Attachment D

CDC Water and Health Study: Pilot for an Epidemiologic Study of Low Pressure Events in Drinking Water Distribution Systems (WRF #4390)

Pilot Evaluation Report

August 2014

Julia Gargano, PhD - Principal Investigator; Epidemiology lead

Vincent Hill, PhD, PE - Co-investigator; Laboratory lead

Elizabeth Adam, MPH - Study Coordinator

Chandra Schneeberger - Environmental Microbiologist

Table of Contents

List of Figures

List of Tables

EXECUTIVE SUMMARY

A team from the Centers for Disease Control and Prevention (CDC) Waterborne Disease Prevention Branch completed a successful pilot study for an epidemiologic study to assess whether individuals exposed to low pressure events (LPE) in a water distribution system are at an increased risk for acute gastrointestinal illness (AGI) or acute respiratory illnesses. The study design and protocols were piloted at one utility site and evaluated by CDC. Information from the pilot evaluation is being used to streamline and improve the study processes, protocol, and methods prior to the full study launch, expected in 2014. Data will be collected from 65 LPEs across 4-5 utility sites. This report describes the design, conduct, and results of a pilot study for the nationwide study.

Introduction

Each year, approximately 240,000 water main breaks occur in the U.S., presenting opportunities for pathogen intrusion into water distribution systems (Kirmeyer et al., 1994). Similar estimates are not available regarding planned maintenance events and repairs. An epidemiologic study in Norway systematically examined LPEs, including main breaks and planned maintenance events, and gastrointestinal illness using a prospective cohort study design, and found that LPEs were associated with a 58% increased risk of AGI in the week following the LPE (Nygard et al., 2007). A similar study in the U.S. is needed to gather relevant health data to determine if LPEs are associated with illness. No existing U.S. data sources can be used to answer this research question. Systematic data collection across many LPEs, with a study design tailored for the purpose of answering the research question, is needed to identify the health impacts of LPEs.

To address this need, the CDC plans to conduct a multisite epidemiologic study to assess whether individuals exposed to LPEs in water distribution systems are at an increased risk for AGI or acute respiratory illnesses. The study goal is to determine whether individuals exposed to LPEs in the water distribution system are at an increased risk for gastrointestinal or respiratory illness. The study aims are to 1) assess the association between exposure to the LPE and self-reported illness during a short observation period following the LPE, 2) compare microbial indicator test results in water samples from LPE and non-LPE (control) areas, and 3) describe the LPE characteristics.

Study Design and Methods

A prospective cohort study design was implemented. Investigators identified LPE exposure areas and unaffected control areas (non-LPE areas). The control areas were matched to LPE areas on pipe material and size, drinking water source, predominant housing type, and census resident age groups. Households from the LPE and non-LPE areas were randomly selected and mailed a survey to elicit information on water use, recent water service, other activities and exposures, and illness symptoms during a short observation period following the LPE. To avoid bias, the survey participants were blinded to the study goal and research question. In the multi-site study that will follow the pilot study reported here, survey responses from LPE and non-LPE areas will be compared to determine if individuals in the LPE-areas are more likely to report illness symptoms. The analysis will control for other factors, such as respondent age or recent travel, which could potentially influence the risk of illness.

An LPE was defined as a water service disruption event causing a presumed loss of water pressure in the distribution system, including unplanned outages or planned maintenance events. For each LPE, water utility personnel completed a standard LPE form, which collected information on the event and repair process, the infrastructure, water source, and soil characteristics, and field descriptions of how the households in the area were affected by the LPE, including field pressure measurements during and after the LPE. The study team selected areas affected by the LPE and matched them with unaffected non-LPE control areas. The utility's internal infrastructure maps and records were used to determine the pipe sizes, materials, and water sources in the area and to create a 'normal flow' map (i.e., before the LPE). The event description information and the LPE form were used to create an 'event hydraulic' map, outlining the boundaries of the LPE and non-LPE areas and any changes in flow direction or magnitude that occurred following the LPE. Utility personnel were also asked to choose exposed and unexposed area engineering attributes from a list to describe and justify the choice of the study areas. The utility's water system maps were used to select areas with matching infrastructure characteristics. U.S. 2010 Census data were used to select areas within the same census tract/block group, or census tracts with matching resident age groups when LPE areas did not fit within the census area boundaries.

Utility personnel collected three ultrafiltration (UF) water samples and three grab samples from each area (within 24 hours of the event for exposed area samples and within 48 hours for control area samples). Ultrafiltration samples were analyzed at CDC and grab samples were analyzed by the utility laboratory. CDC tested for the following analytes: total coliforms/*E. coli,* enterococci, *C. perfringens, s*omatic coliphages, total aerobic endospores, and human-specific *Bacteroides* spp. The utility processed grab samples for total coliforms/*E. coli*, enterococci, heterotrophic plate count (HPC), total hardness/alkalinity, and total organic carbon (TOC). The utility also collected the following field water quality data: temperature, pH, and total chlorine concentration. The utility business support team securely transferred contact information (i.e., names and addresses) for residential customers living within the study areas to CDC, and the CDC team administered the survey. A multiple contact mailing strategy was implemented (Dillman, 2007). Selected households received up to five survey prompts from CDC by postal mail: an advance letter, initial survey packet, thank you/reminder note, second survey packet, and final appeal letter. Respondents had the choice to respond by mail using a provided postage-paid return envelope or on-line using a secure survey website.

The CDC team trained utility personnel prior to the pilot launch. The first part of the training involved practicing the selection of LPE and non-LPE areas over the phone and by email, using work-ups of past breaks and repairs. The CDC team worked with utility business support and IT personnel to develop a utility-specific method of creating customer contact lists from study area maps. The next phase of training consisted of the team responding to mock events in the field. This gave the study team an opportunity to work through the protocol in real-time, and to work through challenges with event notification, data collection, and communication in a field setting. Before the pilot launch, the CDC team traveled to the utility to conduct a project kick-off meeting and on-site training. Additionally, the CDC team and utility communications staff worked together to a develop press release, fact sheets, and other community outreach materials. The community outreach efforts were designed to make the public aware of the study's importance and legitimacy; the study goal was presented as understanding the links between water use habits and health.

Pilot Results

Field and laboratory data were collected from six LPEs over a five-month period. The LPE form was completed for the six LPEs. Three of the events were main breaks, and three were planned repairs or maintenance events;

none of the LPEs resulted in drinking water advisories, such as boil water notices. Two of the main breaks were likely caused by deterioration and aging of the infrastructure, and one of the main breaks was due to an external contractor accidentally sawing through the main. The first planned event was a valve replacement to isolate a residential area from a planned utility worksite for relocating a main, the second planned event involved putting an abandoned line out of service, and the third planned event involved relocating a main within a two-day period. Two of the planned events involved maintenance activities over multiple sequential days; for these events, each day's event/repair was recorded on a separate LPE form. It was not possible to measure pressure readings during the events without violating the observational study design (i.e., interfering with or delaying the repairs to measure the pressure would have caused study-related changes to service), but it was possible to obtain normal pressure readings before or after each of the LPEs.

Twenty-four UF samples and 36 grab samples were collected and analyzed. Aerobic endospores were frequently detected in UF samples and total coliforms were detected in one UF sample. *E. coli*, enterococci, *C. perfringens, s*omatic coliphages, and human-specific *Bacteroides* spp. were not detected in any UF sample. Total coliforms, *E. coli* and enterococci were not detected in grab samples analyzed by the utility, but HPC, TOC, total hardness, alkalinity, and specific conductance were quantified for each grab sample.

A total of 646 households were contacted, and the overall survey response rate was 37%. The response rates for each event ranged from 32-43% and did not appear to vary by event type or size. Additionally, the response rates were similar in LPE (38%) and non-LPE areas (36%). Almost three-quarters of the households (74%) reported using home tap water for drinking in the last 30 days, and nearly all reported using home tap water for potable purposes (99.6%).

One-third of households in LPE areas (33%) reported noticing low pressure during the three weeks following the LPE, and 28% reported noticing a complete loss of water service. Households in non-LPE areas reported noticing low pressure during the three-week period about half as often (16%) as households in LPE areas, and <1% of households in non-LPE areas reported noticing a complete loss of service. Households in both LPE (21%) and non-LPE areas (14%) reported noticing a change in tap water during the three-week period of interest. About 5% of households reported that they were told to boil their water before drinking it, with LPE areas reporting this more often (8%) than non-LPE areas (2%).

Discussion

For each event, it was feasible to use knowledge of the water system and hydraulic principles to select the LPE and non-LPE areas within a few days of the LPE. The LPE form was an effective method for systematically collecting descriptive information about the LPE characteristics. The LPEs took place under varied circumstances, so the form was a useful tool for distilling the many event details to capture common information that could be aggregated across all LPEs. The pressure data on the form were frequently missing. The pressure readings add value to the field data, but the scope of how the pressure measurements can be used is limited because the data are often missing, and the field measurements cannot capture the variability within the system. If a utility has automated pressure sensors already in use, it could be helpful to gather this information in conjunction with the study data to provide additional context about the LPE. The engineering attribute assignments were helpful for making comparisons across the different LPEs during the pilot data analysis phase.

Water sample collection in LPE and non-LPE areas was successfully performed within designated response times. However, weather and logistical constraints precluded testing UF samples for two of the six LPEs studied. Physical and chemical water quality data were readily obtained for water samples, but only two microbial parameters (aerobic endospores and HPC) were consistently detected and quantified in UF or grab samples. In general, water quality data were similar between LPE and non-LPE areas, with the exception of turbidity, for which LPE-area water samples averaged 2.1 NTU and non-LPE areas averaged 0.7 NTU. These pilot data will be used to develop a modified water quality analytical plan for the full study to better optimize effective water quality data collection versus the time and expense required for sample analysis.

The customer service lists were a reliable source of contact information, with deliverable addresses available for 98% of contacted households. The strategy of cold contacting random samples of water utility customers by mail was resource efficient; however, the trade-off might have been a lower response rate. Power calculations were developed with the assumption that a minimum response rate of 40% was needed to answer the primary research question of whether the events are associated with AGI, and the pilot achieved a 37% overall response rate. To improve response rates, the study team will make minor modifications to the survey procedures and will increase efforts to promote the study in the participating communities. The additional efforts to promote the study will be designed to help communicate the study's legitimacy and importance; the study goal will be presented as understanding the links between water use habits and health. The survey itself took customers, on average, 13 minutes to complete, suggesting that the time burden for participation was low.

Most households in LPE areas did not report observing low pressure, complete service loss, or a change in tap water during the observation period following the LPE, indicating that customers were usually unaware of their exposure status. Non-differential survey response in LPE and non-LPE areas and across different events likely indicated that there was limited selection bias. Additionally, if response rates had been substantially higher in exposed LPE areas than unexposed non-LPE areas, it would have raised concern that persons in LPE areas were more concerned about their water quality, which would increase the possibility of bias in the responses about water use and illness. The study design and procedures allowed the study team to collect the data needed to meet the study goal and aims. There were scheduling and data collection challenges during the winter season or during other busy periods at CDC or the utility. To address this, the study team will plan for scheduling conflicts and consider a staggered scale-up to multiple utility sites. During the utility training, the importance of early event notification and communication between the utility and CDC team prior to field data collection will be emphasized for facilitating data collection.

Plans for National Multi-Site Study

The national multi-site study is expected to be launched in 2014. To be eligible to participate, the utility must use a secondary disinfectant, have a history of at least one LPE per month (main breaks or planned repairs), on average, and be able to partner with CDC for a 12-18 month period to complete data collection for approximately 13 low pressure events.

Each utility's participation will help researchers gain an understanding of the health impacts of routine and unplanned distribution system low pressure events, and this understanding can be used to help focus resources toward effectively maintaining the safety and durability of U.S. water systems. Additionally, participation can help utilities gain a better understanding of their customers' water use habits and experiences; CDC can provide each utility with de-identified summary survey data about household water use. The utility and customer results will be combined with others, and the participating utilities will not be identified in any publications.

