (3)	821	7.7
29061	Hopkins	234	14,485	66.1	24.1	5.8	0.7	0.3	18 (2)	8 (2)	1,001	14
29063	Irmo	109	40,577	26.8	68.4	2.1	0.9	0.3	20 (2)	52 (12)	1,358	6.7
29201	Columbia	31	20,805	20.9	70.3	2.4	4.3	0.1	90 (11)	45 (11)	1,134	11
29203	Columbia	167	40,518	81.3	12.4	4.7	1.2	0	194 (23)	60 (14)	5,139	25
29204	Columbia	17	18,523	57.5	38.1	1.8	1.4	0.1	51 (6)	30 (7)	2,044	22
29205	Columbia	17	24,417	20.3	74.0	2.6	2.9	0	29 (3)	36 (9)	1,100	9.0
29206	Columbia	24	19,491	14.5	80.6	5.2	1.7	0.4	59 (7)	28 (7)	873	9.0
29208	Columbia	0.2	756	24.6	64.8	6.5	5.8	0	0 (0)	3 (<1)	12	3.2
29209	Columbia	136	33,523	46.5	47.3	5.0	1.9	0.2	115 (14)	25 (6)	2,106	13
29210	Columbia	13	39,312	55.1	35.4	4.8	3.2	0.2	104 (13)	32 (8)	2,888	15
29212	Columbia	62	29,435	23.9	67.8	5.3	3.6	0.1	111 (13)	40 (9)	1,284	8.7
29223	Columbia	68	51,054	58.3	29.2	7.4	5.0	0.3	22 (3)	39 (9)	3,636	14
29229	Columbia	53	52,289	59.0	29.0	5.7	4.6	0.3	3 (<1)	14 (3)	2,573	9.8
Total	N/A	1,207	406,574	46.4	45.4	4.6	2.8	0.2	830	423	25,969	13

BWA (boil water advisory), ED (Emergency Department), GI (gastrointestinal), SSO (sanitary sewage overflow), UC (Urgent Care)

[a] ref. 19

[b] Number of SSOs from the South Carolina Department of Health and Environmental Control, December 1, 2012 - January 31, 2018

[c] Number of boil water advisories issued by the City of Columbia, South Carolina, December 1, 2012 - January 31, 2018

Table 2.

Descriptive data for Emergency Department and Urgent Care cases with a diagnosis of gastrointestinal illness, January 1, 2013-December 31, 2017.

	n (%)
All	25,969 (100)
Sex	
Male	10,520 (41)
Female	15,449 (59)
Race	
African-American	18,490 (71)
White	6,072 (23)
Hispanic	638 (2)
Asian	94 (<1)
American Indian	23 (<1)
Other	647 (2)
Missing	5 (<1)
Age	
0–4 years	5,066 (20)
5–17 years	3,363 (13)
18–34 years	8,274 (32)
35–64 years	7,045 (27)
≥65 years	2,221 (9)
Admission type	
Emergency Department	14,188 (55)
Urgent Care	11,781 (45)
Length of stay	
0 days	21,486 (83)
1 day	4,483 (17)
Year	
2013	5,198 (20)
2014	4,972 (19)
2015	5,817 (22)
2016	5,118 (20)
2017	4,864 (19)
Month	
January	2,329 (9)
February	2,971 (11)
March	3,153 (12)
April	2,455 (9)
May	1,976 (8)

	n (%)
June	1,788 (7)
July	1,644 (6)
August	1,668 (6)
September	1,776 (7)
October	1,879 (7)
November	2,120 (8)
December	2,210 (9)

Table 3.

Odds ratios and 95% confidence intervals for Emergency Room and Urgent Care diagnoses of gastrointestinal illness following sanitary sewage overflows and/or boil water advisories, for each hazard period (0–4 days, 5–9 days, and 10–14 days) (n=25,969 cases).

