DRINKING WATER QUALITY AND HUMAN HEALTH: IMPACT OF HARMFUL ALGAE AND WATER PIPE BREAKS

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ABSTRACT

Cynthia Jean Lin: Drinking Water Quality and Human Health:
Impact of Harmful Algae and Water Pipe Breaks
(Under the direction of David Richardson)

Many factors within a water system can influence drinking water quality. One example is the presence of cyanobacteria, which can naturally occur in surface water sources of drinking water and produce toxins associated with harmful algal blooms. Another example is the deterioration of drinking water distribution systems, which can lead to pipe breaks. This study assessed how such factors within a large drinking water system serving metropolitan Boston communities may influence human health.

In Aim 1, Poisson regression models were used to estimate the associations between daily measures of cyanobacteria concentration in the water source and emergency department (ED) visits for acute gastrointestinal illness (AGI), respiratory illness, and dermal illness over a 7-year period (7/27/2005 – 9/30/2012). Considering both 2-4 and 5-7 day lag periods, small relative increases in daily ED visits were observed for AGI and respiratory illness when comparing upper quartile levels of cyanobacteria concentrations with the lowest quartile (≤5.0 Areal Standard Units/mL).

In Aim 2, case-crossover methods were used to examine the associations between water pipe breaks and ED visits for AGI. The first part (Aim 2a) examined 385 water main breaks in the City of Boston over a 10-year period (10/1/2002 – 9/30/2012). The second part (Aim 2b) examined a major water pipe break in 2010 that resulted in a boil water order affecting 30 metropolitan Boston communities. Conditional fixed-effects logistic regression models estimated the risk of ED visits for AGI during 0-3 and 4-7 day hazard periods. When restricted to zip codes served primarily by a single water service network, the association between main breaks and ED visits for AGI was slightly elevated during the 0-3 days after a break (Odds Ratio, OR=1.15; 95% Confidence Interval, CI: 0.99-1.34). Furthermore, there was an increased risk of ED visits for AGI during the 0-3 days after the major water pipe break in 2010 (OR=1.32; 95% CI: 1.07-1.61), particularly among children (≤5 years) and adolescents (6-18 years).

This dissertation identified potential health risks related to cyanobacteria in the water source and water pipe breaks in the distribution system. These associations are important to consider given the consequences of a changing climate and aging infrastructure.

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LIST OF ABBREVIATIONS

AGI	Acute gastrointestinal illness
ASU	Areal Standard Units
BWSC	Boston Water and Sewer Commission
CDC	Centers for Disease Control and Prevention
CI	Confidence interval
CWTP	John J. Carroll Water Treatment Plant
DCR	Massachusetts Department of Conservation and Recreation
ED	Emergency department
EPA	U.S. Environmental Protection Agency
ICD-9-CM	International Classification of Disease, Version 9, Clinical Modification
IRR	Incidence rate ratio
MA	Massachusetts
MWRA	Massachusetts Water Resources Authority
MGD	Millions of gallons per day
OR	Odds ratio
SDWA	Safe Drinking Water Act
WHO	World Health Organization

CHAPTER 1. SPECIFIC AIMS

Inadequately treated and contaminated drinking water can result in a wide range of adverse health effects, such as gastrointestinal, respiratory, and dermal symptoms of illness. Within a municipal water system, many factors can influence drinking water quality. The objective of this dissertation was to examine whether two potential contamination events are associated with increased illness. The first was the presence of cyanobacteria, or blue-green algae, in the water source. The second was pipe breaks in the drinking water distribution system. Both questions were analyzed within the context of a large water system operated by the Massachusetts Water Resources Authority (MWRA) that provides drinking water to metropolitan Boston communities.

Specific Aim 1

The first Specific Aim was to estimate the association between daily measures of cyanobacteria in the Wachusett Reservoir and emergency department (ED) visits for acute gastrointestinal, respiratory, and dermal symptoms of illness in metropolitan Boston communities served by MWRA over a 7-year period (7/27/2005 – 9/30/2012). The hypothesis was that higher levels of cyanobacteria in the drinking water source would increase the rate of ED visits for acute gastrointestinal, respiratory, and/or dermal symptoms of illness. This association was expected to be most apparent during up-welling and blooming periods. Also, the effect of cyanobacteria was hypothesized to be strongest in sensitive populations, such as children and elderly.

Specific Aim 2

The second Specific Aim had two parts. The first (Aim 2a) was to estimate the association between water main breaks and ED visits for acute gastrointestinal illness (AGI) over a 10-year period (10/1/2002 – 9/30/2012) in the City of Boston. The second (Aim 2b) was to estimate the association between a major water pipe break in 2010 and ED visits for AGI in metropolitan Boston communities affected by the subsequent boil water order. The overall hypothesis was that the occurrence of water main breaks would have a positive association with subsequent ED visits for AGI. This association was anticipated to be strongest with the major water pipe break in 2010 (Aim 2b). Sensitive populations, such as children and elderly, were expected to be most affected.

Study Significance

Unplanned and unregulated events, such as the amount of cyanobacteria in the source water (1-5) and the occurrence of main breaks (6, 7), are projected to increase over time due to a changing climate and aging infrastructure. Therefore, human exposure to contaminated drinking water may also increase. Harmful algal blooms and water main breaks are widespread(8, 9); therefore, results from this study are applicable to other water systems around the country. A better understanding of the public health impact can aid in the overall decision-making process regarding drinking water regulations, monitoring procedures, and response plans. Since drinking water is a human necessity, uncovering even a small effect could have major public health implications.

Study Innovation

This dissertation project addresses gaps in the literature regarding the human health impact of potential contamination events in municipal drinking water systems. The first Specific Aim provides insight on chronic low levels of cyanobacteria since the existing literature focuses primarily on high bloom levels that resulted in disease outbreaks. Low-level drinking water exposure to cyanobacteria provides a more common scenario experienced by water treatment plants. The second Specific Aim focuses on characterizing the risk of AGI after a main break. While it is established that pressure transients can allow contaminants to enter a drinking water distribution system, there are few epidemiology studies that characterize the subsequent health risks.

CHAPTER 2. BACKGROUND

Drinking Water Exposures

Water is essential to sustain human life(10). Specifically, water is the solvent for biochemical reactions, is essential for cellular homeostasis, absorbs the body heat from metabolic processes, maintains vascular volume, and serves as the medium for transport within the body by supplying nutrients and removing waste(11). Severe dehydration can lead to low blood pressure, rapid heartbeat, and even delirium(12). Serious complications of dehydration include cerebral edema, seizures, and kidney failure(13). Given these health risks, staying hydrated is an important part of maintaining health(14, 15). The Institute of Medicine recommends a daily total water intake of 2.7 liters (91 ounces) for healthy adult women and 3.7 liters (125 ounces daily) for healthy adult men(16). Total water intake can come from all beverages and foods(16).

According to data from the 3rd National Health and Nutrition Examination Survey (NHANES III), adults in the U.S. obtained total water from the following sources: 35-54% from drinking water, 49-63% from other beverages (with juice, carbonated drinks, coffee, and milk being the major sources), and 19-25% from foods (such as fruits, vegetables, soups, ice cream, and meats)(11). Similarly, the Institute of Medicine estimates approximately 80% of people's total water intake comes from drinking water and beverages while the other 20% come from food(16). Although water is present in foods and beverages, plain water (i.e., tap and plain non-carbonated bottled water) is consumed on any given day by 76% of Americans over the age of two(17). Based on nationwide dietary intake data, the average daily intake of plain drinking water is 3.9 cups, with over half (61%) of the overall intake coming from tap water versus bottled water(17). Most (69%) of the plain drinking water consumed occurs at home, with tap water accounting for two-thirds of the water consumed at home(17). Factors affecting water intake may include physical activity, extreme temperatures (hot and cold), and altitude(11). In addition, adult women (≥20 years) are more likely to report drinking water compared to men, especially among those over the age of 60 years(17).

Most people consume and come in contact with tap water(18). Human exposure to contaminants in tap water can occur through ingestion, inhalation, and/or dermal absorption (see Figure 1)(19). Aside from drinking, water is also used for many everyday purposes, from cooking, cleaning, bathing and other basic hygiene, to recreational, agricultural, and industrial activities(20). The average American family uses over 300 gallons of water per day at home(21). With drinking water exposure being essentially universal, studies finding even a small effect on illness could have a major impact on public health(22).

Figure 1: Routes of water exposure: ingestion, inhalation, dermal absorption.
Source: http://sphweb.bumc.bu.edu/otlt/mph-modules/ExposureAssessment/exposureassessment3.html

Drinking Water-Associated Illnesses

When drinking water is not adequately treated, human exposure to waterborne contaminants such as pathogenic microorganism (waterborne pathogens) can lead to subsequent illness(23, 24). In fact, prior to drinking water disinfection, the occurrence of diseases such as cholera and typhoid were common the U.S. and killed thousands(25). Considering the global challenges of producing safe water, the U.S. and other developed countries generally provide wide access to high-quality, safe drinking water supplies(26). Despite the wealth in resources and technologies in developed countries, however, poor quality source water, inadequate treatment, and failing distribution infrastructures still exist and waterborne illnesses associated with drinking water still occur(26-29). Also, a changing climate can impact water quality(4, 30). For example, extreme weather events such as heavy precipitation and flooding can cause heavy runoff events to pollute drinking water sources and increased nutrient loadings can cause extensive algal blooms(4, 30). In addition, floods can threaten the water distribution infrastructure(30, 31). Contaminated drinking water can lead to serious health consequences, especially among sensitive populations (e.g., infants and young children, elderly, pregnant women, immunocompromised groups)(27, 32, 33). According to a review of waterborne disease outbreaks occurring in developed nations, contributing factors include: contamination by wastewater, insufficient knowledge of source water hazards, inadequate disinfection, severe weather (e.g., heavy precipitation and runoff), filtration problems, cross-connections and distribution failures, livestock or wildlife fecal contamination, and changes in plant maintenance or treatment process(26). In the U.S., the majority of drinking water outbreaks have been linked to untreated or inadequately treated groundwater and distribution system deficiencies(4). Aside from factors directly contributing to drinking water outbreaks, there can be income or racial disparities in water infrastructure maintenance and drinking water quality(34, 35). Drinking water-associated illnesses, even if sub-clinical, could result in loss of productivity at work and school for both the affected individuals and their caregivers(36, 37). With acute cases of illness, there can also be added healthcare and medication costs(36).

The types of illness that have been associated with drinking water contaminants (e.g., bacteria, chemicals, parasites, viruses) include acute gastrointestinal illness, acute respiratory illness, skin infections, neurological illness, and inflammation of the liver(19). Acute gastrointestinal illness, which includes a range of symptoms such as diarrhea, vomiting, nausea, and cramps, is often the standard metric for illness associated with microbial contamination of drinking water because it is the broadest indicator of the health effects associated with most waterborne pathogens(38). It is also a convenient measure because it can be evaluated by observation without needing multifaceted sample collection or analytical procedures(38). Cases from the cryptosporidiosis outbreak in Milwaukee shared many similar gastrointestinal symptoms (e.g., diarrhea, abdominal cramping, and nausea) and general signs and symptoms (e.g., fatigue, low-grade fever, muscle aches, and headaches)(39). Acute respiratory illness, often caused by *Legionella spp.*, has also been reported in more recent outbreaks associated with drinking water (40, 41). Other outbreaks, such as skin infections (e.g., *Pseudomonas*), neurological illness (e.g., primary amebic meningoencephalitis), and inflammation of the liver (e.g., hepatitis A), have been observed but are less common(19, 40).

The Centers for Disease Control and Prevention (CDC) defines a waterborne disease outbreak as two or more persons experiencing a similar illness and are epidemiologically linked by time and by location to water exposure(19, 42). The CDC, along with the EPA and the Council of State and Territorial Epidemiologists (CSTE), conduct regular surveillance for waterborne disease outbreaks(19). During the 36-year period from 1971 through 2006, 780 outbreaks were associated with drinking water exposure in the U.S., resulting in 577,094 cases of illness(19). The total number of illnesses, however, was strongly influenced by an estimated 403,000 cases from a single outbreak occurring in 1993 when a filtration process failed to remove *Cryptosporidium* oocysts at a municipal water treatment plant in Milwaukee, Wisconsin(19, 39). This single outbreak was associated with 4,400 hospitalizations(36) and 50 deaths(43). After excluding the Milwaukee outbreak, the average size of a drinking water-associated outbreak was estimated to be 340.5 cases for community water systems and 162.6 cases for non-community water systems(19). In the most recent surveillance report published by the CDC, 32 drinking water-associated outbreaks were reported from 2011 through 2012, accounting for at least 431 cases of illness, 102 hospitalizations, and 14 deaths(41). Although this may appear to be a relatively low public health burden, the authors note that outbreak surveillance data underestimate actual values and should therefore not be used to evaluate the total number of outbreaks or cases of waterborne disease(41).

The challenge in describing the potential significance of waterborne diseases related to drinking water is that they probably occur more often than reported(41, 42, 44, 45). The true impact of drinking water-associated diseases is most likely underestimated due to limitations in available and well-documented surveillance data on drinking water quality, drinking water consumption, and illness(26, 27, 41, 42). Specifically, the factors influencing the underreporting of gastrointestinal infections include the large number of asymptomatic cases, symptomatic cases that do not seek treatment, cases that seek treatment but are not given a specific diagnosis and/or are not asked to provide information regarding exposures, and cases that actually receive a diagnosis but are not then reported(44, 45). Also, since the level of surveillance and reporting activity, as well as reporting requirements, vary across states and localities, it is difficult to produce a comprehensive national statistic(41). Of all the illnesses associated with the massive cryptosporidiosis outbreak in Milwaukee, it has been estimated that the majority (88%) did not seek medical attention and only about 11% seen as outpatient and 1% hospitalized(36). As expected, cases typically sought health care only when the illness was severe or prolonged(39).

To address some of the data limitations of waterborne disease outbreaks, several attempts have been made to quantify the background or endemic levels of waterborne disease. Morris and Levins (1995) estimated an annual incidence of 7.1 million cases of gastrointestinal infections and 1,200 deaths attributable to waterborne disease(45). Colford et al. (2006) estimated a range of 4.26 to 11.69 million cases of acute gastrointestinal illness in the U.S. attributable to drinking water from community drinking water systems(46). Accounting for all waterborne illnesses attributable to drinking water (i.e., not just gastroenteritis), Reynolds et al. (2008) estimated 26 million infections and 13 million illnesses occurring each year in U.S. municipal surface water systems(27).

Waterborne Pathogens

Water contamination can originate from many different sources, including nearby land use practices (fertilizers, pesticides, livestock), naturally occurring chemicals and minerals (e.g., arsenic, radon, uranium), manufacturing processes, and sewer overflows or wastewater releases (47). While most enteric and opportunistic pathogens that can spread by the fecal-oral route can also be transmitted through water, an organism's ability to cause a waterborne disease outbreak depends on its rate of survival in the water environment and its infectious dose(42, 44). Enteric pathogens that can survive but not proliferate in drinking water include *Vibrio cholerae*, *Shigella* spp., *Campylobacter jejuni*, *Giardia lamblia*, and *Cryptosporidium parvum(44)*. *Giardia* and *Cryptosporidium* are two of the most common and bothersome protozoan parasites since they can develop into hard-shelled cysts resistant to chlorine disinfection(24). Other waterborne enteric bacteria include *Salmonella* and certain strains of *Escherichia coli(27, 42)*. Environmental pathogens that can both survive and proliferate in drinking water include a number of opportunistic pathogens, such as *Legionella* spp., *Aeromonas* spp., *Pseudomonas aeruginosa*, and *Mycobacterium avium*(42, 44). There are also toxins produced by certain freshwater harmful algae (e.g., cyanobacteria)(4). Viruses of greatest concern in water include enteroviruses, hepatitis A virus, noroviruses, astrovirus, adenovirus, and rotavirus(27). While viruses cannot multiply in the receiving waters, their infective dose is low, typically ranging from just one to ten infectious units(42).

Aside from microorganisms, other potentially health-threatening water pollutants include toxic minerals and metals (e.g., arsenic, lead, nitrates, nitrites), organic chemicals (e.g., synthetic fertilizers, pesticides, herbicides, pharmaceuticals), radioactive substances (e.g., radon, radioactive runoff from mining, radioactive minerals from coal-fired power plants), and additives and their respective by-products (e.g., chlorine, fluoride, flocculating agents)(24). Newly emerging diseases also provide challenges to ensuring safe drinking water(48). Such challenges include resistance to chlorination or disinfection, resistance to standard medical treatment, zoonotic as well as human transmission, and low infective dose(48).

Given the abundance of potential waterborne pathogens in drinking waters, Messner *et al.* (2006) has stressed the need for addressing exposure to mixtures of pathogens, rather than to an individual pathogen, when considering health risks(27, 38). They contend that there could be an order of magnitude difference between the risk from regulated pathogens (e.g. *Cryptosporidium*) and the risk from the total mixture of pathogens that people may be exposed to from drinking water(38).

Since it is impossible to measure every possible waterborne pathogen, drinking water turbidity has often been used as a proxy measure for potential microbial contamination and the effectiveness of drinking water treatment(22, 49-51). When light penetrates a water sample, turbidity is a measure of the amount of light that is scattered by material in the water (i.e., relative clarity; cloudiness)(52). Pathogens (e.g., viruses, parasites, bacteria), along with clay, silt, finely divided inorganic and organic matter, algae, and plankton, can be among the mix of material found in water(51, 52). While outbreaks of gastrointestinal illness have been linked to extreme turbidity events(39, 53, 54), the findings from epidemiology studies have been inconsistent(22). Mann et al. (2007) reasoned that conflicting results could be due to variations in the mean turbidity level between study settings and differences in modeling strategies(22). Tinker et al. (2010) conducted a study in Atlanta and found a positive association between raw water turbidity and emergency department visits for gastrointestinal illness(55). Furthermore, they did not find an association with filtered water turbidity, thus highlighting the importance of considering source water quality (55). Similarly, Beaudeau et al. (1999) had found an association between raw water turbidity and subsequent antidiarrheal drug sales, but not with filtered water turbidity(56). Recently, Hsieh et al. (2015) found an association between source water turbidity in New York City and emergency department visits for diarrhea among the youngest age groups during the spring season, but concluded that the majority of the temporal variation in diarrhea was due to seasonal illness patterns unrelated to source water turbidity(57). In effluent water, a study in Russia found an association between an increase in water turbidity and an increased risk of self-reported gastrointestinal illness with a lag of 2 days(58).

An etiology was determined for 55% of the 780 outbreaks associated with drinking water occurring from 1971 to 2006 in the U.S(19). Of those, parasites were most frequently identified (18%), followed by non-Legionella bacteria (13%), chemicals (12%), and viruses (8%)(19). *Legionella* (3%) was only identified as the etiologic agent during the latter part of the 31-year period from 2001 to 2006(19). Only six outbreaks (<1%) reported mixed agents (i.e., combination of bacteria, parasites, and/or viruses)(19). Also, demonstrating the limitations in available data, it is important to note that no etiology was reported for 45% of the outbreaks(19). During the cryptosporidiosis outbreak in Milwaukee, physicians usually diagnosed viral gastroenteritis or intestinal flu, without further investigation into the etiologic agent(39). By examining drinking water outbreaks associated with microbial contaminants in developed countries, Onyango et al. (2015) found that the most common pathogens involved were *Campylobacter* spp., *Norovirus* and *Cryptosporidium* spp.(59). Onyango et al. (2015) reported that 75% of cases were linked to a single microbial species, though the remaining 25% had either an unknown microbial agent or multiple etiologies of infection (see Figure 2)(59).

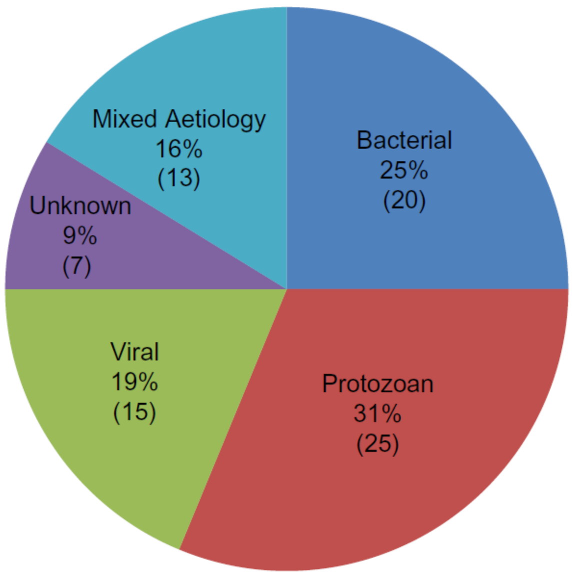

Figure 2: Microbial agents associated with drinking water outbreaks in developed countries.
Source: Onyango et al. 2015 (59)

Maintaining Safe Drinking Water

Safe drinking water depends on several factors that fall into three broad categories (see Figure 3). First, it depends on a well-protected water source (e.g., lakes, streams, reservoirs, wells) that guards against natural and man-made pollution(27). Secondly, it depends on effective treatment processes to remove a variety of potential contaminants in a timely manner(27). Lastly, it depends on a well-maintained distribution system to safely transport clean water to the consumers(27).

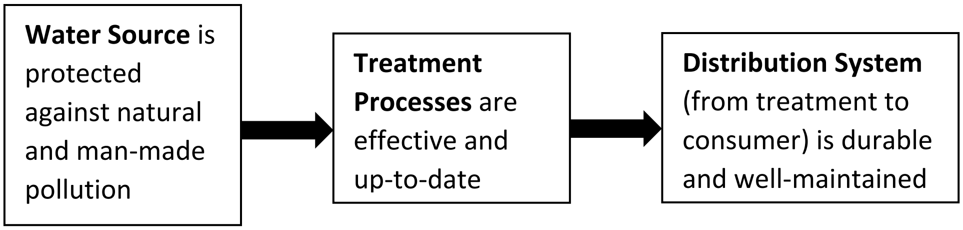

Figure 3: Fundamental stages of ensuring safe drinking water quality.

The U.S. Environmental Protection Agency (EPA) defines drinking water systems as either public or individual(60, 61). There are three types of public water systems: community; non-transient non-community; and transient non-community (see Figure 4 for definitions)(62). Of the approximately 153,530 public drinking water systems, 34% are community systems that serve the same population year-round(62, 63). The majority (82%) of the U.S. population is served by just 8% of the community water systems(63). During the 2009 fiscal year, there were a total of 51,651 community water systems serving 294,339,881 people(63). Individual water systems consist of the use of non-public sources (e.g., bottled water) and private water systems (e.g., ground water wells)(60). In 2010, the majority (87%) of the U.S. population received their water from a public-supply system and only about 14% supplied their own water for domestic use(64, 65).

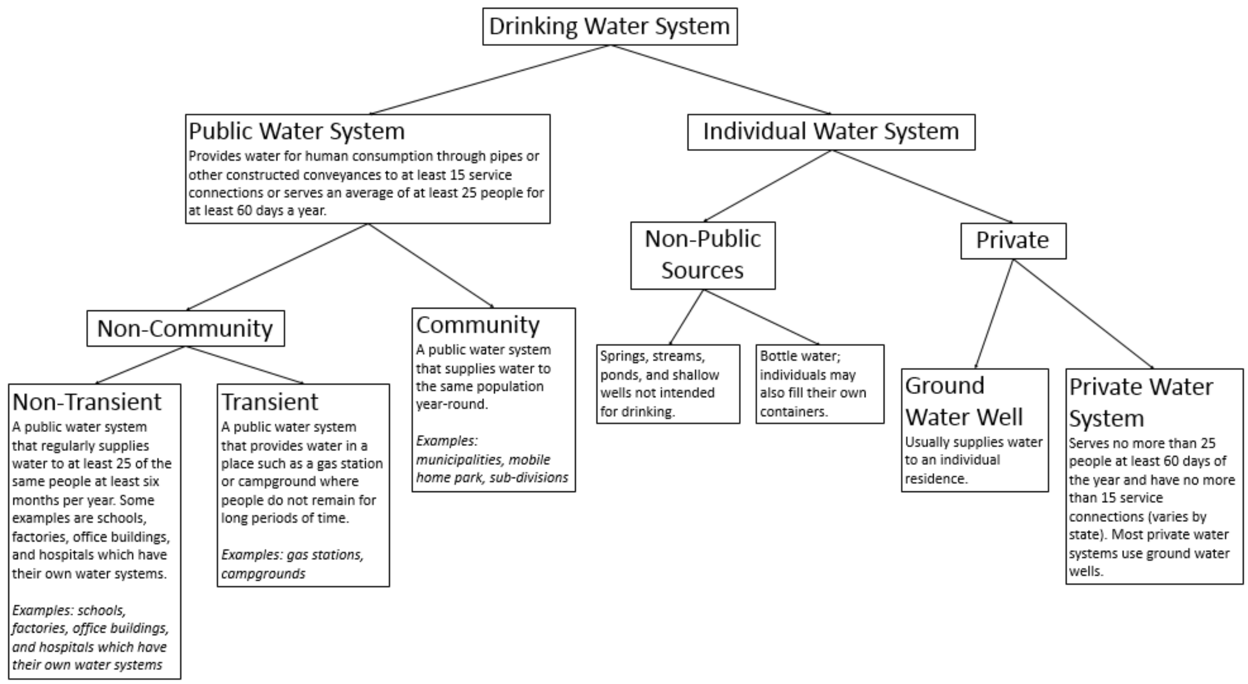

Figure 4: Different types of water systems, as defined by the EPA.
Source: EPA 2015 (62), CDC 2014 (60)

Drinking Water Regulations

The World Health Organization (WHO) produces international drinking water guidelines for the protection of public health(33). These guidelines, which provide a framework for safe drinking water centered on health-based targets, water safety plans, and surveillance, serve as the basis for national drinking water regulations and standards around the world(33). In the U.S., regulated drinking water can come in the form of tap and bottled water. The Food and Drug Administration (FDA) oversees bottled water, while the EPA regulates tap water from public water systems(66-69). Both kinds of water are regularly tested for contaminants, though public water systems are typically assessed more frequently(68). For the protection of public water systems, the Safe Drinking Water Act (SDWA) authorizes the EPA to establish minimum drinking water contaminant standards and requires all system owners or operators to comply with these standards(69, 70). Aside from setting legal limits on drinking water contaminants, the EPA also standardizes water-testing schedules and methods that water systems must follow(71). Under the SDWA, each level of government (e.g., federal, state, tribal), every public water system, and the individual consumer have distinct roles and responsibilities(69, 72-74). Public water systems regulated by the EPA supply drinking water to 90% of the country's population(69). Individual water systems, such as privately owned wells, are not regulated by the EPA so it is up to the individual homeowners to maintain the safety of their water(60).

The National Primary Drinking Water Regulations (NPDWRs or primary standards), established by EPA under the SDWA, requires public water systems to comply with the maximum contaminant levels (MCLs) for a list of contaminants(75). Currently, EPA has drinking water regulations for over 90 contaminants(51, 76). These contaminants include microorganisms, such as *Cryptosporidium*, *Giardia lamblia*, total coliforms, and enteric viruses(51). Public water systems closely monitor bacteria because they can pose a recognizable human health risk and their presence can be easily detected(24). Viruses, while common in water, are more difficult to detect due to their small size (0.004 – 0.1 µm) and inability to be easily grown in cell culture(24, 27, 77, 78). Regulated contaminants also include disinfectants (e.g., chloramines, chlorine), disinfection byproducts (e.g., trihalomethanes, haloacetic acid, bromate, chlorite), inorganic chemicals (e.g., arsenic, lead, fluoride), organic chemicals (e.g., benzene, polychlorinated biphenyls), and radionuclides (e.g., alpha particles, uranium)(51). These regulations are determined by the level that protects public health and the technological capability of the water systems(71). EPA reviews each national primary drinking water regulation at least once every six years and, if needed, revises them according to any new data, information, and technologies(79). See Appendix 1 for list of NPDWRs.

Under SDWA, there are four types of reportable violations: 1) health-based; 2) monitoring and reporting; 3) public notice; and 4) other(80). Health-based violations are related to noncompliance with treatment requirements or exceedances in maximum contaminant or residual disinfectant concentrations(80). Monitoring and reporting violations are related to inconsistent monitoring or not reporting monitoring results on time(80). Public notice violations are related to inadequate consumer alerts of drinking water issues(80). Other violations are related to additional SDWA requirements, such as failing to issue annual consumer confidence reports(80). When SDWA marked its 25th anniversary at the end of 1999, the national goal for drinking water was set to provide water that met all health-based standards to 95% of the population served by public drinking water supplies by 2005(81, 82). In 2002, the level of compliance with these health-based standards was already 94%(81, 83).

For both groundwater and surface water systems during the 2011 fiscal year, 55% of all community water systems had at least one violation of SDWA regulations(84). These community water systems served a total of 95.4 million people(84). Most of the violations were related to monitoring and reporting requirements and public notification or consumer confidence reporting requirements. Only about 10% of all community water systems had a health-related violation (e.g., exceeding a maximum contaminant level or violating a treatment technique)(84). The most common health-related violations during the 2011 fiscal year involved regulations for total coliform (observed in every state), disinfection byproducts (predominantly in 24 states), arsenic (primarily states in the Southwest and Pacific Northwest where arsenic naturally occurs at high levels), and lead and copper (mainly in 15 states)(84). In general, Rubin (2013) found that SDWA violations during the 2011 fiscal year did not vary by source water or size of the community water systems(84). It is important to note, however, that compliance statistics are based on violations reported by states to the EPA Safe Drinking Water Information System, so there can be inaccuracies and underreporting of some data(63).

Resulting from the 1996 SDWA amendments, the EPA requires community water systems to provide customers with an annual drinking water quality report, referred to as a Consumer Confidence Report (CCR)(85). The purpose of the CCR is for water utilities to inform their customers about the drinking water quality(85). Specifically, the CCR describes the local water source and its risk of contamination(85). It also provides a summary on compliance with regulations, including detected contaminant levels(85). About 300 million residents receive water from a water utility that is mandated to provide a CCR to its customers(63). Despite having the potential to be a powerful public resource, however, CCRs have been shown to be inadequate in informing consumers about the safety of their drinking water(86, 87). Also, the public disclosure of information may alter the reporting behavior of water suppliers(88). Since the CCR requirement has been in place, Bennear and Olmstead (2008) found that violations reported by large water suppliers (serving 10,000 or more people) reduced in the state of Massachusetts(88). Specifically, total violations reduced by 30-44% and more severe health violations reduced by 40–57%(88).

In addition to the primary standards, EPA has established National Secondary Drinking Water Regulations (NSDWRs or secondary standards) that provide non-mandatory guidelines regulating 15 contaminants that may cause cosmetic effects (e.g., skin or tooth discoloration) or aesthetic effects (e.g., taste, odor, or color) in drinking water(75). While EPA does not enforce these secondary standards, "secondary maximum contaminant levels" serve as guidelines to assist public water systems in managing their drinking water(75). Although these secondary contaminants are not known to cause health problems, the aesthetic nuisance they can cause may deter consumers from using the water even though it is actually safe to drink(75). See Appendix 2 for list of NSDWRs.

The Contaminant Candidate List (CCL) serves as the first level of evaluation for unregulated drinking water contaminants with a potential for public health concern(89). Published every five years, the CCL contains drinking water contaminants that are known or anticipated to occur in public water systems but are not subject to federal drinking water regulations(89). The list includes pesticides, disinfection byproducts, chemicals used in commerce, waterborne pathogens, pharmaceuticals, and biological toxins(90). After a final CCL is published, the EPA must evaluate at least five contaminants and make a formal decision on whether a national primary drinking water regulation for each contaminant should be developed(89). When making a regulatory determination, EPA considers the following criteria: 1) potential adverse health effect of the contaminant; 2) occurrence of the contaminant in public water systems and levels which threaten public health; and 3) prospect that a regulation would reduce health risks(89). After reviewing the CCL, the Unregulated Contaminant Monitoring Rule allows the EPA to collect data on occurrence and exposure for up to 30 contaminants every five years(91).

Drinking Water Sources

Household tap water generally comes from a treated surface or ground water source. In general, large metropolitan areas rely on surface water supplies while small rural areas rely on ground water(20). Surface water is any body of water that is exposed to the atmosphere(69). That is, surface water accumulates on the ground or in a stream, river, lake, pond, reservoir, or ocean(20). The amount of local surface water can fluctuate depending on the amount of precipitation, factors related to evaporation (e.g., water temperature, air temperature, humidity), and seepage into ground water supplies(20). Untreated surface water is also used for irrigation systems (e.g., dams, canals, and sprinkler systems), industrial purposes, mining, and thermoelectric power generation(69). About 74% of the freshwater used in the United States is surface water(69). The remaining freshwater comes from ground water sources located underground in the pores and spaces in soil, sand, and rock(20, 69). Ground water is obtained by drilling wells and around 46% of U.S. residents rely on a ground water source for drinking water(20, 69). Approximately 15% of the U.S. population relies on a private ground water well system(20). Ground water is also used for agricultural purposes, such as watering crops and livestock(69). Figure 5 illustrates the different water sources.

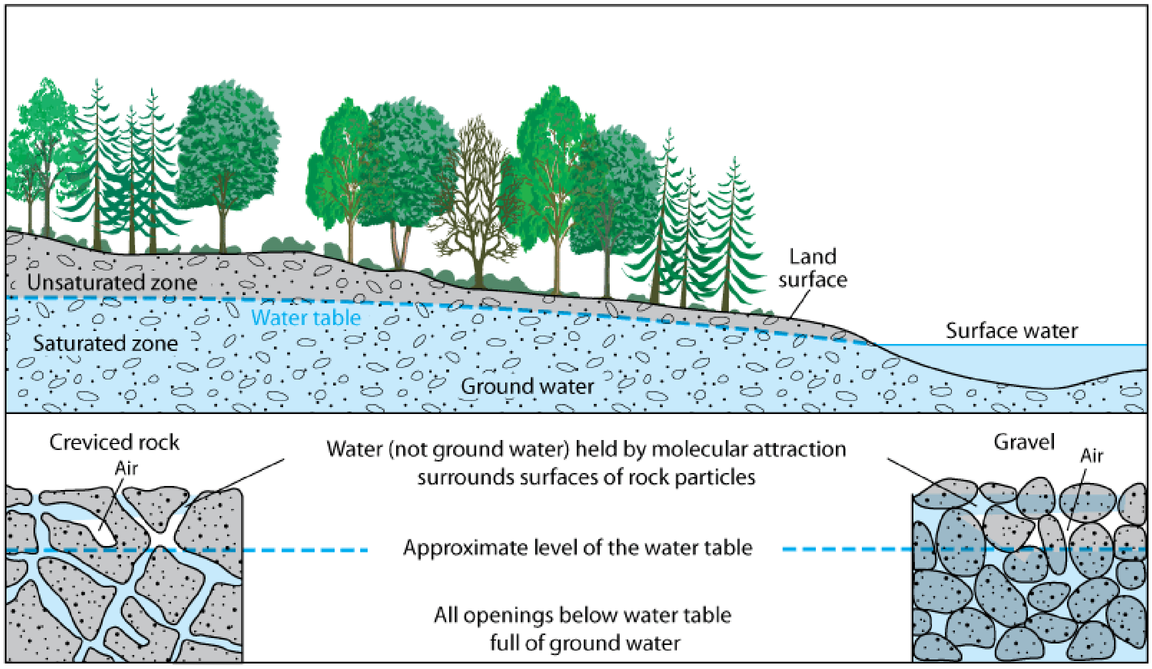

Figure 5: Ground water versus surface water.
Source: United States Geological Survey (USGS)
http://www.cdc.gov/healthywater/drinking/public/water_sources_groundwater_fig.html

Source Water Contamination

Source water can be contaminated by natural and man-made contaminants(69, 92). Surface runoff, along with treated and untreated discharges from industry and wastewater treatment plants, bring pollutants in direct contact with surface water. As more land gets developed and impervious surfaces increase, so does the amount of runoff from precipitation(69). While some contaminants are naturally found in water or result from erosion of natural deposits, others result from fertilizers, pesticides, herbicides, drilling waste, sewage, human and animal fecal waste, leaching from septic tanks, additives and byproducts of drinking water disinfection, and discharge from factories, mills, and refineries(69). Although usually less susceptible, ground water can also be vulnerable to contamination. The most common threats to ground water quality are underground storage tanks, septic systems, landfills, industrial facilities, and agricultural operations(69).