INTRODUCTION

Rationale for National Study of Health Effects Associated with Distribution System Low Pressure Events (LPEs)

Water management and treatment advancements to make safe water widely available across the U.S. have contributed to reduced illnesses and deaths from infectious diseases, considered one of the top 10 public health achievements of the 20th century [(CDC, 1999a), (CDC, 1999b) (Cutler and Miller, 2005)]. However, aging infrastructure undermines the ability of water distribution systems to deliver safe, pressurized drinking water to homes, hospitals, schools, and businesses. Distribution system vulnerabilities, such as water main breaks, cross-connections, back-flow, and pressure fluctuations can result in potential intrusion of microbes and other contaminants into the distribution system (Borchardt et al., 2004; LeChevallier et al., 2003; Swerdlow et al., 1992; Lambertini et al., 2011). National waterborne disease outbreak data show that contamination of water in distribution systems is a risk factor for disease, accounting for approximately 10% of all deficiencies identified in outbreaks occurring in public water systems (Craun et al., 2010).

Each year, approximately 240,000 water main breaks occur in the U.S., presenting opportunities for pathogen intrusion into water distribution systems (Kirmeyer et al., 1994). There are an unknown number of planned maintenance events and repairs. A study conducted in Norway systematically examined LPEs, including main breaks and planned maintenance events, and gastrointestinal illness using a prospective cohort study design, and found that LPEs were associated with a 58% increased risk of acute gastrointestinal illness (AGI) in the week following the LPE (Nygard et al., 2007). An experimental study in non-disinfected public groundwater systems in Wisconsin assessed the impact of common distribution system repairs and maintenance activities on virus concentrations in drinking water, and identified higher virus levels in tap water following some distribution system events, including pipe installation, valve exercising, and cutting open mains (Lambertini et al., 2011). In other intervention trials, the amount of gastrointestinal illness attributed to drinking municipal tap water has ranged from less than 11% (Colford et al., 2005) in the U.S. to 34% (Payment et al., 1991) in Canada. This variation might be due in part to differences in the quality of the underlying source water (Hellard et al., 2001), treatment processes, participant blinding issues (Payment et al., 1991; Payment et al., 1997), or other factors (Colford et al., 2006). A recent meta-analysis concluded that tap water consumption can be associated with endemic gastrointestinal illness when there are distribution system problems, including water outages, lack of routine continuous service, or a lack of disinfectant residuals (Ercumen et al., 2014). Exposure and risk studies are valuable for identifying potential mechanisms for distribution system contamination and for identifying vulnerabilities in the distribution system, but these studies are often not directly linked to human health outcomes, so they cannot be used to assess the LPE impact on community health. Systematic data collection across many LPEs, with a study design tailored for the purpose of answering this research question, is needed to identify the health impacts of LPEs.

The existing evidence base suggests that distribution system vulnerabilities are an important public health problem, but there are no existing U.S. data sources that can be used to systematically assess whether people become ill more often following LPEs in water distribution systems. Outbreak data cannot be used to measure specifically the association between LPE occurrence and illness as LPEs usually impact small portions of the distribution system, resulting in a relatively small number of exposed persons per LPE. An increase in the occurrence of illness over baseline incidence in exposed persons would not typically come to the attention of public health agencies. As an example, in a recent communitywide cryptosporidiosis outbreak linked to contaminated drinking water reservoirs, an epidemiologic survey conducted once the outbreak was detected found that 28% of the community was ill; however, the outbreak was only detected after 5 lab-confirmed cases came to the attention of the health department (DeSilva, 2014). Distribution system events are even more challenging to detect with outbreak surveillance because contamination is often transient and affects a smaller proportion of the population. These health events are unlikely to generate a signal that public health agencies could detect. Additionally, states have different resources to investigate and report outbreaks, so outbreak data are not collected or reported systematically on a national level.

To address this need, the Waterborne Disease Prevention Branch at the Centers for Disease Control and Prevention (CDC) plans to conduct the first epidemiologic study in the U.S. to assess whether individuals exposed to LPEs in the water distribution system are at an increased risk for AGI or acute respiratory illnesses. The project's success hinges on forming strong public health and water utility sector partnerships.

Goal and Aims for the National Study

The goal for the national study is to determine whether individuals exposed to LPEs in water distribution systems are at an increased risk for gastrointestinal or respiratory illness.

The study aims are to 1) assess the association between exposure to the LPE and self-reported illness during a short observation period following the LPE, 2) compare microbial indicator test results in water samples from LPE and non-LPE (control) areas, and 3) describe the LPE characteristics.

Epidemiological Study Design

A prospective cohort study design, a type of observational study, was implemented. In an observational study, the researchers observe the effect of an exposure on an outcome in a target population but do not influence the exposure. This contrasts with an experimental design, such as a clinical trial, where the researchers assign groups of people to an exposure, such as a drug or treatment, and observe the outcome. All research involving human subjects requires an ethical approval process; the approvals for an experimental design are even more stringent. Since this study has ethical approval to conduct an observational study, it is especially important that water utilities participating in the study do not change their water service or repair procedures in any way as a part of the study.

In a prospective cohort study design, the researchers select groups of people who have different exposure-status at baseline to observe over time. When an LPE (exposure) occurred, investigators identified areas affected by the LPE (LPE areas), and similar, but unaffected control areas (non-LPE areas). Because exposures are not randomly assigned, confounders–that is, other factors that differ by exposure status and are associated with illness–could make it appear that outcomes are different between exposed and non-exposed areas, when the exposure of interest does not actually cause the difference in outcome. To control for confounders that could influence the apparent relationship between the LPE and the illness outcome, investigators matched the areas on census resident age groups, pipe material and size, drinking water source, and main housing type, and collected data on other potential confounders using the household survey, such as recent travel or respondent age, for statistical adjustment during data analysis. The study team mailed surveys to random samples of households from the LPE and non-LPE areas to elicit information on water use, recent water service, other activities and exposures, and illness symptoms during a short observation period following the LPE. To avoid bias, the survey participants were blinded to the specific research question about LPEs. The study goal presented to the public through community outreach, the study website, and the household survey materials was to understand links between water use habits and health. In the multi-site study that will follow the pilot study reported here, survey responses from LPE and non-LPE areas will be compared to determine if individuals in the LPE-areas are more likely to report AGI symptoms, controlling for other factors, such as respondent age or recent travel, which could potentially influence the risk of AGI.

For purposes of the study, an LPE was defined as a water service disruption event or incident causing a presumed loss of water pressure in the distribution system, including unplanned outages or planned maintenance events. For each LPE, water utility personnel completed a standard LPE form describing the event and repair process. The study team selected areas affected by the LPE and similar but unaffected non-LPE control areas. Utility personnel collected ultrafiltration water samples and grab samples from both areas; ultrafiltration samples were analyzed at CDC and grab samples were analyzed by the utility laboratory. The utility business support team securely transferred contact information (i.e., names and addresses) for residential customers living within the study areas to CDC, and the CDC team administered the survey.

PLANNING AND PREPARATION FOR PILOT STUDY

Pilot Study Goals and Objectives

The prospective cohort study design and study protocols were piloted at one utility site. The pilot study objectives were to determine if study procedures allow the team to answer the research questions and to familiarize team members with study implementation and procedures. The pilot activities were monitored during data collection and evaluated post-pilot through indicators that broadly measured 6 outcomes: 1) CDC team and utility select appropriate LPE and non-LPE areas, 2) the standard LPE form describing the event is filled out completely at the time of repair, 3) the water sample collection team follows standard operating procedures, 4) the laboratory team follows testing, standard operating procedures, and maintains chain of custody logs, 5) the CDC team follows survey mailing procedures and tracks household participation, and 6) the survey procedures encourage participation and equitable study participation in LPE area and non-LPE area groups. Information from the pilot evaluation is being used to streamline and improve the study processes, protocol, survey, and laboratory methods prior to the full study launch.

Preparations for Pilot Launch

The CDC team trained utility personnel prior to the pilot launch. The first part of the training involved practicing the selection of LPE and non-LPE areas over the phone and by email, using work-ups of past breaks and repairs. The goal was to increase the utility team's familiarity with the study protocol, the CDC team's familiarity with the utility's water system, and for both teams to practice communicating and working together.

Also during this phase of training, the CDC team worked with utility business support and IT personnel to develop a utility-specific method of creating customer contact lists from study area maps. Once the method was developed, study personnel practiced securely transferring customer data to CDC.

The next phase of training consisted of the team responding to mock events in the field. When an eligible event occurred, field teams notified the utility project manager, and the study team made a site visit, filled out the LPE form, and practiced selecting LPE and non-LPE areas with the CDC team. This gave the study team an opportunity to work through the protocol in real-time, and to work through challenges with event notification, data collection, and communication in a field setting.

Before the pilot launch, the CDC team traveled to the utility to conduct a project kick-off meeting and on-site training. CDC staff visited the utility site, toured facilities, and delivered the ultrafiltration water collection supplies. During the kick-off meeting, CDC staff presented the study motivation, goals, and methods to the entire utility community. Additionally, CDC staff trained the field operators on LPE form data collection and trained utility staff on ultrafiltration water sampling.

The CDC team and utility communications staff worked together to develop a press release, fact sheets, and other community outreach materials. The goal of these community outreach efforts was to make the public aware of the study's importance and legitimacy to support survey completion. CDC contact information was included on the outreach materials at the utility's request, and the CDC call center was prepared to field study inquiries.

Establishment of Pilot Study Procedures and Roles

Figure 1 is a flowchart that outlines the pilot study procedures and utility and study team roles. The field operators were responsible for notifying the utility project manager when an LPE occurred. Operators were asked to respond to all LPEs using their normal procedures. The utility project manager was responsible for notifying the CDC team of the LPE; the CDC team was responsible for determining if the LPE was eligible for study inclusion and for giving the go-ahead to the utility to proceed with data collection. If the event was eligible, the utility project manager conducted a site visit to observe the event and to fill out the standard LPE form, gathering information from the operators as needed. Following the site visit, the utility project manager provided the CDC team with the initial event description, LPE form, and a general map of the event area. The utility and CDC team worked together to determine the extent of the LPE and non-LPE areas, and to select matching study areas. Following the event, the utility team collected water samples from the study areas and transferred samples to the appropriate laboratories, following sample collection and handling protocols. The laboratories followed their standard procedures for processing samples and managing data. The utility project manager provided the utility business support team member with a GIS map of the final study areas; the map was linked to a customer service database and lists of contact information were generated. The business support team member securely transferred the contact information to CDC using an encrypted FTP site. The CDC team retrieved the customer service list, selected the survey sample, and began household survey administration. The utility project manager also securely transferred utility grab sample results to CDC using the encrypted FTP site.