	0–4 days OR (95% CI)	p-value	5–9 days OR (95% CI)	p-value	10–14 days OR (95% CI)	p-value
SSO (categorical)	1.13 (1.09, 1.18)	<0.001 ***	0.995 (0.956, 1.04)	0.80	1.01 (0.968, 1.05)	0.72
SSO (continuous)	1.08 (1.06, 1.11)	<0.001 ***	1.01 (0.980, 1.03)	0.66	1.00 (0.977, 1.03)	0.87
BWA (categorical)	1.04 (0.988, 1.08)	0.15	0.986 (0.942, 1.03)	0.57	0.984 (0.939, 1.03)	0.50
BWA (continuous)	1.01 (0.997, 1.03)	0.095	0.991 (0.974, 1.01)	0.28	0.999 (0.982, 1.02)	0.90
SSO and BWA (categorical)	1.13 (1.02, 1.25)	0.02 *	0.917 (0.832, 1.01)	0.08	0.958 (0.865, 1.06)	0.41

* p<0.05

*** p<0.001 p-value is for the odds ratio

BWA (boil water advisory), CI (confidence interval), OR (odds ratio), SSO (sanitary sewage overflow)

Table 4.

Stratified analyses for sanitary sewage overflows and/or boil water advisories during the 0–4 day hazard period (n=25,969 cases).

	SSO Odds Ratio (95% CI)	p-value	BWA Odds Ratio (95% CI)	p-value	SSO and BWA Odds Ratio (95% CI)	p-value
Sex						
Male	1.11 (1.04, 1.18)	0.48	1.08 (1.00, 1.16)	0.14	1.09 (0.925, 1.27)	0.54
Female	1.14 (1.09, 1.21)		1.01 (0.945, 1.07)		1.16 (1.01, 1.32)	
Race						
African-American	1.11 (1.06, 1.17)	0.45	1.03 (0.977, 1.09)	0.63	1.13 (1.01, 1.26)	0.92
White	1.18 (1.08, 1.29)		1.02 (0.922, 1.13)		1.14 (0.898, 1.45)	
Other [a]	1.20 (0.973, 1.47)		1.14 (0.924, 1.39)		1.00 (0.511, 1.89)	
Age						
0–4 years	1.08 (0.982, 1.18)	0.54	1.09 (0.980, 1.21)	0.55	1.20 (0.948, 1.50)	0.43
5–17 years	1.13 (1.01, 1.27)		0.969 (0.844, 1.11)		0.903 (0.656, 1.23)	
18–34 years	1.13 (1.05, 1.21)		1.07 (0.981, 1.16)		1.13 (0.942, 1.35)	
35–64 years	1.14 (1.06, 1.24)		1.01 (0.919, 1.10)		1.11 (0.917, 1.34)	
≥65 years	1.24 (1.08, 1.43)		0.986 (0.835, 1.17)		1.39 (0.974, 1.98)	
Season						
April-Dec	1.14 (1.08, 1.20)	0.78	0.985 (0.929, 1.04)	0.003 **	1.09 (0.968, 1.24)	0.39
Jan-March	1.12 (1.05, 1.20)		1.14 (1.05, 1.24)		1.20 (1.00, 1.44)	

** p<0.01 p-value is for the Breslow-Day and Tarone's homogeneity tests between strata

BWA (boil water advisory), CI (confidence interval), SSO (sanitary sewage overflow)

[a] Other = Hispanic, Asian, American Indian, and other races

Table 5.

Stratified analyses for sanitary sewage overflows and/or boil water advisories during the 5–9 day hazard period (n=25,969 cases).