<u>Source Water Protection</u>

Source water protection is crucial in maintaining safe drinking water supplies(48, 93). Not only does it reduce the public health risks associated with exposures to contaminated water, but it also reduces treatment costs(93). Source water protection relies on the involvement of many different players, from the EPA and other federal agencies, to businesses and industries, to local utilities and resources(93). The EPA and other federal agencies provide the guidance and resources needed for implementing protection(93). For example, the Clean Water Act establishes the basic structure for regulating pollutant discharges and surface water quality standards(93, 94). State and local governments play important roles in applying and assessing locally-relevant protection activities(93). Water utilities can promote the protection of their source waters through education campaigns and community partnerships(93). Businesses and industries can directly contribute to source water protection by reducing their use of harmful contaminants and ensuring proper disposal of their waste products(93).

Studies have suggested that drinking water quality is directly related to land-cover composition of the source areas(95, 96). Thus, protection of the watershed surrounding source waters is an important component of protecting drinking water supplies. Approximately 78% of the contiguous U.S. is situated within a drinking water watershed(96). The supply and purification of fresh water depends on a healthy watershed that serves as a well-balance ecosystem capable of sustaining a variety of environments and many forms of life(97). In a national, watershed-level environmental assessment of over 5,000 drinking water watersheds, drinking water watersheds generally had a high percentage of natural vegetation but a low percentage set aside for conservation(96). Over time, drinking water watersheds may gradually lose their natural vegetation and increase in urban land development(96). Due to increased population and increased pollution, however, many watersheds are in need of protection(97). The EPA's Office of Wastewater Management oversees the safeguard of waters and watersheds in the U.S. and promotes the Clean Water Act by encouraging effective and responsible water practices in addition to watershed protection and restoration(69).

Water Treatment Processes

Since source waters can almost all be potentially impacted by some type of contamination, nearly all public water systems require at least some type of treatment before being distributed to consumers(69). There are various methods of water treatment used by public drinking water systems to ensure safe drinking water. The steps most commonly used by community water systems (mainly surface water treatment) include: coagulation and flocculation; sedimentation; filtration; and disinfection(29, 92, 98). In brief, coagulation neutralizes the negative charge of dissolved particles (e.g., dirt) in the water(29, 98). Flocculation then occurs when particles bind with the chemicals and form larger particles, called flocs(29, 98). During sedimentation, the floc settles to the bottom of the water supply, leaving clearer water on top that can then be more easily filtered(29, 98). In order to remove an assortment of dissolved particles (e.g., dust, parasites, bacteria, viruses, and chemicals), filters vary in composition (e.g., sand, gravel, charcoal) and pore sizes(29, 98). Either before or after filtration, a disinfectant may be added in order to destroy any remaining pathogens and, in the U.S., a residual is required to protect the water from pathogens while in the distribution system(29, 98). Disinfection treatment processes for microbiological contaminants include chlorination, chloramination, ozonation, ultra-violet irradiation and chlorine dioxide disinfection(29, 81, 99). Chlorination is probably the most widely used and generally the most cost-effective method of drinking water disinfection(29). In terms of cost, efficacy, stability, ease of application, and formation of by-products, every disinfectant has its advantages and disadvantages(99).

Since all disinfectants are reactive substances, they will inevitably produce by-products(99). Chlorine-based disinfectants are the most commonly used disinfectants because they are inexpensive, easy to use, and usually effective for bacteria and viruses. However, chlorination is not always effective against parasites and it produces disinfection by-products (e.g., trihalomethanes, haloacetic acids, bromate, chlorite)(99). Disinfectants such as chloramines, ozone, chlorine dioxide, and ultraviolet disinfection are gaining popularity as alternatives to chlorine(99). Of these, ozone has been noted as the most efficient disinfectant for inactivating bacteria, viruses, and protozoa(99). Existing risk assessment studies are inconclusive regarding the public health implications of drinking water exposure to disinfectants and their by-products(100). However, the WHO concludes that the estimated health risks from disinfectants and their by-products are negligible when compared to the actual risks associated with inadequate disinfection(99, 101).

A number of U.S. cities have avoided construction of filtration plants by investing instead in watershed protection to maintain the purity of their drinking water(97, 102). In cities like Boston and Seattle, investing in watershed protection instead of filtration plants was possible because the municipal water authority owned and was able to protect the critical watershed lands(97). In the case of New York City, however, a multifaceted agreement with watershed communities was necessary due to the private ownership of approximately three quarters of the watershed(97). Utilizing an unfiltered surface supply, New York City provides 9 million consumers with approximately 1.5 billion gallons of water per day(30). Without filtration, the city relies on chlorination, fluoridation, and corrosion control to treat the water and also routinely monitors water quality indicators, such as coliform bacteria, turbidity, temperature, and pH(30). In the event that extreme conditions increase turbidity levels, the city may also resort to additional chemical treatments, such as alum and sodium hydroxide(30). Increasingly, many of these unfiltered water systems may be threatened by developments in their watersheds and face greater risk of microbiological and chemical pollution(102). As a result, some cities with unfiltered water systems have been ordered by either the EPA or state government to filter their water or to improve water treatment through use of advanced disinfection technologies such as ozone or ultraviolet light(102).

In-Home Water Treatment

In addition to the typical municipal water treatment, there are several types of in-home water treatment systems that can target a specific or range of contaminants as well as improve taste and odor(103). Contaminants that can be removed by in-home treatment systems include: *Giardia*, *Cryptosporidium*, bacteria, viruses, arsenic, disinfection byproducts, lead, nitrates, pesticides, radium, and radon(77). Over 40% of Americans use some kind of in-home water treatment system, which has become a multi-billion dollar industry(77). In-home water treatment systems range from whole-house systems to simpler point-of-use systems(103). Whole house systems usually treat the water at the point of entry in order to treat all or most of the water entering a residence(103). Consequently, they are typically installed near the water meter (municipal) or pressurized storage tank (well water)(103). Whole-house systems include ultraviolet microbiological systems, water softeners, and whole-house filters for chlorine, taste, odor and particulates(103). Alternatively, point-of-use systems typically treat water at the point of consumption and include water pitchers, faucet filters, and reverse osmosis systems(103). The majority of available home water filters remove *Cryptosporidium*, though some filter designs are more suitable than others(104). Technologies more likely to reduce *Cryptosporidium* include filters with reverse osmosis and those with an absolute pore size of 1 micron or smaller(104). Activated carbon filters are commonly used to treat general taste and odor problems, including the removal of chlorine residuals(24). Although these filters do not remove nitrate, bacteria, or metals, they are one of the best methods for the removal of certain organic chemicals, including some pesticide residues, which adsorb to the surfaces of the carbon particles(24). Obviously, the effectiveness of any in-home water treatment system depends on proper use and maintenance(24). For example, activated carbon filters are designed to filter a certain amount of water and then can become clogged or their contaminant removal capacity has been exceeded rendering them ineffective(77).

In a study investigating home water treatments in rural Arizona, residents with increased household income and education levels were more likely to use home treatments, regardless of the source water quality(105). On the other hand, residents in older homes were less likely to use home treatment(105). In terms of the effectiveness of home treatments studied, the results were inconsistent as some contaminant concentrations increased and others decreased(105). In a randomized intervention trial assessing the use of reverse-osmosis filters in Montreal, 35% of the self-reported gastrointestinal illness was related to the water and considered preventable(106). Nevertheless, in a double-blinded, randomized, controlled intervention study conducted in Australia, the use of a combined 1-µm filtration and ultraviolet treatment did not seem to impact the incidence of self-reported gastrointestinal illness among residents drawing from a high quality water source(107). Similarly, in a triple-blinded, randomized, controlled intervention study conducted in Iowa, the use of a combined 1-µm filtration and ultraviolet treatment did not affect the incidence of self-reported gastrointestinal illness among residents drawing from a microbiologically challenged water source(108).

Water System Failures

In the U.S. and other developed countries with robust treatment technologies, waterborne disease outbreaks still occur due to factors such as poor operational and maintenance practices, aged infrastructure, inadequate monitoring, and failures in the distribution network(29). Drinking water system failures in developed countries can occur in the catchment, water source, treatment, disinfection system, and distribution system(59). Failure types can involve issues with operation and maintenance, breakage of equipment (cracked pipes, malfunctioning pumps, etc.), poor engineering design, inability to treat the capacity or composition of the raw water, inadequate maintenance and monitoring of the plant, and human error(59). Onyango et al. (2015) found that the majority of the outbreaks stemmed from both failures in the management framework (27%) and inadequate infrastructural design (25%)(59). Figure 6 shows the breakdown of causes identified. According to a quantitative microbial risk assessment (QMRA) on microbial health risks due to failures in Swedish drinking water systems, the majority of potential infections resulted from pathogens passing treatment during normal operation and not due to failures(109). The primary water treatment risks identified were related to sub-optimal particle removal or disinfection malfunction(109).

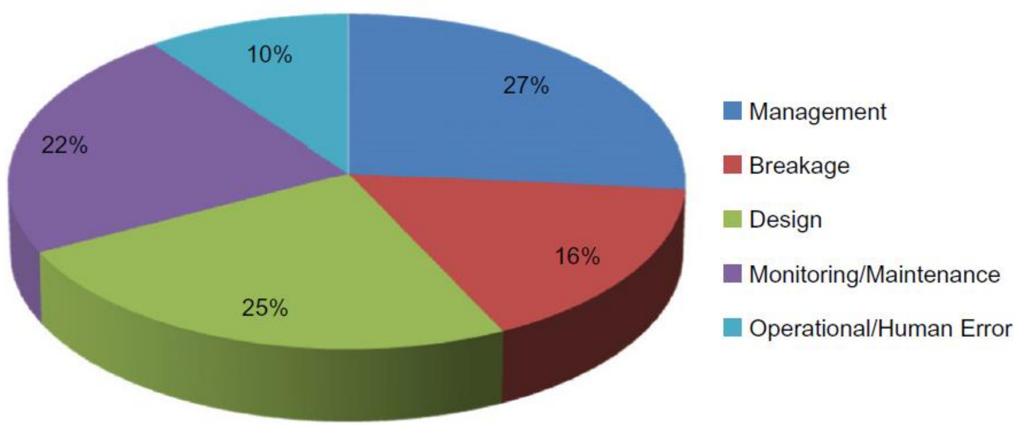

Figure 6: Causes of pathogenic outbreaks.
Source: Onyango et al. 2015 (59)

Aim 1 Background: Harmful Algae

When an excess of nutrients (e.g., nitrogen, phosphorus) enters a waterbody, often due to anthropogenic activities, algae can rapidly grow and inundate the ecosystem(8, 110). Some algal blooms are harmful because they produce toxins and bacterial growth that can cause illness in humans and animals(8, 110). Human exposure to harmful algae can result from contacting polluted water, consuming tainted fish or shellfish, inhaling contaminated water droplets, and drinking contaminated water(110, 111). Harmful algal blooms occur in all 50 states and can have substantial consequences on human health, aquatic ecosystems, and the economy(8).

Cyanobacteria, also referred to as blue-green algae, are microscopic organisms that naturally occur in fresh, estuarine, and marine waters(112). While cyanobacteria have a bacterial ancestry, they are considered to be algae by phycologists due to phenotypic similarities(113). Depending on the species, they can occur as single cells, filaments of cells, or colonies(114). Some species live dispersed in the water (phytoplankton) whereas others grow on sediments (phytobenthos)(115). Cyanobacteria help maintain marine and freshwater ecosystems by producing oxygen (as a by-product of photosynthesis) and by serving as a food source for other organisms(115, 116). However, under certain environmental conditions, such as high nutrient levels, warmer temperatures, and sun exposure, an excessive proliferation of cyanobacteria can form a bloom(5, 114, 115). With a changing climate impacting freshwater and marine environments, harmful algal blooms may end up occurring more often, in more places, and at higher intensities(1-5). Climate impacts potentially affecting algal blooms include: warming water temperature; changes in salinity resulting from droughts; higher carbon dioxide levels; changes in rainfall leading to more nutrient runoff; sea level rise creating more shallow and stable coastal waters; and coastal upwelling bringing nutrients from the ocean floor to the surface(1, 4, 5).

Some cyanobacteria species produce relatively non-toxic taste-and-odor compounds, such as geosmin and 2-methylisoborneol(117-119). These compounds, also found in soil and mushrooms, have strong earthy tastes and odors(117). On the other hand, some cyanobacteria species are often associated with toxic blooms as they produce a complex mixture of hepatotoxins, neurotoxins, and dermatotoxins(115, 116, 119). While taste-and-odor compounds and toxins frequently co-occur, odor alone does not indicate the presence of toxins because toxins still occur more frequently than taste-and-odor compounds(118).

Cyanotoxins are a diverse group of natural toxins that can be produced by a wide variety of planktonic cyanobacteria(112, 115). Most cyanotoxins, including anatoxin-a and microcystins, are produced and contained intracellularly and released in an algal bloom during cell death and lysis(111, 112). However, some cyanotoxins, such as cylindrospermopsin, may be naturally released to the water by the live cyanobacterial cell, existing approximately 50% intracellularly and 50% extracellularly(111). Compared to intracellular toxins, extracellular toxins can be more challenging to remove because they may adsorb to clays and organic material in the water column(111).

Cyanotoxins can be divided into three general groups of chemical structure: cyclic peptides, alkaloids, and lipopolysaccharides(115). Cyclic peptides include microcystins and nodularin, both of which primarily target the liver and are the most frequently found cyanobacterial toxins in freshwater blooms(115). Microcystins are produced by a range of cyanobacterial genera (e.g., *Anabaena*, *Fischerella*, *Gloeotrichia*, *Nodularia*, *Nostoc*, *Oscillatoria*, members of *Microcystis*, *Planktothrix*) and can bioaccumulate in common aquatic vertebrates and invertebrates such as fish, mussels, and zooplankton(112). Of the 80 or so known microcystins, Microcystin-LR is generally considered one of the most toxic(111). Alkaloids can be neurotoxic (e.g., anatoxins, saxitoxins), cytoxic (e.g., cylindrospermopsins), and dermatotoxic (e.g., aplysatoxins, lyngbyatoxins)(115). Lipopolysaccharides, which can be produced by all cyanobacterial genera (but not all species), are considered potential irritant toxins as their fatty acid component generally elicits an irritant of allergenic response in humans and mammals(115). The most commonly identified cyanotoxins in the U.S. are microcystins, cylindrospermopsin, anatoxins, and saxitoxins(112).

The risk for exposure to cyanotoxins is not always obvious since toxins may still be present in the absence of a bloom or visible scum on the water(120). As mentioned above, this is because cyanotoxins are generally contained within cells and only released into surrounding waters during cell death and lysis(120). Therefore, waters that appear to be free of cyanobacteria may actually be contaminated with free toxin(120). Also, treatment methods may lyse cells and release toxins into the water(120). In 2007, EPA identified microcystins, a group of cyanotoxins, in approximately one-third of the nation's lakes(121).

Aside from producing toxins, cyanobacteria can present other treatment challenges for public water systems, including taste and odor and shortened filter run times(117, 122). The occurrence of cyanotoxins in drinking water depends on their concentration in the raw source water and how well the treatment methods are at removing cyanobacteria and cyanotoxins(122). Unfortunately, data on the presence or absence of cyanotoxins in finished drinking water are limited because there is no centralized monitoring program(122). Nevertheless, drinking water treatment plants are increasingly met with the need to monitor and respond to harmful algal blooms(123). In Florida, a survey conducted in 2000 reported that microcystins were the most commonly found toxin in pre- and post-treated drinking water, with finished water concentrations as high as 12.5 μg/L(122). In 33 U.S. drinking water treatment plants in the Northeast and Midwest, a survey conducted in 2003 reported that microcystins were detected at low levels (≤0.36 μg/L) in all finished water samples collected(124). In more recent years, there has been a noticeable increase in the severity of cyanobacterial harmful algal blooms in Lake Erie, a drinking water source for many communities(123). Based on agricultural and meteorological trends that triggered a massive bloom in 2011, scientists predicted that, without any changes to mitigate future projections, nuisance algal blooms would only become more common(3). As predicted, in the summer of 2014, microcystin concentrations were particularly severe in Western Lake Erie(2). In fact, microcystin levels in fully treated tap water were detected at almost three times the WHO limit of 1 µg/L(2). The immediate impact was that over 500,000 residents in and around Toledo, Ohio were warned not to use their water(2, 122). The Toledo event brought national attention to the threat of algal toxins in public water supplies(125). In New York, two municipal systems that draw water from Owasco Lake in the Finger Lakes region began collecting samples for toxin testing after the Toledo event(125). In September 2016, microcystins were detected at low levels (≤0.18 µg/L) in both water systems, first in the untreated water and then in the finished water(125). This incident marked the first time algal toxins have ever been found in treated public drinking water in the state of New York(125).

Drinking water systems that use surface water sources (e.g., lakes, reservoirs) are vulnerable to harmful algal blooms(126). In fact, the lakes and reservoirs that supply drinking water to an estimated 30 to 48 million Americans may sometimes be contaminated by algal toxins(4, 126). Despite this, there are currently no U.S. federal water quality criteria or regulations for harmful algae, such as cyanobacteria or their toxins (cyanotoxins), in drinking or recreational waters(117, 122). Cyanobacteria and cyanotoxins were included on the first and second Contaminant Candidate List (CCL), in 1998 and 2005, respectively(122). Based on toxicological, epidemiology and occurrence studies, cyanotoxins, including anatoxin-a, cylindrospermopsin, and microcystin-LR, were included on the third CCL in 2009 and also on the draft of the fourth CCL in 2015(111, 122). Although the EPA has yet to establish any drinking water standards, they developed health advisories (non-regulatory) for the cyanobacterial toxins microcystins and cylindrospermopsin in 2015(122, 127, 128). Specifically, the EPA recommended that 1) young children and people with preexisting health conditions should not consume water containing more than 0.3 µg/L for microcystins or 0.7 µg/L for cylindrospermopsin; and 2) older children and healthy adults should not consume more than 1.6 µg/L for microcystins and 3.0 µg/L for cylindrospermopsin (122, 127). Other cyanotoxins, such as saxitoxins and anatoxin-a(S), that also occur in U.S. drinking water sources were not directly addressed(111, 122). Also, the International Agency for Research in Cancer considers Microcystin-LR to be a possible human carcinogen (Group 2B) based on some evidence that it may act as a tumor promoter(112, 115). According to the EPA, however, there is insufficient data to assess carcinogenic potential of microcystins in humans due to limitations in the few available human studies (i.e., potential co-exposure to other contaminants) and lack of long-term animal studies evaluating cancer following oral exposure(112).

The fourth Unregulated Contaminant Monitoring Rule (UCMR 4), proposed at the end of 2015, included 10 cyanotoxin chemical contaminants to be monitored between 2018 and 2020 to provide a basis for future regulatory developments(129). Internationally, 18 countries and three U.S. states (Minnesota, Ohio, Oregon) have developed drinking water guidelines for microcystins (see Table 1 and Table 2)(122). Many standards and guideline values have been based on the provisional WHO guideline value of 2,000 cyanobacterial cells/mL for drinking water or 1 μg/L of microcystin-LR(33, 122).

Table 1. International drinking water guidelines for microcystins.

Country	Guideline Value
Brazil, China, Czech Republic, Denmark, Finland, France, Germany, Italy, Japan, Korea, Netherlands, Norway, New Zealand, Poland, South Africa, and Spain	1.0 μg/L microcystin-LR
Australia	1.3 μg/L microcystin-LR (toxicity equivalents)
Canada	1.5 μg/L microcystin-LR

Table 2. U.S. state drinking water guidelines for microcystins.

State	Guideline Value
Minnesota	0.04 μg/L microcystin-LR
Ohio	1 μg/L microcystin
Oregon	1 μg/L microcystin-LR

Harmful Algae and Illness

Human exposure to cyanobacteria and cyanotoxins can occur through direct contact, inhalation of contaminated water droplets (e.g., while showering or during recreational activities), and ingestion (e.g., drinking contaminated water, consuming tainted fish or shellfish)(110, 111). In the U.S., recreational activities during freshwater harmful algal blooms have been associated with waterborne disease outbreaks that include dermatologic, gastrointestinal, respiratory, febrile, ear, and eye symptoms(130-133). Among 11 states participating in the Harmful Algal Bloom-Related Illness Surveillance System (HABISS) program, 458 suspected or confirmed human illnesses and 175 animal morbidity and mortality cases were reported as being associated with bloom events during 2007-2011(134). The data in HABISS, however, only reflects recreational exposures for humans and domestic pets(134). When public drinking water systems are contaminated with harmful algae, there can be a substantial public health impact as large numbers of people may be exposed and become ill(134, 135). Drinking water exposure to harmful cyanobacteria can lead to symptoms of illness, both chronic (e.g., liver and kidney damage) and acute (e.g., gastroenteritis, muscle pain and dermatitis)(116, 133, 135). Toxic cyanobacterial blooms have been associated with human and animal illness in at least 43 states(136). Figure 7 shows the distribution of reports and events related to such blooms. In August 2016, at least 19 states had public health advisories because of cyanobacterial harmful algal blooms(136).

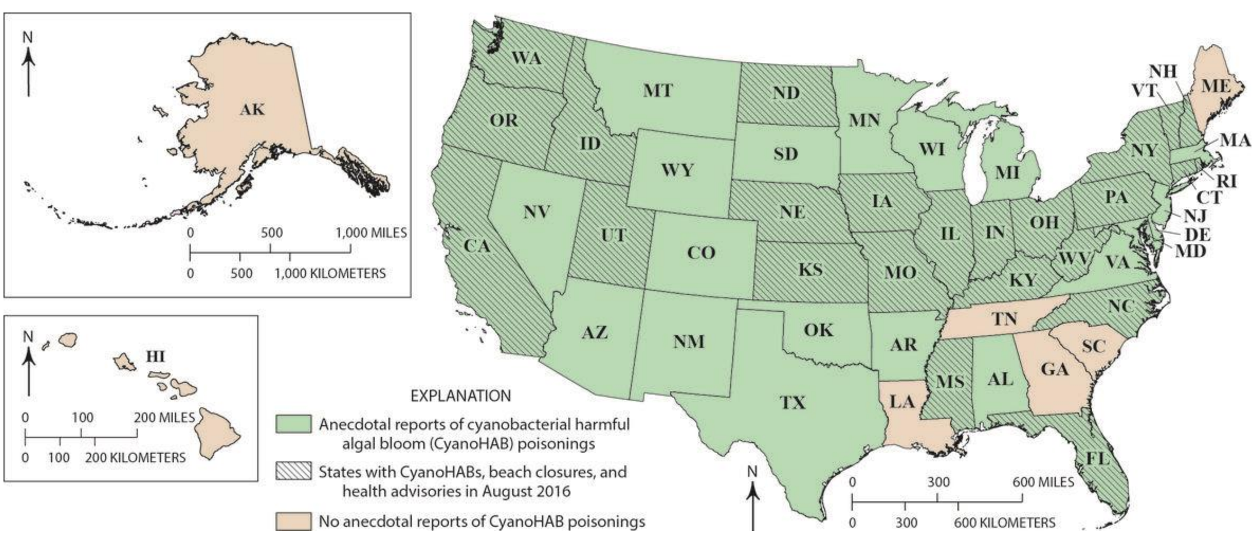

Figure 7: Cyanobacterial harmful algal blooms in the United States.
Source: https://www.usgs.gov/media/images/national-status-cyanohabs-august-2016

Although there are other more frequent causes (e.g., bacterial, viral, protozoal) of drinking water outbreaks, there is epidemiologic evidence for human illness due to cyanobacterial toxins(115). Throughout history, there have been many recorded cases of gastrointestinal and hepatic illness that have been attributed to cyanobacterial toxins in the water supplies(115). Cyanobacterial toxins are generally released during the breakdown of a natural cyanobacterial bloom or with the application of copper sulfate to destroy the bloom (artificial lysis)(115). The earliest reported cases of gastroenteritis from cyanobacteria occurred in 1931 along the Ohio River(115). In 1975, a gastroenteritis outbreak affected over half (62%) of a population supplied by a single reservoir in a Pennsylvania town that was affected by bloom of a cyanobacterium (*Schizothrix calicola*) (133, 137). In 1988, the most deadly outbreak attributed to cyanobacterial toxins in drinking water occurred in Brazil and caused 88 deaths, the majority of whom were children(115, 133). In the summer of 2009, Lévesque et al. (2014) conducted a prospective study of residents who lived in close proximity to lakes affected by cyanobacteria in Quebec, Canada(138). Among participants receiving drinking water from a plant whose source was contaminated by cyanobacteria, an increase in self-reported muscle pain, gastrointestinal symptoms, dermal symptoms, and ear symptoms was observed (138). In Australia, a case-control study suggested that gastrointestinal and dermal symptoms were correlated with increased cyanobacterial cell counts in a drinking water supply that came from a river affected by an extensive bloom(139). During the 10-year period from 1998 to 2008, Beaudeau et al. (2014) found that cyanobacteria in the drinking water source may be associated with a higher risk of Medicare (≥65 years of age) hospital admissions for acute gastrointestinal illness(140). In particular, the association between cyanobacteria and acute gastrointestinal illness was weakly significant over 8-12 day lags and peaked over 23-27 day lags(140). The rationale for the long latency of the effects for cyanobacteria was unclear and the authors suggested a need for further investigation(140). Gastrointestinal illness has been a common outcome in studies of cyanobacteria exposure via drinking water ingestion and accidental recreational intake(141). While acute toxicity is the most evident problem in cyanobacterial poisoning, there may also be chronic effects(115, 133). As mentioned earlier, there is some evidence suggesting Microcystin-LR may act as a tumor promoter and the International Agency for Research in Cancer considers it to be a possible human carcinogen (Group 2B)(112, 115). Human studies and long-term animal studies, however, are limited(112). Human studies suggesting a link between cyanobacteria and malignant disease come primarily from the southeast coastal area of China, where ponds and ditches that serve as drinking water regularly suffer from intense cyanobacterial blooms(115, 133). A few epidemiologic studies have suggested that populations obtaining water from ponds and ditches have a much higher incidence of primary liver cancer than those using river or well water(115, 133).

Certain subgroups of the general population may be more susceptible to the health effects of cyanotoxins. As with any microbial contaminant, infants and children, pregnant women, the elderly, and immunocompromised persons may be at higher risk for becoming ill after drinking contaminated water(102, 142). In particular, individuals with liver or kidney conditions (e.g., hepatitis, liver cirrhosis, other toxic liver injuries, kidney damage) may be more susceptible to cyanobacterial toxins(143). In an extreme scenario, when water used for dialysis was contaminated with microcystins in Brazil, a number of fatalities among end-stage renal failure patients occurred(115, 144). Also, infants and children are another susceptible group who are at a higher risk, relative to adults, due to their lower body weight (thus swallowing more water per body weight than adults) and developmental stage(143). While developmental effects of different cyanotoxins (e.g., microcystins, saxitoxin, anatoxin-a, cylindrospermopsin) have been observed in fish embryos and mouse models, the impact on human development has not been established(143).

Globally, cyanotoxins have been detected in raw and finished waters and direct ingestion of contaminated drinking water is a common route of exposure(144). Increased risks to human illness have been linked to the ingestion of high levels of cyanotoxin in water; however, the effect of chronic low levels not well-documented or understood(144). There are challenges to addressing the potential public health impacts because the risks associated with exposure vary across organisms, toxins, and routes of exposure(134). As noted by Hudnell (2010), the least characterized risks are perhaps those from repeated, low-level, multi-route exposures to cyanotoxins in surface and drinking waters(128).

Water Treatment for Harmful Algae

The management of cyanobacterial blooms in surface water is complex. In order to protect consumers from exposure, the primary management objectives are to prevent, monitor, and, if necessary, remove cyanobacteria and their toxins(119). Preventing the occurrence of algal blooms involves the control and management of nutrients from outside and from within the lake or reservoir(119). Monitoring involves the routine counting and identification of phytoplankton, and analysis of toxins if cyanobacteria are predominant(119). To eradicate a bloom of cyanobacteria, an algaecide, usually copper sulfate, can be applied(115, 119). If applied correctly, algaecides are effective at eliminating blooms; however, they can induce cell lysis and subsequent release of intracellular toxins(115, 119). In addition, copper sulfate can pose ecological and public health risks through copper accumulation in sediments(115, 119). In order to avoid these negative consequences, algaecides should only be used under very specific conditions(115). In essence, there are no simple restorative measures once a bloom occurs in surface water(119).

Research on cyanotoxin removal is ongoing(123). While certain drinking water treatment processes can remove cyanobacterial toxins, their efficacy range from 60% to 99.9%(4). An ineffective treatment method not only compromises water quality, but it can also bring about severe treatment disruption or treatment plant shutdown(4). Factors that impact cyanotoxin removal include the cyanobacterial species and cell density, coagulant type and dose, pH, natural organic material, and operational parameters such as flocculation time, frequency of filter backwashing and clarifier sludge removal(122, 145). Existing operations working to address cyanotoxins are modifying the locations where treatment chemicals are applied, the types and concentrations of chemicals applied, and the pH at which the processes are operated(123). Recent research has focused on the impacts of pH and hydrogen peroxide addition on ozone contactor efficiency(123). While chlorination has demonstrated some potential in treating microcystins during oxidation and disinfection processes, chlorine-based processes (chlorine, chloramines and chlorine dioxide) have not been found to successfully treat other cyanotoxins (e.g., anatoxin-a)(146, 147).

Water treatment processes are typically based on either the retention or degradation of contaminants(119). Retention-based treatments include coagulation/flocculation/sedimentation, sand filtration, membrane filtration, and activated carbon(119). Degradation-based treatments include ultraviolet irradiation and photocatalysis, ozonation, and chlorination and chloramination(119). While retention-based treatments generally require more regular maintenance (e.g., cleaning procedures, backflushing, replacement of activated carbon and membranes), degradation-based treatments may produce potentially harmful by-products (e.g., trihalomethanes)(119).

Although intracellular microcystins make up the majority of the total microcystin concentration in source water, extracellular microcystins (either dissolved in water or bound to other materials) still make up a portion (<30%)(122). Therefore, it is essential that treatment processes consider the presence of both intracellular and extracellular microcystins(122). In the absence of cell damage, conventional water treatment (e.g., coagulation, flocculation, sedimentation, rapid granular filtration) can be effective at removing intact cells and the majority of intracellular toxins(122). In fact, 60 to 95% of cells and intracellular microcystins can be removed during sedimentation and up to 99.9% can be removed through filtration(122). If toxins are released into the water, however, conventional treatments need additional processes such as chemical oxidation, adsorption, biodegradation or reverse osmosis, and nanofiltration(122). Studies have suggested that conventional drinking water treatment followed by oxidation or activated carbon may remove both intracellular and extracellular microcystins up to 99.99% of total microcystins to achieve concentrations below 0.1 µg/L in treated water(122).

Ozone has been commonly used in developed countries, more in Europe than in North America, to remove potentially harmful organic pollutants and for disinfection(29, 116). The biggest advantage ozone has over chlorination is its ability to disinfect *Cryptosporidium(29)*. It has also been shown to be an effective method for destroying microcystins and nodularins(116, 119, 148). Ozonation can be applied just once or several times during various phases of the water treatment process(148). Since ozone will oxidize most organic materials in the water, its concentration must be above the ozone demand of the organic material in the raw water(116, 148). Combining ozonation and chlorination can successfully remove the most common extracellular toxins(119).

Although effective at oxidizing extracellular microcystins, chemical oxidation using chlorine, potassium permanganate, or ozonation can also impair cell integrity(122). Impaired cell integrity can lead to cell lysis, which would subsequently increase the concentrations of extracellular microcystins(122). One solution to this is to simply apply a conventional (or alternative) filtration process first to remove the majority of intact cells(122). As expected, the removal efficiency of filtration depends on the size of the filter's pores(122). In general, microfiltration (0.1–10 μm) and ultrafiltration (1–100 nm) membranes can remove both cyanobacterial cells and intracellular microcystins(122). For the removal of extracellular microcystins, however, ultrafiltration is inconsistent (35 to 70% removal) and microfiltration is ineffective(122). On the other hand, nanofiltration (around 1 nm) and reverse osmosis membranes (0.1 nm) can effectively remove intracellular and extracellular microcystins (82 to 100% removal)(119, 122).

Table *3* provides a summary of different cyanotoxin treatment processes(111). Although there are ways to efficiently remove or transform individual toxins, there is not one ideal method that can simultaneously remove all the cyanotoxins in a mixture(119).

Table 3. Cyanotoxin treatment processes and relative effectiveness.

Treatment Process	Relative Effectiveness
Intracellular Cyanotoxins Removal (Intact Cells)	
Pre-treatment oxidation	Oxidation often lyses cyanobacteria cells releasing the cyanotoxin to the water column. If oxidation is required to meet other treatment objectives, consider using lower doses of an oxidant less likely to lyse cells (potassium permanganate). If oxidation at higher doses must be used, sufficiently high doses should be used to not only lyse cells but also destroy total toxins present (see extracellular cyanotoxin removal).
Coagulation/Sedimentation/ Filtration	Effective for the removal of intracellular toxins when cells accumulated in sludge are isolated from the plant and the sludge is not returned to the supply after sludge separation.
Membranes	Study data are limited; it is assumed that membranes would be effective for removal of intracellular cyanotoxins. Microfiltration and ultrafiltration are effective when cells are not allowed to accumulate on membranes for long periods of time. Can clog and form biofilms.
Flotation	Flotation processes, such as Dissolved Air Flotation (DAF), are effective for removal of intracellular cyanotoxins since many of the toxin-forming cyanobacteria are buoyant.
Extracellular Cyanotoxins Removal (Dissolved)	
Membranes	Depends on the material, membrane pore size distribution, and water quality. Nanofiltration is generally effective in removing extracellular microcystin. Reverse osmosis filtration is generally applicable for removal of extracellular microcystin and cylindrospermopsin. Cell lysis is highly likely. Further research is needed to characterize performance.
Potassium Permanganate	Effective for oxidizing microcystins and anatoxins. Further research is needed for cylindrospermopsin.
Ozone	Very effective for oxidizing extracellular microcystin, anatoxin-a, and cylindrospermopsin.
Chloramines	Not effective.
Chlorine dioxide	Not effective with doses used in drinking water treatment.
Chlorination	Effective for oxidizing extracellular cyanotoxins as long as the pH is below 8; ineffective for anatoxin-a.
Ultraviolet Radiation	Effective at degrading microcystin and cylindrospermopsin but at impractically high doses.
Activated Carbon	Powdered activated carbon (PAC): Effectiveness varies highly based on type of carbon and pore size. Wood-based activated carbons are generally the most effective at microcystin adsorption. Carbon is not as effective at adsorbing saxitoxin or taste and odor compounds. Doses in excess of 20mg/L may be needed for complete toxin removal. Granular activated carbon (GAC): Effective for microcystin but less effective for anatoxin-a and cylindrospermopsins.