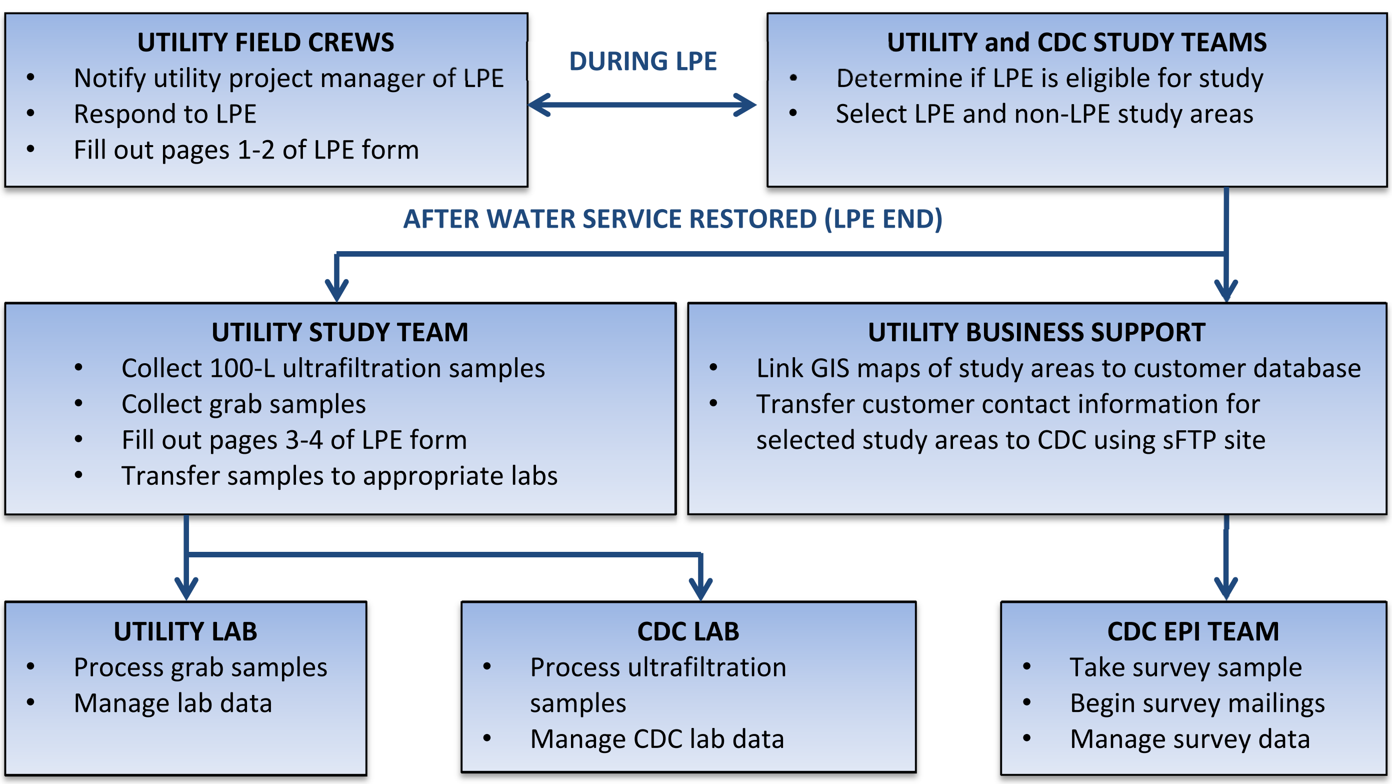

Figure 1. Pilot study procedures and utility and study team roles

Selection of LPE and Non-LPE Areas

The most challenging aspect of the protocol was the selection of the matching LPE and non-LPE areas. During each event, the study team selected the LPE and non-LPE areas using knowledge of the water system and hydraulic principles; a standard list of engineering attributes was developed to guide decision-making (Table 1).

Table 1. Attribute classification for selection of LPE exposed and unexposed areas

Exposed area attributes
1. Areas with known lower steady state pressures
2. Smaller diameter mains nearby or in direct hydraulic connection to LPE
3. Higher elevation than main break location (assuming there is no nearby storage to compensate for the elevation)
4. Near lower flow areas such as dead ends, pressure zone boundaries
5. Away from pressure release valves, pumps, or storage facilities that float on the system, which would allow water to be released into the system to compensate for lower pressure caused by LPE
6. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair)
Unexposed area attributes
1. Nearby but different pressure zone
2. No recent main breaks or LPEs in the vicinity
3. If in same pressure zone, served by pump or storage facility that floats on system
4. If in same pressure zone, area served by larger diameter mains with routinely good steady state pressures
5. Areas in the middle of the grid (away from low flow sections, dead ends, pressure zone boundaries)
6. Other, please describe

Water Sample Collection and Testing Methods

For each LPE, utility study personnel collected distribution system water samples from residential hose bibs in both the LPE area and the non-LPE area. Water sample sites (selected by the water utilities) were not linked to household survey addresses. These samples were intended to be representative of the water in the distribution system in areas affected by the LPE and in areas serving the unaffected addresses included in the study. The exact location of all samples were determined by the water utility's field team and had to meet specific criteria. Three, ~100-L drinking water samples were collected from the exposed area on the same day as the LPE: one upstream of LPE within five service connections, one downstream of LPE within five service connections, and one at the water utility personnel's discretion within the exposed area. In addition, three ~100-L drinking water samples were collected from the unexposed area within 48 hours of the LPE.

Prior to sample collection, the following water quality parameters were measured and recorded at each site: water temperature by Standard Method (SM) 2550B (Field) (for all Standard Methods, please refer to APHA, 2005), total chlorine according to SM 4500CL-G (Field), pH by SM 4500H-B (Field), turbidity by SM 2130B (Field) and specific conductance by SM 2510B (Field). Grab samples for water quality testing were collected in sterile bottles, according to analyte method requirements, and large-volume (~100 L) water samples were collected using dead-end ultrafiltration (Smith and Hill, 2009). Samples were shipped in coolers to the CDC Environmental Microbiology Laboratory in Atlanta, as well as the utility laboratory, for testing within 30 hours of collection. The utility processed grab samples for the following analytes: total coliforms and *E. coli* (SM 9223B), enterococci

[American Society for Testing and Materials (ASTM) # D6503 99], heterotrophic plate count (HPC) (SM 9215D), total hardness (SM2340B), alkalinity as $CaCO_3$ (SM 2320B), calcium (EPA 200.7-DW), magnesium (EPA 200.7-DW) and total organic carbon (TOC) (SM 5310C). The CDC Environmental Microbiology Laboratory processed the ultrafilter samples by backflushing with a solution consisting of 0.01% Tween™80, 0.01% sodium polyphosphate (NaPP), and 0.001% Antifoam Y-30 (Smith and Hill, 2009). Each concentrated water sample was analyzed using the following enumerative methods: total coliforms and *E. coli,* by SM 9223B - Colilert Quanti-Tray 2000 (IDEXX Laboratories) enterococci by Enterolert Quanti-Tray 2000 (IDEXX Laboratories), *C. perfringens* by membrane filtration and culture onto mCP agar (USGS, 2007), and aerobic endospores according to SM 9218B. For somatic coliphages and human-specific *Bacteroides* spp. analysis, the concentrated water samples were further concentrated by polyethylene glycol (PEG) precipitation (Hill et al., 2010), and the final pellet was then divided for analysis. One-half of the pellet was analyzed for somatic coliphage by single-agar layer plaque assay (SM 1602), and 750 µL was extracted for human-specific *Bacteroides* spp. testing by real-time polymerase chain reaction (PCR) (Haugland et al., 2010).

Household Survey

A multiple contact mailing strategy was implemented (Dillman, 2007). Selected households received 5 survey prompts from CDC by postal mail: an advance letter, initial survey packet, thank you/reminder note, second survey packet, and final appeal letter. Respondents had the choice to respond by mail using a provided postage-paid return envelope or on-line using a secure survey website, accessed using an ID and password provided in the survey packet.

Data Analysis

All analyses were performed in SAS version 9.3 (SAS Institute Inc., Cary NC) using a p-value <0.05 to indicate statistical significance. Levels of laboratory parameters were summarized as untransformed (crude) means and standard deviations; for values below the limit of detection (LOD), ½ the LOD value was substituted (Hornung and Reed, 1990). Correlations between parameters were evaluated using Spearman correlations. To test for statistically significant differences in laboratory parameters by LPE status, appropriate data transformations were identified to achieve approximately normal distributions (PROC TRANSREG). The transformed values were modeled using a random effects model (PROC MIXED) to account for the matched design and non-independence of observations from the same LPE. Survey data were summarized using descriptive percentages of both household-level and individual-level data, but no statistical comparisons between LPE and non-LPE area responses were performed because there was insufficient statistical power due to the small scope of the pilot study.

Scope of Data Collected During Pilot Study

Since the pilot study was designed to test the design and procedures for the national study, rather than to answer the research questions for the national study, the scope was much smaller. Pilot study data collection was not intended to provide an evidence base for making inferences about the research questions. The pilot study data are being used to inform modifications to study processes and methods prior to the full launch of the national study. Table 2 summarizes the pilot data collected and explains how the data are being used to improve study procedures before the full study launch.

Table 2. Summary of pilot data collection and how data were used in the pilot evaluation

Database	Data description	Purpose for evaluation
LPE form Access database	Pages 1-2 of LPE form – event and repair description	Form and data quality
	Pages 3-4 of LPE form – parameters for water samples, chain of custody	Form and data quality; exploratory lab analyses; chain of custody compliance
CDC event records CDC network drive/hard copies	Records of emails, maps, demographic information, checklists for all events	Burden of work for utility; format and quality of field data; data management and organization
Utility laboratory Excel booklets	Grab sample results	Exploratory lab analyses; which parameters to include in full study; give clarification on when/where to take samples
CDC laboratory Access database	Ultrafiltration sample results	Exploratory lab analyses; which parameters to include in full study; give clarification on when/where to take samples
Household survey SQL database	Secure storage for paper and web survey data	Data management; format and data quality; content; response rate and timing
Household survey Access interface	Secure storage for customer contact information, mailing schedule, and tracking mailing and participation	Mailing management; response rate and timing
Climate data SAS database	NOAA quality controlled local climate data	Plan for integrating data into study analyses

PILOT STUDY RESULTS

The study team collected field and laboratory data from the six LPEs from December 2013 to March 2014. Data collection for the household survey administration was completed in May 2014. A total of 646 households were surveyed, LPE forms were completed for each event, and 24 ultrafiltration samples and 36 grab samples were collected and analyzed. Data were collected and stored securely in several databases, housed at CDC.

Detailed descriptions of each LPE and the decision making process for selecting the study areas are in the Appendix. The utility's internal infrastructure maps were used to determine the pipe sizes, materials, and water sources in the area and create a 'normal flow' map (i.e., before the LPE). The event description information and the LPE form were used to create an 'event hydraulic' map, outlining the boundaries of the LPE and non-LPE areas and any changes in flow direction or magnitude that occurred following the LPE. The utility's engineering department modeled the break or repair scenarios for three events; the hydraulic modeling results supported the study team's choices of the areas. As quality assurance for the pilot study, it was helpful to use the hydraulic models to check the choice of the study areas. However, the modeling results were unavailable until a few days after the event, so it would not have been possible to use the models in real-time to select the areas. It was also not possible to obtain the field pressure measurements during the events. During the emergency events, the operators were focused on responding to the event, and interfering with their work to obtain the pressure readings would have caused study-related delays in restoring water service. During the planned events, the study team was able to demonstrate low pressure by verifying no water service at home hose bibs but was not able to obtain pressure measurements. The study team was able to obtain 'normal' pressure readings once the water service was restored.

The utility's water system maps were used to select areas with similar pipe size, material, and water source, and the repair site visit was used to locate areas with a complete or partial main housing type match. For 4/6 events, it was not possible to locate LPE and non-LPE areas within the same census block group or tract; the areas potentially exposed to the LPE were usually larger than the census area boundaries. As an alternative, the areas were matched on the census age groups (i.e., percent of people in the census tract <18 years and percent of people in the census tract 65 years and older).

Although a few items were missing from the LPE forms, such as the description of the pipe interior when the repair prevented close observation, LPE forms were nearly complete for all events. The customer service lists were securely transferred to CDC for all LPEs. A late customer list delayed survey administration for one event; this event took place over the winter holiday season, which made it difficult to coordinate personnel leave schedules. The field water parameters, chain of custody information, and utility grab sample results were complete for all water samples. For two events, the ultrafiltration shipments did not arrive at CDC within the 30 hour processing window. One shipment was lost during a winter storm that shut down Atlanta, and one was not collected at CDC's request because of a scheduling conflict with another CDC resource-intensive project.