	SSO Odds Ratio (95% CI)	p-value	BWA Odds Ratio (95% CI)	p-value	SSO and BWA Odds Ratio (95% CI)	p-value
Sex						
Male	0.982 (0.922, 1.05)	0.60	0.993 (0.923, 1.07)	0.81	0.861 (0.733, 1.01)	0.32
Female	1.00 (0.953, 1.06)		0.982 (0.924, 1.04)		0.953 (0.840, 1.08)	
Race						
African-American	0.991 (0.947, 1.04)	0.07	0.982 (0.929, 1.04)	0.92	0.886 (0.792, 0.991)	0.39
White	1.05 (0.962, 1.15)		1.00 (0.910, 1.11)		1.06 (0.832, 1.34)	
Other [a]	0.822 (0.670, 1.01)		0.980 (0.799, 1.20)		0.964 (0.582, 1.56)	
Age						
0–4 years	0.995 (0.909, 1.09)	0.82	0.960 (0.863, 1.07)	0.88	0.923 (0.729, 1.16)	0.55
5–17 years	1.02 (0.909, 1.13)		1.03 (0.902, 1.18)		0.801 (0.591, 1.08)	
18–34 years	0.963 (0.898, 1.03)		1.01 (0.928, 1.09)		0.910 (0.769, 1.08)	
35–64 years	1.03 (0.949, 1.11)		0.966 (0.883, 1.06)		1.02 (0.847, 1.24)	
≥65 years	0.990 (0.861, 1.14)		0.971 (0.823, 1.15)		0.778 (0.531, 1.12)	
Season						
April-Dec	1.01 (0.964, 1.07)	0.24	0.947 (0.895, 1.00)	0.01 *	0.930 (0.825, 1.05)	0.68
Jan-March	0.965 (0.905, 1.03)		1.08 (0.992, 1.17)		0.889 (0.742, 1.06)	

* p<0.05 p-value is for the Breslow-Day and Tarone’s homogeneity tests between strata

BWA (boil water advisory), CI (confidence interval), SSO (sanitary sewage overflow)

[a] Other = Hispanic, Asian, American Indian, and other races

Table 6.

Stratified analyses for sanitary sewage overflows and/or boil water advisories during the 10–14 day hazard period (n=25,969 cases).

	SSO Odds Ratio (95% CI)	p-value	BWA Odds Ratio (95% CI)	p-value	SSO and BWA Odds Ratio (95% CI)	p-value
Sex						
Male	1.01 (0.943, 1.07)	0.90	0.988 (0.917, 1.06)	0.89	1.01 (0.857, 1.19)	0.41
Female	1.01 (0.959, 1.06)		0.981 (0.924, 1.04)		0.925 (0.808, 1.06)	
Race						
African-American	0.988 (0.944, 1.03)	0.02*	0.967 (0.915, 1.02)	0.44	0.956 (0.850, 1.07)	0.71
White	1.12 (1.02, 1.22)		1.02 (0.922, 1.12)		0.923 (0.712, 1.19)	
Other [a]	0.861 (0.700, 1.06)		1.08 (0.879, 1.32)		1.17 (0.679, 1.96)	
Age						
0–4 years	0.984 (0.899, 1.08)	0.48	0.937 (0.840, 1.04)	0.50	1.06 (0.836, 1.34)	0.52
5–17 years	1.01 (0.899, 1.12)		1.07 (0.939, 1.23)		1.07 (0.785, 1.46)	
18–34 years	0.970 (0.904, 1.04)		0.990 (0.912, 1.07)		0.848 (0.708, 1.02)	
35–64 years	1.06 (0.983, 1.14)		0.993 (0.908, 1.09)		0.987 (0.808, 1.20)	
≥65 years	1.04 (0.906, 1.20)		0.913 (0.771, 1.08)		0.955 (0.645, 1.39)	
Season						
April-Dec	0.988 (0.939, 1.04)	0.23	0.932 (0.880, 0.986)	0.0009 ***	0.918 (0.809, 1.04)	0.24
Jan-March	1.04 (0.974, 1.11)		1.10 (1.02, 1.20)		1.04 (0.872, 1.25)	

*** p<0.001 p-value is for the Breslow-Day and Tarone's homogeneity tests between strata

BWA (boil water advisory), CI (confidence interval), SSO (sanitary sewage overflow)

[a] Other = Hispanic, Asian, American Indian, and other races