Source: EPA-810F11001 (https://www.epa.gov/sites/production/files/2014-08/documents/cyanobacteria_factsheet.pdf)

Aim 2 Background: Drinking Water Distribution Systems

After the treatment of water, public water systems rely on a distribution system made up of a complex, interconnected series of pipes, storage facilities, pumps, and valves to transport drinking water from the water source or treatment plant to the consumer (see Figure 8)(6, 149). A water main is any pipe that distributes potable water to more than one property(150). From a main, water reaches an individual property through a service line(150). Aside from providing an uninterrupted supply of pressurized safe drinking water to all consumers, distribution systems also deliver fire protection needs to facilities such as homes, schools, hospitals, and businesses(149). Based on surveys of water utilities, there are about 1 million miles of piping, 24,000 storage tanks, 6.8 million fire hydrants, 69.5 million service lines, and 14.6 million valves in the U.S.(6, 151). According to a study of utilities across the U.S. and Canada, 264 people are served per 1 mile of pipe regardless of utility size(152). Public water systems in the U.S. produce 34 billion gallons of drinking water each day, over half of which is used by residential customers(6). Although the majority (>80%) of water used by residential customers is used for activities other than human consumption (e.g., sanitary service, landscape irrigation), distribution systems are designed to supply water that is safe for human consumption(6).

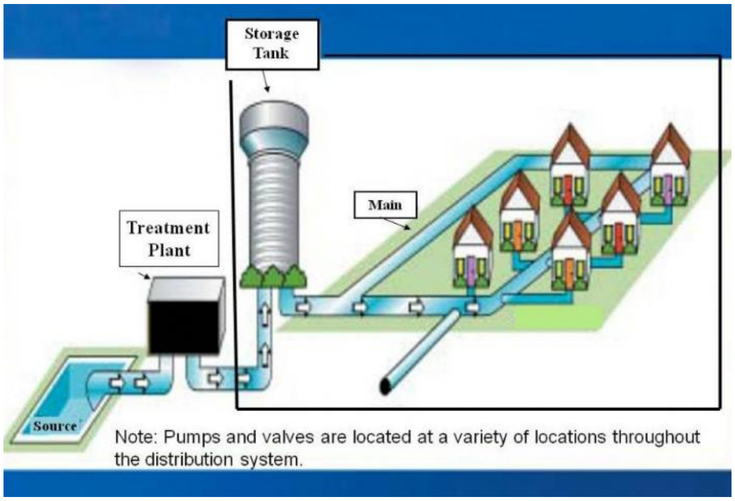

Figure 8: Drinking water distribution system.
Source: https://www.epa.gov/dwsixyearreview/drinking-water-distribution-systems

Ideally, the quality of treated water from the time it leaves the treatment plant until the time it is consumed should not change(6). In reality, however, complex physical, chemical, and biological reactions can cause substantial changes in water quality during distribution(6). Thus, distribution systems are a potential source of contamination that can lead to waterborne disease outbreaks(6).

Most drinking water regulations focus on water quality standards at the treatment plant and not within the distribution system(6). The few rules under SDWA that address the degradation of distribution system water quality include the Lead and Copper Rule, the Surface Water Treatment Rule, the Total Coliform Rule, and the Disinfectants/Disinfection By-Products Rule(6). These rules focus on measurements taken within the distribution system and in tap water samples(6). In addition, there are a number of state regulations and plumbing codes that influence distribution system water quality, from requirements for design, construction, operation, and maintenance of distribution systems to cross-connection control programs(6).

Regardless, regulations only address certain aspects of distribution system water quality rather than the integrity of the entire distribution system(6).

Unplanned Disruptions in Distribution

Due in part to the EPA regulations governing public water systems using surface water, waterborne disease outbreaks associated with untreated surface water systems have declined since 1971, with none reported between 1991 and 2002(153). Also, treatment deficiencies, such as inadequate filtration of surface water, have declined over the years(153). Instead, disruptions in the distribution infrastructure have become the main culprit of waterborne disease outbreaks in recent years(153). During 2001-2002, these disruptions were responsible for over half of all waterborne disease outbreaks(153).

The pipes that make up water distribution systems can vary considerably in material and age(6, 154). From the 1880s to the early 1930s, grey cast iron pipes were manufactured by pouring molten cast iron in upright sand molds placed in a pit(155). In 1920s and 1930s, a new manufacturing process improved the material uniformity by casting the pipes horizontally in molds made of sand or metal that spun as the molds were cooled externally with water(155). In 1948, the composition of the iron was changed to produce ductile iron pipe; however, industrial production of ductile iron pipe did not begin until the late 1960s(155). By 1982, virtually all new iron pipes were ductile iron(155). In the 1970s, plastic (e.g., polyvinyl chloride) pipes were also introduced(6). As distribution systems age, they can deteriorate due to corrosion, materials erosion, and external pressures(102, 149). This deterioration can lead to breaches in pipes and storage facilities, intrusion due to water pressure fluctuation, and main breaks(102, 149). In order to keep up with aging water systems and distribution pipes, the water industry will have to make substantial investments in pipe assessment, repair, and replacement(6). The EPA's Drinking Water Infrastructure Needs Survey and Assessment, published in 2013, estimated that drinking water utilities need $384.2 billion over the next 20 years (from 2011 to 2030) for infrastructure projects to ensure that water systems continue to provide safe drinking water to the public(154). In a study of drinking water systems in 19 U.S. cities, the Natural Resources Defense Council, reported that many cities (e.g., Atlanta, Boston, Washington, D.C.) were built toward the end of the 19th century and that the water supply infrastructure is breaking down(102). In fact, an estimated 240,000 main breaks occur each year, wasting over two trillion gallons of treated drinking water(9). The report also revealed that an increase in the frequency of periodic spikes in contamination in many cities may be an indication that aging equipment and infrastructure are overwhelmed(102).

A pressure transient (also known as surge or water hammer) in a drinking water pipeline results from an abrupt change in the velocity of water(156). Rapid changes in pressure and flow are inevitable and can strain any water system(6). The loss of water pressure can impede water delivery by decreasing the water supply, reducing fire suppression capability, and increasing the risk of water contamination via intrusion(6). Pressure loss can occur as a result of pipe breaks, major leaks, excessive pressure loss due to friction at pipe walls (head loss), pump or valve failures, and pressure surges(6). When water spends a longer duration in the distribution system due to low flows, disinfectant residuals decline and sediments can accumulate and allow microbes to grow(6). Among pressure transients that resulted in a negative pressure, Gullick et al. (2004) found that most were caused by the sudden shutdown of pumps at a pump station due to either unintentional (e.g., power outages) or intentional (e.g., pump stoppage or startup tests) situations(156). High water pressures can also impair water delivery by exacerbating the wear on valves and fittings, increasing leaks, and potentially trigger new leaks or breaks(6).

Several studies have shown that pressure transients can lead to the intrusion of contaminants into the distribution system(6, 154, 157). When transient pressure events occur in distribution systems, groundwater can enter into treated drinking water through pipeline leaks(6, 157). Specifically, an intrusion event occurs when contaminated water from the environment surrounding the pipe flows into the distribution system through leakage points, submerged air valves, faulty seals, or other openings(157, 158). This can happen when the pressure of water outside or surrounding a water pipe exceeds the internal pressure(156). It is not uncommon for water systems to lose more than 10% of the total water production through leaks in the pipelines and the percent of leakage (unaccounted for water) can range as high as 32% (157, 159). Mora-Rodríguez et al. (2012) noted three factors required to generate pathogen intrusion: 1) the *mechanism* that forces the intrusion event; 2) the *way of entrance* for possible contaminants; and 3) the *pollution source*(158). A typical intrusion scenario is illustrated in Figure 9. LeChevallier et al. (2003) reported that fecal indicators and culturable human viruses are present in the soil and water external to the distribution system, thus capable of entering the water system during a negative pressure event(157). Likewise, Karim et al. (2003) collected soil and water samples collected external to drinking water pipelines from eight utilities in six states and detected total coliform and fecal coliform bacteria in about half of all samples(160). Viruses were also detected in soil and water using both culturable and molecular methods(160). When drinking water is contaminated with a virus, the virus concentration tends to be high and the risk of infection could be substantial(161). While the intrusion of many types of pathogens is possible, the extent to which mixtures of pathogens may enter the distribution system and survive has not been well-established(38). Also of note, while engineering standards require drinking water pipes to be at least 0.5 to 3 meters away from sewer lines, microbes can travel several meters in short periods of time under certain conditions(157, 162). According to Friedman et al. (2004), the locations and system types that are most susceptible to developing low pressure conditions are pumped (i.e., non-gravity) system, distribution system mains one to two miles downstream of pumps (in relatively simple hydraulic connection to the pump), high elevation areas, areas with low static pressures, areas far away from overhead storage, and upstream and downstream of active valves in high flow areas(163). Furthermore, locations with the highest intrusion potential include sites with frequent leaks or main breaks, areas with high water table (i.e., submerged mains), flooded air-vacuum valve vaults, and high-risk cross-connection locations(163).

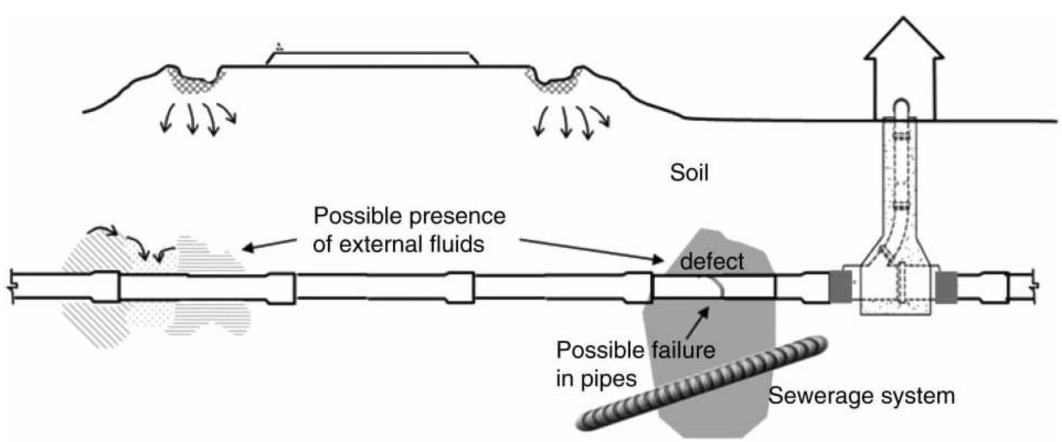

Figure 9: Pathogen intrusion factors.
Source: Mora-Rodríguez et al. 2012 (158)

In the absence of external contamination, water quality can still deteriorate when transformations (e.g., biofilm growth, nitrification, leaching, internal corrosion) occur within the pipes(6). A biofilm, which usually exists as patches but can also by continuous, is a complex mixture of microbes, organic and inorganic material which can accumulate on the inner surface of a distribution pipe(164). Biofilms form when corrosion in the distribution system pipes produces tubercles that increase the surface area of the pipe and provide niches to protect bacteria and other organisms from disinfection(164, 165). As a result, when flow disruptions occur, biofilms can release pathogens into the water(164, 166). Opportunistic pathogens that have been associated with biofilms differ from the primary waterborne pathogens entering the distribution system during a low pressure or intrusion event(164). Opportunistic bacterial pathogens commonly found in biofilms that are of most concern include Legionella pneumophila, Mycobacterium avium complex, and Pseudomonas aeruginosa(164). Biofilms can also increase pipe corrosion, consume disinfectant residual, impair pipe hydraulics, hinder the utility of total coliforms as indicator organisms, generate bad tastes and odors, and promote the exchange of resistance or virulence factors between the mixed microbial population in close proximity with each other(44, 164).

Many water utilities face the constant challenges of an aging distribution infrastructure and chronic water main breaks(6, 7). The average age of failing water mains has been estimated to be 47 years old(152). Despite this, water pipes that were installed in many cities during periods of greatest population growth and urban expansion (e.g., late 1800s, around World War I, during the 1920s, and post-World War II) are still in use today(7). According to U.S. water industry data, main breaks occur an average of 700 times per day(6). The increasing numbers of main breaks is a public health concern because of the potential relationship between waterborne disease outbreaks and main breaks(7). As illustrated in Figure 10 by Mora-Rodríguez et al. (2012), there are 3 types of breaks: 1) joint failures caused by cross-sectional tension in pipe union; 2) circumferential failure caused by longitudinal tension; and 3) longitudinal failures caused by cross-sectional tension (radial tension)(158). The severity of each break can range depending on the severity of the corrosion(158).

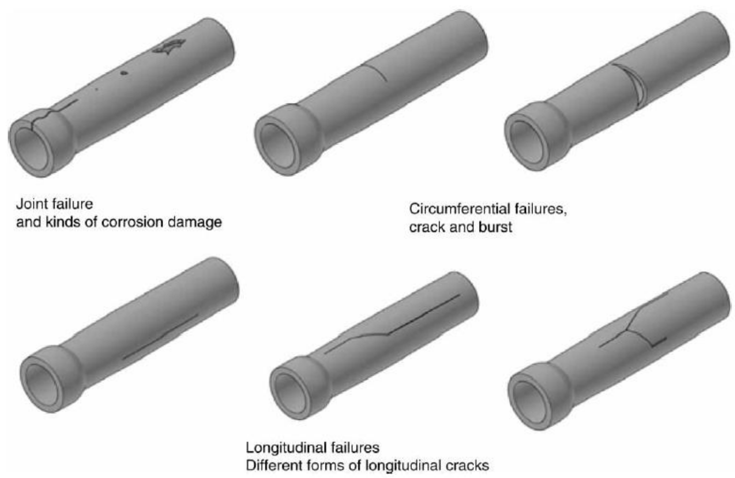

Figure 10: Different types of failures in pipes.
Source: Mora-Rodríguez et al. 2012 (158)

The rate at which water mains need to be replaced or renovated depends on a number of factors, including the age and material of the pipe, soil characteristics, weather conditions, and construction methods(154). Pipes become vulnerable to breaks when environmental and operational stresses overwhelm the structural integrity of pipes, especially when the pipes have already been compromised by factors such as corrosion, degradation, inadequate installation, or manufacturing(155, 158). Table 4 summarizes common problems of different pipe materials that can result in pipe failures(6). Water utilities, especially those in colder climates, often observe a peak in main breaks when the air temperature approaches the freezing point, 0°C(167). In some cases, the increase in main break frequency occurs when the air temperature passes the freezing point (e.g., during late fall or early spring)(167). Different pipe materials are also of consideration as they can respond differently to air and water temperature(167). Rajani et al. (2012) reported that the temperature factors that most influenced water main breaks included the average mean air temperature, the maximum increase and decrease in air temperature, and the speed (intensity) at which air temperature fluctuates over a specific period of time(167). While air temperature had an impact on main breaks, water temperature had the most impact on observed breaks, especially in cast iron pipes(167). Besides temperature, there are many other factors that contribute to pipe deterioration(168, 169). The major causes of main breaks and deterioration include inadequate design, improper installation, pressure transient, soil movement, internal corrosion (chemical, galvanic, bacterial), external corrosion (galvanic, electrolytic or stray current, biochemical or bacterial), temperature differential, manufacturing defects, and impact caused by the construction or maintenance of other utilities(169). Kleiner & Rajani (2002) presented three types of factors affecting water main deterioration: static, dynamic, and operational(168). Table 5 provides examples for each type.

Table 4. Common problems of different pipe materials.

Pipe Material (common sizes)	Problems
PVC and Polyethylene (4-36 in.)	Excessive deflection, joint misalignment and/or leakage, leaking connections, longitudinal breaks from stress, exposure to sunlight, too high internal water pressure or frequent surges in pressure, exposure to solvents, hard to locate when buried, damage can occur during tapping
Cast/Ductile Iron (4-64 in.) (lined and unlined)	Internal corrosion, joint misalignment and/or leakage, external corrosion, leaking connections, casting/manufacturing flaws
Steel (4-120 in.)	Internal corrosion, external corrosion, excessive deflection, joint leakage, imperfections in welded joints
Asbestos-Cement (4-35 in.)	Internal corrosion, cracks, joint misalignment and/or leakage, small pipe can be damaged during handling or tapping, pipe must be in proper soil, pipe is hard to locate when buried
Concrete (12-16 to 144-168 in.) (pre-stressed or reinforced)	Corrosion in contact with groundwater high in sulfates and chlorides, pipe is very heavy, alignment can be difficult, settling of the surrounding soil can cause joint leaks, manufacturing flaws

Source: National Research Council 2006 (6)

Table 5. Factors affecting pipe breakage rates.

Type of Factor	Examples
Static	Pipe material, diameter, wall thickness, soil (backfill) characteristics, installation
Dynamic	Age, temperature of soil and water, soil moisture, soil electrical resistivity, bedding condition, dynamic loadings
Operational	Replacement rates, cathodic protection, water pressure

Source: Kleiner & Rajani 2002 (168)

Before a main break happens, the pipes usually show other kinds of failure that will generate leaks during distribution(158). In a survey of 26 utilities, Kirmeyer et al. (2001) reported that 85% had some kind of leak detection program, with leak detection techniques ranging from a leakage correlator, comparison of metered sales to water production data, and electronic noise detection(159). A large main break is often identified by unexpected low pressure readings, excessive pumping, or a drop in reservoir levels in a specific area(6). Since small breaks are harder to find, water utilities often encourage their customers to help identify water main leaks and breaks(170-174). Signs of a faulty water main include water seeping up out of the ground or pavement, water running down the street at a constant stream, water accumulating at an unusual location, buckled pavement, sinkholes, rises from the ground, water leaking around a water manhole, water leaking out of a fire hydrant nozzle cap, leaking service line, and, in extreme situations, a loss of water service(170-174).

Between 1971 and 1998, 113 waterborne outbreaks (18% of all waterborne outbreaks) were caused by disruptions in the distribution system(29). Between 1981 and 2010, 9,000 cases of illness resulted from 57 waterborne outbreaks that were associated with disruptions in the distribution system(175). The majority of these outbreaks were caused by microbial pathogens (see Figure 11)(175). Although disruptions in the distribution system represent only a small fraction of contamination events, the resulting health outcomes can be severe(175). For example, one of the largest outbreaks of *Escherichia coli* O157:H7 infection occurred at the end of 1989 into early 1990 in rural Missouri(176). *Escherichia coli* O157 was transmitted through a municipal water system after 45 water meters were replaced and two water mains ruptured(176). This resulted in 243 cases with bloody diarrhea or diarrhea and abdominal cramps(176). Among these cases, 32 were hospitalized, 4 died, and 2 had the hemolytic uremic syndrome(176).

The most common faults related to waterborne outbreaks were cross-connections and back siphonage(175). Other distribution deficiencies include breaking or leaking water mains, corrosion or leaching of metals, contamination during storage, contamination during repair or installation of water mains, pressure fluctuations, contamination of household plumbing, and inadequate separation of water mains and sewer(29, 175). As shown in Figure 12, the distribution deficiency associated with waterborne outbreaks is not always known(175). Waterborne outbreaks have also been associated with low water pressure and intermittent supply(175). For example, in January 2010, below-freezing temperatures in Alabama led to system-wide failures due to breaks in water mains and service lines(177). As a result, approximately 18,000 residents lost access to municipal water for up to 12 days(177). An investigation led by the CDC revealed significant dose-response relationships between increased duration of lost water service or pressure and acute gastrointestinal illness(177). In particular, acute gastrointestinal illness was more prevalent among residents who lost both water service and water pressure, residents who lost water service for at least 7 days, and residents who lost water pressure for at least 7 days(177). In another example from August 2012, a *Giardia intestinalis* outbreak occurred in a Utah neighborhood after the drinking water distribution system transitioned from one public water system to another(41). The transition likely caused a low pressure scenario that temporarily allowed contaminated water to flow through a previously unknown cross-connection into the drinking water system(41). After the cross-connection was fixed, no additional illnesses were reported(41).

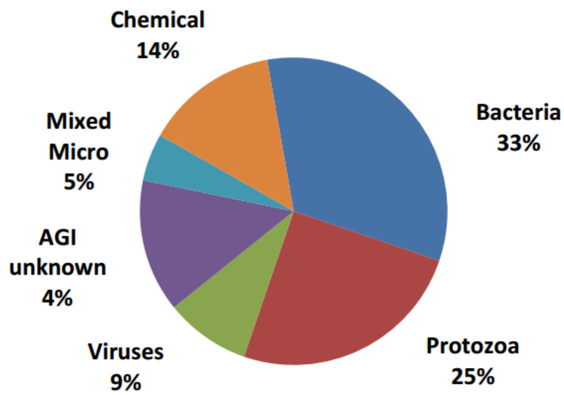

Figure 11: Etiologic agents of U.S. waterborne outbreaks associated with disruptions in the distribution infrastructure from 1981 to 2010.
Source:
http://www.who.int/water_sanitation_health/publications/Water_safety_distribution_systems_2014v1.pdf

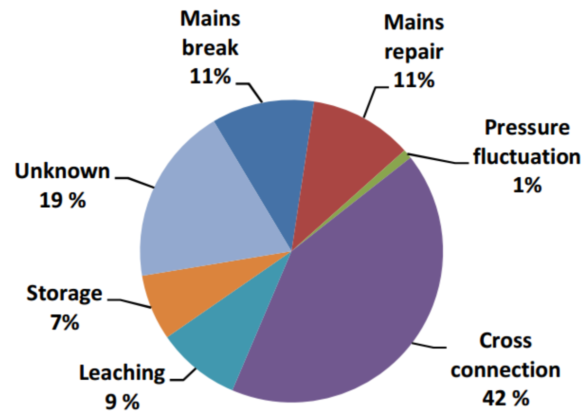

Figure 12: Disruptions in the distribution system that were associated with U.S. waterborne outbreaks from 1981 to 2010.
Source:
http://www.who.int/water_sanitation_health/publications/Water_safety_distribution_systems_2014v1.pdf

Unplanned Disruptions and Waterborne Illnesses

Estimating the association between microbial intrusion events in a distribution system and public health risk is difficult due to the many assumptions that have to be made(157, 178). For example, an intrusion event is contingent on a sequence of events, from the occurrence of an adverse pressure condition, to the presence of an outside contamination source, to the availability of an external pathway for contamination(157, 178). In addition, population exposure depends on several factors, such as the type and concentration of pathogen entering the system and then reaching the consumers' taps, the duration and magnitude of intrusion, and the consumers' drinking habits(157, 178). A quantitative microbial risk assessment (QMRA) is one method of estimating the association between microbial intrusion events and illness(178). For example, Westrell et al. (2003) used a QMRA to evaluate the microbial risks due to failures in Swedish drinking water systems(109). Findings suggested that the majority of annual infections were likely due to pathogens passing treatment during normal operations rather than failure events, thus suggesting an endemic presence(109). Among the three model organisms included, rotavirus caused the largest number of potential infections, followed by *Campylobacter jejuni*(109). In contrast to the current focus on minimizing the risk of *Cryptosporidium*, the calculated risk of *Cryptosporidium* infections was the lowest(109). In another QMRA, Yang et al. (2011) evaluated various factors influencing the risk of viral infection from intrusion due to low/negative pressure transients in distribution systems(179). The risk of infection from intrusion was most sensitive to the duration and the number of nodes experiencing negative pressures(179).

In a systematic review of 20 papers and meta-analysis of 14, tap water consumption was found to be associated with gastrointestinal illness in faulty distribution networks(180). System deficiencies, such as water outages, were also associated with increased gastrointestinal illness(180). In a Swedish study, water treatment and disruptions in the distribution infrastructure during a three year period were not associated with telephone inquiries to a national healthcare network for symptoms of gastrointestinal illness(181). A limitation, however, was that there were only 14 major disruptions(181). In contrast, Shortridge et al. (2014) found an association between the number of pipe breaks and the internet search volume for symptoms of gastrointestinal illness(182). This positive correlation provided support that distribution system disturbances may increase mild cases of gastrointestinal illness that do not necessitate a doctor's visit(182). In the United Kingdom, a postal questionnaire-based study conducted from February 2001 to May 2002 found a strong association (Odds Ratio = 12.5; 95% Confidence Interval: 3.5-44.7) between reported low water pressure at the tap and self-reported diarrhea(183). Results suggested that up to 15% of gastrointestinal illness in the general population could be related to drinking water that has been contaminated from a burst water main or other loss of pressure in the distribution system(183). In Norway, a cohort study conducted during 2003-2004 found that reports of gastrointestinal illness increased during the week after an episode of main breaks or maintenance work on the water distribution system(184). In addition, consumers living far from the treatment plant had the highest risk of gastrointestinal illness(184). Similarly, a study in Russia found that decreased chlorine residuals further away from the plant was associated with higher rates of gastrointestinal illness(185). In addition to gastrointestinal symptoms, Huang et al. (2011) considered eye and skin infections in relation to water outages in Taiwan(186). Water outages, which can occur when water supply pipes are broken, were positively associated with receiving medical care for gastroenteritis, eye infections, and skin infections(186). These results appeared strongest during warmer temperatures (186). Even though the water outages averaged less than a day (15.7 hours), increased risks for illness were also observed during 10-day lag periods(186).

As described earlier, the longer duration water spends in a distribution system, the more likely it is to encounter contamination due to lower disinfectant residuals and more sediments accumulating both of which allow microbes to grow(6). Tinker et al. (2009) used estimates of residence time to assess the association between distribution system contamination and endemic gastrointestinal illness among the population served by two large drinking water utilities in the metro Atlanta, Georgia area(187). The authors found a modest increased risk for emergency department visits for gastrointestinal illness among people living in zip codes with the longest residence time (mean=47.40-74.41 hours, depending on the utility and years) compared to people living in zip codes with intermediate residence times (mean=18.45-33.42 hours, depending on the utility and years)(187). In an attempt to reduce exposure misclassification with a more spatially refined characterization of water residence time, Levy et al. (2016) did a follow-up analysis using residence times based on residential address and proximity to the nearest distribution system node (pipe intersection)(188). The authors observed an increased odds of illness (but with a large amount of uncertainty in the estimates) when comparing long residence times (≥90th percentile) with intermediate residence times (11th to 89th percentile)(188). In addition, they reported that only residence times greater than 2 days (48 hours) were associated with increased risk of gastrointestinal illness, with residence times greater than 4 days (96 hours) having the strongest associations(188). Past studies that did not find an association with shorter residence times (e.g., 0.3 h to 34 h in Montreal(189); 24–36 h in Melbourne(107)) simply may not have reached durations needed to cause elevated risks of illness(188).

Due to a lack of quality long-term data on negative pressure transients, mains breaks, and maintenance work, there are few epidemiology studies on the association between disruptions in the distribution infrastructure and related illnesses. A 2006 report prepared for the EPA by the Water Science and Technology Board of the National Research Council concluded that epidemiology studies explicitly studying the distribution system component of waterborne disease are in need(6). It described limitations of recent studies, such as not focusing on specific distribution failures that could lead to gastrointestinal illness or being unable to detect any link between illness and drinking water(6). In particular, the report emphasized the need to conduct properly designed studies with sufficient power to estimate the risk of endemic disease associated with drinking water distribution systems(6). Exposure to contaminated drinking water from main breaks could be much greater than what has been documented given the high occurrence of main breaks and the challenges of detecting any subsequent contamination that may be highly localized(7). In addition, any health effect uncovered could be underestimated due to the underreporting of illness(7, 190).

CHAPTER 3. STUDY DESIGN, MATERIALS, AND METHODS

Overview

This dissertation examined whether two types of potential contamination events are associated with increased illness. The first was cyanobacteria, or blue-green algae, in the water source. The second was pipe breaks in the drinking water distribution system. Both questions were studied within the context of a large water system operated by the Massachusetts Water Resources Authority (MWRA) that provides drinking water to metropolitan Boston communities.

Massachusetts Water Resources Authority

The Massachusetts Water Resources Authority (MWRA) is a state public authority established in 1984 to provide wholesale water and sewer services to 2.5 million people in 61 metropolitan Boston communities. Specifically, MWRA serves 890,000 households and 5,500 businesses. It supplies an average of 215 millions of gallons per day (mgd) to 2.2 million people and 5,500 industrial users in 51 communities. While some these communities only receive a partial supply or emergency back-up, 33 of the water communities receive full water service (see Table 6). Figure 13 shows a map of the MWRA service areas. (191, 192)

Table 6. MWRA communities with full water service.

Community	MWRA Service
Arlington	Water and Sewer
Belmont	Water and Sewer
Boston	Water and Sewer
Brookline	Water and Sewer
Chelsea	Water and Sewer
Chicopee*	Water
Clinton	Water and Sewer
Everett	Water and Sewer
Framingham	Water and Sewer
Lexington	Water and sewer
Lynnfield Water District	Water
Malden	Water and Sewer
Marblehead	Water
Medford	Water and Sewer
Melrose	Water and Sewer
Milton	Water and Sewer
Nahant	Water
Newton	Water and Sewer
Norwood	Water and Sewer
Quincy	Water and Sewer
Reading	Water and Sewer
Revere	Water and Sewer
Saugus	Water
Somerville	Water and Sewer
South Hadley Fire District #1*	Water
Southborough	Water
Stoneham	Water and Sewer
Swampscott	Water
Waltham	Water and Sewer
Watertown	Water and Sewer
Weston	Water
Wilbraham*	Water
Winthrop	Water and Sewer

*Located in Central Massachusetts; water not treated at the John J. Carroll Water Treatment Plant where there was a change primary disinfection.
Source: http://www.mwra.com/02org/html/whatis.htm

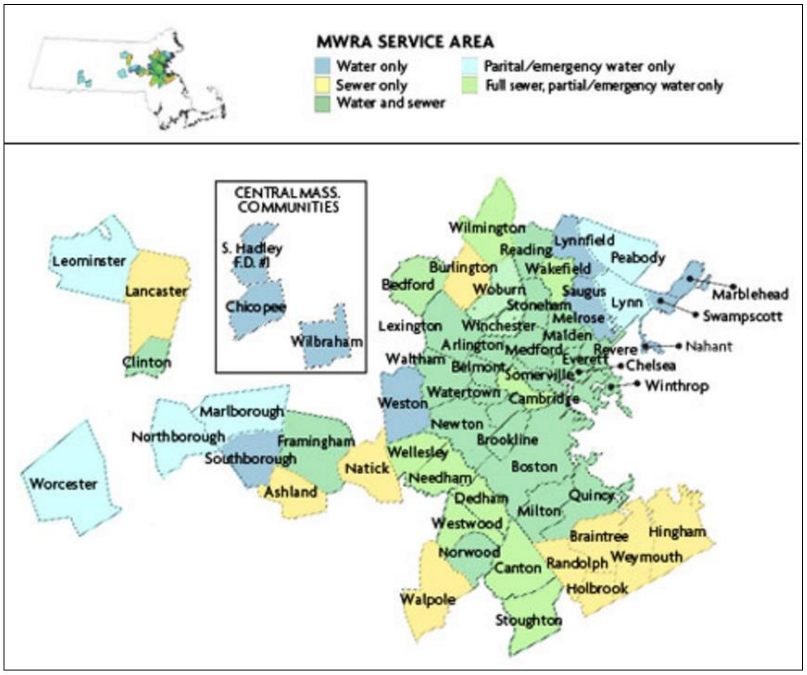

Figure 13: Massachusetts Water Resources Authority (MWRA) service areas.
Source: http://www.mwra.com/02org/html/whatis.htm

History

As one of the oldest cities in the U.S., Boston has one of the oldest public water supply systems, dating all the way back to 1652 when wooden pipes were used to provide domestic water and fire protection. In the 1848 municipal system, wooden pipes were eventually replaced with lead pipes. This early system flowed by gravity through a series of distribution reservoirs. Between 1875 and 1898, seven major reservoirs were constructed and the four pressure zones were established: Boston Low; Southern High; Northern Low; and Northern High. From 1897 to 1905, the Wachusett Reservoir was constructed and, at the time, it became the largest man-made water supply reservoir in the world, with 65 billion gallons supplying 118 mgd. Like before, the use of gravity flow allowed the water to be transported by aqueduct without pumping. In 1919, the Metropolitan District Commission was created by an act which consolidated responsibility for water, sewage and parks into one agency. In the 1920s, an inadequate water supply was projected by 1930 and plans were put in place to add the Ware River and the Quabbin Reservoir. The construction of the Quabbin Reservoir began in 1936 and required the flooding of four towns. It was eventually filled with water from the Swift River and the Ware River. At the time, the 412 billion gallon reservoir became the largest man-made reservoir in the world. The Quabbin Reservoir, located 60 miles from Boston, was another source that could be gravity-operated and did not require filtration. Around the same time, the high service Pressure Aqueduct System was constructed to deliver water to the Metropolitan area. As sections of the Pressure Aqueduct came on line, the need for pumping was reduced since more of the service area could be supplied by gravity. Around 1951, several pump stations were constructed to supply the fast growing suburbs. Soon enough, however, thousands of miles of aging pipelines were leaking millions of gallons of water and no set plans were in place for upgrades. In addition, the sewer system was unable to meet increasing demands and became a major cause of harbor pollution. In 1982-1983, the Metropolitan District Commission faced lawsuits regarding improper sewage discharge and violations of the Clean Water Act. In 1985, when the system was in serious need of an overhaul, MWRA stepped in and assumed responsibility for the delivery and distribution of water to 46 communities primarily in the metropolitan Boston area.(193, 194)

From 1988 to 1990, a leak detection survey of 6,085 miles of community pipes revealed that 30 million gallons per day was lost in community systems. Repairs were subsequently carried out and, in 1991, MWRA implemented leak detection regulations requiring communities to complete leak detection surveys every two years. In addition, all MWRA distribution pipes (286 miles) are checked annually for leaks and repairs made promptly. In November 2003, the

MetroWest Water Supply Tunnel was brought on line (see Figure 14). Prior to July 27, 2005, water treatment occurred at several different facilities as it traveled to the metropolitan Boston area(195). Since July 27, 2005, all water treatment for the metropolitan Boston area was centralized at the John J. Carroll Water Treatment Plant (CWTP) at Walnut Hill in Marlborough. MWRA is currently provides water to 51 communities. The water system is managed as a partnership with the Massachusetts Department of Conservation and Recreation (DCR), which still maintains responsibility for managing the reservoir watersheds.(193-195)

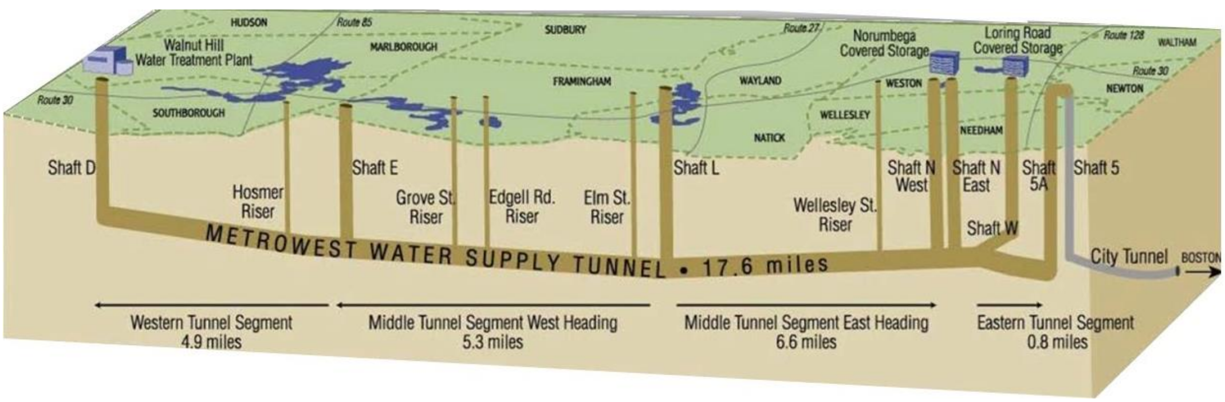

Figure 14: MetroWest Water Supply Tunnel.
Source: http://www.ecs.umass.edu/cee/reckhow/courses/seminar/presentations/Laskey%20HH%20Lecture%202014.pdf

Water Source

MWRA's water comes from the Quabbin and Wachusett Reservoirs, located approximately 65 and 35 miles west of Boston, respectively. MWRA and DCR regularly monitor reservoir levels at Quabbin (412 billion gallon capacity) and Wachusett (65 billion gallon capacity). The reservoirs are naturally filled by rain and snow fed in by nearby streams. While Wachusett levels are kept relatively fixed, Quabbin levels fluctuate with precipitation and watershed runoff. To protect the reservoirs, forest and wetlands cover over 85% of the surrounding watershed lands. In addition, about 75% of the total watershed land cannot be built on. While recreational activities (e.g., shoreline fishing, hiking, biking, snowshoeing) are permitted, public access is carefully regulated and controlled. Regulations strictly prohibit activities with direct water contact (e.g., swimming, wading) and dogs are not allowed. To ensure the quality of the water, DCR routinely tests and patrols the streams and reservoirs. MWRA also tests water samples (over 1,600 per month) throughout the entire system (from the reservoirs to the consumers' taps). (196-199)

Water Treatment

From the Wachusett reservoir, it takes approximately five hours for water to move southeast to the treatment plant(200). The water system has always been unfiltered and relies primarily on disinfection(201). There is no sedimentation, coagulation, or flocculation process; however, raw water turbidity is normally <0.50 Nephelometric Turbidity Units (NTUs)(201). Between 1998 and 2005, chlorine was the primary disinfectant, with chloramine as the secondary (residual) disinfectant to maintain sanitary condition throughout the distribution system(195, 202). Primary disinfection was done at the Cosgrove Disinfection facility and corrosion control and chloramination was done at other facilities to the east. Since July 27, 2005, all water treatment for the metropolitan Boston area (all communities listed in Table 6 except Chicopee, South Hadley Fire District #1, and Wilbraham) was centralized at CWTP and the primary disinfectant changed to ozone while the secondary (residual) disinfectant remained chloramine(195, 202). All other facilities were taken out of service after CWTP went on line.