Data Collected Using the LPE Form

During the LPEs, the operators and utility project manager completed the LPE form to describe the event and the repair procedures. The LPE form provides a standardized mode to collect descriptive information about the LPE characteristics. Three of the events were main breaks, and three were planned repairs or maintenance events (Table 3). Two of the main breaks were likely caused by deterioration and aging of the infrastructure, and one of the main breaks was due to an external contractor accidentally sawing through the main. The first planned event was a valve replacement to isolate a residential area from a utility worksite for relocating a main, the second planned event involved putting an abandoned line out of service, and the third planned event involved relocating a main twice in a two-day period. Two of the planned events involved maintenance activities over multiple sequential days; for these events, each day's events were recorded on a separate LPE form.

For one main break, the utility project team assessed that there was high potential for contamination, for a second main break the utility project team assessed that there was moderate potential for contamination, and for a third main break and all three planned events, the utility project team assessed that were was low potential for contamination (Table 4). In two of the main breaks, the pipe was submerged in trench water before or during the repair; in one main break, the pipe was submerged in trench water while the operators were tightening the bolts but not during pipe installation. The replacement parts were swabbed with chlorine in 3/6 events, the main was flushed after the repair in 5/6 events, and the main was chlorinated after the repair in 0/6 events. For all of the events, no precipitation was reported during the repair, and no sewage lines or reclaimed lines were adjacent or in close proximity to the main being repaired (data not shown).

The (affected) pipe sizes varied from 2"- 8" diameter, and the pipe ages from < 20 years to approximately 50 years (Table 5). The pipe depth ranged from 3'- 4.5', and the soil type was usually sand. The pipe material was PVC in four events, ductile iron in one event, and galvanized material in one event. The water source was a surface and groundwater blend for five events, and 100% groundwater for one event.

Each event had a different extent of exposure, including the duration of low pressure and the number of households affected. For the main breaks, the utility estimated the number of households affected by the break before it was isolated and in the repair area (Table 6). For the planned events, the utility estimated the number of households in areas that were completely or partially valved off for the procedure. The main housing type was often single family homes; condos or apartments were also present in two events. The number of households exposed to low pressure ranged from 16 to 166, and the duration of low pressure ranged from 45 minutes to seven hours. There were no reports of a boil water advisory or notice administration. The team was unable to take pressure readings during the events (Table 7). In the three planned events, and in one of the main breaks that caused minimal damage, the study team was able to demonstrate low pressure once the area was valved-off by verifying no water service at home hose bibs or assuming zero pressure when the area was completely valved off. In two of the breaks, where water flooded the street, the study team was unable to estimate the pressure at all. The study team was able to get normal pressure readings for all six events.

Table 3. Event, response, and repair type for six pilot LPEs

LPE	Cause	Response	Repair type
Main break	Deterioration, blowout in old, weak pipe; water rushed into street, damaged home and tree	Emergency	Clamp repair, but pipe broke again after clamped
Valve replacement	Main needed to be moved in preparation for installation of new storm drain; valve broke during repair causing larger area than expected to be valved off	Planned maintenance	Valve installation; valve off area (multi-day)
Main break	Older pipe leaking at bell and spigot joint; contractor installing sidewalk reported leak	Emergency	Cut and replace section of pipe; valves shut down to isolate break
Main break	Contractor burying phone lines sawed through 6" main, caused blowout	Emergency	Cut and replace section of pipe
Abandon line	Cross-connection between out-of-service line & in-service line caused leaking in street; repair to abandon line and stop leak	Planned repair	Abandon old main by cutting it and adding valve; valve off area
Main relocation	Main needed to be moved in preparation for installation of traffic signal pole	Planned maintenance	Cut and replace and offset section of pipe; valve off area (multi-day)

Table 4. Event and repair description for six pilot LPEs

LPE	Operator assessment of potential for contamination	Pipe in trench water	Parts swabbed with Chlorine	Main flushed after repair	Main chlorinated after repair
Main break	High	Yes - water from main before and during repair	No	Yes	No
Valve replacement	Low	No	Yes	Yes	No
Main break	Low	Yes - water in pit when tightening bolts, not during installation	No	Yes	No
Main break	Moderate	Yes - water from main before repair crew arrived	Yes	Yes	No
Abandon line	Low	Yes for out-of-service line, but homes connected to in-service line	No	No	No
Main relocation	Low	No	Yes	Yes	No

Table 5. Characteristics of infrastructure, water source, and soil type for six pilot LPEs

LPE	Pipe dia.	Est. Pipe age (years)	Pipe depth	Material	Pipe interior [a]	Operator's description of pipe interior	Water source	Soil
Main break	8"	33	3'	PVC (white)	--	Did not see	Blended	Sand, clay
Valve replacement	6"	Don't know	3'	Ductile Iron	2	No tubercles, fairly clean	Blended	Sandy, shells (beach)
Main break	6"	48	3'	PVC	1	Brown, slimy biofilm	Blended	Sand
Main break	6"	48	4'	PVC	1	Light coating of biofilm, good condition	Blended	Sand
Abandon line	2"	45	3', 6"	Galvanized	3	Very corroded on outside and rusty and pitted on inside	Blended	Sand
Main relocation	8"	<20	4', 6"	PVC	1	Good condition, no tubercles. Small amount of smooth biofilm	100% Groundwater	Sand

[a] Interior condition of pipe rated on a scale of 1 to 5, with 1 = smooth and 5 = highly tuberculated

Table 6. Field description of how households were affected by the six pilot LPEs

LPE	Exposed area	Main housing	No. homes exposed to low pressure	Low pressure duration (hr)	No. homes lost service	Loss of service (hr)
Main break	Area affected by break & valved off area	Single family homes; condos	154	7	31	0.5
Valve replacement	Valved off area	Single family homes; condos/apartments	85	3	85	3
Main break	Area affected by break & valved off area	Single family homes	23	1.8	23	1.8
Main break	Area affected by break & valved off area	Single family homes	166	3.5 [a]	3	5.5
Abandon line	Valved off area	Single family homes	16	0.75	16	0.75
Main relocation	Valved off area	Single family homes	130	4	130	4

[a] One-hundred-sixty-six homes experienced low pressure for 3.5 hours; three of these experienced an additional 5.5 hours of complete service loss.

Table 7. Study LPE-area pressure readings for six pilot LPEs

Type	Exposed area	Pressure at break/work site (psi)	Means of verification	Pressure after break/work (psi)
Main break	Area affected by break & valved off area	--	Unable to measure because of damage from main break	76; 83
Valve replacement	Valved off area	0	Assumed 0 because valved off	60; 64
Main break	Area affected by break & valved off area	0	Opened home hose bibs, verified no water	69; 69; 67
Main break	Area affected by break & valved off area	--	Unable to measure	53; 53;64
Abandon line	Valved off area	0	Opened home hose bibs, verified no water	53[a]; 65[a]; 65[a]
Main relocation	Valved off area	0	Assumed 0 because valved off	83; 82; 80

[a] Pressure readings taken before the area was valved off for the planned repair.

Water Samples

Field water quality data and grab sample testing data were obtained for all six LPEs. Water quality data from the UF sampling was also obtained for four of the six LPEs. Overall mean levels of the various parameters for the field and grab sample water quality parameters are summarized in Table 8.

Crude mean values by exposure status for the six events and p-values from random effects models are shown in Table 9. Most of the water quality parameters had similar crude mean values between LPE and non-LPE areas; however, the p-values indicate a statistically significant ($p<0.05$) difference by exposure status for some parameters. This is mainly because the random effects models isolate the within-event differences between the water in exposed and unexposed areas while taking into account the variability in water characteristics between events. Total hardness, specific conductance, turbidity, and TOC varied significantly ($p<0.05$) between LPE and non-LPE areas; the only parameter for which the crude means appeared meaningfully different was turbidity (2.1 NTU in LPE areas vs. 0.7 in non-LPE areas, $p = 0.001$). For total hardness, specific conductance, and TOC, the crude means were similar and the standard deviations overlapped substantially, indicating that the variability associated with the LPE was smaller than variability between events in the values of these parameters. Mean HPC values were higher in LPE areas than non-LPE areas, though not significantly. Because the event involving a groundwater source had higher TOC levels compared to the five events involving blended water and appeared to be an outlier for this parameter (not shown), the comparisons were repeated after excluding the groundwater-associated event. TOC levels remained significantly different between exposed and unexposed areas, mean levels were lower in both exposed and unexposed areas (1.4 and 1.3 mg/L), and standard deviations were much smaller (0.1 and 0.1).

Statistical correlations between parameters using all data (i.e., with LPE areas and non-LPE areas combined) were also tested (Figures 2-3). Figure 2 shows the distribution and the correlations among turbidity, HPC, TOC, aerobic endospores, and total chlorine. Turbidity and HPC were positively correlated ($r = 0.33$, p-value = 0.04) and HPC and total chlorine were inversely correlated ($r = -0.32$, $p = 0.06$). TOC and HPC were also found to be inversely correlated ($r = -0.41$, p-value = 0.01). However, after excluding the event involving a groundwater source, this correlation was reduced in magnitude and was no longer statistically significant ($r = -0.30$, $p = 0.11$). Figure 3 shows the distribution of total hardness, alkalinity, pH, temperature, and total chlorine and the correlations between the parameters. Many of the field parameters were statistically correlated. Total hardness was correlated with alkalinity, pH, temperature, total chlorine, TOC, and specific conductance. Additionally, alkalinity was correlated with temperature, TOC, and specific conductance, and pH was correlated with specific conductance.

The detection rates of the UF samples are listed in Table 10. There was 1 total coliform positive from an LPE-area sample ($n = 24$). No samples were positive for *E. coli*, enterococci, *C. perfringens*, somatic coliphages, or human-specific *Bacteroides.* Aerobic endospore testing yielded the most detections for UF samples. Seventy-five percent of the samples were positive (18/24) for aerobic endospores. There was not an apparent difference in aerobic endospore detections or concentrations between LPE area and non-LPE area samples.

Table 8. Distribution of field and grab sample water quality parameters following six LPEs (n = 36)

Parameter	Mean	SD	Median	Min	Max	25th Pctl	75th Pctl
Calcium (mg/L)	77.0	3.4	77.1	70.0	82.7	76.2	79.2
Magnesium (mg/L)	6.4	0.8	6.7	4.7	7.2	5.9	7.1
Turbidity (NTU)	1.4	1.3	1.1	0.2	7.0	0.7	1.4
Total Hardness (mg/L)	218.5	11.0	221.0	194.0	236.0	217.0	224.5
Alkalinity (as $CaCO_3$ mg/L)	167.2	18.1	160.0	140.0	200.0	150.0	180.0
pH	7.6	0.1	7.7	7.4	8.0	7.6	7.8
Temperature (°C)	21.9	1.6	21.9	18.3	25.7	21.0	23.3
Total Chlorine (mg/L)	3.4	0.5	3.6	2.0	4.2	3.2	3.7
TOC (mg/L)	1.7	0.7	1.5	1.2	3.4	1.4	1.5
HPC (CFU/mL)	128.9	150.5	56.5	3.0	640.0	12.5	200.0
Specific conductance (µmhos/cm)	555.3	47.8	571.0	448.0	611.0	534.0	590.0

Table 9. Distribution of water quality parameters by exposure status from six LPEs

Parameter	LPE areas				Non LPE-areas				P-value
	N	Mean	SD	Median	N	Mean	SD	Median	
Calcium (mg/L)	18	76.5	3.0	76.6	18	77.5	3.7	77.3	
Magnesium (mg/L)	18	6.3	0.8	6.7	18	6.4	0.9	6.6	
Total Hardness (mg/L) [a]	18	217.1	10.2	220.5	18	219.9	12.0	221.0	0.02
Alkalinity (as $CaCO_3$ mg/L)	18	167.2	18.7	160.0	18	167.2	18.1	160.0	1.00
pH	18	7.6	0.2	7.6	18	7.7	0.1	7.7	0.07
Temperature (°C)	18	21.9	1.8	21.9	18	21.9	1.4	21.8	0.99
Total Chlorine (mg/L)	18	3.5	0.5	3.6	18	3.4	0.4	3.4	0.34
Specific conductance (µmhos/ cm) [a]	18	545.3	49.4	568.0	18	565.2	45.4	583.0	<0.001
Aerobic endospores (CFU/100 mL)	12	0.3	0.5	0.0	12	0.2	0.4	0.0	0.65
Turbidity (NTU) [a]	18	2.1	1.6	1.4	18	0.7	0.4	0.8	0.001
TOC (mg/L) [a]	18	1.8	0.8	1.5	18	1.7	0.8	1.4	0.01
HPC (CFU/mL)	18	163.6	182.0	120.0	18	94.2	104.6	46.0	0.85