In April 2014, ultraviolet light disinfection was added to achieve *Cryptosporidium* inactivation. Table 7 and Figure 15 show the treatment steps since ultraviolet disinfection was added. Downstream of the CWTP, there is no re-chlorination and no community practice booster chlorination or phosphate addition(202). According to personal communications with MWRA, major changes observed after the primary disinfection changed to ozone were a large decrease in taste and odor complaints (likely due to algae) and a large reduction in trihalomethanes (disinfection by-products). Also, MWRA claims that ever since CWTP has been on line, it has exceeded current regulatory requirements for inactivation of *Giardia*, provided *Cryptosporidium* inactivation, and reduced the formation of regulated disinfection by-products.(195, 198, 201-203)

Table 7. Water treatment steps at the John J. Carroll Water Treatment Plant (CWTP).

Treatment	Current Dose	Purpose
Ozone	1.5-4.0 mg/l	Primary disinfectant, to achieve 99.9% *Giardia* inactivation
Sodium bisulfite	0.0-3.5 mg/l	To remove ozone
Ultraviolet Light (Added in April 2014)		Second primary disinfectant, to inactivate chemically resistant parasites such as *Cryptosporidium*
Sodium hypochlorite (chlorine)	3-4 mg/l	For residual disinfection, to protect water as it travels through the pipe network
Sodium hydrofluorosilicic acid (fluoride)	0.6 mg/l	For dental health
Aqueous ammonia	0.6-0.85 mg/l	To combine with chlorine to form monochloramine for residual disinfection
Sodium carbonate	35-37 mg/l	To raise the alkalinity of the water for pH buffering; to minimize lead and copper leaching from home plumbing
Carbon dioxide	4.5-8.5 mg/l	To adjust pH to final level

Source: http://www.mwra.state.ma.us/04water/html/watsys.htm

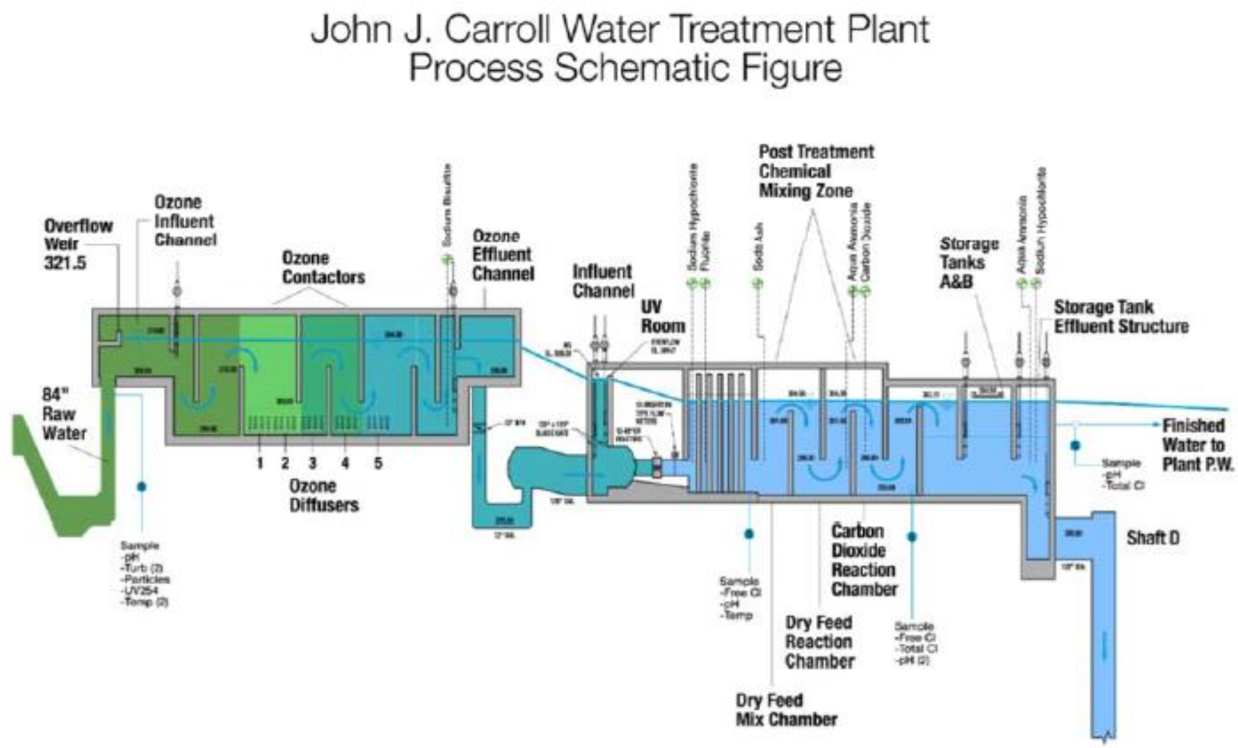

Figure 15: Water Plant Process Schematic (since the addition of ultraviolet disinfection in April 2014).
Source: MWRA, 2017. Optimal Corrosion Control Treatment Evaluation Review.(195)

The MWRA system is the second largest unfiltered water system in the U.S., after New York City(204). Through watershed management practices to protect existing sources, both cities qualify for Filtration Avoidance Determination(205). Under the EPA's 1989 Surface Water Treatment Rule, public surface water providers are required to filter their water unless a waiver is granted based on water quality and watershed protection(206). In 1999-2000, MWRA successfully defended its comprehensive strategy to protect and improve drinking water (through watershed protection, its new $261 million treatment facility to provide ozonation/chloramination disinfection, and its community pipe rehabilitation program) and avoided having to spend $180 million in filtration facilities, as requested by the EPA. U.S.

District Judge Richard G. Stearns concluded that the EPA failed to show that filtration of MWRA water was required either as a matter of cost-benefit or scientific necessity.(207, 208)

It is possible, under certain conditions, that the consequences of an unfiltered water system can impact the individual consumers. For example, according to the Town of Reading which uses MWRA water, in-home filters may need to be changed more often due to the unfiltered water supply. In particular, during certain times of the year when the source water reservoirs experience algae blooms, in-home filters may quickly become saturated and thus decline in performance. To reduce required filter changes, suggestions have been made to only filter drinking water and not all the water entering the house.(209)

Distribution System

After water is treated at the CWTP, it enters the distribution network and is sent through the MetroWest Water Supply Tunnel and the Hultman Aqueduct before being stored in covered tanks. From there it is drawn into distribution mains and many smaller community pipes. Local pipes serve each street and eventually carry water to the consumer.(198) The distribution networks are gridirons, meaning water can reach any service line by at least two different paths. This ensures permanent feeding and avoiding dead-ends. Figure 16 illustrates the entire MWRA water system, from source to community.

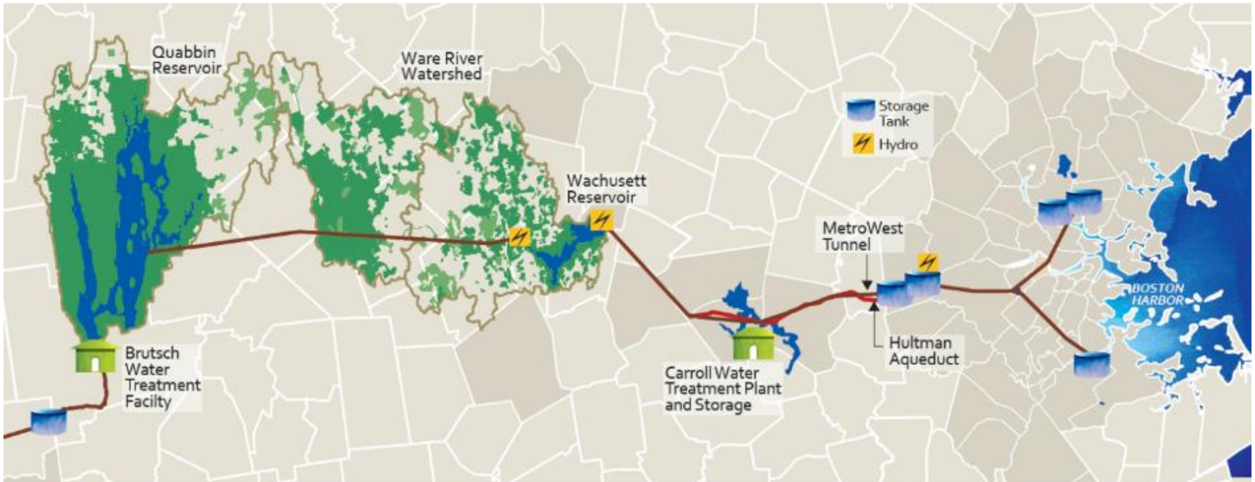

Figure 16: Massachusetts Water Resources Authority (MWRA) water system.
Source: http://www.mwra.com/annual/waterreport/2014results/images/2014watermap.png

The travel time for water, from source to tap, is complex because it depends on many sections of the water system. Figure 17, provided by a hydraulic modeling specialist at MWRA, illustrates the range of travel times for each section of the system. At the beginning of the system, the travel time from the Quabbin Reservoir into the Wachusett Reservoir typically range from 10-11 hours at an average rate of 300 mgd. Water remains in the Wachusett Reservoir from any time between 3 weeks to 6 months. Then, it takes about 4 hours from the Wachusett Reservoir to the treatment plant. From the treatment plant, the water continues east to the Norumbega Covered Storage Facility, taking 14 to 16 hours depending upon system demands. Since the storage facility is a “flow thru” design, the water remains in the tank for 8 to 12 hours. East of the Norumbega facility, the Metrowest tunnel and the Hultman Aqueduct carry water to a storage tank at Loring Road to supply the Boston Low service area or continue east along the City Tunnel which feeds both the City Tunnel Extension to the North and the Dorchester Tunnel to the South. Shafts along each of these tunnel sections bring water up riser pipes that feed the distribution system. Since MWRA is a wholesaler, the water supply enters the communities through large metered connections. Based on the ground elevation, the water system is divided into seven pressure zones. The number of metered connections in each community depends on the size and geography of a community. For example, the City of Boston has 29 meters serving two pressures zones and the town of Marblehead has only one metered connection. Once the water passes through the metered connection, it enters the community system which is owned and operated by the local community. In general, the travel time from the Wachusett Reservoir to one of the larger Boston metered connections in their high system ranging from 40 to 50 hours depending upon system demands. For a town like Marblehead, which is located at the far Northeastern portion of the system, the travel times from the Wachusetts Reservoir range from 60 to 70 hours.(200)

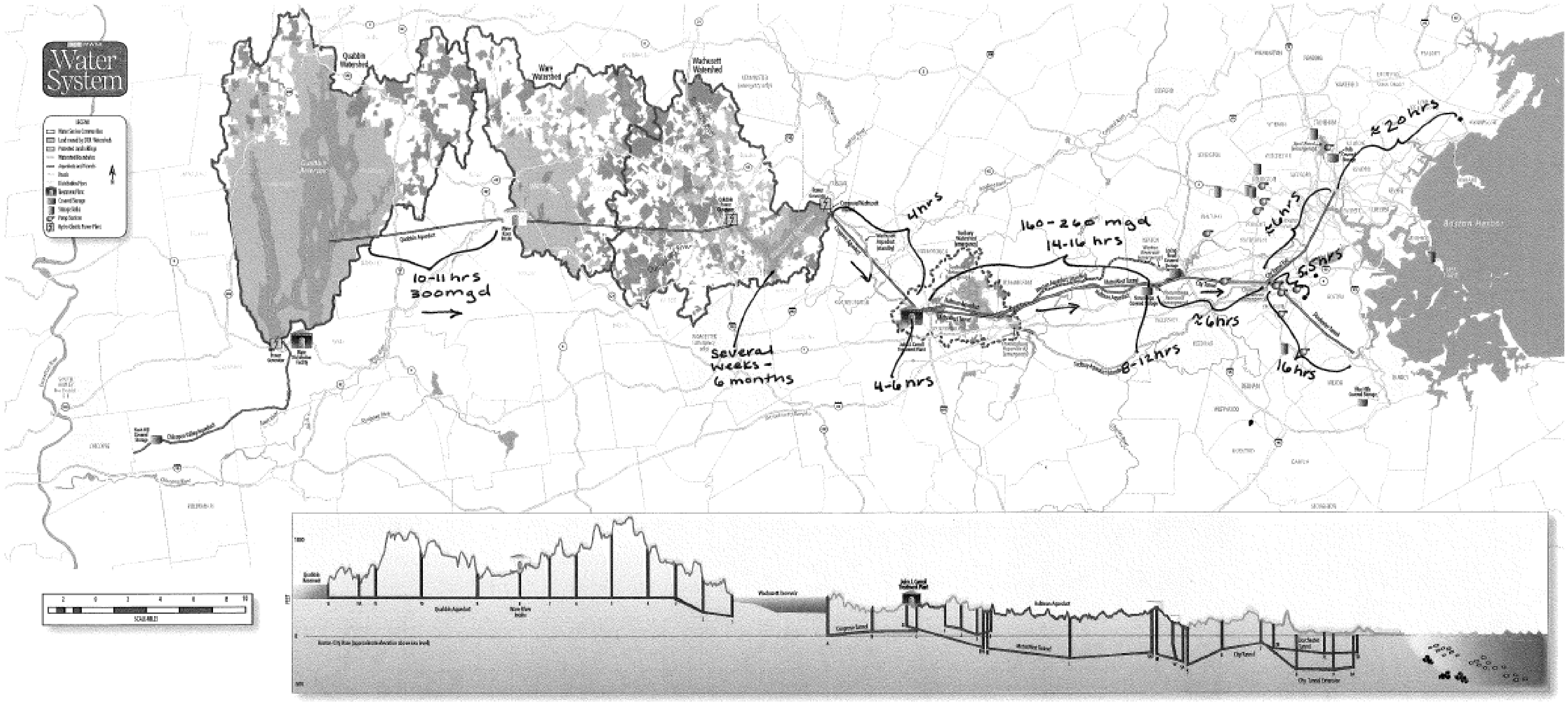

Figure 17: Range of water travel times for each section of the MWRA system.

Source: MWRA hydraulic modeling specialist

Prior to July 2005 (before the switch to CWTP), the travel times may have differed since water was treated at several facilities as it travelled to the metropolitan Boston area. According to a 1998 Waterworks System Handbook, the travel time from Cosgrove Disinfection facility, where primary disinfection was conducted, to the Norumbega facility was 11-12 hours. Table 8 provides times from Norumbega to the first meter in each community.(201, 210)

Table 8. Approximate travel times from the Norumbega facility to select communities, prior to 2005.

Community	Winter Travel Time (Hours) (Average 215 mgd)	Summer Travel Time (Hours) (Average 275 mgd)
Arlington	18	14
Belmont	11	8
Boston	7	5
Brookline	7	5
Chelsea	24	18
Everett	20	15
Lexington	15	11
Lynnfield	31	23
Malden	20	15
Marblehead	38	28
Medford	21	16
Milton	24	18
Nahant	47	35
Newton	3	2
Norwood	29	22
Quincy	28	21
Revere	25	18
Saugus	26	19
Somerville	36	27
Swampscott	42	31
Waltham	8	6
Watertown	14	10
Winthrop	32	23

Study Population

This dissertation research includes residents of metropolitan Boston communities that receive full water service from MWRA. All residents are assumed to have regular contact with tap water, whether through drinking, cooking, cleaning, bathing, and/or other basic hygiene. MWRA-served communities are primarily urban so there is a low prevalence of private well use. Due to data limitations, however, the actual fraction of the population using bottled water, private well water, and/or in-home water treatment was unknown.

By using emergency department (ED) data, the study population only includes residents with access to healthcare. In April 2006, Massachusetts passed a comprehensive healthcare reform law to reduce the number of people without health insurance. In 2007, all Massachusetts adults (with a few exceptions) were required to have health insurance (or else they would lose their personal income tax deduction on their 2007 state taxes). A slight increase in ED visits across the state of Massachusetts has been associated with the implementation of the health care reform(211).

Health Outcomes

Massachusetts Healthcare Data

Emergency department (ED) and hospital outpatient data were obtained from the Commonwealth of Massachusetts Center for Health Information and Analysis for a 10-year period (10/1/2002 – 9/30/2012). ED visits are a reasonable and valid way to study population health because they play a vital role in the health care system and provide data concerning important aspects of public health, medical, and social problems(212). ED data also contribute to public health surveillance by capturing the onset of infectious disease outbreaks or other medical emergencies(212). Environmental epidemiology studies that have used ED data include studies of air pollution and asthma(213), ambient temperature and heat-related illness(214), extreme precipitation and gastrointestinal illness(215), and flooding and gastrointestinal illness(216). As with any secondary data source, there are possible limitations such as the completeness of data, consistency in coding and classification of diseases, and representativeness of the study population(212). ED data may only capture a subset of the outcome of interest and not reflect the total population burden(190). For example, regarding gastrointestinal illness, only the most severe cases may seek immediate medical attention at the ED and those experiencing milder symptoms may opt to recover at home(190).

ED visits included emergency departments in Massachusetts' acute care hospitals and satellite emergency facilities. Hospital outpatient data included patients who received observation services but were not admitted to the hospital. Hospital outpatient visits are often transferred from the ED (217-219). The yearly databases were compiled from quarterly hospital reports and collected for administrative purposes. They were made available to the public through an application process and did not contain information that could be used to identify an individual; the data were considered anonymous.

These data were determined exempt (category 4 – existing data, public or deidentified) from Institutional Review Board evaluation by the Office of Human Research Ethics at the University of North Carolina at Chapel Hill (Study #: 17-0381). They were also exempt from Institutional Review Board evaluation by the U.S. Environmental Protection Agency's Human

Subjects Research Protocol Officer as they were not considered human subjects data under the Common Rule (40 CFR 26).

Each data observation included patient-level information, including town and zip code of residence, age, sex, primary diagnosis code (International Classification of Disease, Version 9, Clinical Modification, ICD-9-CM), and five associated diagnosis codes. These data have been used in the past to examine the association between extreme weather events (e.g., flooding, extreme precipitation) and ED visits for gastrointestinal illness(215, 216, 220).

Use of ICD-9-CM diagnosis codes in healthcare

ICD-9-CM codes are managed by The National Center for Health Statistics, and the Medicare and Medicaid Services. This coding process is done for all medical services at all types of health facilities, including inpatient/outpatient facility, physician office, and diagnostic services. The main purpose of ICD-9-CM codes is to report diseases and signs and symptoms for data and billing purposes. For example, diagnosis coding provides documentation of medical necessity for health insurance claims.(221)

Gastrointestinal Illness (Aims 1 & 2)

Acute gastrointestinal illness (AGI) was an outcome of interest for both Aim 1 and Aim 2. AGI was defined using ICD-9-CM diagnosis codes. Several studies assessing drinking water quality have used ICD-9-CM diagnostic codes to define healthcare visits for AGI. In a study of drinking water turbidity, Schwartz et al. (2010) used primary diagnosis of gastrointestinal related illness (001 to 009.9 and 558.9) or associated general symptoms such as electrolyte disorders (276), nausea and vomiting (787), and abdominal pain (789)(50). In another study of drinking water turbidity, Tinker et al. (2010) used the following codes: infectious gastrointestinal illness (001–004, 005.0, 005.4, 005.89, 005.9, 006–007, 008.0, 008.42–008.44, 008.47, 008.49, 008.5, 008.6, 008.8, 009), non-infectious gastrointestinal illness (558.9), and nausea and vomiting plausibly related to gastrointestinal illness (787.01–787.03, 787.91)(55). The authors included non-infectious gastrointestinal illness because infectious cases of gastrointestinal illness are often misclassified as non-infectious(55). In a study of the release of partially treated sewage into drinking water sources, Redman et al. (2007) used specified gastrointestinal infections (001–009.9), unspecified gastroenteritis (558.9), and diarrhea (787.91)(222). In a study of water outages, Huang et al. (2011) used similar codes to Schwartz et al. (2010) but added 535, 536.2, 555, 558.2, 558.9, 567, 568.9, and 578(186).

Few studies on harmful algae or cyanobacteria have used ICD-9-CM diagnosis codes. For recreational water exposure to Florida Red Tide blooms, Kirkpatrick et al. (2010) used 535.0-537.9 and 557.0-558.0 (223) and Hoagland et al. (2014) used all diseases of the digestive system (520.0–579.9)(224).

Based on what has been used in the literature, the ICD-9-CM codes listed in Table 9 were considered in defining AGI in Aims 1 and 2. The codes in bold font were ultimately selected for this study. Using similar codes for AGI in the Massachusetts data, Wade et al. (2014) found an association between flooding and an increased risk of visiting the ED for AGI(216).

Table 9. ICD-9-CM diagnosis codes that have been used to define acute gastrointestinal illness.

ICD-9-CM Code	Diagnosis	Schwartz (50)	Redman (222)	Tinker (55)	Huang (186)	Wade (216)
001-009.9	**Intestinal Infectious Diseases: Cholera; Typhoid and paratyphoid fevers; Other salmonella infections; Shigellosis; Other food poisoning (bacterial); Amebiasis; Other protozoal intestinal diseases; Intestinal infections due to other organisms; Ill-defined intestinal infections**	**x**	**x**		**x**	**x**
001-004	Cholera; Typhoid and paratyphoid fevers; Other salmonella infections; Shigellosis			X		
005.0	Staphylococcal food poisoning			x		
005.4	Food poisoning due to Vibrio parahaemolyticus			x		
005.89	Other bacterial food poisoning			x		
005.9	Food poisoning, unspecified			x		
006-007	Amebiasis; Other protozoal intestinal diseases			x		
008.0	Escherichia coli [E. coli]			x		
008.42-008.44	Pseudomonas; Campylobacter; Yersinia enterocolitica			x		
008.47	Other gram-negative bacteria - Gram-negative enteritis NOS			x		
008.49	Other specified bacteria - Other			x		
008.5	Bacterial enteritis, unspecified			x		
008.6	Enteritis due to specified virus			x		
008.8	Other organism, not elsewhere classified - Viral: enteritis NOS, gastroenteritis			x		
009	Ill-defined intestinal infections			x		
276	Disorders of fluid, electrolyte, and acid-base balance	x				
535	Gastritis and duodenitis				x	
536.2	Persistent vomiting				x	
555	Regional enteritis				x	
558.2	Toxic gastroenteritis and colitis				x	
558.9	**Other and unspecified noninfectious gastroenteritis and colitis**	**x**	**x**	**x**	**x**	**x**
567	Peritonitis and retroperitoneal infections				x	
568.9	Unspecified disorder of peritoneum				x	
578	Gastrointestinal hemorrhage				x	
787	Symptoms involving digestive system	x			x	x
787.0 (787.01-787.03)	**Nausea and vomiting (Nausea with vomiting; Nausea alone; Vomiting alone)**			**x**		**x**
787.01	Nausea with vomiting					x
787.03	Vomiting alone					x
787.4	Visible peristalsis					x
787.9	Other symptoms involving digestive system					x
787.91	**Diarrhea**		**x**	**x**		**x**
789	Other symptoms involving abdomen and pelvis	x			x	

*Diagnosis codes in bold font were selected for this study.

Dermal Symptoms of Illness (Aim 1)

Unlike AGI, ICD-9-CM diagnosis codes for dermal symptoms of illness have rarely been used in studies of healthcare visits, especially in relation to waterborne pathogens. In a study of water outages by Huang et al. (2011), the group of skin diagnoses selected included: infectious skin diseases (680-686), acariasis (133), mycoses of skin (110 and 111), and rashes (782.1)(186). Based on this list, the ICD-9-CM codes used to define dermal symptoms of illness in Aim 1 are listed in Table 10.

Respiratory Symptoms of Illness (Aim 1)

A number of air quality studies have used ICD-9-CM diagnostic codes to define healthcare visits for respiratory outcomes(225-227). Generally, respiratory outcomes have been defined broadly using ICD-9-CM codes 460-519, which includes chronic obstructive pulmonary disease, asthma, pneumonia, and acute respiratory infections(225-227). Few studies of waterborne exposures have used ICD-9-CM codes to define respiratory illness. In studies of human exposure to Florida red tides formed by *Karenia brevis*, the same ICD-9-CM codes (460-519) used in air quality studies were used(224, 228). Based on this list, along with a few additional codes for cough, wheezing, and shortness of breath, ICD-9-CM codes used to define respiratory illness in Aim 1 were selected and are listed in listed in Table 10.

Table 10. ICD-9-CM diagnosis codes used to define study outcomes.

ICD-9-CM Code	Diagnosis
Gastrointestinal	
001-009.9	Intestinal Infectious Diseases: Cholera; Typhoid and paratyphoid fevers; Other salmonella infections; Shigellosis; Other food poisoning (bacterial); Amebiasis; Other protozoal intestinal diseases; Intestinal infections due to other organisms; Ill-defined intestinal infections
558.9	Other and unspecified noninfectious gastroenteritis and colitis
787.0	Nausea and vomiting
787.91	Diarrhea
Dermal	
782.1	Rash and other nonspecific skin eruption
136.9	Unspecified infectious and parasitic diseases
686.9	Unspecified local infection of skin and subcutaneous tissue
692	Contact dermatitis and other eczema
691.8	Other atopic dermatitis and related conditions
Respiratory	
460	Acute nasopharyngitis [common cold]
461	Acute sinusitis
465.9	Acute Upper Respiratory Infection (Not Otherwise Specified)
493	Asthma
786.2	Cough
786.07	Wheezing
786.05	Shortness of breath

Abbreviation: ICD-9-CM, International Classification of Disease, Version 9 Clinical Modification

Data Quality Assurance

This project only involved secondary data analyses. All data were obtained directly from the source (e.g., MWRA, BWSC, Commonwealth of Massachusetts Center for Health Information and Analysis) and documents describing procedures and quality operations are available.

In addition, each analysis began with a careful examination of all relevant variables. Frequency tables were used to summarize categorical variables. Measures of distribution and graphical representation were used to summarize continuous variables. Each variable was checked for implausible values, outliers, and missing data. If there was more than a trivial amount of missing data for a certain variable (>5% of study population), an analysis was conducted to determine whether an imputation method would be appropriate.

Aim 1 Materials and Methods

The objective of Aim 1 was to estimate the association between daily measures of total cyanobacteria in the Wachusett Reservoir and emergency department (ED) visits for acute gastrointestinal, respiratory, and dermal symptoms of illness in metropolitan Boston communities served by MWRA over a 7-year period (7/27/2005 – 9/30/2012).

Study Population

For consistency regarding water treatment and travel times, this study was restricted to only when the John J. Carroll Water Treatment Plant (CWTP) was on line (July 27, 2005 – September 30, 2012). This study included a subset of MWRA communities that met the following criteria: 1) received full water service from MWRA; 2) located 20-35 miles from the intake at Wachusett Reservoir (estimated using ArcMap); and 3) received water after the Norumbega Covered Storage Facility. Figure 18 highlights the 22 study communities in relation to the Wachusett Reservoir, CWTP, and Norumbega Covered Storage Facility. These communities include Arlington, Belmont, Boston, Brookline, Chelsea, Everett, Lexington, Lynnfield, Malden, Medford, Melrose, Milton, Newton, Norwood, Reading, Revere, Saugus, Somerville, Stoneham, Waltham, Watertown, and Weston. Based on the 2010 U.S. Census, the total population of these communities was around 1.4 million.

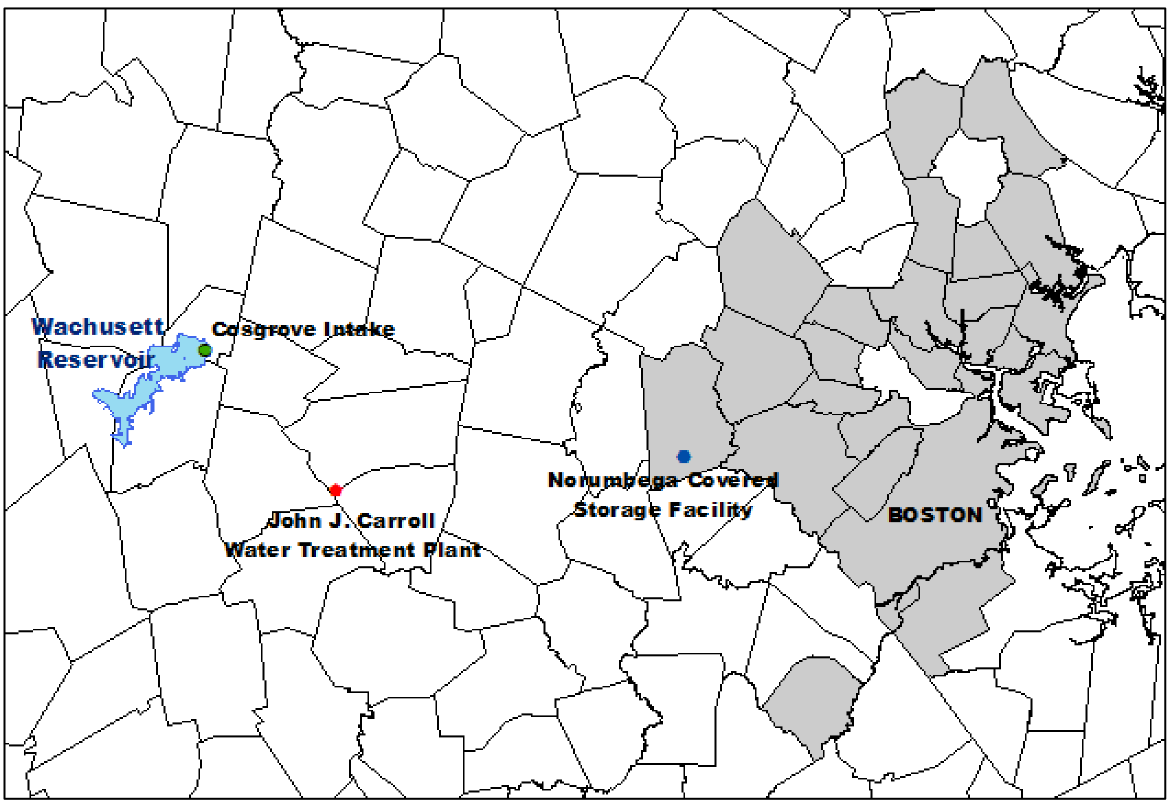

Figure 18. Metropolitan Boston Communities included in Aim 1.

Health Outcomes

Emergency department (ED) data were used to capture acute symptoms of gastrointestinal, respiratory, and dermal illnesses, all of which have been related to exposure to cyanobacteria and/or their toxins(133, 138, 139, 229).

Cyanobacteria Exposure

The MWRA and the Massachusetts Department of Conservation and Recreation (DCR) provided cyanobacteria data from the Wachusett Reservoir. Water samples were collected weekly during the winter (October 1- April 30) and twice per week during the summer (May 1- September 30, Mondays and Thursdays). In the winter, no samples were collected if the reservoir was ice covered. Increased monitoring occurred whenever there were concerns, such as counts above early trigger levels, increased consumer complaints, and/or other information suggesting a bloom threat (e.g., weather, nutrient, dissolved oxygen). Trigger levels were based on “nuisance algae” known to cause taste and odor problems in the water (e.g., Anabaena, Synura, Dinobryon, Chrysosphaerella, Uroglenopsis).(230)

Routine grab samples were collected at various depths near the Cosgrove Intake which transfers water from the Wachusett Reservoir to the CWTP(230). Depending on the weather and other relevant conditions, one of two sampling locations was used – Basin North (BN) 3417 (by boat) or from Cosgrove Intake (see Figure 19). Location BN 3417 was sampled preferentially by DCR as it was not impacted by turbulence at the Intake, wind driven effects, etc. However, Cosgrove Intake was used if conditions did not allow for sampling from Location BN 3417. Cyanobacteria densities were quantified using a Sedgewick-Rafter (S-R) Cell(231). The method used, including 10 field count, three strips count, and full S-R cell count, is documented in Standard Methods 18th Edition (230-232). Phytoplankton densities were expressed as Areal Standard Units (ASUs; equivalent to 400 square microns) per milliliter(231).

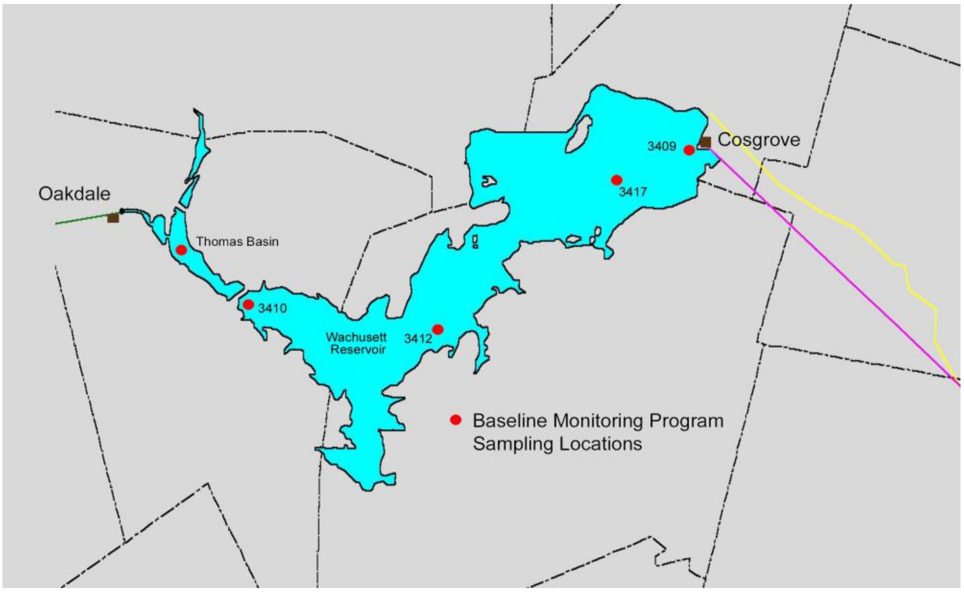

Figure 19: Wachusett sampling locations.

MWRA generally uses overall maximum measures, irrelevant of depth, to determine monitoring and treatment decisions. Based on MWRA's procedures, a daily measure of total cyanobacteria was based on the daily maximum, regardless of the location or depth of sample collection. Linear interpolation was used to address days without sample collection (83%) in order to form a daily time-series of cyanobacteria (Figure 20). During the winter, concentrations were low and relatively stable.(230) Cyanobacteria genera included, but were not limited to, *Anabaena*, *Aphanocapsa*, *Aphanothece*, *Chroococcus*, *Coelosphaerium*, *Dactylococcopsis*, *Gloeocapsa*, *Gomphosphaeria*, *Merismopedia*, *Microcystis*, *Oscillatoria*, and *Rhabdoderma*. Figure 21 shows an example of Microcystis, a genus of freshwater cyanobacteria, observed at the Cosgrove Intake in the Wachusett Reservoir on July 20, 2015.

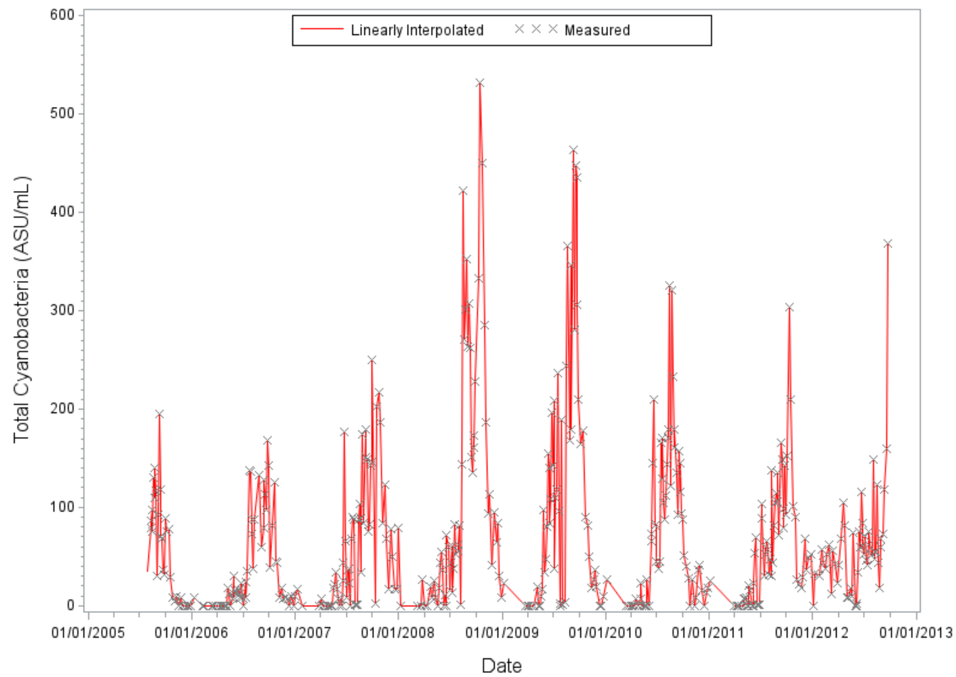

Figure 20. Time-series of Total Cyanobacteria in Wachusett Reservoir, 7/27/2005-9/30/2012.

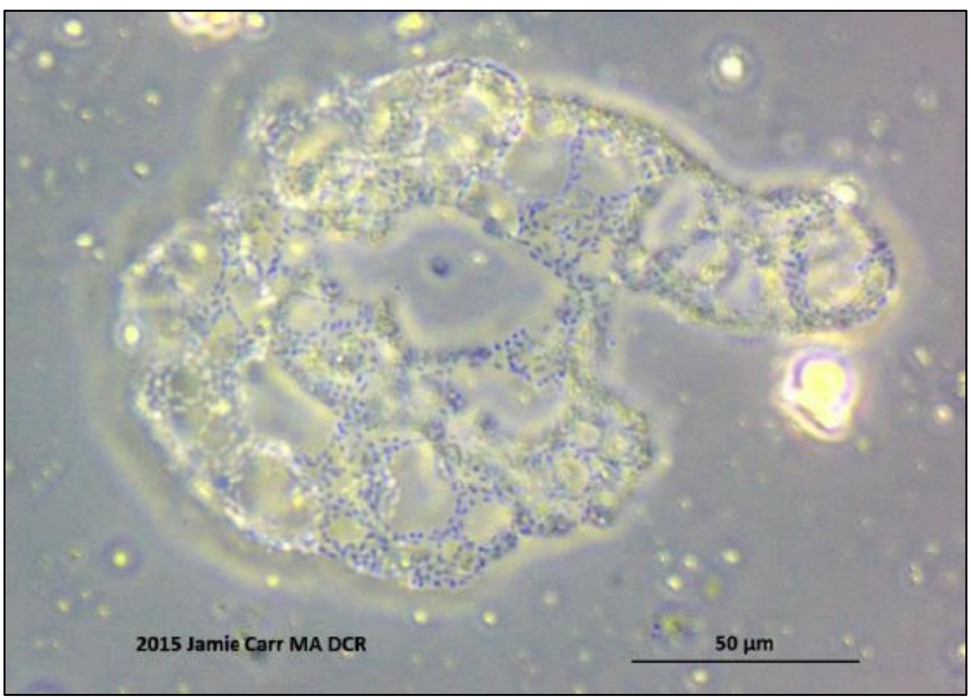

Figure 21: Microcystis observed in the Wachusett Reservoir in July 2015.
Source: Massachusetts Department of Conservation and Recreation(231)

Latency between Cyanobacteria Measurement and ED visits

According to a hydraulic modeling specialist at MWRA, it takes about 4 hours for water to travel from the Wachusett Reservoir to the treatment plant. From the treatment plant, the water continues east to the Norumbega Covered Storage Facility, taking 14 to 16 hours depending on system demands. Since the storage facility is a "flow thru" design, the water remains in the tank for 8 to 12 hours before leaving. In general, the travel time from the Wachusett Reservoir to the City of Boston ranges from 40 to 50 hours depending on system demands.(200)

The time it takes water to travel from the Wachusett Reservoir to each study community varies depending on system demands and distance travelled. By selecting communities within 20-35 miles of the Wachusett Reservoir, water travel times were estimated to be similar (within a day of each other) and take a minimum of 2-3 days. The health effects of cyanobacteria were expected to be acute (i.e., without an incubation period), occurring within 0-2 days of exposure. In a previous study, drinking water contaminated by cyanobacteria was associated with symptoms of illness (e.g., muscle pain, gastrointestinal, skin, and ear) within 0-3 days of exposure (138). Given the acute nature of expected symptoms, the time it might take to visit the ED was estimated to be within 0-2 days. Accounting for the travel time and lag to visit the ED, a 2-4 and 5-7 day lag between cyanobacteria measurement and ED visit were considered in the analysis. For each lagged period of exposure, daily maxima of total cyanobacteria were summed together.

Other Variables

Mean daily air temperature for Boston were obtained from the National Climatic Data Center. Mean daily water temperature in the Wachusett Reservoir were obtained from MWRA. To form a daily time series of water temperature, linear interpolation was used to address days without a measurement (13%). Rain gauge data were obtained from the Boston Water and Sewer Commission.

Statistical Analysis

Poisson regression models were used to estimate the associations between varying levels of cyanobacteria in the Wachusett Reservoir and daily rates of ED visits for acute gastrointestinal, respiratory, and dermal symptoms of illness. Potential confounders were time-dependent factors related to both cyanobacteria and symptoms of illness. Long-term trends and seasonal variations were modeled using indicator variables for year, month, and day of the week. This also addressed the consistent increase in ED utilizations after the implementation of the Massachusetts health care reform in 2006(211). For gastrointestinal illness, air temperature, water temperature, and extreme precipitation were also considered potential confounders. For respiratory illness, air temperature was considered a potential confounder.

Total cyanobacteria were categorized into quartiles and the lowest quartile served as the reference category. Results are reported as incidence rate ratios (IRR) and 95% confidence intervals (CI) to describe the relative change in the rate of ED visits between quartiles of cyanobacteria. Due to the potential for differences in susceptibility by age, the analyses were also stratified by age group. Data management and statistical analyses were conducted using SAS 9.4(233).

Aim 2a Materials and Methods

The objective of Aim 2a was to estimate the association between water main breaks and ED visits for acute gastrointestinal illness (AGI) over a 10-year period (10/1/2002 – 9/30/2012) in the City of Boston.

Study Population

Boston's water system is operated by the Boston Water and Sewer Commission (BWSC) and delivers potable water to over a million people each day(234).   The 2010 Census reported a resident population of 617,594 for the City of Boston(235). BWSC also serves schools and universities, hospitals, businesses, industries, and private and public institutions throughout the city(236).

Health Outcomes

Waterborne pathogens often cause acute gastrointestinal illness (AGI)(33). While the type of pathogen and length of incubation period can vary, they often cause a range of similar symptoms such as diarrhea, vomiting, nausea, and abdominal cramping(33, 38). Symptoms can develop in less than a day for some viruses (e.g., norovirus)(237), within a few days for some bacteria (e.g., *Campylobacter*)(238), and up to a week or more for some parasites (e.g., *Cryptosporidium*, *Giardia*)(239, 240). AGI was defined using ICD-9-CM diagnosis codes described earlier. Both primary and associated diagnosis codes were included; however, a sensitivity analysis based on only the primary diagnosis code was also conducted to examine the robustness of results.

<u>Main Break Exposure</u>

Main break records were obtained from BWSC for the entire study period. These records are maintained by BWSC Field Engineering Department(241). Aside from the location of the break, the data included details such as the pipe material and type of break. It was hypothesized that ED visits for any AGI caused by a main break would occur within a week of the break. This hazard period was examined as two mutually exclusive intervals: 0-3 days and 4-7 days. The different hazard periods accounted for various amounts of time that it could take for contaminated water to enter the distribution system after a main break, reach the consumer, and cause AGI symptoms that ultimately result in an ED visit. Figure 22 summarizes the total number of main breaks by zip code during the entire study period.

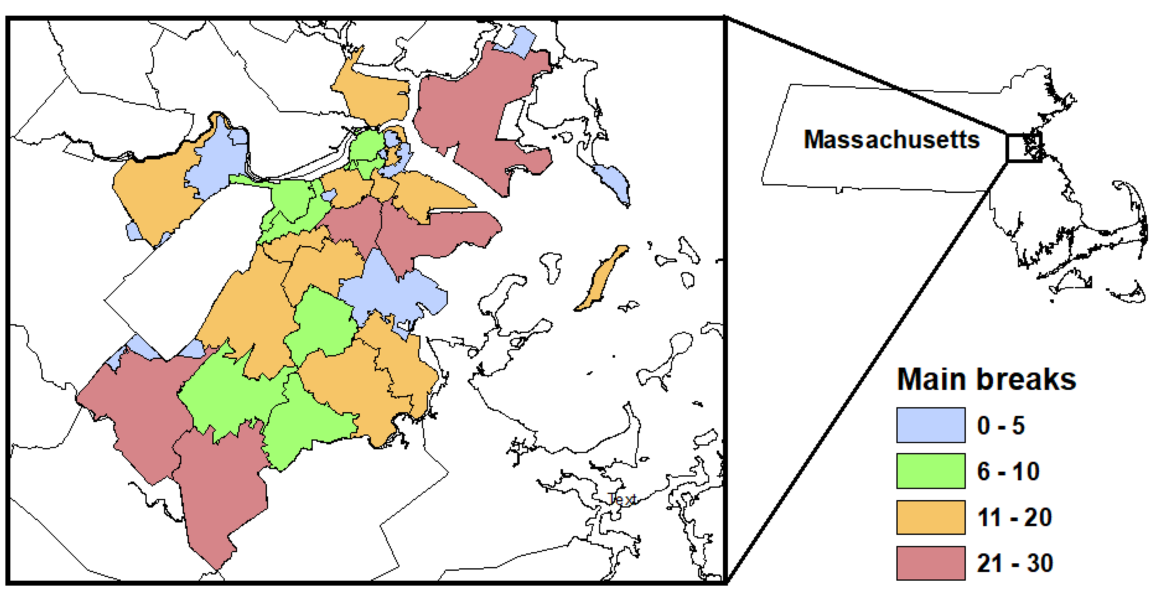

Figure 22. Number of main breaks by zip codes in Boston, 10/1/2002 – 9/30/2012.

Statistical Analysis

A case-crossover study design was used to examine the association between main breaks and ED visits for AGI. In a case-crossover study, cases effectively serve as their own control at different point(s) in time(242). This type of study design was suitable because a main break is a brief exposure and any related AGI would be a transient effect(242, 243). Using a time-stratified bi-directional approach matched on zip code and day of week, control date(s) were selected two weeks before and/or after the ED visit within 42-day time-stratified periods(244). Conditional fixed-effects logistic regression models were used to estimate the risk of visiting the ED for AGI following a main break. This type of regression model has been shown to be unbiased when a time-stratified bi-directional approach is used for referent selection(244, 245). Results are reported as odds ratios (OR) and 95% confidence intervals (CI) to describe the relative increase in odds of ED visit for AGI after a main break. Data management and statistical analyses were conducted using Stata SE Version 13 and the *xtlogit* command was used to fit the conditional logistic regression models(246).

The analysis was also stratified by potential effect modifiers, including age, sex, median household income, and type of pipe break (e.g., circumferential, blowout). Age and sex were considered potential effect modifiers due to possible differences in immune status and drinking water intake(17, 247, 248). Since individual-level socioeconomic status was unavailable, median household income was assessed at the zip code level(249). Median household income, obtained from Esri(249), is a useful summary measure of the general economic condition for each zip code. In Boston, median household income at the zip code level ranged from $29,000 to $127,000 and the median was $50,000. The analysis was stratified by the following categories: <50th percentile (<$50,000); 50th-<75th percentile ($50,000-<$84,000); 75th-100th percentile (≥$84,000). Finally, the type of break was also considered a potential effect modifier because it could affect the volume of water that is released and hence the potential for contamination(158, 250).

Sensitivity Analysis

As shown in Figure 23, Boston's water is distributed through five major water service networks: Southern Low; Northern Low; Southern High; Southern Extra-High; and Northern High(241). Approximately 90% of Boston's water is delivered through Southern Low and Southern High, with most of the remaining water delivered through Northern Low(241). Since service networks are independent of each other, main breaks only affect the network it occurs in(251). In a sensitivity analysis, the case-crossover analysis was restricted to zip codes served primarily (90%) by one service network. In order to do so, zip codes had to first be summarized by service network.

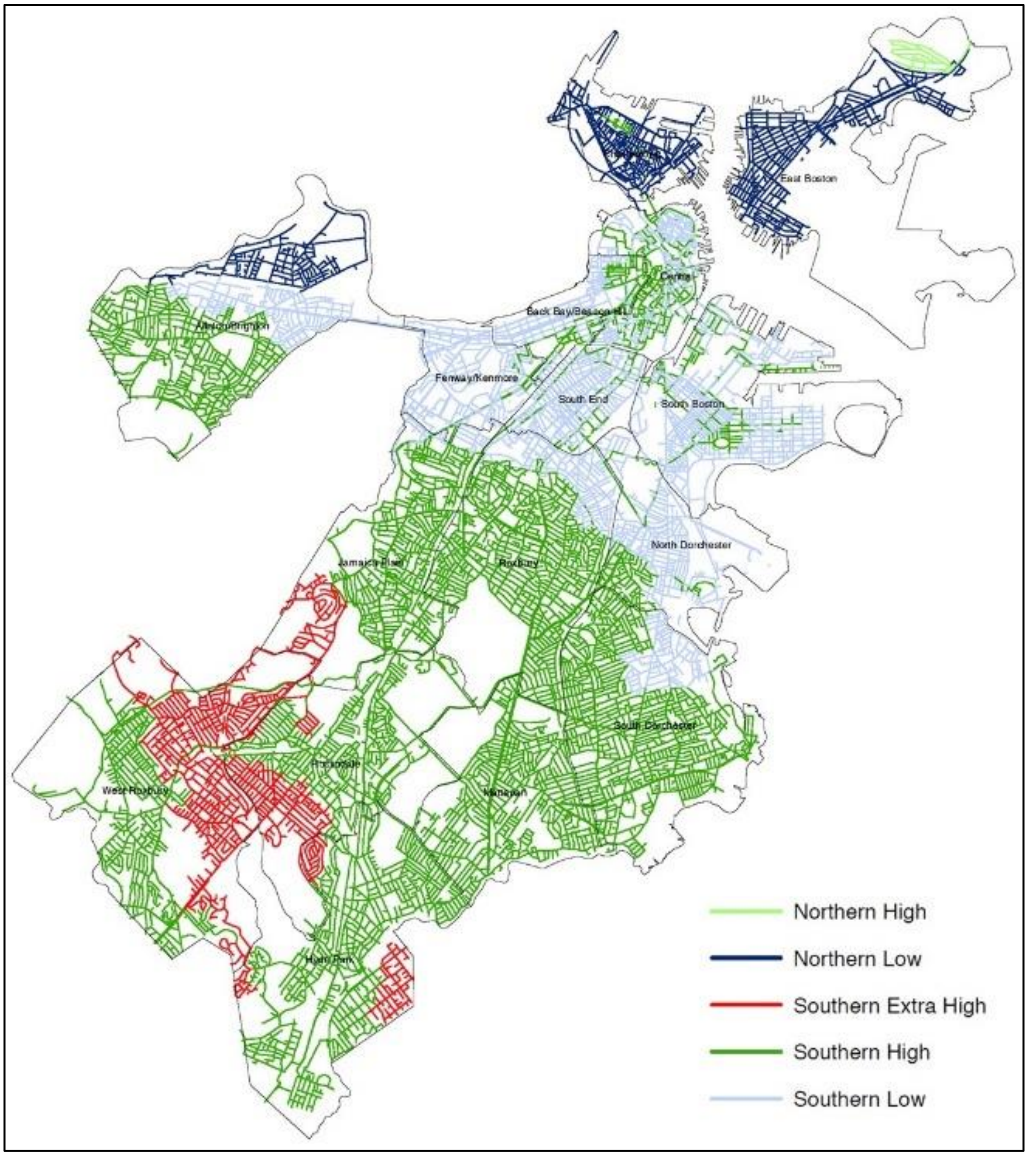

Figure 23. Boston Water Service Areas.
Source: CDM Camp Dresser & McKee Inc., 2011.

Summarizing Zip Codes by Service Network

Since Boston's water service networks were unavailable as datasets in vector GIS format, an image file (.tiff) was first imported into ArcGIS and converted from a color 3-band (R-G-B) raster file to a gray-scale single-band file, wherein each different color on the original map was converted to a gray-scale value (e.g. the Southern Extra High red service network might be represented as 75% gray in the converted raster file). The conversion from 3-band to single band allowed for the separation and classification of the different service networks based on their pixel values (e.g. 100% black, 50% black, etc.), yielding a raster dataset with 5 classes- one for each service network. After the 3-band raster file was processed to create a 5-class raster file, it needed to be georeferenced to align to its proper location in the real world to allow for more advanced spatial analyses (e.g. population per service area per zip code). Up to this point, both the original 3-band raster and the derived 5-class raster were only digital images depicting water service networks. The 5-class map was georeferenced in ArcGIS 10.5 using a GIS layer of ZIP Codes as the control/reference layer. When georeferencing, it is necessary to identify locations in the unreferenced dataset (the 5-class raster) and their corresponding locations in the real world. Once identified, the unreferenced dataset is processed (warped, stretched, twisted), yielding a new dataset that exists in its correct location in the real world.

A Census block shapefile (obtained from the U.S. Census Bureau) was joined with Census block population data (obtained from the National Historical Geographic Information System) based on common FIPS (Federal Information Processing Standard) codes that uniquely identify census units. Census blocks with no population living inside them were excluded. Then, Census blocks were converted from polygons to point features based on the centroid within each block. The location of each point feature determined the zip code for the entire block. This was done using a Spatial Join, whereby the attributes of the features that points fall within were appended to the points.

To model the population that is served by each water service network, the 5-class raster dataset described above was converted to a vector GIS file. In this file, the pixels assigned to each water service network were converted to polygons (e.g. in the output GIS file, pixels for service area 1 became polygon features, pixels for service area 2 became polygon features, etc.). With this file created, block centroids could be assigned to water service networks based on spatial overlap or proximity. For this analysis, the location of each census block point feature determined the service network for the entire block (as opposed to assigning blocks to water service areas based on the amount of overlap of between block polygons and water service polygons). Census block points that fell within the boundaries of a water service polygon were assigned to that water service area. Census block points that did not overlap with a service network were assigned to the network in closest proximity. It was assumed that the closest service network would be connected to the Census block through individual property water lines not shown on the service network map.

Since residential data for patients admitted to the emergency department were at the zip code level, the water service networks had to be summarized at the same geographic scale. To do this, Census block populations were aggregated by service network for each zip code and compared to the total zip code population. The main limitation was that the service network data was not available as a map file containing location details (e.g., address, coordinates, place information). Consequently, only the networks visible in the image file could be quantified and any overlapping of networks could not be addressed. Most overlapping was between the Southern Low and Southern High networks and limited to Downtown Boston.

Aim 2b Materials and Methods

The objective of Aim 2b was to estimate the association between a major water pipe break on May 1, 2010 and ED visits for AGI in metropolitan Boston communities affected by the subsequent boil water order.

Study Population

The Massachusetts Water Resources Authority (MWRA) provides drinking water to residents living primarily in metropolitan Boston communities(198). At around 9:30 a.m. on May 1, 2010, a coupling that secured segments of a 10-foot diameter water pipe broke along a major distribution line(252). Approximately two million residents were affected by a boil water order that follow this major water pipe break(252-254). Figure 24 highlights the 30 Boston metropolitan communities that were affected. They included Arlington, Belmont, Boston, Brookline, Canton, Chelsea, Everett, Hanscom Air Force Base, Lexington, Lynnfield, Malden, Marblehead, Medford, Melrose, Milton, Nahant, Newton, Norwood, Quincy, Reading, Revere, Saugus, Somerville, Stoneham, Swampscott, Wakefield, Waltham, Watertown, Winchester, and Winthrop. These communities were located approximately 3 to 23 miles from the water pipe break. For the purposes of this study, these communities were considered exposed.

Negative Control Exposure

In a separate analysis, communities unaffected by the pipe break served as a negative control to assess whether AGI also increased at the time of the event(255). Communities receiving water unaffected by the pipe break were selected as a negative control exposure if they were 1) located in relatively close proximity (<40 miles) of the break and 2) had a Census population of at least 40,000 residents to ensure a sample size comparable to the truly exposed communities. These communities included Attleboro, Billerica, Brockton, Cambridge, Framingham, Haverhill, Lawrence, Lowell, Lynn, Methuen, Peabody, Salem, Taunton, Weymouth, and Worcester. Although Framingham receives full water service from MWRA, it was unaffected by the pipe break. Peabody is partially supplied by MWRA but was also unaffected. The remaining communities are not served by MWRA, though Cambridge and Worcester have access to MWRA for emergency/back-up supplies. Figure 24 highlights these 15 communities serving as negative controls. These communities were located approximately 7 to 31 miles away from the water pipe break.

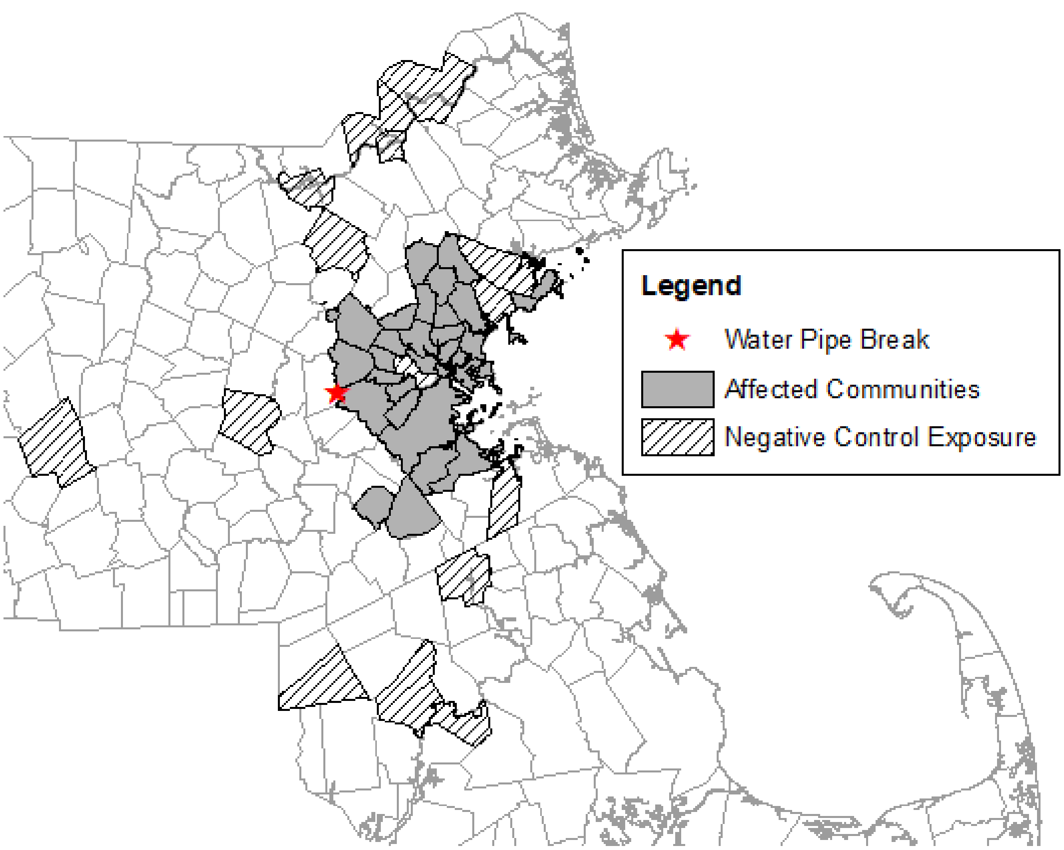

Figure 24. Massachusetts communities studied in relation to the 2010 water pipe break.

Health Outcome

As with Aim 2a, AGI was defined using ICD-9-CM diagnosis codes from ED visits. Both primary and associated diagnosis codes were included; however, a sensitivity analysis based on only the primary diagnosis code was also conducted to examine the robustness of results.

Pipe Break Exposure

It was hypothesized that any ED visit for AGI caused by the water pipe break would occur within a week of the break. Despite the magnitude of the situation, the broken pipe was repaired in less than two days and the boil water order was lifted within 3 days(252). The one-week hazard period encompassed the time it would take for contaminated water to enter the distribution system and reach the consumer, the pathogen incubation period, and the time for an affected person to visit the ED. The hazard period was examined as two mutually exclusive intervals: 0-3 days and 4-7 days. The 0-3 day period encompassed the duration of the boil water order. The later 4-7-day hazard period accounted for a longer time lag from the pipe break to exposure, infection, onset of AGI symptoms, and visiting the ED. The length of these hazard periods were optimal for capturing the effect of pathogens with an incubation period of no more than a few days.

Statistical Analysis

A case-crossover study design was used to examine the association between the major water pipe break and AGI. This type of study design, in which cases effectively serve as their own control at different point(s) in time, was applicable because the water pipe break was a brief exposure with potentially transient effects on AGI(242, 243). Control times were selected bidirectionally, two weeks before and two weeks after the pipe break(244, 256).

Conditional fixed-effects logistic regression models were used to estimate the risk of visiting the ED for AGI following the pipe break. This type of regression model is the standard for case-crossover studies(243). Only case-control groups with discordant exposures contribute information to the analysis(257); therefore, this analysis was confined to a 64-day period (April 3, 2010 through June 5, 2010) based on all possible discordant exposure scenarios. Results are reported as odds ratios (OR) and 95% confidence intervals (CI) and interpreted as the relative increase in odds of ED visit for AGI after the water pipe break.

The analysis was also stratified by potential effect modifiers. Age and sex were considered potential effect modifiers due to possible differences in immune status, risk for AGI, and drinking water intake(17, 247, 248). In addition, the analysis was stratified by distance from the pipe break in order to examine whether closer communities were impacted earlier, or more seriously, than further communities. A sensitivity analysis in which AGI was defined based on only the primary diagnosis code was conducted to examine the robustness of results. Lastly, attributable fractions and population attributable fractions were calculated using the odds ratio and proportion of exposed cases(258). Data management and statistical analyses were conducted using Stata SE Version 13 and the *xtlogit* command was used to fit the conditional logistic regression models(246).

CHAPTER 4. CYANOBACTERIA IN AN UNFILTERED DRINKING WATER SYSTEM AND EMERGENCY DEPARTMENT VISITS FOR GASTROINTESTINAL, RESPIRATORY, AND DERMAL ILLNESS

Introduction

Cyanobacteria, also referred to as blue-green algae, are microscopic organisms that naturally occur in fresh, estuarine, and marine waters(112). Cyanobacteria help maintain marine and freshwater ecosystems by producing oxygen (as a by-product of photosynthesis) and by serving as a food source for other organisms(115, 116). Under certain environmental conditions, such as high nutrient levels, warmer temperatures, and sun exposure, cyanobacteria can form a bloom(5, 114, 115). Occasionally, cyanobacterial blooms produce a complex mixture of hepatotoxins, neurotoxins, and dermatotoxins(115, 116, 119). The most commonly identified cyanotoxins in the U.S. are microcystins, cylindrospermopsin, anatoxins, and saxitoxins(112). In 2007, the U.S. Environmental Protection Agency (EPA) identified microcystins in approximately one-third of the nation's lakes(121).

In the U.S., many drinking water systems that use surface water sources (e.g., lakes, reservoirs) are vulnerable to harmful algal blooms and may be periodically contaminated by algal toxins(126). Data on the presence or absence of cyanotoxins in finished drinking water are limited because there is no centralized monitoring program(122). Nevertheless, drinking water treatment plants are increasingly met with the need to monitor and respond to harmful algal blooms(123). In 2000, microcystins were the most commonly found toxin in pre- and post-treated drinking water in Florida, with finished water concentrations as high as 12.5

μg/L(122). In 33 U.S. drinking water treatment plants in the Northeast and Midwest, a survey conducted in 2003 reported that microcystins were detected at low levels (≤0.36 μg/L) in all finished water samples collected(124). In more recent years, there has been a noticeable increase in the severity of cyanobacterial harmful algal blooms in Lake Erie, a drinking water source for many communities(123). In the summer of 2014, microcystin levels in fully treated tap water from Western Lake Erie were high enough (3.2 μg/L) to make the city of Toledo, Ohio issue a warning not to use the water(2). In September 2016, microcystins were detected at low levels (≤0.18 μg/L) for the first time in treated public drinking water in the state of New York(125).

Human exposure to cyanobacteria can occur in everyday and recreational settings, through direct contact, ingestion (e.g., drinking contaminated water, eating tainted fish or shellfish), and even inhalation of contaminated water droplets (e.g., in the shower or during recreational activities)(110, 111). In the U.S., recreational activities during freshwater harmful algal blooms have been associated with waterborne disease outbreaks that include dermatologic, gastrointestinal, respiratory, febrile, ear, and eye symptoms(130-133). Drinking water exposure to harmful cyanobacteria can lead to symptoms of illness both acute (e.g., gastroenteritis, muscle pain and dermatitis) and chronic (e.g., liver and kidney damage)(116, 133, 135). In the summer of 2009, Lévesque et al. (2014) conducted a prospective study of residents who lived in close proximity to lakes affected by cyanobacteria in Quebec, Canada(138). Among participants receiving drinking water from a plant whose source was contaminated by cyanobacteria, an increase in self-reported muscle pain, gastrointestinal symptoms, dermal symptoms, and ear symptoms was observed (138). In Australia, a case-control study suggested that gastrointestinal and dermal symptoms were correlated with increased cyanobacterial cell counts in a drinking water supply that came from a river affected by an extensive bloom(139). While high levels of cyanotoxin in drinking water have been linked to human health risks, the effect of chronic low levels is not well-documented or understood(128, 144).

The risk for exposure to cyanotoxins is not always obvious since they can be present in the absence of a bloom or visible scum on the water(120). In other words, waters that appear to be free of cyanobacteria may actually be contaminated with free toxin(120). Therefore, water treatment processes need to consider the presence of both intracellular and extracellular cyanotoxins(122). In the absence of cell damage, conventional water treatment (e.g., coagulation, flocculation, sedimentation, and filtration) can be effective at removing intact cells and the majority of intracellular toxins(122). If toxins are released into the water, however, conventional treatments need additional processes such as chemical oxidation, adsorption, biodegradation or reverse osmosis, and nanofiltration(122).

The Massachusetts Water Resources Authority (MWRA) provides wholesale water and sewer services to 2.5 million people in 61 metropolitan Boston communities (191, 192). The MWRA system does not use conventional water treatment (e.g., filtration) and instead relies on protecting existing sources through strict watershed management practices(205). The objective of this analysis was to estimate the association between cyanobacteria levels in the MWRA water source and the rate of emergency department visits for acute gastrointestinal, respiratory, and dermal illness in metropolitan Boston communities in Massachusetts during a 7-year period (July 27, 2005 – September 30, 2012).

Methods

Massachusetts Water Resources Authority

The Massachusetts Water Resources Authority (MWRA) provides drinking water to residents living in the metropolitan Boston area(198). MWRA's water comes from the Quabbin and Wachusett Reservoirs, located approximately 65 and 35 miles west of Boston, respectively (196-199). The surrounding watershed lands are protected by forest and wetlands (>85% coverage) and about 75% cannot be built on (196-199).

Since July 27, 2005, water from the Wachusett reservoir serving the metropolitan Boston area has been treated at the John J. Carroll Water Treatment Plant (CWTP). The treatment process has always been unfiltered and relies primarily on disinfection. The primary disinfectant is ozone and the secondary (residual) disinfectant is chloramine. For consistency regarding water treatment and travel times, this study was restricted to only when CWTP was on line (July 27, 2005 – September 30, 2012).

Study Population

This study included a subset of MWRA communities that met the following criteria: 1) received full water service from MWRA; 2) located 20-35 miles from the intake at Wachusett Reservoir (estimated using ArcMap); and 3) received water after the Norumbega Covered Storage Facility. Figure 25 highlights the 22 study communities in relation to the Wachusett Reservoir, CWTP, and Norumbega Covered Storage Facility. These communities include Arlington, Belmont, Boston, Brookline, Chelsea, Everett, Lexington, Lynnfield, Malden, Medford, Melrose, Milton, Newton, Norwood, Reading, Revere, Saugus, Somerville, Stoneham, Waltham, Watertown, and Weston. Based on the 2010 U.S. Census, the total population of these communities was around 1.4 million.

Cyanobacteria

The MWRA and the Massachusetts Department of Conservation and Recreation (DCR) provided cyanobacteria data from the Wachusett Reservoir. Water samples were collected weekly during the winter (October 1- April 30), and twice per week during the summer (May 1- September 30, Mondays and Thursdays). In the winter, no samples were collected if the reservoir was ice covered. Increased monitoring occurred whenever there were concerns, such as counts above early trigger levels, increased consumer complaints, and/or other information suggesting a bloom threat (e.g., weather, nutrient, dissolved oxygen). Trigger levels were based on “nuisance algae” known to cause taste and odor problems in the water (e.g., Anabaena, Synura, Dinobryon, Chrysosphaerella, Uroglenopsis). Linear interpolation was used to address days without sample collection (83%) in order to form a daily time-series of cyanobacteria (Figure 26). During the winter, concentrations were low and relatively stable.(230)

Grab samples were collected at various depths near the Cosgrove Intake which transfers water from the Wachusett Reservoir to the CWTP(230). Cyanobacteria densities were quantified using a Sedgewick-Rafter (S-R) Cell(231). The method used, including 10 field count, three strips count, and full S-R cell count, is documented in Standard Methods 18th Edition (230-232). Phytoplankton densities were expressed as Areal Standard Units (ASUs; equivalent to 400 square microns) per milliliter(231). A daily measure of total cyanobacteria was based on the daily maximum, regardless of the depth of sample collection. Cyanobacteria genera included, but were not limited to, *Anabaena*, *Aphanocapsa*, *Aphanothece*, *Chroococcus*, *Coelosphaerium*, *Dactylococcopsis*, *Gloeocapsa*, *Gomphosphaeria*, *Merismopedia*, *Microcystis*, *Oscillatoria*, and *Rhabdoderma*.