[a] Statistically significant difference between LPE and non-LPE area

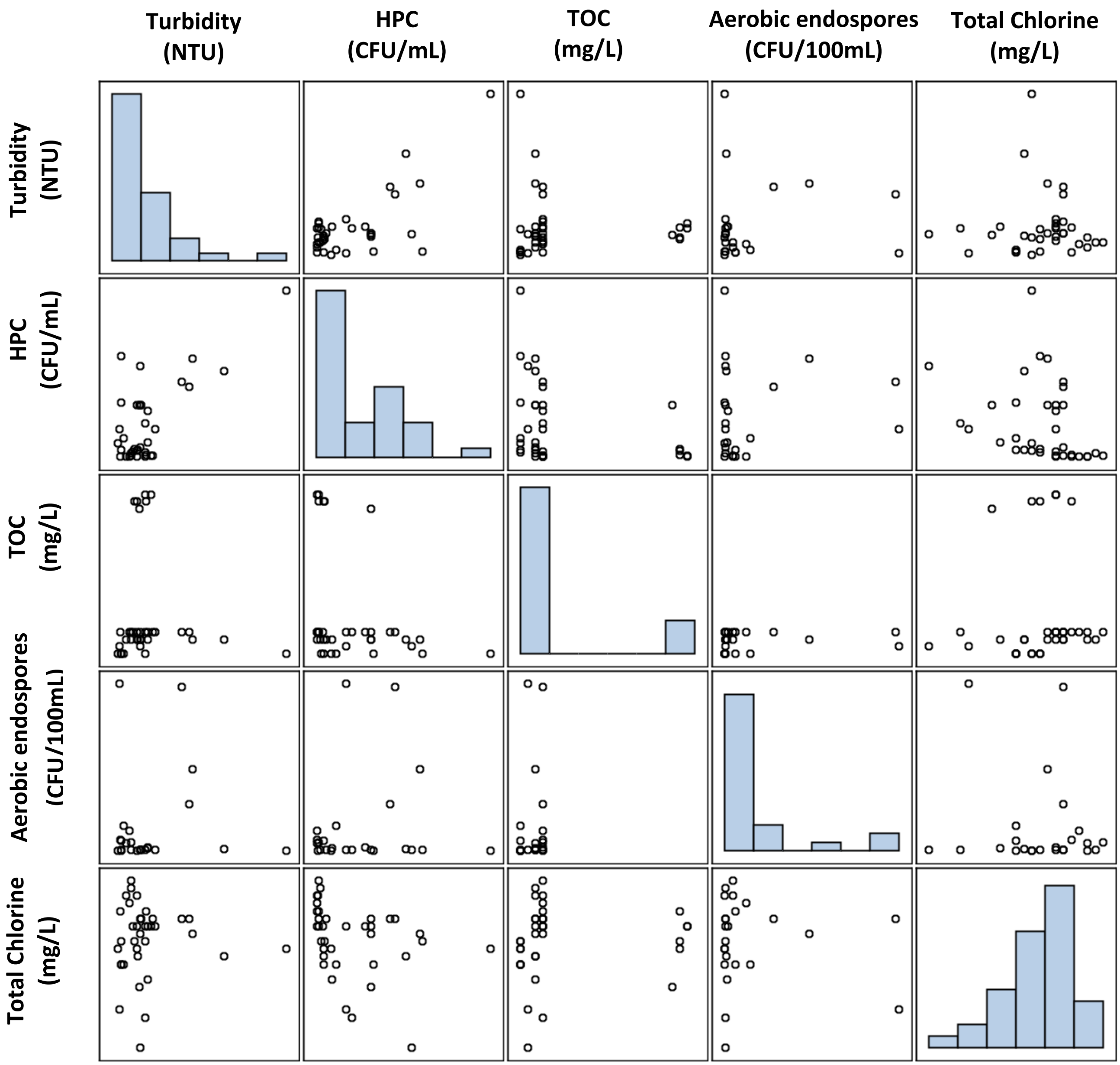

Figure 2. The distribution of turbidity, HPC, TOC, aerobic endospores, and total chlorine and the correlations between the parameters. Data for all water samples, including those collected from LPE areas and non-LPE areas, are included. Scatter plots indicate correlations between parameter indicated on row and parameter indicated in column. The histograms show the overall distribution of the indicated parameter across all samples.

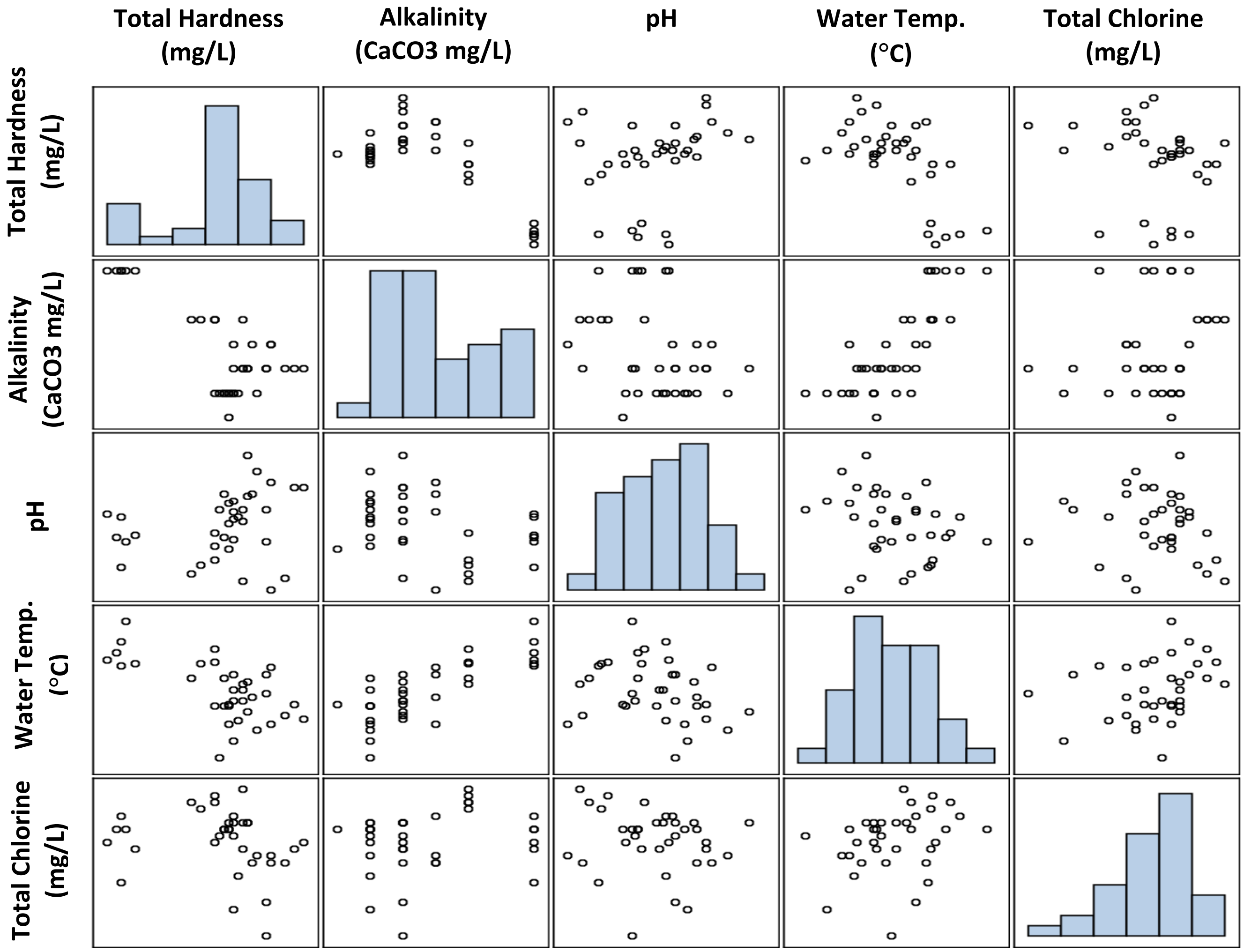

Figure 3. The distribution of total hardness, alkalinity, pH, temperature, and total chlorine and the correlations between the parameters. Data for all water samples, including those collected from LPE areas and non-LPE areas, are included. Scatter plots indicate correlations between parameter indicated on row and parameter indicated in column. The histograms show the overall distribution of the indicated parameter across all samples.

Table 10. Detection rates using ultrafiltration (n = 24)

UF-associated tests	Number of detections	%
Total coliforms	1	4.2
E. coli	0	0
Enterococci	0	0
C. perfringens	0	0
Somatic coliphages	0	0
Total aerobic endospores	18	75.0
Bacteroides spp.	0	0

Household Survey

A total of 646 households were contacted, and the overall survey response rate was 37% (Table 11). Two percent of selected households could not be contacted by mail because the addresses were undeliverable. The response rates for each event ranged from 32-43% and did not appear to vary by event type or size. Additionally, the response rates were similar in LPE (38%) and non-LPE areas (36%).

Throughout the pilot, the CDC team tracked the day of completed survey receipt and the mode of response. There was an apparent boost in survey response following each of the mail prompts from CDC (Figure 4). The majority of respondents chose to respond by mail (70%); 30% completed the survey using the secure website. The website surveys took an average of 13.3 minutes to complete, a median of 11 minutes, a minimum of 5 minutes, and a maximum of 56 minutes.

Almost three-quarters of the households (74%) reported using home tap water for drinking in the last 30 days, and nearly all reported using home tap water for potable purposes (99.6%), defined as: rinsing produce, brushing teeth, drinking, making ice, mixing cold drinks, or mixing infant formula (Table 12). The majority of households reported using tap water for cooking or making hot drinks (96%), and 18% reported using tap water for medical uses, defined as: nebulizer, neti pot, or contact lens care. Reported home tap water uses were similar between LPE and non-LPE areas.

Most households (71%) reported tap water as a type of water household members drink most often at home. Thirty-six percent (36%) reported bottled water as a type of water household members drink most often at home, and 29% reported only commercially bottled water as the type of water household members drink most often at home. This differed some in LPE and non-LPE areas, with households in LPE areas reporting tap water use for drinking more often and exclusive bottled water use less often.

A minority of households reported having a private well (7%), which was similar in LPE and non-LPE areas. Over a third of households (35%) reported using a water softener, and water softener use was reported more often in non-LPE areas than in LPE areas. The majority of households reported using some type of point-of-use water filter (68%).

The housing type reported most often was a house (89%), followed by an apartment or condominium (7%) (Table 13). The reported housing type differed in LPE and non-LPE areas, with almost all households in the non-LPE areas reporting living in a house (97%), compared to about 80% of households in LPE areas. The remaining households in the LPE areas reported living in an apartment, condominium, duplex, villa, or cluster home. Housing type was a matching characteristic, so it is not clear if the match was not good or if respondents did not fully represent the selected areas. Sixty-four percent (64%) of households reported pets living in the home or yard, with more households in LPE areas reporting having pets (72%) compared to non-LPE areas (56%). Very few households reported livestock or animal enclosures within 50 yards of the household.