Emergency Department Visits

Emergency department (ED) data were used to capture acute symptoms of gastrointestinal, respiratory, and dermal illnesses that have been related to exposure to cyanobacteria and/or their toxins(133, 138, 139, 229). ED data were obtained from the Commonwealth of Massachusetts Center for Health Information and Analysis for the 7-year study period (July 27, 2005 – September 30, 2012). These included visits to emergency departments in Massachusetts' acute care hospitals and satellite emergency facilities. Patients receiving observation services but not admitted to the hospital were also included since these hospital outpatient visits are often transferred from the ED (217-219).

Acute gastrointestinal, respiratory, and dermal symptoms of illness were defined using ED visit diagnosis codes (International Classification of Disease, Version 9 Clinical Modification, ICD-9-CM). Acute gastrointestinal illness (AGI) was defined using any of the following ICD-9-CM diagnosis codes: 001-009.9 (intestinal infectious diseases); 558.9 (other and unspecified noninfectious gastroenteritis and colitis); 787.0 (nausea and vomiting); 787.91 (diarrhea). Respiratory illness was defined using: 460 (acute nasopharyngitis; common cold); 461 (acute sinusitis); 465.9 (acute upper respiratory infection); 493 (asthma); 786.2 (cough); 786.07 (wheezing); 786.05 (shortness of breath). Dermal irritation was defined using: 782.1 (rash and other nonspecific skin eruption); 136.9 (unspecified infectious and parasitic diseases); 686.9 (unspecified local infection of skin and subcutaneous tissue); 692 (contact dermatitis and other eczema); 691.8 (other atopic dermatitis and related conditions). Both primary and associated diagnosis codes were considered.

Latency between cyanobacteria measurement and ED visits

According to a hydraulic modeling specialist at MWRA, it takes about 4 hours for water to travel from the Wachusett Reservoir to the treatment plant. From the treatment plant, the water continues east to the Norumbega Covered Storage Facility, taking 14 to 16 hours depending on system demands. Since the storage facility is a “flow thru” design, the water remains in the tank for 8 to 12 hours before leaving. In general, the travel time from the Wachusett Reservoir to the City of Boston ranges from 40 to 50 hours depending on system demands.(200)

The time it takes water to travel from the Wachusett Reservoir to each study community varies depending on system demands and distance travelled. By selecting communities within 20-35 miles of the Wachusett Reservoir, water travel times were estimated to be similar (within a day of each other) and take a minimum of 2-3 days. The health effects of cyanobacteria were expected to be acute and immediate (i.e., without an incubation period), occurring within 0-2 days of exposure. In a previous study, drinking water contaminated by cyanobacteria was associated with symptoms of illness (e.g., muscle pain, gastrointestinal, skin, and ear) within 0-3 days of exposure (138). Given the acute nature of expected symptoms, the time it might take to visit the ED was estimated to be within 0-2 days. Accounting for these different time components, a 2-4 and 5-7 day lag between cyanobacteria measurement and ED visit were considered in the analysis. For each lagged period of exposure, daily measures of total cyanobacteria were summed together.

Other Variables

Mean daily air temperature for Boston were obtained from the National Climatic Data Center. Mean daily water temperature in the Wachusett Reservoir were obtained from MWRA. To form a daily time series of water temperature, linear interpolation was used to address days without a measurement (13%). Rain gauge data were obtained from the Boston Water and Sewer Commission.

Statistical Analysis

Poisson regression models were used to estimate the associations between varying levels of cyanobacteria in the Wachusett Reservoir and daily rates of ED visits for acute gastrointestinal, respiratory, and dermal symptoms of illness. Potential confounders were time-dependent factors related to both cyanobacteria and symptoms of illness. Long-term trends and seasonal variations were modeled using indicator variables for year, month, and day of the week. This also addressed the consistent increase in ED utilizations after the implementation of the Massachusetts health care reform in 2006 (see Figure 27 for time-series of ED visits)(211). For AGI, air temperature, water temperature, and extreme precipitation were also considered potential confounders. For respiratory illness, air temperature was considered a potential confounder.

Total cyanobacteria were categorized into quartiles and the lowest quartile served as the reference category. Results are reported as incidence rate ratios (IRR) and 95% confidence intervals (CI) to describe the relative change in the rate of ED visits between quartiles of cyanobacteria. Due to the potential for differences in susceptibility by age, the analyses were also stratified by age group. Data management and statistical analyses were conducted using SAS 9.4.

Results

Emergency department visits for acute gastrointestinal illness

Table 11 describes the characteristics of the ED visits for gastrointestinal, respiratory, and dermal symptoms of illness during the 7-year study period (7/27/2005-9/30/2012) in the 22 Metropolitan Boston communities. There were a total of 60,826 visits for AGI (of which 46% had a primary diagnosis), 48,802 for respiratory (5% primary), and 1,161 for dermal (76% primary). The average number of daily ED visits was 23.2 for AGI, 18.6 for respiratory, and less than 1 for dermal (Table 12). There were slightly more females than males with ED visits for AGI (56%) and respiratory illness (58%). The distribution by age were similar for ED visits for AGI and dermal illness, with over a third of the ED visits among young children (≤5 years). Also, the elderly (≥65 years) had the fewest visits (~5%). For respiratory illness, the majority (70%) of ED visits were among adults (19-64 years), followed by the elderly (21%).   For AGI and respiratory illness, there were more whites (41% AGI; 58% respiratory) compared to other racial groups. For dermal symptoms of illness, there were more blacks (44%).

As shown in Figure 27, there was a gradual increase in ED utilizations during the first half of the study period before starting to level out in 2010. A seasonal trend was evident for AGI as it peaked in the winter months. Respiratory and dermal symptoms were relatively constant by month and season.

Cyanobacteria in the reservoir

Total cyanobacteria levels in the Wachusett Reservoir ranged from 0 - 532.5 ASU/mL during the study period (Table 12). The distribution was highly right-skewed. The mean level was 58.0 ASU/mL (standard deviation = 80.5) while the median was 24.4 ASU/mL. As shown in Figure 26, there was a seasonal trend throughout the study period. Cyanobacteria levels generally peaked in the late summer and early fall.

Model results

Table 13 summarizes the association between cyanobacteria in the Wachusett Reservoir and daily ED visits for each health outcome. In particular, the incidence rate ratio (IRR) describes the change in the rate of ED visits for each quartile of total cyanobacteria relative to the lowest quartile. All models were adjusted for time trends using indicator variables for year, month, and day of the week. The addition of air temperature, water temperature, and/or extreme precipitation did not meaningfully change the magnitude or direction of any estimates for AGI. Similarly, the addition of air temperature did not alter any estimates for respiratory illness.

Compared to the lowest quartile of total cyanobacteria (≤5.0 ASU/mL), the rate of ED visits for respiratory illness increased by 6% (IRR=1.06; 95% CI: 1.02-1.11) in the highest quartile (≥80.2 ASU/mL) and 7% (IRR=1.07; 95% CI: 1.04-1.11) in the second highest quartile (24.4-80.2 ASU/mL) during the 2-4 day lag period. A similar increase was observed during the 5-7 day lag period. In other words, the rate of ED visits for respiratory illness increased by 3-8% in each quartile for both the 2-4 and 5-7 lag periods.

Similarly, the rate of ED visits for AGI increased by 3-6% in the top two quartiles for both lag periods. In particular, the rate of ED visits increased by 6% (IRR=1.06; 95% CI: 1.03-1.10) in the highest quartile and 5% in the second highest quartile during the 2-4 day lag period. A similar increase was observed during the 5-7 day lag period.

For the rate of ED visits for dermal ailments, the second lowest quartile (5.0-24.4 ASU/mL) was associated with a 21% increase during the 2-4 day lag period (IRR=1.21; 95% CI: 1.01-1.46) and a 27% increase during the 5-7 day lag period (IRR=1.27; 95% CI: 1.06-1.52). However, these associations did not remain statistically significant in the third and fourth quartiles.

In stratified analyses, the younger (≤18 years) and older (≥65 years) age groups appeared to be more strongly affected by increasing levels of cyanobacteria. Among the youngest children (≤5 years), the highest quartile of cyanobacteria was associated with increased rates of respiratory illness (IRR=1.27; 95% CI: 1.01-1.60) and dermal ailments (IRR=1.54; 95% CI: 1.01-2.35). Among older children and adolescents (6-18 years), the rates of AGI were 11-14% higher in the top two quartiles of cyanobacteria compared to the lowest quartile. Among the elderly, the rates of ED visits for respiratory illness increased with each quartile for both lag periods. However, the linear trend did not deviate much from a null association of 1 during the 2-4 day lag period (IRR=1.0015; 95% CI: 1.0003-1.0027) or 5-7 day lag period (IRR=1.0018; 95% CI 1.0006-1.0030).

Discussion

As a changing climate impacts freshwater and marine environments (e.g., warming water temperature, higher carbon dioxide levels, changes in rainfall leading to more nutrient runoff), harmful algal blooms may occur more often, in more places, and at higher intensities(1-5). Although the U.S. only has non-regulatory health advisories for two cyanobacterial toxins, cyanobacteria is recognized as a potential drinking water contaminant in public water systems around the world(33, 122). In this study, the upper quartile levels of cyanobacteria were associated with slightly increased rates of ED visits for AGI and respiratory illness when compared to the lowest quartile. The results for dermal illness were inconclusive due to the small number of ED visits and inconsistent findings by quartile.

These findings were consistent regardless of whether additional variables (air temperature, water temperature, extreme precipitation) were included. It is possible that the indicator variables for time adequately controlled for the influence of temperature. In addition, extreme precipitation may not have been a true confounder due to the temporal and spatial lags between cyanobacteria levels in the reservoir and subsequent ED visits in the city. The potential for residual confounding should still be further investigated.

While the magnitude of a relative measure is informative, it does not necessarily translate to the public health significance. Incorporating estimated baseline rates provides more meaning to the relative measures. Table 12 summarizes the average number of visits per day for each health outcome (AGI=23.2; respiratory=18.6; dermal=0.4). Table 14 shows the estimated number of ED visits for each quartile of cyanobacteria, holding the time variables at their respective reference levels. The very low baseline rate (0.4) for dermal ailments means that any relative increase would have a minimal impact. For example, the 21% increase in the second quartile with a 2-4 day lag (IRR=1.21; 95% CI: 1.01-1.46) is equal to a rate difference of only 0.9 (0.50-0.41). Considering an estimated population of 1.4 million in the study area, this would be equivalent to an excess of 4.5 visits per million person-weeks ((0.9/1.4)*7). Even with a baseline rate around 20 for both AGI and respiratory illness, the relative increase observed (<10%) does not compare with much of an absolute increase (<2 visits/day).

This study only considered short lag periods (less than a week) because cyanobacteria were expected to have acute toxic effects(138). Also, prolonging lag periods can allow for other factors to influence the association of interest. The 2-4 and 5-7 day periods may have reflected differences in the severity of illness or the time to seek medical care; however, cyanobacteria appeared to have similar effects in both periods. Using Medicare data over a 10-year period from 1998 to 2008, Beaudeau et al. (2014) reported finding an association between cyanobacteria and AGI that was weakly significant over 8-12 day lags and peaked over 23-27 day lags(140). The rationale for the long latency of the effects was unclear(140).

Strengths

A strength of this study was having 7 years of data to estimate the association between low levels of cyanobacteria and ED visits for AGI, respiratory, and dermal illness. It is often a challenge to have quality long-term data on algae in drinking water supplies, let alone speciated data such as cyanobacteria. Fortunately, MWRA has been collecting algae data in the Wachusett Resevoir since the early 1990s so their methods have been in place for a while.

Another strength of this study was the large population served by MWRA. As mentioned above, the study population was approximately 1.4 million. This provided the statistical power to detect a small effect, which was expected given the low levels of cyanobacteria.

Limitations

The use of ED data likely captured the most severe cases of illness. As a result, the overall effects of cyanobacteria could be underestimated. Residents experiencing milder symptoms of illness may have opted to recover at home or visit their primary care provider. Unfortunately, this is a limitation of using administrative healthcare data.

Another limitation was that cyanobacteria measurements were taken in the reservoir prior to treatment. Therefore, it may not be an accurate representation of the concentrations in the treated water delivered to consumers. Of note, however, is that MWRA used an unfiltered treatment process that relies primarily on disinfection (ozone) to achieve *Giardia* inactivation(195). While ozone has been shown to destroy certain types of cyanotoxins, its efficacy depends on the ozone demand of organic material in the raw water(148). In addition, ozonation of raw waters containing high cyanobacteria cell concentrations can lead to cell lysis and release of intracellular toxins(148). In the absence of filtration, it may have been possible for cyanobacteria to survive the disinfection treatment process(122).

Future Directions

While total cyanobacteria did not indicate the presence of toxins, several species of cyanobacteria are known to produce toxins. Since the end of 2014, MWRA began collecting data on toxins, such as microcystins. It would be useful to include toxins data in future analyses.

Conclusion

This study provides support that low levels of cyanobacteria can have an effect on acute symptoms of gastrointestinal and respiratory illnesses in an unfiltered water system. Building upon this work can help water utilities and health departments develop algae response plans.

Figures

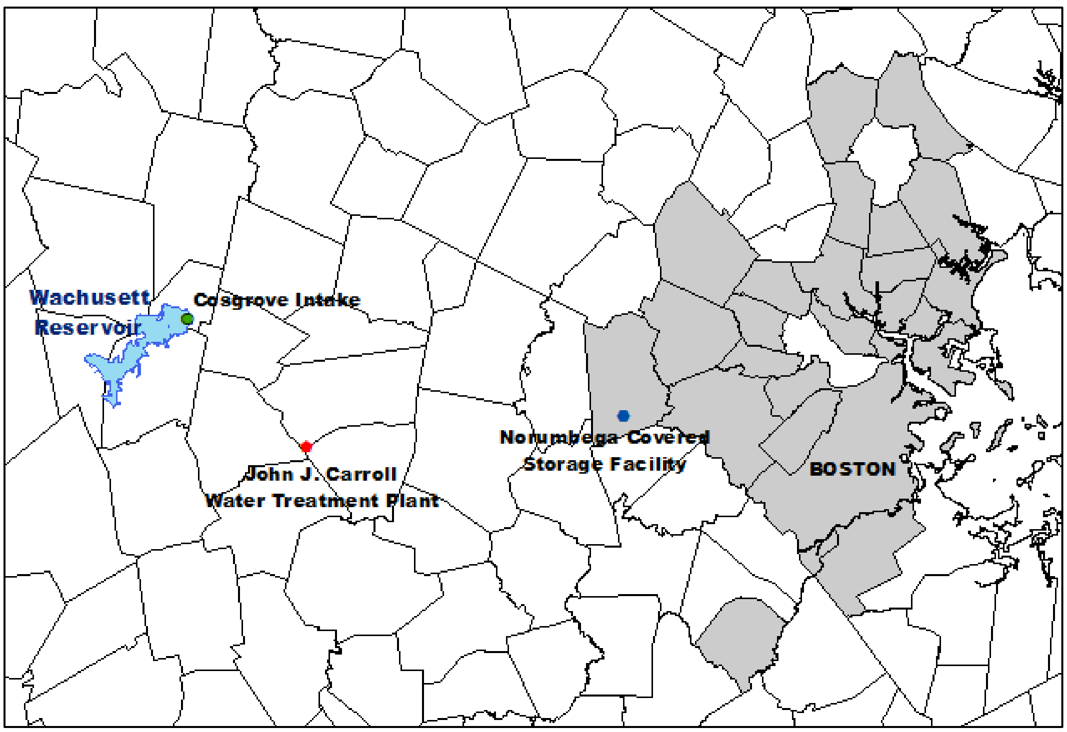

Figure 25. Metropolitan Boston Communities included in analysis.

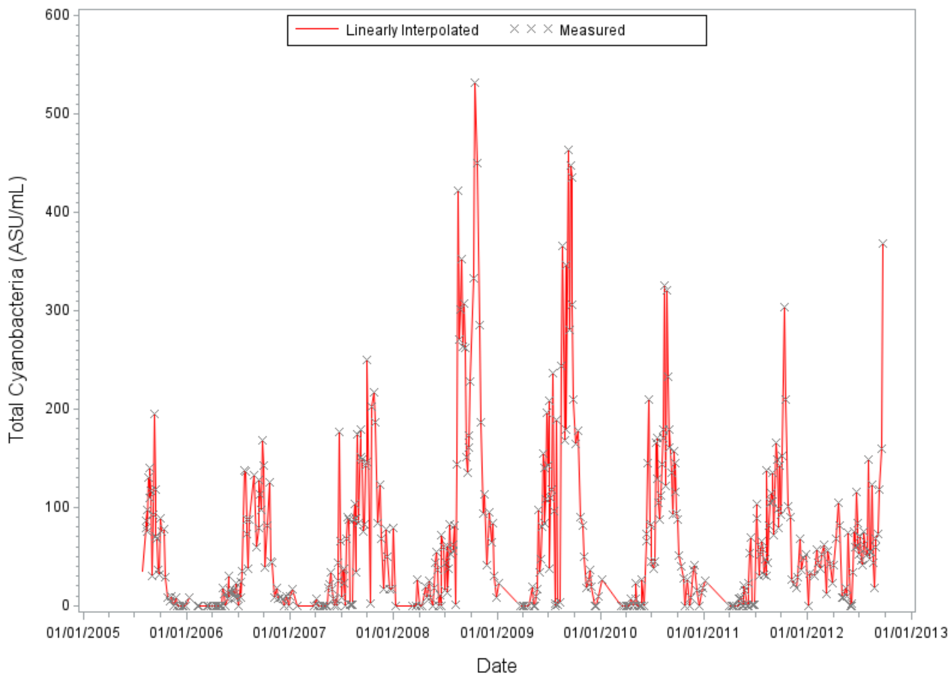

Figure 26. Time-series of Total Cyanobacteria in Wachusett Reservoir, 7/27/2005-9/30/2012.

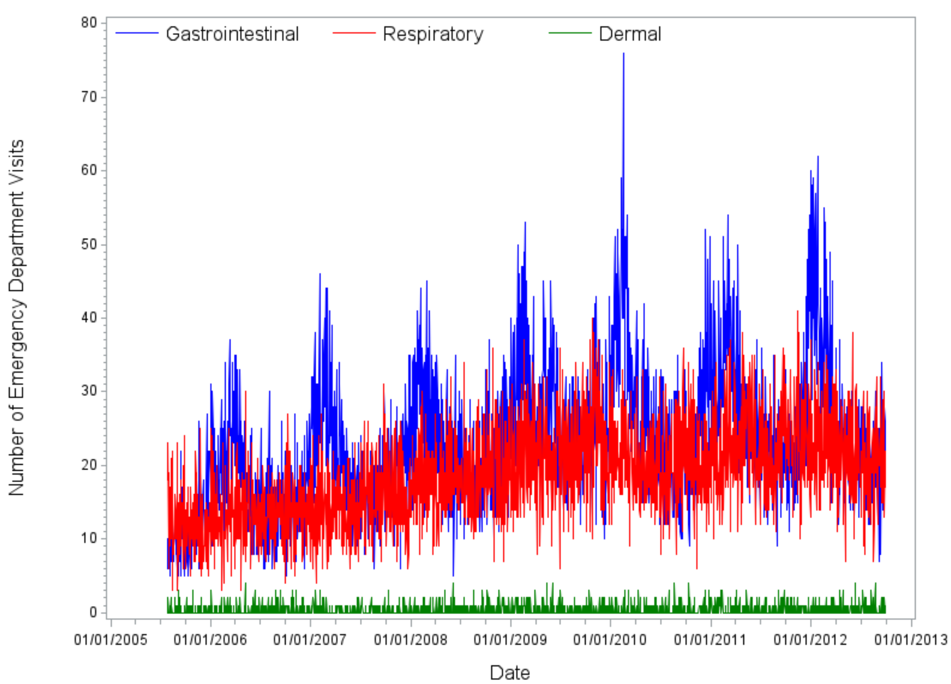

Figure 27. Time-series of Emergency Department Visits in the Metropolitan Boston area, Massachusetts, 7/27/2005-9/30/2012.

Tables

Table 11. Emergency department visits in the Metropolitan Boston area, Massachusetts, 7/27/2005-9/30/2012.

	Gastrointestinal		Respiratory		Dermal	
	N	%	N	%	N	%
Total	60,826	100%	48,802	100%	1,161	100%
Type of Visit						
Emergency Department	59,514	98%	43,550	89%	1,117	96%
Outpatient*	1,312	2%	5,252	11%	44	4%
Age						
Children (≤5 years)	22,151	36%	1,477	3%	431	37%
Youth/Adolescents (6-18 years)	10,099	17%	2,988	6%	197	17%
Adults (19-64 years)	25,608	42%	34,255	70%	483	42%
Elderly (≥65 years)	2,968	5%	10,082	21%	50	4%
Sex						
Female	33,983	56%	28,187	58%	577	50%
Male	26,840	44%	20,614	42%	584	50%
Primary Diagnosis	28,012	46%	2,411	5%	888	76%
Race						
White	25,048	41%	28,085	58%	239	21%
Black	14,567	24%	9,495	19%	512	44%
Hispanic	12,546	21%	6,861	14%	225	19%
Other	6,712	11%	3,182	7%	144	12%

*Hospital outpatient visits included patients who received observation services but were not admitted to the hospital.

Table 12. Summary of daily measures considered in analysis.

Variable	Days of observation	Mean	Standard Deviation	Min	10th Percentile	25th Percentile	Median	75th Percentile	90th Percentile	Max
ED Visits for Gastrointestinal Illness	2623	23.19	9.18	5	13	17	22	28	35	76
ED Visits for Respiratory Illness	2623	18.61	6.29	3	11	14	18	23	27	41
ED Visits for Dermal Irritations	2623	0.44	0.70	0	0	0	0	1	1	4
Total Cyanobacteria (ASU/mL)	2617	57.96	80.49	0	0	5.00	24.43	80.24	154.26	532.54

Abbreviations: ED, emergency department; ASU/mL, Areal Standard Units per milliliter.

Table 13. Cyanobacteria in the Wachusett Reservoir and emergency department visits in Metropolitan Boston, Massachusetts, 7/27/2005-9/30/2012.

	Gastrointestinal			Respiratory			Dermal		
	# visits	2-4 day lag IRR* (95% CI)	5-7 day lag IRR* (95% CI)	# visits	2-4 day lag IRR* (95% CI)	5-7 day lag IRR* (95% CI)	# visits	2-4 day lag IRR* (95% CI)	5-7 day lag IRR* (95% CI)
Cyanobacteria (per 10 ASU/mL)	60,687	1.0007 (1.0002, 1.0012)	1.0006 (1.0001, 1.0011)	48,678	1.0003 (0.9997, 1.0008)	1.0005 (1.0000, 1.0010)	1,155	0.9989 (0.9954, 1.0024)	0.9992 (0.9957, 1.0028)
Q1 (≤5.0 ASU/mL)	15,696	1.0	1.0	11,136	1.0	1.0	246	1.0	1.0
Q2 (5.0-24.4 ASU/mL)	17,015	1.00 (0.97, 1.02)	0.99 (0.97, 1.01)	12,382	1.04 (1.01, 1.07)	1.03 (1.00, 1.06)	299	1.21 (1.01, 1.46)	1.27 (1.06, 1.52)
Q3 (24.4-80.2 ASU/mL)	15,074	1.05 (1.02, 1.08)	1.03 (1.00, 1.06)	12,596	1.07 (1.04, 1.11)	1.07 (1.03, 1.10)	313	1.19 (0.96, 1.48)	1.03 (0.83, 1.29)
Q4 (≥80.2 ASU/mL)	12,902	1.06 (1.03, 1.10)	1.04 (1.01, 1.08)	12,564	1.06 (1.02, 1.11)	1.08 (1.04, 1.12)	297	1.16 (0.90, 1.49)	1.24 (0.96, 1.59)
Children (≤5 years)									
Cyanobacteria (per 10 ASU/mL)	22,092	1.0005 (0.9996, 1.0014)	1.0005 (0.9996, 1.0014)	1,469	1.0027 (0.9998, 1.0056)	1.0013 (0.9984, 1.0042)	430	1.0019 (0.9963, 1.0075)	1.0013 (0.9957, 1.0069)
Q1	5,744	1.0	1.0	296	1.0	1.0	92	1.0	1.0
Q2	6,484	1.01 (0.97, 1.05)	1.00 (0.96, 1.04)	390	1.13 (0.95, 1.34)	1.03 (0.87, 1.22)	122	1.44 (1.07, 1.94)	1.28 (0.96, 1.71)
Q3	5,533	1.07 (1.02, 1.12)	1.02 (0.97, 1.07)	372	1.12 (0.92, 1.38)	1.07 (0.87, 1.30)	102	1.17 (0.81, 1.68)	1.03 (0.72, 1.49)
Q4	4,331	1.06 (1.00, 1.13)	1.04 (0.98, 1.11)	411	1.27 (1.01, 1.60)	1.08 (0.86, 1.36)	114	1.54 (1.01, 2.35)	1.22 (0.79, 1.86)
Youth/Adolescents (6-18 years)									
Cyanobacteria (per 10 ASU/mL)	10,087	1.0004 (0.9991, 1.0016)	1.0005 (0.9992, 1.0017)	2,974	0.9995 (0.9975, 1.0016)	0.9991 (0.9970, 1.0012)	195	1.0015 (0.9927, 1.0103)	1.0012 (0.9924, 1.0101)
Q1	2,588	1.0	1.0	658	1.0	1.0	43	1.0	1.0
Q2	2,883	1.01 (0.95, 1.07)	1.00 (0.94, 1.06)	728	1.01 (0.90, 1.13)	1.15 (1.02, 1.29)	51	1.23 (0.79, 1.93)	1.59 (1.01, 2.51)
Q3	2,476	1.13 (1.05, 1.22)	1.14 (1.06, 1.22)	740	1.08 (0.94, 1.24)	1.13 (0.99, 1.30)	53	1.20 (0.70, 2.05)	1.43 (0.82, 2.50)
Q4	2,140	1.11 (1.02, 1.21)	1.11 (1.01, 1.21)	848	1.06 (0.90, 1.24)	1.07 (0.91, 1.25)	48	1.29 (0.70, 2.39)	1.49 (0.79, 2.82)
Adults (19-64 years)									
Cyanobacteria (per 10 ASU/mL)	25,549	1.0007 (0.9999, 1.0015)	1.0005 (0.9997, 1.0013)	34,176	0.9998 (0.9992, 1.0005)	1.0002 (0.9996, 1.0009)	480	0.9955 (0.9898, 1.0011)	0.9961 (0.9905, 1.0018)
Q1	6,583	1.0	1.0	7,909	1.0	1.0	106	1.0	1.0
Q2	6,899	0.97 (0.94, 1.01)	0.97 (0.94, 1.01)	8,682	1.03 (0.99, 1.06)	1.02 (0.98, 1.05)	115	1.02 (0.76, 1.37)	1.11 (0.83, 1.48)
Q3	6,302	1.00 (0.96, 1.05)	0.99 (0.95, 1.04)	8,848	1.06 (1.02, 1.10)	1.06 (1.01, 1.10)	144	1.15 (0.83, 1.59)	0.91 (0.65, 1.28)
Q4	5,765	1.03 (0.98, 1.09)	1.00 (0.95, 1.06)	8,737	1.02 (0.98, 1.07)	1.05 (1.00, 1.10)	115	0.88 (0.60, 1.30)	1.08 (0.74, 1.58)

	Gastrointestinal			Respiratory			Dermal		
	# visits	2-4 day lag IRR* (95% CI)	5-7 day lag IRR* (95% CI)	# visits	2-4 day lag IRR* (95% CI)	5-7 day lag IRR* (95% CI)	# visits	2-4 day lag IRR* (95% CI)	5-7 day lag IRR* (95% CI)
Elderly (≥65 years)									
Cyanobacteria (per 10 ASU/mL)	2,959	1.0026 (1.0003, 1.0048)	1.0023 (1.0001, 1.0046)	10,059	1.0015 (1.0003, 1.0027)	1.0018 (1.0006, 1.0030)	50	0.9987 (0.9824, 1.0152)	1.0058 (0.9905, 1.0214)
Q1	781	1.0	1.0	2,273	1.0	1.0	5	1.0	1.0
Q2	749	1.04 (0.93, 1.17)	1.00 (0.90, 1.12)	2,582	1.07 (1.01, 1.14)	1.04 (0.98, 1.11)	11	1.49 (0.49, 4.56)	2.31 (0.76, 7.03)
Q3	763	1.04 (0.90, 1.19)	1.07 (0.93, 1.23)	2,636	1.11 (1.03, 1.19)	1.09 (1.01, 1.17)	14	2.30 (0.72, 7.32)	1.42 (0.39, 5.14)
Q4	666	1.14 (0.98, 1.34)	1.15 (0.98, 1.35)	2,568	1.19 (1.09, 1.29)	1.19 (1.09, 1.29)	20	1.50 (0.41, 5.48)	3.62 (0.96, 13.65)

Abbreviations: Q, quartile; ASU/mL, Areal Standard Units per milliliter; IRR, incidence rate ratios; 95% CI, 95% confidence intervals.

*Adjusted for month, year, day of week.

Table 14. Estimated number of emergency department visits per day, by cyanobacteria quartile.

	Gastrointestinal		Respiratory		Dermal	
	2-4 day lag Rate* (95% CI)	5-7 day lag Rate* (95% CI)	2-4 day lag Rate* (95% CI)	5-7 day lag Rate* (95% CI)	2-4 day lag Rate* (95% CI)	5-7 day lag Rate* (95% CI)
Cyanobacteria Q1 (≤5.0 ASU/mL)	22.3 (21.4, 23.4)	22.6 (21.6, 23.7)	21.1 (20.1, 22.2)	21.1 (20.1, 22.2)	0.41 (0.30, 0.56)	0.40 (0.29, 0.55)
Cyanobacteria Q2 (5.0-24.4 ASU/mL)	22.3 (21.3, 23.2)	22.4 (21.5, 23.4)	21.9 (20.9, 22.9)	21.8 (20.8, 22.8)	0.50 (0.37, 0.67)	0.51 (0.38, 0.69)
Cyanobacteria Q3 (24.4-80.2 ASU/mL)	23.5 (22.5, 24.6)	23.4 (22.4, 24.4)	22.6 (21.6, 23.7)	22.5 (21.5, 23.6)	0.49 (0.36, 0.66)	0.41 (0.30, 0.57)
Cyanobacteria Q4 (≥80.2 ASU/mL)	23.8 (22.7, 24.9)	23.6 (22.5, 24.7)	22.4 (21.4, 23.5)	22.7 (21.7, 23.9)	0.47 (0.35, 0.65)	0.50 (0.36, 0.68)

Abbreviations: Q, quartile; ASU/mL, Areal Standard Units per milliliter; 95% CI, 95% confidence intervals.

*At reference levels for time variables (day of week = Wednesday; month = June; year = 2009).

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CHAPTER 5. MAIN BREAKS AND EMERGENCY DEPARTMENT VISITS FOR ACUTE GASTROINTESTINAL ILLNESS, A 10 YEAR LONGITUDINAL STUDY IN BOSTON, MASSACHUSETTS

Introduction

Drinking water distribution systems are aging and deteriorating in many U.S. cities built before the end of the 19th century (e.g., Atlanta, Boston, Philadelphia)(102, 149). This deterioration can lead to breaches in pipes and storage facilities, main breaks, and intrusion of contaminants due to water pressure fluctuations(102, 149). Any deficiency within a system can potentially jeopardize the quality of drinking water supplied for human consumption(6).

In the U.S., there are an estimated 240,000 main breaks each year, wasting over two trillion gallons of treated drinking water(9). Pipes become vulnerable to breaks when environmental and operational stresses overwhelm their structural integrity, especially when they have already been compromised by factors such as corrosion and degradation(155, 158). A main break can cause abrupt changes in flow rate and water pressure within a drinking water pipeline(6, 156). When the flow rate drops, water spends a longer duration in the distribution system, disinfectant residuals decline, and sediments can accumulate and allow microbes to grow(6). When there is an abrupt reduction in water pressure and the external pressure exceeds the internal pressure (known as a negative pressure event), contaminants from the surrounding environment can enter the distribution system through leakage points, faulty seals, or other openings(6, 156-158). Depending on the environment surrounding a water pipe, a variety of pathogens can enter the water system during a negative pressure event resulting from a main break(157, 160). In particular, indicators of fecal pollution (e.g., fecal coliform bacteria, total coliform) and culturable human viruses have been detected in the water and soil external to drinking water pipelines(157, 160).

Waterborne disease outbreaks have occurred due to failures in water distribution systems(29, 153). Due to the unplanned and circumstantial nature of such failures, it can be difficult to study and to estimate related health risks(157, 178). A few epidemiology studies have found associations between pipe breaks or low pressure events and subsequent illness. For example, the number of pipe breaks in the U.S. was associated with the internet search volume for symptoms of gastrointestinal illness(182). In Norway, main breaks were associated with self-reported gastrointestinal illness in Norway(19). In the United Kingdom, low water pressure at the tap was associated with self-reported diarrhea(183).

Studies have yet to examine main breaks in a distribution system and clinical diagnoses of gastrointestinal illness over an extended period. The objective of this analysis was to estimate the association between water main breaks and the risk of emergency department visits for acute gastrointestinal illness over a 10-year period in Boston, Massachusetts.

Methods

Study Population

Boston's water system is operated by the Boston Water and Sewer Commission (BWSC) and delivers potable water to over a million people each day(234). The 2010 Census reported a resident population of 617,594 for the City of Boston(235). BWSC also serves schools and universities, hospitals, businesses, industries, and private and public institutions throughout the city(236).

Emergency Department Visits for Acute Gastrointestinal Illness

Waterborne pathogens often cause acute gastrointestinal illness (AGI)(33). While the type of pathogen and length of incubation period can vary, they often cause a range of similar symptoms such as diarrhea, vomiting, nausea, and abdominal cramping(33, 38). Symptoms can develop in less than a day for some viruses (e.g., norovirus)(237), within a few days for some bacteria (e.g., *Campylobacter*)(238), and up to a week or more for some parasites (e.g., *Cryptosporidium*, *Giardia*)(239, 240). AGI was defined using diagnosis codes (International Classification of Disease, Version 9 Clinical Modification, ICD-9-CM) from emergency department (ED) visits. Both primary and associated diagnosis codes were included; however, a sensitivity analysis based on only the primary diagnosis code was also conducted to examine the robustness of results. Based on earlier studies that have also used ICD-9-CM diagnosis codes to assess drinking water-related AGI, the following codes were used to define AGI: 001-009.9 (intestinal infectious diseases); 558.9 (other and unspecified noninfectious gastroenteritis and colitis); 787.0 (nausea and vomiting); and 787.91 (diarrhea) (50, 55, 186, 216).

ED administrative data were obtained from the Commonwealth of Massachusetts Center for Health Information and Analysis for a 10 year period from October 1, 2002 through September 30, 2012. These data included visits to emergency departments in Massachusetts' acute care hospitals and satellite emergency facilities. They also included patients who received observation services but were not admitted to the hospital. These hospital outpatient visits are usually transferred from the ED, though not included in the ED database to avoid duplicate reporting(217-219). Only 2.8% of AGI diagnoses in our data were hospital outpatient visits.

Main Break Exposure

Main break records were obtained from BWSC for the entire study period. These records are maintained by BWSC Field Engineering Department(241). Aside from the location of the break, the data included details such as the pipe material and type of break. It was hypothesized that ED visits for any AGI caused by a main break would occur within a week of the break. This hazard period was examined as two mutually exclusive intervals: 0-3 days and 4-7 days. The different hazard periods accounted for various amounts of time that it could take for contaminated water to enter the distribution system after a main break, reach the consumer, and cause AGI symptoms that ultimately result in an ED visit.

Statistical Analysis

A case-crossover study design was used to examine the association between main breaks and ED visits for AGI. In a case-crossover study, cases effectively serve as their own control at different point(s) in time(242). This type of study design was suitable because a main break is a brief exposure and any related AGI would be a transient effect(242, 243). Using a time-stratified bi-directional approach matched on zip code and day of week, control date(s) were selected two weeks before and/or after the ED visit within 42-day time-stratified periods(244). Conditional fixed-effects logistic regression models were used to estimate the risk of visiting the ED for AGI following a main break. This type of regression model has been shown to be unbiased when a time-stratified bi-directional approach is used for referent selection(244, 245). Results are reported as odds ratios (OR) and 95% confidence intervals (CI) to describe the relative increase in odds of ED visit for AGI after a main break. Data management and statistical analyses were conducted using Stata SE Version 13 and the *xtlogit* command was used to fit the conditional logistic regression models(246).

The analysis was also stratified by potential effect modifiers, including age, sex, median household income, and type of pipe break (e.g., circumferential, blowout). Age and sex were considered potential effect modifiers due to possible differences in immune status and drinking water intake(17, 247, 248). Since individual-level socioeconomic status was unavailable, median household income was assessed at the zip code level(249). Median household income, obtained from Esri(249), is a useful summary measure of the general economic condition for each zip code. In Boston, median household income at the zip code level ranged from $29,000 to $127,000 and the median was $50,000. The analysis was stratified by the following categories: <50th percentile (<$50,000); 50th-<75th percentile ($50,000-<$84,000); 75th-100th percentile (≥$84,000). Finally, the type of break was also considered a potential effect modifier because it could affect the volume of water that is released and hence the potential for contamination(158, 250).

Boston's water is distributed through five major service networks which are independent of each other(241). Therefore, main breaks affect only the network they occur in(251). A sensitivity analysis restricted the analysis to only zip codes served primarily by a single water service networks. The proportion of each zip code population served by a water network was estimated in ArcGIS using census block populations combined with a map of the service networks and zip codes. In the sensitivity analysis, only zip codes with 90% or more of their population covered by one network were included.

Results

Main breaks

During the study period from October 1, 2002 through September 30, 2012, there were 385 main breaks recorded in Boston, Massachusetts. There was at least one main break in 29 Boston zip codes. Figure 28 summarizes the total number of main breaks by zip code during the entire study period. Annual totals ranged from 29 to 51 breaks. Most breaks occurred during the winter months, with almost half (47.5%) occurring in December, January, and February.

The material of pipes was primarily pit cast iron (52.2%), cement-lined cast iron (28.6%), and cement-lined ductile Iron (11.7%). The size of pipes ranged from 4 to 48 inches, with 45% of breaks occurring in 8-inch pipes and 27% in 12-inch pipes. The most common break type was circumferential (n=231; 60.0%) followed by blowout (n=117; 30.4%). Break type was related to pipe size, with 78.4% of circumferential breaks occurring in 4-8 inch pipes and 74.4% of blowout breaks in larger 10-16 inch pipes.

Emergency department visits for acute gastrointestinal illness

Table 15 describes the characteristics of the ED visits for AGI during the 10-year study period in Boston. There were 32,530 ED visits for AGI, of which 53.5% had a primary diagnosis. There were slightly more females (55.1%) than males. Over a third (39.5%) of the ED visits were among young children (≤5 years). Only 3.7% were among elderly (≥65 years). There were also more blacks (40.9%) compared to whites (23.0%) and Hispanics (23.4%). The majority (64.2%) of AGI visits were from those who resided in zip codes with a median household income less than $50,000. Only 6.5% of AGI visits were from those who resided in zip codes with a median household income of $84,000 or more.

Case-crossover analysis

As shown in Table 16, there was no overall association between main breaks and ED visits for AGI during the 0-3 day hazard period (odds ratio, OR=1.05; 95% confidence interval, CI: 0.94-1.17) and subsequent 4-7 day period (OR=0.97; 95% CI: 0.87-1.08). This null association remained when AGI was defined more specifically using only primary diagnosis codes (OR=1.01; 95% CI: 0.87-1.17). There was also no difference by sex.

Among elderly residents (≥65 years), the odds of visiting the ED for AGI was elevated during the 0-3 days after a main break (OR=2.12; 95% CI: 1.20-3.74). In other words, elderly residents were two times more likely to visit the ED for AGI during the 0-3 days after a main break. This association was strengthened when main breaks were restricted to only blowout breaks (OR=5.27; 95% CI: 1.43-19.36). In contrast, when limited to only circumferential breaks, the association was attenuated and not as strong (OR=1.61; 95% CI: 0.83-3.14). No associations among the elderly were observed during the subsequent 4-7 day hazard period for any type of main break (OR=0.80; 95% CI: 0.48-1.35), or for only blowout breaks (OR=0.96; 95% CI: 0.36-2.56), or only circumferential breaks (OR=0.66; 95% CI: 0.35-1.27).

Residents living in zip codes with a median household income less than $50,000 were at a 17% increased odds of visiting the ED for AGI during the 0-3 days after a main break (OR=1.17; 95% CI: 1.01-1.35). This association was consistent when main breaks were restricted to only circumferential breaks (OR=1.27; 95% CI: 1.05-1.52). However, when limited to only blowout breaks, there was no association (OR=1.03; 95% CI: 0.80-1.32). Similar with the other analyses, there was no association observed during the 4-7 day hazard period (OR=0.98; 95% CI: 0.85-

1.13). Residents living in zip codes with a higher median household income (>$50,000) were not at an increased odds of visiting the ED for AGI in the days following a main break.

As shown in Table 17, the odds of visiting the ED for AGI during the 0-3 days after a main break was slightly elevated (OR=1.15; 95% CI: 0.99-1.34) when the analysis was restricted to only zip codes (n=9) served primarily (≥90%) by one water service network. Among the elderly, the association observed for all zip codes during the 0-3 day hazard period was strengthened (OR=3.70; 95% CI: 1.29-10.62) though imprecise due to a small sample size (n=437). Among older children and adolescents (6-18 years), the odds of visiting the ED for AGI was also elevated during the same 0-3 day hazard period (OR=1.44; 95% CI: 1.01-2.04). Among residents living in zip codes with a median household income less than $50,000, the association during the 0-3 day hazard period (OR=1.15; 95% CI: 0.98-1.36) was similar to what was observed with all zip codes. Lastly, when restricted to only circumferential breaks, the overall association during the 0-3 day period strengthened (OR=1.22; 95% CI: 0.99-1.51).

Discussion

Overall, the occurrence of a main break did not affect the odds of visiting the ED for AGI during the following week. This was consistent when using a more specific definition of AGI based on only primary diagnosis codes. However, higher risks in certain subpopulations suggest they may be more vulnerable to AGI following main breaks.

Impact of main breaks among the elderly

Elderly residents (≥65 years) were at an increased odds of visiting the ED for AGI in the 0-3 days after a main break (OR=2.12; 95% CI: 1.20-3.74). Based on this result, as many as 53%

of elderly ED visits for AGI in the 0-3 days following a main break could be attributed to the main break (attributable fraction = (2.12-1)/2.12 = 0.53). Since ED visits for AGI are generally rare and there were relatively few elderly cases (n=1,191), the attributable fraction only accounts for 16 excess cases (0.53*31=16.3). Due to their declining immune function, the elderly may be more susceptible to certain infections(259, 260). It is also possible that they have different drinking water habits or perhaps they do not effectively receive or respond to main break notices. Understanding why elderly residents are more vulnerable to the effects of drinking water contamination caused by main breaks could help with future prevention efforts.

Median household income

Median household income was used to summarize the general neighborhood economic condition of each zip code(249). The hypothesis was that the overall economic condition of a residential area might influence the maintenance of its water infrastructure and, therefore, the impact of a main break. Although there have been documented instances of low-income communities without guaranteed access to safe drinking water, there have been few studies examining disparities in drinking water infrastructure(35). In 2010, the median household income in Boston was $50,684(261). In this analysis, 64.2% of ED visits for AGI lived in a zip code with a median household income below $50,000. In a crude analysis, zip code median household income was not associated with ED visits for AGI. Residents living in zip codes with a median household income less than $50,000, however, were 17% more likely to visit the ED for AGI in the 0-3 days after a main break (OR=1.17; 95% CI: 1.01-1.35). This suggests that main breaks occurring in zip codes with a lower median income (<$50,000) may pose a greater risk for AGI. Without individual-level socioeconomic data, it is difficult to explain why residents of these zip codes may be more susceptible. It is possible that fewer resources are used to maintain and rehabilitate the infrastructure in these zip codes. That is, if the pipes are already deteriorating and then a main break causes a sudden change in water pressure, there could be more entry points (e.g., leaks) to allow contaminants into the drinking water supply.

Potential pathogens

When a main break occurs, there are many potential pathogens in the environment that could enter the distribution pipes and contaminate the drinking water supply(27, 38). The associations during the 0-3 day hazard period suggests a quick progression from the main break to being exposed to contaminated water, being infected by a pathogen, experiencing AGI symptoms, and visiting the ED. In other words, the pathogens involved probably had a short incubation period (e.g., enteric viruses).

Break type as an effect modifier

Main breaks often occurred during the colder months because a drop in temperature, especially fluctuations around the freezing point, can place added geologic stresses on the distribution system(6, 167). Besides temperature, there are other factors that can contribute to main breaks, such as soil movement, internal corrosion, external corrosion, pressure transients, and damage from construction or other utilities (e.g., electric, natural gas, cable)(168, 169). Pipe size, ranging from 4 to 48 inches in diameter, was related to break type. Smaller pipes (≤10 inches in diameter) mostly broke circumferentially (78.5%), which is analogous to a pencil snapping(250, 251). Circumferential breaks result in a clean shear opening of the pipe around its circumference and leave a small opening all around the pipe(250). Breaks in larger pipes (>10 inches in diameter) often resulted in a blowout (57.6%), which is when a large hole opens on the side of the pipe and allows a substantial volume of water to escape(72). In this analysis, blowout breaks strengthened the association among elderly residents (≥65 years). If blowout breaks allow a more substantial volume of water to escape, there could be a greater likelihood of microbial intrusion into the drinking water supply at nearby leakage points(158). The increased effect among elderly residents (OR=5.27; 95% CI: 1.43-19.36) may indicate that drinking water contamination caused by blowout breaks has more of an effect among elderly residents.

Strengths

A strength of this study was having 10 years of data to estimate the association between water main breaks and ED visits for AGI. One of the major challenges to measuring the related health effects of main breaks is having quality long-term data on main breaks. Existing studies have been limited to one to two years due to data availability(182, 184). Fortunately, BWSC has been recording water mains breaks since 1975(241).

The case-crossover design eliminated confounding by self-matching on determinants (e.g., age, sex, race, socioeconomic status) that are constant within individuals over the 42-day sampling period(242, 257). Also, the two week period between case and control time(s) automatically matched on day of week, thus controlling for any confounding by day of week(244). In addition, the two week period prevented any autocorrelation between case and control times by ensuring independent exposure windows(257). Lastly, conditional logistic regression estimates have been shown to be unbiased when using a time-stratified bi-directional approach to select control time(s)(244, 245).

Another strength of this study was being able to incorporate water service networks in a sensitivity analysis. Since main breaks only affect the water service network they occur in(251), zip codes served by more than one network will not be entirely exposed by a given main break. By restricting the analysis to only zip codes served primarily (≥90%) by one water service network, any misclassification of exposure due to having multiple water service networks in a zip code was reduced. This sensitivity analysis yielded a slightly elevated overall association (OR=1.15; 95% CI: 0.99-1.34) compared to the main analysis (OR=1.05; 95% CI: 0.94-1.17) for the 0-3 day hazard period. In addition, stratified results were strengthened (e.g., for the elderly, for only circumferential breaks) or remained (e.g., for lower income zip codes). This may suggest that the more specific exposure definition reduced misclassification.

Limitations

There were a few data limitations that may have attenuated the association between main breaks and AGI. For example, this analysis used ED visits, which capture only the most severe cases of AGI requiring immediate medical attention. Consequently, the burden of AGI due to main breaks would be underestimated. By using internet search volume for symptoms of gastrointestinal illness, Shortridge et al. (2014) suggested that water pipe breaks may increase mild cases of AGI that may not result in a doctor's visit(182). Unfortunately, hospital-based administrative databases do not have information needed to describe such mild cases of AGI.

A limitation of the main breaks data was that there was no marker of break severity, such as the duration of the break and how much water was lost. In other words, all breaks were treated equally even though the magnitude and impact of main breaks can vary. A large main break is often identified by unexpected low pressure readings, excessive pumping, or a drop in reservoir levels in a specific area(6). Since small breaks are harder to find, water utilities often encourage their customers to help identify water main leaks and breaks(170-174). Signs of a faulty water main include water seeping up out of the ground or pavement, buckled pavement, and a leaking service line(170-174). Depending on size and location, some breaks may go unnoticed for hours(241). In addition, the main breaks included in the analysis do not represent all water pipe breaks since service line breaks are often the responsibility of an individual property owner and therefore not necessarily recorded by the water utility (150).

Another limitation was that main break exposure was based on zip code of residence even though people may spend time in other zip codes for various reasons (e.g., school, work, healthcare, business, entertainment, etc.). Similarly, people visiting Boston from elsewhere may have been exposed to a main break but would not have been included in the analysis. In addition, without individual-level data on water consumption, other factors affecting tap water exposure (e.g., bottled water use, in-home water filters) was unknown. Somewhat analogous to the mobility of people, the water in the distribution system is not confined within zip code. Rather, water is distributed within its service network which could span several zip codes(241, 251). In addition, the direction of flow can change depending on consumer demand(251). In order to simplify the analysis, main break exposure was based on zip code under the assumption that main breaks have a localized impact that does not spread across multiple zip codes. Due to these exposure limitations, there was some inevitable mixing and misclassification of exposure. Nevertheless, zip code was the most detailed residential variable available in the ED database. This is often the case when using administrative data in order to protect the privacy and confidentiality of potentially person-identifiable data. Zip codes have been used in past studies of drinking water quality and ED visits for AGI(55, 187). For example, Tinker et al. (2010) assigned residential zip codes to water treatment plants in Atlanta and observed a small association between raw water turbidity at the treatment plant and ED visits for AGI(55).

Conclusion

This study identified elderly residents (≥65 years) as a sensitive subgroup that may be particularly susceptible to AGI resulting in an ED visit after a main break. In addition, there may be a slightly elevated risk in areas with a lower median household income. Any effect is important to consider, especially in cities with aging systems that experience more main breaks. Boston's water system is made up of approximately 1,018 miles of pipe(236) and the number of main breaks ranged from 29 to 51 breaks per year. This is considerably less than the national average of 240 to 270 breaks per 1,000 miles of water main(6). For comparison, Philadelphia estimated an average of 212 breaks per 1,000 miles for the year 2001(6). As the water infrastructure ages around the country, main breaks will continue to occur and likely increase in frequency(102). With an estimated 240,000 main breaks occurring each year(9), even a small effect on the risk of illness is of great public health concern. Although this study may not be generalizable to smaller water systems (e.g., rural areas) with fewer families served by distribution pipes, main breaks are universal and water is likely contaminated a similar way. Understanding the health consequences can help water utilities and health departments establish and improve preparedness and response plans.

Figures

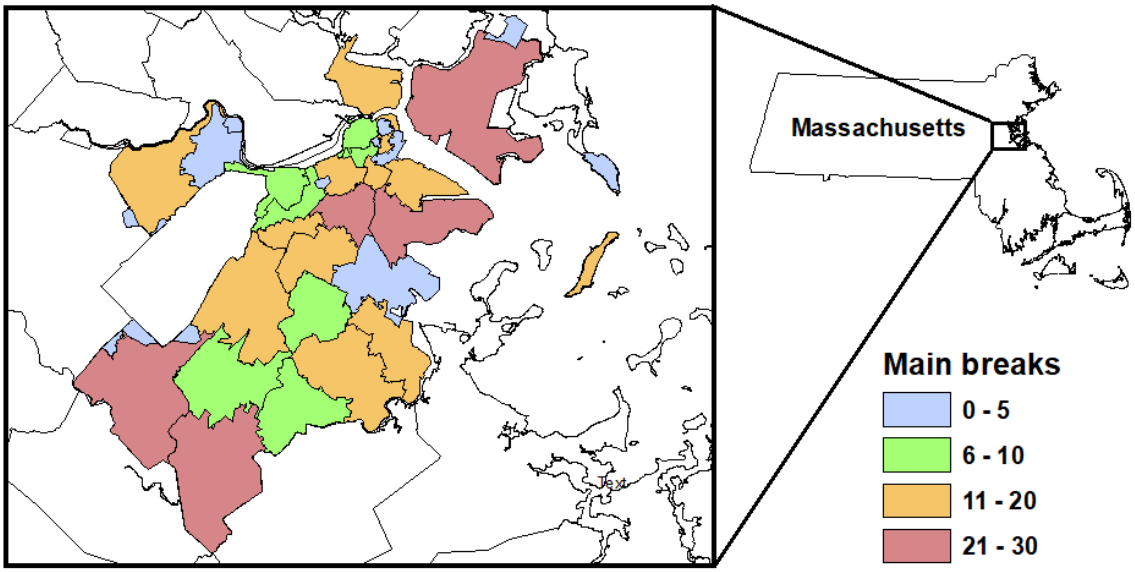

Figure 28. Number of main breaks by zip codes in Boston, Massachusetts, Oct. 1, 2002 – Sept. 30, 2012.

Tables

Table 15. Descriptive summary of emergency department visits for acute gastrointestinal illness in Boston, Massachusetts (October 1, 2002 - September 30, 2012).

	N	%
Total	32,530	100%
Type of Visit		
Emergency Department	31,624	97.21%
Hospital Outpatient*	906	2.79%
Age		
Young Children (≤5 yrs)	12,853	39.51%
Youth/Adolescents (6-18 yrs)	5,742	17.65%
Adults (19-64 yrs)	12,744	39.18%
Elderly (≤65 yrs)	1,191	3.66%
Sex		
Female	17,910	55.06%
Male	14,620	44.94%
Primary Diagnosis	17,393	53.47%
Race		
White	7,472	22.97%
Black	13,294	40.87%
Hispanic	7,596	23.35%
Other	3,073	9.45%
Missing	1,095	3.37%
Median Household Income**		
<$50,000	20,897	64.24%
$50,000-<$84,000	9,525	29.28%
≥$84,000	2,108	6.48%

*Hospital outpatient visits included patients who received observation services but were not admitted to the hospital.

**Median Household Income based on zip code of residence.

Table 16. Association between water main breaks and emergency department visits for acute gastrointestinal illness in Boston, Massachusetts (October 1, 2002 - September 30, 2012).

		Odds Ratio (95% Confidence Interval)	
	Number of visits	0-3 days after main break	4-7 days after main break
Any type of break and any diagnosis for AGI	32,530	1.05 (0.94, 1.17)	0.97 (0.87, 1.08)
Young Children (≤5 years)	12,853	0.93 (0.78, 1.11)	1.07 (0.90, 1.28)
Youth/Adolescents (6-18 years)	5,742	1.11 (0.86, 1.44)	0.85 (0.66, 1.10)
Adults (19-64 years)	12,744	1.07 (0.89, 1.28)	0.95 (0.79, 1.13)
Elderly (≥65 years)	1,191	2.12 (1.20, 3.74)	0.80 (0.48, 1.35)
Females	17,910	1.06 (0.92, 1.23)	0.94 (0.81, 1.09)
Males	14,620	1.03 (0.87, 1.21)	1.00 (0.85, 1.18)
Median Household Income*			
<$50,000	20,897	1.17 (1.01, 1.35)	0.98 (0.85, 1.13)
$50,000 - <$84,000	9,525	0.89 (0.74, 1.08)	0.91 (0.76, 1.10)
≥$84,000	2,108	0.82 (0.50, 1.33)	1.14 (0.72, 1.81)
Any type of break and any primary diagnosis for AGI	17,393	1.01 (0.87, 1.17)	1.01 (0.87, 1.17)
Circumferential break and any AGI	32,530	1.09 (0.95, 1.25)	0.89 (0.78, 1.01)
Blowout break and any AGI	32,530	0.98 (0.79, 1.21)	1.18 (0.96, 1.46)

Abbreviation: AGI, acute gastrointestinal illness

*Median Household Income based on zip code of residence.

Table 17. Sensitivity analysis including only zip codes served primarily (≥90%) by one water service network.

	Number of visits	Odds Ratio (95% Confidence Interval) 0-3 days after main break	4-7 days after main break
Any type of break and any diagnosis for AGI	15,365	1.15 (0.99, 1.34)	0.99 (0.85, 1.16)
Young Children (≤5 years)	5,981	0.93 (0.73, 1.18)	1.02 (0.80, 1.31)
Youth/Adolescents (6-18 years)	2,838	1.44 (1.01, 2.04)	0.86 (0.60, 1.22)
Adults (19-64 years)	6,109	1.19 (0.93, 1.52)	1.07 (0.83, 1.37)
Elderly (≥65 years)	437	3.70 (1.29, 10.62)	0.72 (0.33, 1.57)
Females	8,529	1.09 (0.89, 1.33)	0.84 (0.68, 1.04)
Males	6,836	1.23 (0.97, 1.56)	1.21 (0.96, 1.52)
Median Household Income*			
<$50,000	13,320	1.15 (0.98, 1.36)	0.96 (0.81, 1.13)
$50,000 - <$84,000	1,247	1.07 (0.53, 2.17)	1.02 (0.52, 2.01)
≥$84,000	798	1.13 (0.63, 2.03)	1.53 (0.85, 2.73)
Any type of break and any primary diagnosis for AGI	8,148	1.13 (0.91, 1.40)	1.04 (0.84, 1.29)
Circumferential break and any AGI	15,365	1.22 (0.99, 1.51)	0.91 (0.74, 1.12)
Blowout break and any AGI	15,365	1.09 (0.85, 1.40)	1.14 (0.88, 1.49)

Abbreviation: AGI, acute gastrointestinal illness

Note: Zip codes served primarily (≥90%) by one water service network estimated in ArcMap using census block populations combined with a map of the service networks and zip codes.

*Median Household Income based on zip code of residence.

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CHAPTER 6. EMERGENCY DEPARTMENT VISITS FOR ACUTE GASTROINTESTINAL ILLNESS AFTER A MAJOR WATER PIPE BREAK IN 2010

Introduction

On the morning of Saturday, May 1, 2010, a major water pipe broke near Boston, Massachusetts, releasing millions of gallons of water and disrupting the drinking water supply for nearly two million residents(252, 254). By the late afternoon, Massachusetts Governor Deval Patrick issued a boil water order for the City of Boston and 29 nearby communities (Figure 29) and declared a state of emergency(252, 262). Affected residents were instructed to boil their water through several modes of communication including the local media (e.g., radio, television, local papers), reverse 911 calls or texts, and highway signs(252, 253). In some communities, emergency officials drove through neighborhoods using bullhorns and loudspeakers to inform residents(252, 253). Within a week of the pipe break, a survey conducted in waiting rooms at Boston Medical Center revealed that the most common ways of learning about the boil water order were by word of mouth, television, and telephone/cellphone calls(263). By the early morning of May 4th, the boil water order had been lifted for all affected communities(252).

Water pipe breaks are a public health concern because they can cause a rapid change in water pressure and allow contaminants from the surrounding environment to enter the distribution system through openings such as leakage points, submerged air valves, and faulty seals(6, 154, 156-158). Depending on the physical condition of the distribution network, abrupt changes in water pressure following a pipe break can lead to the intrusion of contaminants throughout the network, not just at the location of the pipe break(158). Fecal indicator bacteria and culturable human viruses have been detected in the soil and water external to drinking water pipelines, thus making them capable of entering the water system during a negative pressure event(157, 160). Intestinal parasites (e.g., *Cryptosporidium*, *Giardia*) have also been found in soil(264, 265). Several studies have reported an association between tap water consumption in faulty distribution networks and gastrointestinal illness(180). In the United States, Shortridge & Guikema (2014) found an association between the number of pipe breaks and the internet search volume for symptoms of gastrointestinal illness(182). In the United Kingdom, Hunter et al. (2005) suggested that up to 15% of gastrointestinal illness in the general population could be related to drinking water contaminated by low water pressure events such as a burst water pipe(183). In Norway, Nygard et al. (2007) observed that reports of gastrointestinal illness increased during the week after the occurrence of main breaks or maintenance work on the water distribution system(184).

Few epidemiology studies have explicitly studied how distribution failure events may contribute to the occurrence of waterborne illnesses(6). The major water pipe break near Boston in May 2010 provided an opportunity to study this using existing healthcare data. The aim of this analysis was to estimate the association between the pipe break and the risk of emergency department visits for acute gastrointestinal illness (AGI).

Methods

Study Population

The Massachusetts Water Resources Authority (MWRA) provides drinking water to residents living primarily in metropolitan Boston communities(198). At around 9:30 a.m. on May 1, 2010, a coupling that secured segments of a 10-foot diameter water pipe broke along a major distribution line(252). Approximately two million residents were affected by a boil water order that follow this major water pipe break(252-254). Figure 29 highlights the 30 Boston metropolitan communities that were affected. They included Arlington, Belmont, Boston, Brookline, Canton, Chelsea, Everett, Hanscom Air Force Base, Lexington, Lynnfield, Malden, Marblehead, Medford, Melrose, Milton, Nahant, Newton, Norwood, Quincy, Reading, Revere, Saugus, Somerville, Stoneham, Swampscott, Wakefield, Waltham, Watertown, Winchester, and Winthrop. These communities were located approximately 3 to 23 miles from the water pipe break. For the purposes of this study, these communities were considered exposed.

Negative Control Exposure

In a separate analysis, communities unaffected by the pipe break served as a negative control to assess whether AGI also increased at the time of the event(255). Communities receiving water unaffected by the pipe break were selected as a negative control exposure if they were 1) located in relatively close proximity (<40 miles) of the break and 2) had a Census population of at least 40,000 residents to ensure a sample size comparable to the truly exposed communities. These communities included Attleboro, Billerica, Brockton, Cambridge, Framingham, Haverhill, Lawrence, Lowell, Lynn, Methuen, Peabody, Salem, Taunton, Weymouth, and Worcester. Although Framingham receives full water service from MWRA, it was unaffected by the pipe break. Peabody is partially supplied by MWRA but was also unaffected. The remaining communities are not served by MWRA, though Cambridge and Worcester have access to MWRA for emergency/back-up supplies. Figure 29 highlights these 15 communities serving as negative controls. These communities were located approximately 7 to 31 miles away from the water pipe break.

Emergency Department Visits for Acute Gastrointestinal Illness

Acute gastrointestinal illness (AGI) is often the most common recognizable health endpoint following infection with waterborne pathogens(33, 38). Incubation periods can vary by type of pathogen – from less than a day for some viruses (e.g., norovirus)(237) to a few days for some bacteria (e.g., *Campylobacter*)(238). Some parasites (e.g., *Cryptosporidium*, *Giardia*) have a longer incubation period on average (~7 days), though it can range from a day to two weeks(240, 266, 267). These different types of pathogens often cause similar symptoms such as diarrhea, vomiting, nausea, and cramps(33, 38). AGI is also a convenient measure because it does not usually require any sample collection or analytical test(38). AGI was defined using the primary and five associated diagnosis codes (International Classification of Disease, Version 9 Clinical Modification, ICD-9-CM). Several prior studies assessing drinking water quality and AGI have used ICD-9-CM codes(50, 55, 186, 216); building on what has been used in the literature, the following ICD-9-CM diagnosis codes were used to define AGI: 001-009.9 (intestinal infectious diseases); 558.9 (other and unspecified noninfectious gastroenteritis and colitis); 787.0 (nausea and vomiting); and 787.91 (diarrhea).

Emergency department (ED) data, including hospital outpatient data, were obtained from the Commonwealth of Massachusetts Center for Health Information and Analysis for the year 2010. ED data included visits to emergency departments in Massachusetts' acute care hospitals and satellite emergency facilities. Hospital outpatient data included patients who received observation services but were not admitted to the hospital. Patients receiving observation services are usually transferred from the ED, though they are not included in the ED database to avoid duplicate reporting(217-219). Only 2.2% of AGI diagnoses were from hospital outpatient visits.

Pipe Break Exposure

It was hypothesized that any ED visit for AGI caused by the water pipe break would occur within a week of the break. Despite the magnitude of the situation, the broken pipe was repaired in less than two days and the boil water order was lifted within 3 days(252). The one-week hazard period encompassed the time it would take for contaminated water to enter the distribution system and reach the consumer, the pathogen incubation period, and the time for an affected person to visit the ED. The hazard period was examined as two mutually exclusive intervals: 0-3 days and 4-7 days. The 0-3 day period encompassed the duration of the boil water order. The later 4-7-day hazard period accounted for a longer time lag from the pipe break to exposure, infection, onset of AGI symptoms, and visiting the ED. The length of these hazard periods were optimal for capturing the effect of pathogens with an incubation period of no more than a few days.

Statistical Analysis

A case-crossover study design was used to examine the association between the major water pipe break and AGI. This type of study design, in which cases effectively serve as their own control at different point(s) in time, was applicable because the water pipe break was a brief exposure with potentially transient effects on AGI(242, 243). Control times were selected bidirectionally, two weeks before and two weeks after the pipe break(244, 256).

Conditional fixed-effects logistic regression models were used to estimate the risk of visiting the ED for AGI following the pipe break. This type of regression model is the standard for case-crossover studies(243). Only case-control groups with discordant exposures contribute information to the analysis(257); therefore, this analysis was confined to a 64-day period (April 3, 2010 through June 5, 2010) based on all possible discordant exposure scenarios. Results are reported as odds ratios (OR) and 95% confidence intervals (CI) and interpreted as the relative increase in odds of ED visit for AGI after the water pipe break.

The analysis was also stratified by potential effect modifiers. Age and sex were considered potential effect modifiers due to possible differences in immune status, risk for AGI, and drinking water intake(17, 247, 248). In addition, the analysis was stratified by distance from the pipe break in order to examine whether closer communities were impacted earlier, or more seriously, than further communities. A sensitivity analysis in which AGI was defined based on only the primary diagnosis code was conducted to examine the robustness of results. Lastly, attributable fractions and population attributable fractions were calculated using the odds ratio and proportion of exposed cases(258). Data management and statistical analyses were conducted using Stata SE Version 13 and the *xtlogit* command was used to fit the conditional logistic regression models(246).

Results

Among residents of the 30 communities affected by the water pipe break, there were 1,818 ED visits with at least one diagnosis code for AGI during the study period (April 3, 2010 through June 5, 2010). Over a third (n=756; 42%) had a primary diagnosis of AGI. The majority (80%) of all visits were among adults (19-64 years) and young children (≤5 years) and there were slightly more females (n=1,027; 56%) than males. Table 18 summarizes characteristics of ED visits for AGI in the communities affected by the pipe break; the table also reports characteristics of ED visits for AGI in the communities selected as the negative control.

There was a 32% increased odds for visiting the ED for AGI during the 0-3 days after the pipe break (OR=1.32; 95% CI: 1.07-1.61; Table 19). This association was of smaller magnitude during the 4-7 day hazard period (OR=1.17; 95% CI: 0.93-1.47). The associations were similar in males and females. When the analysis was restricted to visits with a primary diagnosis for AGI, the association strengthened for both the 0-3 day hazard period (OR=1.48; 95% CI: 1.10-1.98) and the 4-7 day hazard period (OR=1.34; 95% CI: 0.93-1.93).

As illustrated in Figure 30, the odds for visiting the ED for AGI after the water pipe break varied by age group, with the increased odds most consistent among children and adolescents (≤18 years). In particular, the odds ratio among youth/adolescents (6-18 years) was elevated during both 0-3 and 4-7 day hazard periods. Adults (>18 years) were not at an increased odds for visiting the ED for AGI. Due to the small number of cases, effect estimates for the elderly (≥65 years) were imprecise.

When the analysis was stratified by distance from the water pipe break, the communities less than the median distance (<12 miles) away were at an increased odds for visiting the ED for AGI during the 0-3 day hazard period (OR=1.46; 95% CI: 1.15-1.84) but not during the 4-7 day hazard period (OR=0.95; 0.62, 1.46). There were no associations for the communities over 12 miles from the break (0-3 day OR=1.18; 95% CI: 0.90, 1.54).

In a separate analysis using the negative control exposure, there was no association between the time of the major water pipe break and ED visits for AGI during both the 0-3 day hazard period (OR= 0.99; 95% CI: 0.78-1.25) and the 4-7 day hazard period (OR= 0.83; 95% CI: 0.65-1.08).

Based on the overall association (OR=1.32), almost a quarter (24%) of ED visits for AGI 0-3 days after the pipe break could be attributed to the break. Using the proportion of ED visits that occurred 0-3 days after the break (152/1818=0.08), the population attributable fraction was 2% (0.08*0.24=0.02). In other words, an estimated 2% of all ED visits for AGI during the 64-day study period in the affected communities would not have occurred had the break never happened.

Discussion

Water pipe break and acute gastrointestinal illness

The major water pipe break in May 2010 provided the opportunity to investigate the association between a water pipe break and ED utilization for AGI. Wang et al. (2011) reported that the Massachusetts Department of Public Health did not observe a notable rise in disease reports after the break(263). The present study, however, found an increased risk of ED visits for AGI during the week after the pipe break. This association was strongest during the immediate 0-3 days after the break (OR=1.32; 95% CI: 1.07-1.61) when the boil water order was in effect. Since ED visits for AGI are rare (<1%), attributing 24% of the visits to the break only amounts to 36.5 excess cases during the 0-3 days after the pipe break (0.24*152=36.5). There was also a suggestive positive association during the 4-7 days after the break (OR=1.17; 95% CI: 0.93-1.47). These findings were further supported by a negative control exposure yielding a null effect. When AGI was defined based on only the primary diagnosis code, the association strengthened for both the 0-3 day hazard period (OR=1.48; 95% CI: 1.10-1.98) and the 4-7 day hazard period (OR=1.34; 95% CI: 0.93-1.93). This may indicate that the more specific outcome definition reduced misclassification (i.e., ED visits that were not waterborne AGI).

Age appeared to modify the risk of visiting the ED for AGI after the water pipe break. In particular, the risk was highest among children and adolescents (≤18 years). Children may differ from adults in how they are exposed to environmental contaminants and how they react to it when exposed(268). In contrast to the youngest age group (≤5 years), the increased association among the youth/adolescents (6-18 years) during the 0-3 day hazard period (OR=1.59; 95% CI: 0.99-2.55) was persistent during the 4-7 day hazard period (OR=1.75; 95% CI: 0.97-3.14). It is not clear why this may be, but perhaps parents took longer to become aware of, or respond to, symptoms in older children. Although the oldest age group (≥65 years) is also a sensitive sub-group, effect estimates were too imprecise to make any meaningful conclusions due to the small number of AGI cases (n=66).