One-third of households in LPE areas (33%) reported noticing low pressure during the three weeks following the LPE, and 28% reported noticing a complete loss of service (Table 14). Households in non-LPE areas reported noticing low pressure during the 3-week period about half as often (16%), and <1% of households in non-LPE areas reported noticing a complete loss of service. Households in both LPE (21%) and non-LPE areas (14%) reported noticing a change in tap water during the 3-week period of interest. About 5% of households reported that they were told to boil their water before drinking it, with LPE areas reporting this more often (8%) than non-LPE areas (2%). The utility did not conduct any boil water notices, orders, or advisories.

Table 11. Summary of pilot study data collection for six LPEs

Event	Size	Households Surveyed, n	Response, n (%)
Main break	Large	160	65 (43)
Valve replacement	Medium	82	26 (33)
Main break	Small	56	19 (35)
Main break	Large	160	59 (38)
Abandon line	Small	28	12 (43)
Main relocation	Large	160	52 (33)

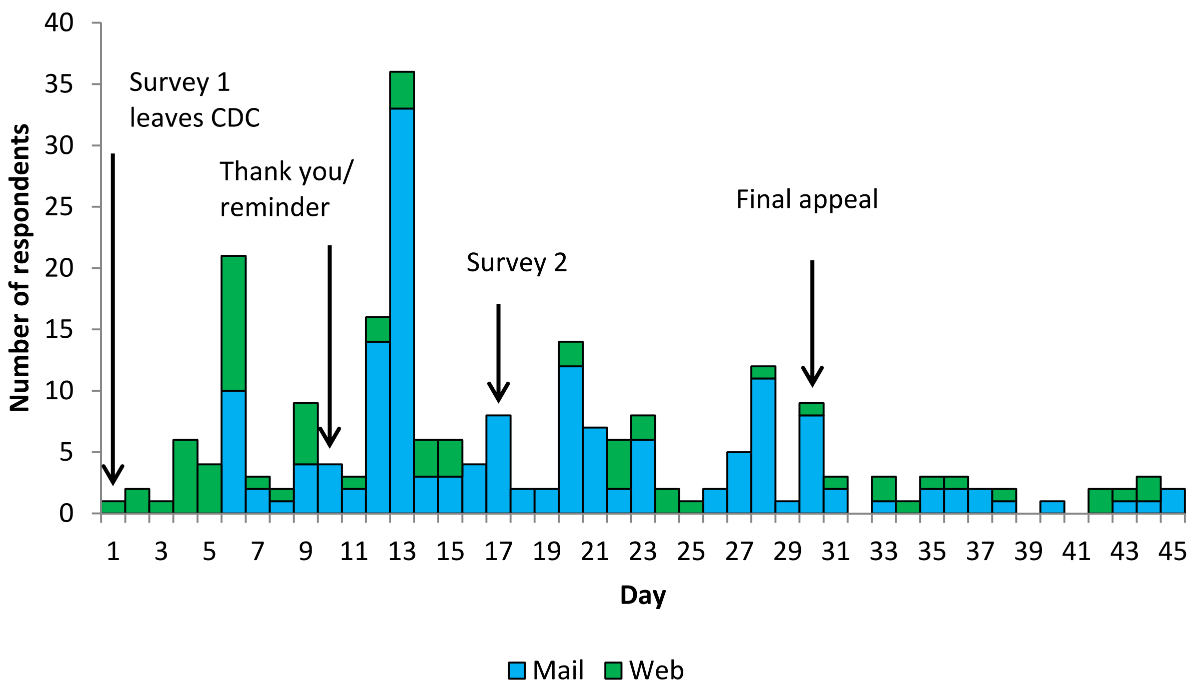

Figure 4. Number and day of survey response, by mode of response (n = 231). Two additional mail surveys were received outside of the 6-week window and are not included in this figure or in survey analyses.

Table 12. Reported household water use (n = 231 households)

Characteristic	Overall (n = 231)	LPE area (n = 117)	Non-LPE area (n = 114)
	%	%	%
Home tap water use in last 30 days			
Drinking	74.0	76.1	71.9
Potable uses (Rinsing produce, brushing teeth, drinking, making ice, mixing cold drinks, mixing infant formula)	99.6	99.2	100.0
Hot water consumption (cooking, making hot drinks)	96.1	94.9	97.4
Medical uses (nebulizer, neti pot, contact lens)	17.8	18.8	16.7
At home, water type household members drink most often			
Any tap water	70.6	76.1	64.9
Any bottled water	36.4	31.6	41.2
Only bottled water	28.6	23.1	34.2
Home has private well	6.9	7.7	6.1
Home has water softener	34.6	27.4	42.1
Home uses water filter	68.4	71.8	64.9

Table 13. Reported household characteristics (n = 231 households)

Characteristic	Overall (n = 231)	LPE area (n = 117)	Non-LPE area (n = 114)
	%	%	%
Housing type			
House	88.7	80.3	97.4
Apartment or condominium	6.9	12.0	1.8
Mobile home	0.0	0.0	0.0
Other (duplex, villa, or cluster home)	3.5	6.8	0.0
Pets living in home or yard	64.1	71.8	56.1
Livestock or animal enclosures within 50 yards of household			
Livestock	1.3	0.0	2.6
Cats/dogs	0.9	1.7	0.0

Table 14. Reported water change during 3-week period following the LPE (n = 231 households)

Characteristic	Overall (n = 231)	LPE area (n = 117)	Non-LPE area (n = 114)
	%	%	%
Noticed low pressure	24.7	33.3	15.8
Don't know	6.9	4.3	9.7
Noticed complete loss of service	14.7	28.2	0.9
Don't know	1.3	0.9	1.8
Noticed change in tap water [a]	17.3	20.5	14.0
Change in odor	7.8	8.6	7.0
Change in taste	5.6	7.7	3.5
Change in color	7.8	10.3	5.3
Told to boil water before drinking it	4.8	7.7	1.8
Don't know	1.3	1.7	0.9

[a] One household from non-LPE area wrote in other category of calcium deposits

DISCUSSION

Determining LPE Exposure Areas

It was feasible to use knowledge of the water system and hydraulic principles to select the LPE and non-LPE areas within a few days. It was essential that the areas were selected quickly and correctly, so that utility business support had enough time to construct the customer service list and transfer it to CDC on time for the first survey mailing. Incorrectly classifying the LPE and non-LPE areas would violate a fundamental assumption of the epidemiologic cohort study design, and delayed survey administration could result in recall bias or decreased participation. The standardized list of engineering attributes worked well for describing and justifying the selection of the study areas. Alternative methods for selecting study areas would have been to select areas with a pre-determined pressure measurement threshold, such as < 20 psi, or to use hydraulic modeling to select areas with pressure loss. Field pressure measurements were not used to determine LPE eligibility because of challenges in consistently obtaining the pressure readings, especially during emergency repairs. Additionally, not all utilities have hydraulic modeling capacity and given the study time constraints, it was preferable to use the field assessment from the operators to define the study areas, rather than a hydraulic model.

Matching LPE and Non-LPE Areas

For each event, it was feasible and straightforward to match the study areas on the infrastructure characteristics of pipe size and material, main housing type, and water source. The census area match was not always possible because some events were larger than anticipated and did not fit neatly within the census boundaries; however, the CDC team was able to use census data to find comparable populations in different census tracts. In the national study, the infrastructure matching characteristics will be prioritized over the census area match because differences in respondent demographics can be adjusted for in the analysis using the self-reported information from the survey.

Describing and Justifying the Choice of Study Areas

The LPE form was a useful tool for distilling the many event details to capture common information that could be aggregated across all LPEs.

The engineering attributes were designed as guidelines to help the utility teams select adjacent, less obvious LPE-areas (exposed areas) that should be avoided for the control non-LPE (unexposed) area selection. The standard attributes list was helpful for distilling the many event details down to the factors that directly related to whether an area was or was not affected by the LPE. In addition to helping with the selection of the study areas, since each LPE took place under varying circumstances, it was helpful to use the attribute assignments to facilitate comparisons across the different LPEs during the pilot data analysis phase.

Water Samples

Several statistically significant differences by LPE status were observed (see Table 9), although the crude mean values sometimes seemed similar and standard deviations were large. Variance components analysis revealed that all water sample parameter values were highly correlated within each event, whereas the differences between the events were comparatively large (data not shown). It is statistically possible, especially with non-independent samples, for the ranges of values in comparison groups to overlap substantially but still be statistically significantly different (Van Belle and Steven, 1998). When matching is present, as in this study design, it is possible to have an even greater overlap between the distributions of values and still maintain statistical significance because values are compared within the matched sets rather than across all values (in this case, within LPEs). The crude means were presented in this report to summarize the general levels of these parameters in the water samples, but they do not adequately take into account the distributions of the parameters or the study design.

The pilot data were also used to inform changes to the analytical suite of indicators and water parameters. HPC concentrations were higher in LPE-area water samples, but the variability for this parameter was substantial. It is possible that adding testing for adenosine triphosphate (ATP), a molecule found in living cells, to the analytical suite could provide similar differential data because the test detects live microorganisms, but with less variability because it is a non-culture parameter.

Many statistical correlations among the field parameters were observed, although the small size of the dataset limits the conclusions that can be drawn and the reasons for many of these correlations are not clear. In the multi-site study, additional analyses of the water quality and microbial indicators data will be explored, including comparing samples collected upstream and downstream of the repair site and correlating water quality parameters with household survey data.

Household Survey

In the pilot, the survey response rates were similar among LPE and non-LPE areas and across events, but the overall response rate of 37% was lower than expected. Non-differential response in LPE and non-LPE areas and across different events suggests the survey procedures encouraged equitable participation in the LPE and control areas, which likely indicated that there was limited selection bias. Additionally, if response rates had been substantially higher in exposed LPE areas than unexposed non-LPE areas, it would have raised concern that persons in LPE areas were more concerned about their water quality, which would increase the possibility of information bias in the responses about water use and illness. The multiple mailing contact strategy encouraged participation, evidenced by boosts in survey response following the mail prompts.

The customer service lists were a reliable source of contact information, with deliverable addresses available for 98% of contacted households. The pilot survey response rate of 37% was comparable to recent CDC surveys about waterborne illnesses. A CDC survey that was administered after a community-wide drinking water outbreak used water utility billing information to contact households for a postal survey and attained a 33% response rate (Ailes et al., 2013). A CDC and National Park Service survey about illness, including AGI, and injury among backcountry travelers attained a 39% response rate among respondents that consented to participate prior to the survey administration; respondents specified a preferred method of either e-mail or postal contact, and researchers implemented a multiple contact strategy (Rajasingham et al., 2013). Additionally, the pilot survey response rate was similar to a series of population studies on gastrointestinal illness and drinking water consumption patterns in Canada, in which researchers used a similar strategy of selecting random samples of households from contact lists, first contacting households with an advance letter, and then utilizing a multiple contact strategy, although these studies used a telephone mode of survey administration (44%) (Jones et al., 2007; Thomas et al., 2006). The strategy of cold contacting random samples of water utility customers by mail was resource efficient compared to conducting in-person interviews; however, the trade-off might have been a lower response rate. Higher response rates are more likely to be achieved in in-person interviews (59%) (Arnold et al., 2013). Power calculations were developed with the assumption that a minimum response rate of 40% was needed to answer the primary research question of whether the events were associated with AGI. The goal for the pilot was to reach a 60% response rate to ensure generalizability of findings and to provide enough statistical power to conduct stratified analyses by utility disinfectant type. System data demonstrated that the web-based survey took customers, on average, 13 minutes to complete, suggesting that the time burden for participation was low.

The majority of survey respondents reported drinking and using tap water for potable purposes, and this was similar in the LPE and non-LPE areas. Most households in LPE areas did not report observing low pressure, complete service loss, or a change in tap water during the three weeks following the LPE, indicating that customers were usually unaware of their exposure status. Respondents reported noticing low pressure in LPE-areas about twice as often as in non-LPE areas, although less than 1% of respondents in the non-LPE areas reported noticing a complete water service loss. A minority of households mistakenly thought they were under a boil water notice, advisory, or order. This was uncommon, but occurred more in LPE-areas, so it is possible that customers misinterpreted a work notice communication, such as a door hanger, from the utility.