When the analysis was stratified by distance from the water pipe break, the closer communities less than 12 miles away were at an increased risk of ED visits for AGI during the 0-3 day hazard period (OR=1.46; 95% CI: 1.15-1.84). To assess if this was due to disproportionate effects of Boston's large population, a sensitivity analysis excluding Boston was conducted and the association remained (OR=1.50; 95% CI: 1.02-2.21). In the communities further (>12 miles) away, there was no association between the pipe break and ED visits for AGI. It is possible that the risk of AGI was highest immediately (0-3 days) after the pipe break in the closer communities because their water was impacted first. Consequently, the closer communities may have had more time to drink contaminated water before becoming aware of, or responding to, the boil water order.

This study may have underestimated the impact of the pipe break on the burden of AGI because ED visits only capture the most severe cases of AGI requiring immediate medical attention. Shortridge et al. (2014) provided support that distribution system disturbances may increase mild cases of AGI that do not necessitate a doctor's visit(182). Unfortunately, administrative databases lack the information necessary to capture such mild cases of AGI. Although it is also possible that the boil water order and widespread media attention increased the rate of ED visits for psychosomatic illnesses, the Mayor's 24-hour hotline had a scripted response for concerned residents(252):

> "Please do not go to an emergency room unless you are seriously ill and/or have been advised by your health care provider to seek immediate care. Please do not go to an emergency room to be checked out because you drank tap water and are concerned. There is no testing that can be done at emergency rooms for patients who are not in need of emergency care."(252)

Water exposure after pipe break

A strength of this analysis was that the pipe break and subsequent boil order were clearly defined events that help determine exposure to potential water contamination.

Estimating the association between drinking water contamination and risk of illness is difficult due to the many assumptions that have to be made(157, 178). For example, a contamination event is contingent on a sequence of events, from the occurrence of an adverse pressure condition, to the presence of an outside contamination source, to the availability of an external pathway for contamination(157, 178). In addition, population exposure depends on factors such as the type and concentration of pathogen entering the system and then reaching the consumers' taps, the duration and magnitude of contamination, and the consumers' drinking habits(157, 178).

While the pipe was being repaired, water pressure had to be maintained throughout the system in order to sustain sanitation needs (e.g., flushing toilets), to keep up with fire protection requirements, and to prevent contamination from backflow(252). As a result, the distribution system was reconfigured to use backup water supplies treated only with emergency chlorination(252). However, the water authority claimed that, according to samples taken from throughout the affected area, the water quality was not atypical for a normal day at that time of year(269). Out of over 800 water samples collected and tested each day, there were very few (two to three) total coliform positive samples and no *E. coli* positive samples on each day of testing(252). This meant that water was always available at the tap and uninformed or preoccupied residents could easily consume it without first boiling it. Furthermore, the boil water order focused on direct ingestion through eating and drinking(252). Exposure through other pathways was still possible, such as through bathing/showering. Despite aggressive efforts to inform the public about the boil water order(252, 253), there would inevitably be residents who do not get the message in time. A survey conducted the week after the pipe break among a convenience sample (n=533) at Boston Medical Center found that 97% were aware of the order(263). However, the authors estimated that 34% of those who lived in affected communities were potentially exposed to contaminated water(263). Potential exposure was defined according to three criteria: 1) awareness of the order; 2) timing of receipt of the message; and 3) action taken upon receipt of the message(263).

There are numerous potential pathogens in the environment and in untreated water that can contaminate drinking water supplies under conditions such as a distribution system failure(27, 38). The association during the 0-3 day period after the break suggests that the pathogens involved had a short incubation period (e.g., enteric viruses). Since the backup water supplies were treated only with chlorine, parasites like cryptosporidium would be a concern since their outer shell can protect them from chlorine disinfection(266). Apart from the ineffectiveness of chlorine treatment for some parasites in the backup water supplies, those parasites may also be present in the soil(264, 265) surrounding the distribution pipes and could infiltrate the system when the pressure initially drops. Given that parasites generally have a longer incubation period (average 7 days)(266, 267), it is possible that the slightly elevated (but statistically insignificant) association during the 4-7 day hazard period (OR=1.17; 95% CI: 0.93-1.47) was driven by parasitic infections. Unfortunately, without routine cultures being performed, the non-specific definition of AGI may dilute associations due to etiologies unrelated to the pipe break.

A limitation of this study is that exposure was based on community of residence even though people likely commute to other communities for work and other activities. This would result in some mixing and misclassification of exposure. However, since the pipe break occurred on a Saturday, less people would be commuting to work or school. Aside from not knowing the exact location of exposure, information on individual water consumption, such as bottled water use and in-home filter use, was unavailable.

Case-crossover study design

The case-crossover method was appropriate because the duration of the pipe break was brief (fixed within two days) and the onset of AGI, if any, was expected to be rapid and short-lived(38, 242, 252). By having cases serve as their own control, this self-matching design eliminates confounding by individual characteristics that do not vary over a short time period, such as sex, race, and socioeconomic status(242, 257). Selecting control times on the same day of week as the case time controlled for any confounding due to day of week(244). Also, the two week gap between case and control times ensured that exposure during the 0-3 and 4-7 day hazard periods was independent of exposure during the control period, thus preventing any autocorrelation between case and control periods(257).

Conclusion

This study provides evidence for an association between a recent major water pipe break and AGI in the United States. Understanding the health implications of water pipe breaks will help inform public health prevention and response plans. This is especially pertinent as drinking water systems age and the likelihood of pipe breaks increases(102, 149).

Figures

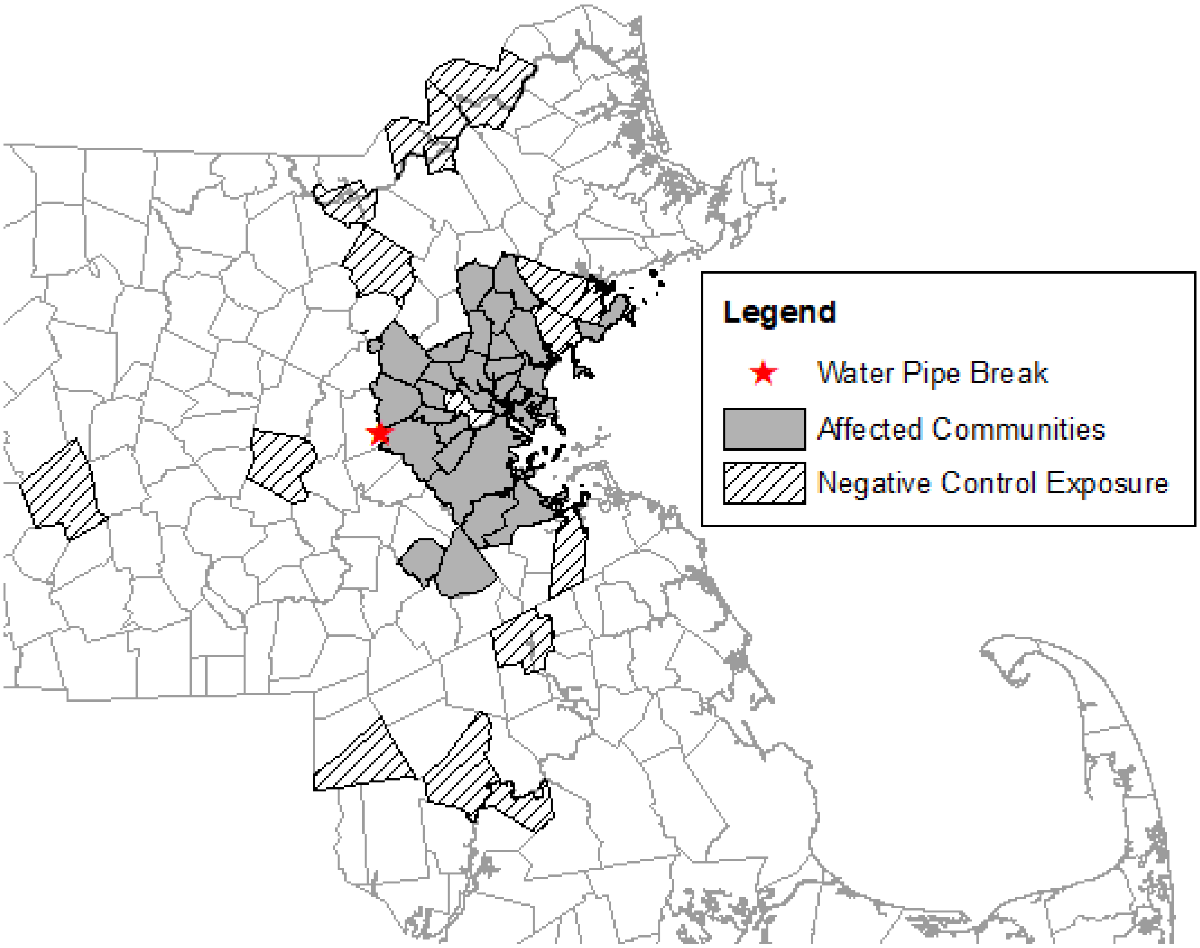

Figure 29. Massachusetts communities studied in relation to the 2010 water pipe break.

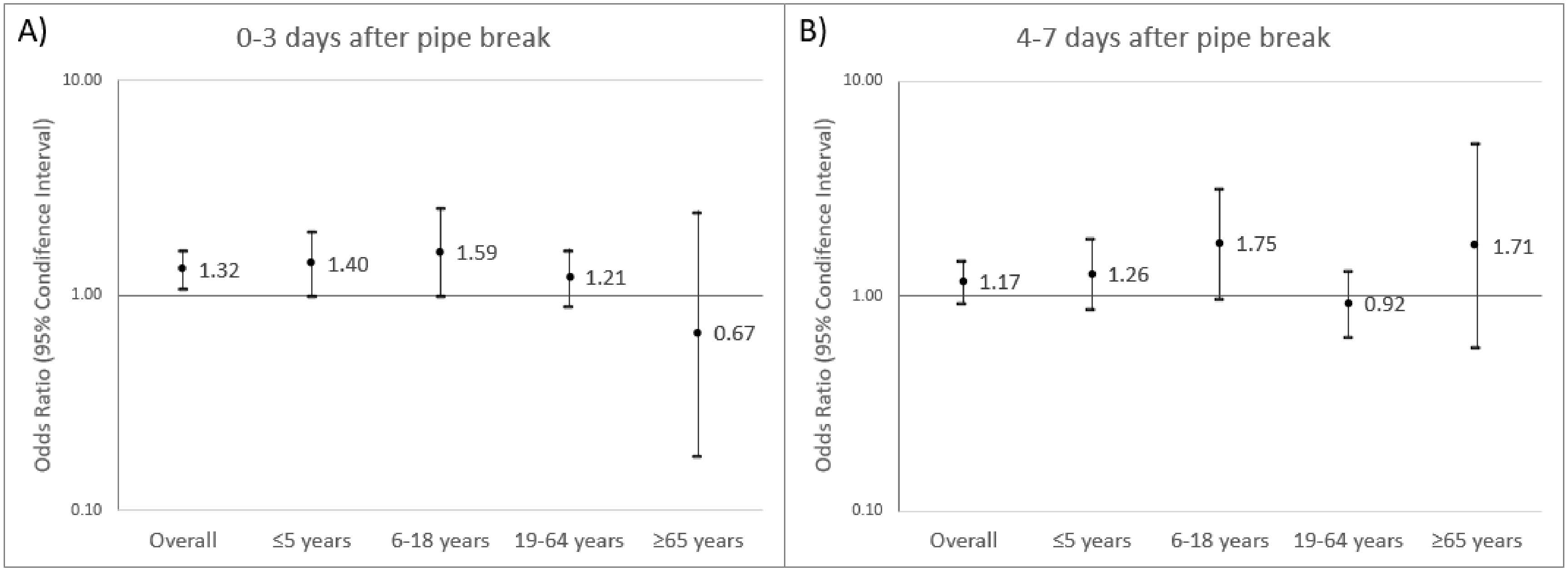

Figure 30. Odds ratios and 95% confidence intervals for emergency department visits for acute gastrointestinal illness in the A) 0-3 and B) 4-7 days following the major water pipe break, by age group.

Tables

Table 18. Descriptive summary of emergency department visits for acute gastrointestinal illness (April 3, 2010 - June 5, 2010).

	Communities affected by pipe break (n=30)		Communities serving as negative control exposure (n=15)	
	N	%	N	%
Total	1,818	100%	1,558	100%
Type of Visit				
Emergency Department	1,777	97.7%	1,521	97.6%
Hospital Outpatient*	41	2.3%	37	2.4%
Age				
Children (≤5 yrs)	650	35.8%	599	38.5%
Youth/Adolescents (6-18 yrs)	297	16.3%	240	15.4%
Adults (19-64 yrs)	805	44.3%	650	41.7%
Elderly (≥65 yrs)	66	3.6%	69	4.4%
Sex				
Female	1,027	56.5%	865	55.5%
Male	791	43.5%	693	44.5%
Primary Diagnosis	756	41.6%	706	45.3%
Race				
White	769	42.3%	719	46.2%
Black	408	22.4%	173	11.1%
Hispanic	374	20.6%	461	29.6%
Other	217	11.9%	182	11.7%
Missing	50	2.8%	23	1.5%

*Hospital outpatient visits included patients who received observation services but were not admitted to the hospital.

Table 19. Association between the major water pipe break and emergency department visits for acute gastrointestinal illness in Boston metropolitan communities.

		Odds Ratio (95% Confidence Interval)	
	Number of visits	0-3 days after pipe break	4-7 days after pipe break
Acute Gastrointestinal Illness*	1,818	1.32 (1.07, 1.61)	1.17 (0.93, 1.47)
Among Young Children (≤5 years)	650	1.40 (0.99, 1.99)	1.26 (0.86, 1.83)
Among Youth/Adolescents (6-18 years)	297	1.59 (0.99, 2.55)	1.75 (0.97, 3.14)
Among Adults (19-64 years)	805	1.21 (0.89, 1.65)	0.92 (0.65, 1.31)
Among Elderly (≥65 years)	66	0.67 (0.18, 2.46)	1.71 (0.58, 5.10)
Among Females	1,027	1.33 (1.01, 1.76)	1.15 (0.84, 1.57)
Among Males	791	1.30 (0.96, 1.75)	1.19 (0.85, 1.66)
Among residents living <12 miles from the break	1,365	1.46 (1.15, 1.84)	0.95 (0.62, 1.46)
Among residents living >12 miles from the break	453	1.18 (0.90, 1.54)	1.13 (0.73, 1.75)
Any primary diagnosis for acute gastrointestinal illness	756	1.48 (1.1, 1.98)	1.34 (0.93, 1.93)

*Primary and associated diagnoses

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CHAPTER 7. DISCUSSION

Summary of Findings

There are many factors within a municipal water system that can influence drinking water quality. In this dissertation, I examined whether two types of potential contamination events are associated with increased illness. The first was cyanobacteria, or blue-green algae, in the water source. The second was pipe breaks in the drinking water distribution system. I analyzed both questions within the context of a large water system operated by the Massachusetts Water Resources Authority (MWRA) that provides drinking water to metropolitan Boston communities.

In the first Specific Aim, I estimated the association between daily cyanobacteria measures in the water source and the rate of emergency department (ED) visits in the metropolitan Boston service area for symptoms of acute gastrointestinal illness (AGI), respiratory illness, and dermal ailments. Over a 7-year period (7/27/2005 – 9/30/2012), there was a small relative increase in daily ED visits for AGI and respiratory illness when comparing upper quartile levels of cyanobacteria with the lowest quartile (≤5.0 ASU/mL). In addition, the younger and older age groups appeared to be more strongly affected for respiratory illness.

The second Specific Aim had two parts. In the first part, I used a case-crossover study design to estimate the association between water main breaks and ED visits for AGI over a 10-year period (10/1/2002 – 9/30/2012) in the City of Boston. Overall, there was no association between main breaks and ED visits for AGI during the 0-3 day hazard period (OR=1.05; 95% CI:

0.94-1.17) and subsequent 4-7 day period (OR=0.97; 95% CI: 0.87-1.08). However, stratified analyses revealed an increased risk during the 0-3 day period among the elderly (OR=2.12; 95% CI: 1.20-3.74) and among residents living in zip codes with a median household income less than $50,000 (OR=1.17; 95% CI: 1.01-1.35). When the analysis was restricted to zip codes served primarily by a single water service network, the overall association became slightly elevated (OR=1.15; 95% CI: 0.99-1.34) and stratified results (by age and median household income) were strengthened. In the second part of this Specific Aim, I focused on a major water pipe break in 2010 that resulted in a boil water order affecting nearly two million residents. Using another case-crossover study design, I estimated the association between the major water pipe break and subsequent ED visits for AGI. Overall, there was an increased risk for visiting the ED for AGI during the 0-3 days after the pipe break when the boil water order was in effect (OR=1.32; 95% CI: 1.07-1.61). This association was most apparent in children and adolescents. In addition, there was no association using a negative control exposure in a separate analysis.

Strengths

A strength of this dissertation project was that there were many years of data available. In the first Specific Aim, I used 7 years of data to estimate the association between low levels of cyanobacteria and ED visits for AGI, respiratory, and dermal illness. It is often a challenge to have quality long-term data on algae in drinking water supplies, let alone speciated data such as cyanobacteria. Fortunately, MWRA has been collecting algae data in the Wachusett Resevoir since the early 1990s so their methods have been in place for a while. In the second Specific

Aim, I used 10 years of data to estimate the association between water main breaks and ED visits for AGI. Existing studies have been limited to one to two years due to data availability(182, 184). Conveniently, the Boston Water and Sewer Commission has been recording water mains breaks since 1975(241). Another strength of this dissertation project was the large population served by MWRA. This provided the statistical power to detect a small effect, which is often the case with environmental epidemiology studies.

In the second Specific Aim, there were a few advantages to using a case-crossover study design. The self-matching design eliminated confounding by determinants that are constant within individuals over the sampling period (e.g., age, sex, race, socioeconomic status)(242, 257). Also, the two week period between case and control time(s) automatically matched on day of week, thus controlling for any confounding by day of week(244). In addition, the two week period prevented any autocorrelation between case and control times by ensuring independent exposure windows(257). Lastly, conditional logistic regression estimates have been shown to be unbiased when using a time-stratified bi-directional approach to select control time(s)(244, 245).

In the analysis of Boston main breaks, a strength was being able to incorporate water service networks in a sensitivity analysis. Since main breaks only affect the water service network they occur in(251), zip codes served by more than one network will not be entirely exposed by a given main break. By restricting the analysis to only zip codes served primarily (≥90%) by one water service network, any misclassification of exposure due to having multiple water service networks in a zip code was reduced. This sensitivity analysis yielded a slightly elevated overall association (OR=1.15; 95% CI: 0.99-1.34) compared to the main analysis

(OR=1.05; 95% CI: 0.94-1.17) for the 0-3 day hazard period. In addition, stratified results were strengthened (e.g., for the elderly, for only circumferential breaks) or remained (e.g., for lower income zip codes). This may suggest that the more specific exposure definition reduced misclassification.

In the analysis of the major water pipe break, a strength was that the pipe break and subsequent boil order were clearly defined events that help determine exposure to potential water contamination. Estimating the association between drinking water contamination and risk of illness is difficult due to the many assumptions that have to be made(157, 178). For example, a contamination event is contingent on a sequence of events occurring and population exposure depends on factors such as the duration and magnitude of contamination(157, 178).

Limitations

This dissertation used ED visits, including hospital outpatient visits, to capture acute symptoms of illness defined using ICD-9-CM diagnosis codes. A limitation of using ED visits is that it only characterizes a subset of residents who may have experienced the outcomes of interest. That is, ED visits represent those who required immediate medical attention. As a result, the burden of illness due to cyanobacteria and main breaks may have been underestimated. For example, by using internet search volume for symptoms of AGI, Shortridge et al. (2014) suggested that water pipe breaks may increase mild cases of AGI that may not result in a doctor's visit(182). Residents experiencing milder symptoms of illness may have opted to recover at home or visit their primary care provider. Unfortunately, hospital-based administrative databases do not have information needed to describe such mild cases of AGI.

In the first Specific Aim, a limitation was that cyanobacteria measurements were taken in the reservoir prior to treatment. Therefore, it may not be an accurate representation of the concentrations in the treated water delivered to consumers. Of note, however, is that MWRA used an unfiltered treatment process that relies primarily on disinfection (ozone) to achieve *Giardia* inactivation(195). While ozone has been shown to destroy certain types of cyanotoxins, its efficacy depends on the ozone demand of organic material in the raw water(148). In addition, ozonation of raw waters containing high cyanobacteria cell concentrations can lead to cell lysis and release of intracellular toxins(148). In the absence of filtration, it may have been possible for cyanobacteria to survive the disinfection treatment process(122). Given the unconventional treatment process, results may not be applicable to water systems that use filtration or different treatment processes.

In the second Specific Aim, a limitation was that water pipe break exposure was based on zip code or town of residence even though people likely commute to other communities for work and other activities (e.g., school, healthcare, business, entertainment, etc.). Similarly, visitors coming from unaffected localities may have been exposed to a water pipe break but would not have been included in the analysis even if they visited the ED. In addition, without individual-level data on water consumption, other factors affecting tap water exposure (e.g., bottled water use, in-home water filters) could not be accounted for. These limitation could have resulted in some mixing and misclassification of exposure.

In the Boston main breaks analysis, a limitation was that there was no marker of main break severity, such as the duration of the break and how much water was lost. In other words, all breaks were treated equally even though the magnitude and impact of main breaks can vary. A large main break is often identified by unexpected low pressure readings, excessive pumping, or a drop in reservoir levels in a specific area(6). Since small breaks are harder to find, water utilities often encourage their customers to help identify water main leaks and breaks(170-174). Signs of a faulty water main include water seeping up out of the ground or pavement, buckled pavement, and a leaking service line(170-174). Depending on size and location, some breaks may go unnoticed for hours(241). In addition, the main breaks included in the analysis do not represent all water pipe breaks since service line breaks are often the responsibility of an individual property owner and therefore not necessarily recorded by the water utility (150).

Another limitation in the Boston main breaks analysis was that exposure was based on zip code with the assumption that main breaks have a localized impact that does not spread across multiple zip codes. However, the water in the distribution system is not confined within zip code. Rather, water is distributed within its service network which could span several zip codes(241, 251). In addition, the direction of flow can change depending on consumer demand(251). Due to these exposure limitations, there was some inevitable mixing and misclassification of exposure. Nevertheless, zip code was the most detailed residential variable available in the ED database. This is often the case when using administrative data in order to protect the privacy and confidentiality of potentially person-identifiable data. Zip codes have been used in past studies of drinking water quality and ED visits for AGI(55, 187). For example, Tinker et al. (2010) assigned residential zip codes to water treatment plants in Atlanta and observed a small association between raw water turbidity at the treatment plant and ED visits for AGI(55).

Significance

The drinking water emergency in Flint, Michigan brought concerns about drinking water safety to the national spotlight. Safe drinking water depends on a well-protected water source, effective treatment processes, and a well-maintained distribution system. The results of my dissertation identified potential health risks related to different stages of a drinking water system, specifically cyanobacteria in the water source and water pipe breaks in the distribution system. If causal, the observed associations are important to consider given the consequences of a changing climate(4, 30). For example, heavy runoff events can increase nutrient loadings in drinking water sources and cause extensive algal blooms(4, 30) and water main breaks can be susceptible to extreme temperature fluctuations(167). In addition, drinking water reservoirs and distribution pipes are aging. Observing even a small effect on risk of illness could have a substantial public health impact, particularly when a large community is affected.

Aging Reservoirs

Many reservoirs in the U.S. are now at or approaching old age as they were designed to last 50 to 100 years(270). As of 2013, the median age of large reservoirs owned by different federal agencies ranged from 49-70 years(270). Another measure of a reservoir's age is the amount of water storage capacity that has been lost due to ongoing sedimentation(270). Aging reservoirs can lead to hydrological, sedimentological, and morphological changes(270). These changes can ultimately affect the presence of cyanobacteria because a change in algal composition often complements the transitional trophic changes in aging reservoirs, especially with increased nutrient input(271). A recent survey of aging lakes and reservoirs in Virginia suggested future concerns for the increased presence of cyanobacteria(271). There has also been a noticeable increase in the severity of cyanobacterial harmful algal blooms in Lake Erie, a drinking water source for about 11 million people(123, 272). In the summer of 2014, microcystin concentrations were particularly severe in Western Lake Erie(2). In fact, microcystin levels in fully treated tap water were detected almost three times the WHO limit of 1 µg/L and over 500,000 residents in and around Toledo, Ohio were warned not to use their water(2, 122). The Toledo event brought national attention to the threat of algal toxin in public water supplies(125). In February 2018, Governor Andrew Cuomo of New York recognized the impending threat of harmful algal blooms in the state's drinking water sources and announced a series of summits to address the issue(273). In March 2018, the Ohio EPA proposed to designate the open waters of Lake Erie's Western Basin as impaired for recreation due to harmful algae and drinking water due to occurrences of microcystin(274). The least characterized health risks are those from repeated, low-level, multi-route exposures to cyanotoxins in surface and drinking waters(128). The results of the first Specific Aim suggest that cyanobacteria at chronic low levels in the water source may slightly increase the risk of AGI and respiratory illness, especially among younger and older age groups.

Aging Water Distribution Systems

As drinking water distribution systems age, they can deteriorate due to corrosion, materials erosion, and external pressures(102, 149). This deterioration can lead to breaches in pipes and storage facilities, intrusion due to water pressure fluctuations, and main breaks(102, 149). An estimated 240,000 main breaks occur each year, wasting over two trillion gallons of treated drinking water(9). Due to a lack of quality long-term data on negative pressure transients, mains breaks, and maintenance work, there are few epidemiology studies on the association between disruptions in the distribution infrastructure and related illnesses. Limitations of existing studies include not focusing on specific distribution failures that could lead to illness and not having sufficient power to estimate the risk of endemic disease associated with drinking water distribution systems(6). The results of the second Specific Aim suggest that the risk of AGI may depend on the magnitude of the main break, especially among children, elderly, and lower income residents.

In order to keep up with aging distribution pipes, the water industry will have to make substantial investments in pipe assessment, repair, and replacement(6). According to the EPA's Drinking Water Infrastructure Needs Survey and Assessment, drinking water utilities will need an estimated $384.2 billion over the next 20 years (from 2011 to 2030) for infrastructure projects to ensure that water systems continue to provide safe drinking water to the public(154). According to the American Water Works Association, upgrading existing water systems to meet the drinking water infrastructure needs of a growing population will require at least $1 trillion(9). Piratla et al. (2015) created an empirical model based on data collected from 11 different large diameter water main breaks to estimate the overall impact costs of main breaks(275). Health risk accounted for the least share of the overall cost of impact, whereas repair and property damage accounted for the greatest share(275). While such impact models can be useful, they are only as informative as the studies and assumptions they are based on. Given the limited number of studies that have quantified the health risk of main breaks, the results of this dissertation project could help improve the model inputs related to health risk.

Local Impact

The Triangle region of North Carolina (Raleigh, Durham, and Chapel Hill) has also felt the impact of main breaks and harmful algae. In February 2017, a major water main break caused a "Do Not Use, Do Not Drink" directive to be issued for about 25 hours in the Carrboro-Chapel Hill community(276). This emergency was complicated by a treatment error (an accidental overfeed of fluoride) that occurred less than a day before the main break(276). The 12-inch water main break resulted in loss of water service to about 250 people, about 1.3 million gallons of water lost from storage, a damaged road, and flooded residences(276). Also, over a 2-year study period, from 2014 to 2016, four cyanotoxins (microcystin, anatoxin-a, cylindrospermopsin, and β-N-methylamino-L-alanine) were detected in Jordan Lake, a major drinking water reservoir for nearly 300,000 people in Morrisville, Cary, and Apex(277). Multiple toxins were detected at 86% of the tested sites and during 44% of the sampling events. Although concentrations were low, the recurrence of multiple cyanotoxins throughout the year confirmed their ubiquitous nature(277).

Recommendations

Cyanobacteria and water main breaks can threaten drinking water quality and public health. Many states provide guidance and emergency response procedures for main breaks and boil water orders; however, there are no federal regulations. Regarding cyanobacteria, cyanotoxins, and other harmful algae, EPA has yet to establish any drinking water standards(128), though the EPA did develop health advisories (non-regulatory) for the cyanobacterial toxins microcystins and cylindrospermopsin in 2015(122, 127).

Given the influences of aging infrastructure and climate change, more and more drinking water utilities around the country will be met with the need to monitor and respond to harmful algae and water main breaks. The results of this dissertation suggest that it may be important to monitor chronic low levels of cyanobacteria, not just bloom events. Understanding the implications of cyanobacteria in drinking water reservoirs will better inform monitoring and management decisions. Also, proactively rehabilitating deteriorated water pipes can help minimize the consequence and severity of water main breaks.

It is important to bring awareness to the potential health effects of low-level cyanobacteria and water main breaks so that water utilities and public health departments can implement relevant prevention and response plans. A limitation is often having enough funds to implement prevention and rehabilitation plans since the majority of funding for drinking water infrastructure in the U.S. comes from revenue generated by rate payers (and the rate structure can greatly vary across the country)(9). The American Society of Civil Engineers recommends increasing funding at the federal level through the State Revolving Loan Fund, the Water Infrastructure Finance and Innovation Act, and a federal Water Infrastructure Trust Fund(9).

Future Directions

To build upon the work of this dissertation, I have several suggestions for future research. For the first Specific Aim, it would be interesting to consider other methods of harmful algae detection that are being developed to rely less heavily on grab samples and laboratory techniques (e.g., satellite images, remotely deployed biosensors). It would also be informative to include toxins data since not all species of cyanobacteria produce toxins. In recent years, water utilities including MWRA and the City of Raleigh have started collecting data on cyanotoxins (e.g., microcystin, cylindrospermopsin). Lastly, to incorporate treatment efficacy and refine the exposure definition, it would be meaningful to consider post-treatment measures of cyanobacteria if available in the future. For the second Specific Aim, it would be interesting to incorporate a measure of main break severity. This could include real-time monitoring data on water pressure fluctuations. In addition, it would be worthwhile to further explore vulnerable groups.

Conclusion

This dissertation examined whether two types of potential contamination events within a drinking water system are associated with increased illness. A small relative increase in daily ED visits was observed for AGI and respiratory illness when comparing upper quartile levels of cyanobacteria concentrations in the source water with the lowest quartile (≤5.0 ASU/mL). A slightly elevated association between main breaks and ED visits for AGI was also observed when focusing on zip codes served primarily by a single water service network. When a major water pipe broke in 2010, an increased risk for visiting the ED for AGI was observed during the 0-3 days after the pipe break when a boil water order was in effect. Sensitive populations included younger and older age groups as well as residents living in zip codes with a median household income less than $50,000.

APPENDIX 1: NATIONAL PRIMARY DRINKING WATER REGULATIONS

Contaminant	Type of Contaminant
Cryptosporidium	Microorganisms
Giardia lamblia	Microorganisms
Heterotrophic plate count (HPC)	Microorganisms
Legionella	Microorganisms
Total Coliforms (including fecal coliform and E. Coli)	Microorganisms
Turbidity	Microorganisms
Viruses (enteric)	Microorganisms
Bromate	Disinfection Byproducts
Chlorite	Disinfection Byproducts
Haloacetic acids (HAA5)	Disinfection Byproducts
Total Trihalomethanes (TTHMs)	Disinfection Byproducts
Chloramines (as Cl2)	Disinfectants
Chlorine (as Cl2)	Disinfectants
Chlorine dioxide (as ClO2)	Disinfectants
Antimony	Inorganic Chemicals
Arsenic	Inorganic Chemicals
Asbestos (fiber > 10 micrometers)	Inorganic Chemicals
Barium	Inorganic Chemicals
Beryllium	Inorganic Chemicals
Cadmium	Inorganic Chemicals
Chromium (total)	Inorganic Chemicals
Copper	Inorganic Chemicals
Cyanide (as free cyanide)	Inorganic Chemicals
Fluoride	Inorganic Chemicals
Lead	Inorganic Chemicals
Mercury (inorganic)	Inorganic Chemicals
Nitrate (measured as Nitrogen)	Inorganic Chemicals
Nitrite (measured as Nitrogen)	Inorganic Chemicals
Selenium	Inorganic Chemicals
Thallium	Inorganic Chemicals
Acrylamide	Organic Chemicals
Alachlor	Organic Chemicals
Atrazine	Organic Chemicals
Benzene	Organic Chemicals
Benzo(a)pyrene (PAHs)	Organic Chemicals
Carbofuran	Organic Chemicals
Carbon tetrachloride	Organic Chemicals
Chlordane	Organic Chemicals
Chlorobenzene	Organic Chemicals
2,4-D	Organic Chemicals
Dalapon	Organic Chemicals
1,2-Dibromo-3-chloropropane (DBCP)	Organic Chemicals
o-Dichlorobenzene	Organic Chemicals
p-Dichlorobenzene	Organic Chemicals

Contaminant	Type of Contaminant
1,2-Dichloroethane	Organic Chemicals
1,1-Dichloroethylene	Organic Chemicals
cis-1,2-Dichloroethylene	Organic Chemicals
trans-1,2-Dichloroethylene	Organic Chemicals
Dichloromethane	Organic Chemicals
1,2-Dichloropropane	Organic Chemicals
Di(2-ethylhexyl) adipate	Organic Chemicals
Di(2-ethylhexyl) phthalate	Organic Chemicals
Dinoseb	Organic Chemicals
Dioxin (2,3,7,8-TCDD)	Organic Chemicals
Diquat	Organic Chemicals
Endothall	Organic Chemicals
Endrin	Organic Chemicals
Epichlorohydrin	Organic Chemicals
Ethylbenzene	Organic Chemicals
Ethylene dibromide	Organic Chemicals
Glyphosate	Organic Chemicals
Heptachlor	Organic Chemicals
Heptachlor epoxide	Organic Chemicals
Hexachlorobenzene	Organic Chemicals
Hexachlorocyclopentadiene	Organic Chemicals
Lindane	Organic Chemicals
Methoxychlor	Organic Chemicals
Oxamyl (Vydate)	Organic Chemicals
Polychlorinated biphenyls (PCBs)	Organic Chemicals
Pentachlorophenol	Organic Chemicals
Picloram	Organic Chemicals
Simazine	Organic Chemicals
Styrene	Organic Chemicals
Tetrachloroethylene	Organic Chemicals
Toluene	Organic Chemicals
Toxaphene	Organic Chemicals
2,4,5-TP (Silvex)	Organic Chemicals
1,2,4-Trichlorobenzene	Organic Chemicals
1,1,1-Trichloroethane	Organic Chemicals
1,1,2-Trichloroethane	Organic Chemicals
Trichloroethylene	Organic Chemicals
Vinyl chloride	Organic Chemicals
Xylenes (total)	Organic Chemicals
Alpha particles	Radionuclides
Beta particles and photon emitters	Radionuclides
Radium 226 and Radium 228 (combined)	Radionuclides
Uranium	Radionuclides

Source: https://www.epa.gov/ground-water-and-drinking-water/table-regulated-drinking-water-contaminants; https://www.epa.gov/sites/production/files/2016-06/documents/npwdr_complete_table.pdf

APPENDIX 2: NATIONAL SECONDARY DRINKING WATER REGULATIONS

Contaminant	Secondary Maximum Contaminant Level
Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 (color units)
Copper	1.0 mg/L
Corrosivity	noncorrosive
Fluoride	2.0 mg/L
Foaming Agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5-8.5
Silver	0.10 mg/L
Sulfate	250 mg/L
Total Dissolved Solids	500 mg/L
Zinc	5 mg/L

Source: https://www.epa.gov/sites/production/files/2016-06/documents/npwdr_complete_table.pdf

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