Lessons Learned

Through the process of piloting the procedures for selecting the study LPE and non-LPE areas, the utility and CDC team were able to communicate and work together effectively; this will be especially important during the multi-site study to ensure consistency across the different utility sites. The pilot also highlighted several communication challenges. The utility operators were not always able to notify the utility project manager of eligible events early enough into the repair for the study team to observe the full event/repair during the site visit. Similarly, the utility sometimes gave delayed notification to the CDC team. This was especially difficult to prevent in emergency response situations. The importance of timely event notification will be emphasized during utility trainings. The area selection process was much easier when the utility team was able to make a site visit and observe the entire event/repair and when the CDC team was able to assist with the study area selection while the utility team was still in the field.

The engineering attributes list and LPE form will be revised to streamline data collection and reduce the burden on the utility staff. The pressure data on the LPE form were frequently missing. It was not possible to measure pressure readings during the events without violating the observational study design (i.e., interfering with or delaying the repairs to measure the pressure would have caused study-related changes to service). The pressure readings add value to the field data, but the scope of how the pressure measurements can be used in this study is limited because of how the data are collected. The three field readings measured during the event can provide snapshot measurements but cannot capture the variability within the system. This, coupled with frequently missing data, limits the ability to use the pressure readings to measure LPE-exposure or to relate the data to the human health outcomes. It might be helpful to use the pressure measurements in real-time to help identify the extent of the LPE-areas or to consider the duration or extent of low pressure in the analyses, but the study design does not lend itself to that, and that information is not necessarily needed to answer the study question. For study purposes, other information, such as verifying a loss of water service at home hose bibs or checking for customer complaints of lost service, can be used to corroborate the selection of the LPE-areas using the engineering attributes. If a utility has automated pressure sensors already in use, it could be helpful to gather this information in conjunction with the study data to provide additional context about the LPE.

Most of the data collection for the pilot took place during the winter, which allowed the study procedures to be tested under worst-case conditions; the utility was in its busy season, responding to multiple main breaks and needs for repairs, there were two extreme weather events that shut down the Atlanta CDC office, and survey administration fell within the winter holiday season, when residents were potentially not home to receive the survey. These seasonal issues will be considered when planning for the scale-up to multiple utility sites. Possible solutions include staggered utility enrollment and a study break during the winter holiday season.

Additionally, because the CDC Environmental Microbiology Laboratory must sometimes respond to public health emergencies that temporarily limit the lab's capacity for research projects, it will not be feasible to collect ultrafiltration samples for each of the 65 LPEs in the multi-site study**.** Ultrafiltration samples will be collected from about 2/3 of all events to allow for efficient progress on the epidemiologic study at times when the CDC lab is unable to receive samples. Utilities will work with CDC to verify event eligibility before proceeding with a study response; at that time, CDC will let them know whether to collect the ultrafiltration samples.

Survey response rates were lower than anticipated. To improve response rates, the study team will make minor modifications to the survey procedures and will increase efforts to promote the study in the participating communities. Nearly half of the page views for the study website (46%) occurred in the 30 days following the press release, before any survey materials were mailed out, suggesting that additional ongoing publicity in the study communities has potential to motivate participants. For the multi-site study, the study team will implement additional community outreach throughout the study period to improve community acceptance of the study and to boost response rates.

The majority of respondents chose to return the survey by postal mail, using the provided return envelope. The data quality of the web surveys was higher than the paper surveys because data verification rules and question skip patterns were built into the survey interface. Since the web survey instructions and access information were printed on the survey materials, rather than sent electronically to customers, it might have been inconvenient for respondents to access a computer, type the link to the website, and log-in to take the survey. To encourage web survey participation and possibly increase overall survey response rates, the study team will send the survey link electronically to customers that have email addresses on file (approximately 10% of pilot utility customers).

EVALUATION OF PILOT STUDY AND PLANNING FOR NATIONAL STUDY

Evaluation of Pilot Study

Six outcomes were used to evaluate the success of the pilot study.

1) CDC team and utility select appropriate LPE and non-LPE areas

The operator and study team's selection of the matched LPE and non-LPE areas was completed accurately and efficiently using knowledge of the water system and hydraulic principles. Hydraulic models were developed for three events, and results corroborated the selection of the study areas based on the field assessment and knowledge of the water system.

2) The standard LPE form describing the event is filled out completely at the time of repair

The LPE form was nearly complete for all six events, with the exception of a few items that the team was unable to measure or observe, such as pressure readings and interior conditions of pipes.

3) The water sample collection team follows standard operating procedures

Grab water sample collection was complete for all events. UF sample collection was incomplete for two events, due to a winter storm and CDC laboratory staffing capacity. All standard operating procedures were followed for water sample collection and shipment.

4) The laboratory team follows testing, standard operating procedures, and maintains chain of custody logs

The water sample chain of custody information and field water parameters were complete for all events. Utility and CDC laboratories followed laboratory procedures and maintained appropriate records.

5) The CDC team follows survey mailing procedures and tracks household participation

A secure web survey and database were developed specifically for this project to manage utility customer data, collect survey data, and track participation. CDC contacted over 600 households following a total of six events. The study team maintained the privacy of the utility customer data, and tracked participation.

6) The survey procedures encourage participation and equitable study participation in LPE area and non-LPE area groups.

Survey response rates were in line with studies that used similar survey administration methods. Response rates were similar in LPE (exposed) and non-LPE (unexposed) areas, suggesting there was limited bias. The survey item response rate was high.

Conclusions

The pilot was effective for testing the study design and procedures but the findings are not necessarily generalizable to all utilities that might participate in the multi-site study. The study was piloted at one utility site, and utility practices and capacities to accommodate research projects vary. The pilot utility is located in the southeast region of the U.S. and serves approximately 427,000 people (EPA, 2014). Utilities of different sizes and in different regions might encounter additional or different challenges in applying the study protocols, so the utility roles and study protocols will need to be adapted to each site. An additional difference is that the pilot field data collection took place during December to March, and the multi-site study will be implemented year-round. The frequency of main breaks and repairs is expected to vary seasonally.

Additionally, the pilot was much smaller in scope than the multi-site study. The multi-site study will collect data from 65 events, whereas data were collected from six events for the pilot. This limits the inferences that can be made about the data. For example, the pilot utility was a chloraminated system, and the study areas were most often served by blended source water (five events) and groundwater (one event). Thus, the pilot laboratory findings might not be generalizable to systems or events with different water characteristics.

Overall, the pilot study demonstrated that the study design and procedures will allow the study team to collect the data needed to meet the study goal and aims. Field, laboratory, and epidemiologic components of the study were well-coordinated and data collection proceeded smoothly. Following minor modifications to the study materials and protocols, the study team will be ready to implement the full study to determine whether LPEs are associated with illness.

Next Steps and Information for Prospective Utilities

The multi-site study is expected to be launched in 2014. To be eligible to participate, the utility must use a secondary disinfectant, have a history of at least one LPE per month (main breaks or planned repairs), on average, and be able to partner with CDC for a 12-18 month period to complete data collection for approximately 13 low pressure events.

Additionally, the utility should be able to use knowledge of the water system and hydraulics to identify LPE and non-LPE areas following the event and communicate the area selection to CDC using basic hydraulic maps (i.e., pipe diameters, normal flow direction, changes to flow during the event, areas valved-off during the repair). The maps can be hand-drawn or computer-generated and should help explain the reasoning behind the choice of the study areas. The utility must be able to generate contact information lists for residential customers within the study areas and securely transfer the lists to CDC. The CDC team will help set up the method for securely transferring the customer contact information to CDC.

The project's success hinges on forming strong public health and water utility sector partnerships. Participation from utilities across the country will help researchers gain an understanding of the health impacts of routine and unplanned distribution system low pressure events, and this understanding can be used to help focus resources toward effectively maintaining the safety and durability of U.S. water systems. Additionally, participation can help utilities gain a better understanding of their customers' water use and experiences; CDC can provide each utility with de-identified summary survey data about household water use. The utility and customer results will be combined with others, and the participating utilities will not be identified in any publications.

For more information, please contact the project team:

Julia Gargano (CDC Epidemiologist)

jgargano@cdc.gov

APPENDIX: PILOT STUDY LOW PRESSURE EVENTS AND DECISION-MAKING

LPE 1

Low pressure was caused by 1) a blowout in an 8” PVC main, and 2) the repair process, which involved partially or completely valving off an area to isolate the break and replace 10’ of pipe. Operators attempted to conduct a clamp repair; the pipe broke again after it was clamped, which complicated the repair. The cause of the main break was likely deterioration and aging. The break caused water to flood the street; water undermined the foundation of a home and a tree. The utility study team assessed that there was high potential for contamination. Muddy trench water, primarily water from the main, entered the pipe before and during the repair. An estimated 154 homes were exposed to low pressure either during the break or when the operators valved off the surrounding areas to isolate the break site. The total time of low pressure was estimated to be seven hours. Of these 154 homes, an estimated 31 lost complete water service when the operator completely valved off a smaller area to isolate the repair site and cut and replace the section of pipe; these homes were without service for approximately 30 minutes. The area was flushed following the repair.

The selection of the exposed and unexposed study areas was challenging because the break took place in a looped portion of the system. Since the loop was fed by large mains (i.e., 48”, 12”, 12”) and the break and repair areas were nearly in a dead end off of the loop, it was reasonable to assume that the normal flow direction in the loop would not change as a result of the break, and that there would be limited impact to areas outside of the valved-off area once the break area was isolated. The following exposed area attributes were used to describe the choice of the exposed area.

Table A 1. Exposed area selection for LPE 1

Selected exposed area attributes	Reasoning
2. Smaller diameter mains nearby or in direct hydraulic connection to LPE.	True, there were smaller diameter mains nearby or in direct hydraulic connection to the main that had the break.
4. Near lower flow areas such as dead ends, pressure zone boundaries.	True, the area near the break was nearly in a dead end.
5. Away from PRVs, pumps, or storage facilities that float on the system, which would allow water to be released into the system to compensate for lower pressure caused by LPE	True
6. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	The selected exposed area was partially or completely valved off to complete the repair.

The selection of the unexposed area was challenging because the area was selected within the same census tract, for demographic matching purposes, and with the same pipe size and material, water source, and housing type as the exposed area. These matching criteria led the study team to select an area in close geographic proximity to the exposed area, which meant that the unexposed area was also part of the looped system. Although it was expected that there would be limited impact to areas outside of the repair area once the break area was valved off, it was important to be sure that the selected unexposed area was not affected before the break was isolated. The unexposed area attributes were used to describe the choice of the unexposed area.

Table A 2. Unexposed area selection for LPE 1

Selected unexposed area attributes	Reasoning
2. No recent main breaks or LPEs in the vicinity.	True, also no customer complaints.
4. If in same pressure zone, area served by larger diameter mains with routinely good steady state pressures.	True, fed from the N or S, depending on demand, by 12" mains in the loop.
6. Other, please describe	Exposed area nearly in a dead end, so impact to surrounding areas could be limited.

Since the validity of the choices of study areas depended on several assumptions, hydraulic models, developed by the utility's engineering department, for three scenarios (i.e., normal - pre-break, during break - before area valved off, and during repair- after area valved off) were used to evaluate the choices made based on the field assessment and engineering principals. Overall, the models supported choices of exposed and unexposed areas, of normal flow direction, and the assumption that flow direction in the loop did not change during the event. The model showed small pressure loss in the exposed area (~ 5 psi) and at the boundary of the unexposed area (~1 psi) during the break, before the area was valved off. The model showed limited impact to areas outside of valved-off area once the break area was valved off.

LPE 2

Low pressure was caused by an area being valved-off and restored multiple times over a two-day period as part of a larger planned maintenance event. The operators installed several new valves in the affected area, so they could isolate the area for a procedure to relocate a main to accommodate new storm drain installation. The new valves allowed the operator to complete the main relocation within an isolated area that did not contain any service connections to homes. On the day before the event, the operator flushed the area and exercised the valves to prepare for the procedure; the area was valved off for several hours. On the day of the event, the operator tried to isolate the area, but a valve broke and needed replacement. A larger area was valved off, the operator replaced the broken valve, and restored service to some of area. The operator installed a new valve to isolate the street from the planned work site for the main relocation. Water flowed out of the main during installation. The main was flushed and service was restored. The main relocation was completed the next day, with no service connections affected. The utility study team assessed that there was low potential for contamination. The main was flushed extensively on the days before and after the repair. There was a small amount of flow (i.e., positive pressure) during the installation of the new valve. Pumps removed water from the pit, so that pipe ends were never submerged in water. Pipes and valves were swabbed with chlorine before installation of the new valve. An estimated 85 homes were exposed to low pressure when operators valved off the area over the two-day period. The approximate time of water loss was three hours on the day of the event.

The selection of the exposed area was relatively straightforward for this event, since it only included areas that had been valved off by the utility operator. The following exposed area attribute was selected:

Table A 3. Exposed area selection for LPE 2

Selected exposed area attributes	Reasoning
6. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	The exposed area was valved off and restored multiple times over two-day period.

The exposed area did not meet study eligibility criteria of 80% occupied housing within the census tract; the area was located within a strip of beach area in a tract with 52% occupied housing. However, utility water usage data suggested ~70-90% of homes had normal residential usage in the last 60 days, so the event was included. The unexposed area was similar to the exposed area; it was also located on an adjacent beach strip within a census tract that had 69% occupied housing. Both of these strips were fed predominantly from the N to S by 16” mains. Additionally, the exposed area was fed by a subaqueous line from the unexposed area. These exposed and unexposed areas were not in the same census tracts, but the census age groups were similar (i.e., percent of census tract less than 18 years old and percent of census tract 65 years and older). The areas had the same water source, and similar pipe sizes and materials; the unexposed area had slightly larger pipes. The unexposed area attributes were used to describe the choice of the unexposed area.

Table A 4. Unexposed area selection for LPE 2

Selected unexposed area attributes	Reasoning
4. If in same pressure zone, area served by larger diameter mains with routinely good steady state pressures.	True, served by 16” main, flow from N to S.

LPE 3

Low pressure was caused by the repair process to stop a leak at the bell and spigot joint of an older (i.e., ~50 years old) 6” PVC main. A contractor installing sidewalks discovered a leak when digging up a driveway and reported it to the water utility; during the repair, residents informed operators that the ground in the area had been soggy for years, suggesting that the leak might have been present for several years. The cause of the leak was likely due to the gaskets on the joint deteriorating. Operators valved off the area and cut and replaced a 3’ section of pipe. The utility study team assessed that there was low potential for contamination. The water in the repair trench was below the pipe level during the pipe installation. The new pipe dipped into the pit water while the bolts were being tightened, but the utility personnel did not feel this would create risk for contamination since the bolts were already sealed. An estimated 23 homes experienced low pressure due to a loss of service when the operators valved off the area to complete the repair. The homes were without service for a little less than two hours. The area was flushed following the repair.

The selection of the exposed study area was relatively straightforward. The neighborhood selected as the exposed area was fed by a single 12” main; smaller mains off of this line fed homes in a circular flow pattern. One of these smaller mains was the main with the leak. Because of these hydraulic circumstances, it was assumed that all of the homes in the neighborhood were affected by the event and no additional areas outside of the neighborhood would be impacted. The following exposed area attributes were used to describe the choice of the exposed area.

Table A 5. Exposed area selection for LPE 3

Selected exposed area attributes	Reasoning
1. Areas with known lower steady state pressures.	True
2. Smaller diameter mains nearby or in direct hydraulic connection to LPE.	True, smaller diameter mains in neighborhood with circular flow pattern (exposed area)
3. Higher elevation than main break location (assuming there is no nearby storage to compensate for the elevation).	True, there is a downhill slant from N to S in this area.
5. Away from PRVs, pumps, or storage facilities that float on the system, which would allow water to be released into the system to compensate for lower pressure caused by LPE	True
6. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	The exposed area was completely valved off to complete repair; utility team member verified homes had no water service at hose bibs

The unexposed area selection was also straightforward. The unexposed area was upstream of the exposed area, fed off of the same 12” main that fed the exposed area, and was also a smaller neighborhood fed by small mains with a circular flow pattern. Both areas had similar housing type, pipe sizes and materials, and the same water source. The areas were in different census tracts, but the census age groups were similar (i.e., percent of census tract less than 18 years old and percent of census tract 65 years and older). Both census areas had over 80% occupied housing. The unexposed area attributes were used to describe the choice of the unexposed area.

Table A 6. Unexposed area selection for LPE 3

Selected unexposed area attributes	Reasoning
1. Nearby but different pressure zone.	The unexposed area is uphill from the exposed area and is closer to the pump station, so there might be a difference in pressures.
3. If in same pressure zone, served by pump or storage facility that floats on system.	True, served by pump station
4. If in same pressure zone, area served by larger diameter mains with routinely good steady state pressures.	True, served by 12” main
6. Other, please describe	The unexposed area is upstream of the exposed area; no reversal of flow or additional affected areas outside of exposed neighborhood, so confident area is upstream.

LPE 4

Low pressure was caused by 1) a pump station that directly fed the study areas going into “fill mode” causing a slight, ~ 7 psi, drop in pressure at the pump station, 2) a blowout in a 6” main, and 3) the repair process, which involved completely valving off a small area to isolate the break and replace a section of pipe. The main break occurred after a contractor who was burying phone lines accidentally sawed through a 6” main. During the break, water from the north and south and from small mains in the exposed neighborhood traveled to the break site and flooded the road. The utility study team assessed that there was moderate potential for contamination. The cut pipe was submerged in drinking water from the pipe before the repair crews arrived and before the break was valved off, for about 3.5 hours. A pump was used to remove water from the pit before the repair started. An estimated 166 homes were exposed to low pressure for about 3.5 hours during the break, before the area was valved off. Of these 166 homes, three lost complete water service when the operator valved off a smaller area to isolate the repair site; these homes were without service for an additional 5.5 hours. During this time, the remaining homes were back-fed from surrounding areas, so most residents had water service. The area was flushed following the repair.

The selection of the exposed and unexposed areas was complicated by the presence and activity of the nearby pump station, since this pump station directly fed both the exposed and unexposed areas. The study team was concerned that the unexposed area could have potentially experienced a loss of pressure or flow change when the pump station experienced a dip in pressure, either before or during the break. Utility operators assessed that the dips in pressure at the pump station would not have affected the unexposed area. Through this inquiry, the study team learned that the pump stations at this utility do not automatically adjust for drops in pressure in the system, and that it is important to follow up with the operator before using this unexposed area attribute. A second concern was the uncertainty of how the pump station being in “fill mode” affected the surrounding areas during the break. The utility operator consensus was that since the break was in the main directly fed by the pump station, “fill mode” allowed the pump station to contribute water to the break, but could not compensate for pressure loss in the exposed subdivision. The break was in the main feeding the subdivision, and the small, dead end mains in the subdivision allowed water to rush from the surrounding area to the break site; this entire subdivision was selected as the exposed area. The following exposed area attributes were used to describe the choice of the exposed area.

Table A 7. Exposed area selection for LPE 4

Selected exposed area attributes	Reasoning
1. Areas with known lower steady state pressures.	True, area served by this pump station is known low pressure area
2. Smaller diameter mains nearby or in direct hydraulic connection to LPE.	True, smaller mains in subdivision (exposed areas) served by main with break.
4. Near lower flow areas such as dead ends, pressure zone boundaries.	True, smaller mains in subdivision (exposed areas), were dead ends, which caused water to rush out of area from break site.
6a. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	Pump station went into fill mode just before break, which caused ~7 psi dip in pressure at pump station before the break
6b. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	Customer complaint of very low water pressure about two hours after the break, before repair was completed

The unexposed area had the same water source from the pump station and similar housing type and pipe sizes and materials. The exposed and unexposed areas were in different census tracts, but the census age groups were similar (i.e., percent of census tract less than 18 years old and percent of census tract 65 years and older). Both areas had over 80% occupied housing. The following unexposed area attributes were used to describe the choice of the unexposed area.

Table A 8. Unexposed area selection for LPE 4

Selected unexposed area attributes	Reasoning
2. No recent main breaks or LPEs in the vicinity.	True, also no customer complaints in area
3. If in same pressure zone, served by pump or storage facility that floats on system.	True, operator closed fill valve after break, allowing pressure at pump station to increase (no automatic response to pressure drop).
4. If in same pressure zone, area served by larger diameter mains with routinely good steady state pressures.	True, served by 24” main from pump station and 16” main from north.

The study team suggested that exposed area attributes 1 and 6a could have also been applied to the unexposed area. The utility operators felt that the unexposed area would not be affected. A hydraulic model, developed by the utility's engineering department, was used to estimate pressures in the exposed and unexposed study areas during the break scenario. The hydraulic model estimated very low pressures in the exposed area subdivision during the break (4-11 psi). The hydraulic modeling results also showed that the unexposed area might have been affected by a ~3 psi drop in pressure, but that the overall pressure estimates remained high (61-70 psi). Because the differential exposure in the two areas was so large and the exposure of a 3 psi drop could be of similar magnitude of diurnal pressure variation, the hydraulic model supported the utility operators' choice of exposed and unexposed areas.

LPE 5

Low pressure was caused by an operator valving off a small area to install a valve to put an abandoned line out of service. The abandoned line was still connected to the line with home service connections and was leaking into the street. The utility team assessed that there was very low potential for contamination because the valve installation was on the abandoned main, which did not have service connections to homes. However, the abandoned main was in the same pit as the in-service line, and there was a cross-connection somewhere between the lines, which was the source of the leak. Following the repair, a customer complained of a black substance in the drinking water; the utility team believed it was biofilm but could not flush the area because it was a dead end and the blow off valve for flushing was corroded shut. An estimated 16 homes were exposed to low pressure for about 45 minutes when operators valved off the area.

The selection of the exposed area was relatively straightforward, since it was limited to the area that was valved off by the utility operator. The exposed area had a uni-directional flow pattern and there were no alternative water feeds to the area, so it was assumed that no additional areas outside of valved off area should have been affected by the event. The following attributes applied, although #2, 4, 5, and 6a might not have been directly related to why the area was selected as exposed to low pressure during the event.

Table A 9. Exposed area selection for LPE 5

Selected exposed area attributes	Reasoning
2. Smaller diameter mains nearby or in direct hydraulic connection to LPE.	True, 4" line with service connections to homes connected to older main
4. Near lower flow areas such as dead ends, pressure zone boundaries.	True, dead end street with lower demand; low flow area
5. Away from PRVs, pumps, or storage facilities that float on the system, which would allow water to be released into the system to compensate for lower pressure caused by LPE.	True
6a. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	Blow off at end of street inoperable; unable to flush to end of street. Not able to flush for several years
6b. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	Exposed area valved off during repair; homes lost water service.

It was straightforward to match the exposed and unexposed areas on the infrastructure characteristics. The exposed area was on a peninsula with water-front properties. The unexposed area was also made up of several similar peninsulas. The flow patterns in both areas were similar; both were dead-ends, fed by a 24" main that reduced to 6" mains that served the areas uni-directionally. Both areas had similar housing types, pipe sizes and materials, and the same water source from a nearby pump station. The areas were not in the same census tract, and the census age groups did not match exactly. A greater proportion of the exposed tract population was 65 years and older, although the areas had similar proportions of the population under 18 years old. The exposed area had 76% occupied housing, and the unexposed area had 80% occupied housing.

The unexposed area was upstream of the exposed area and closer to the pump station. The 24” main from the pump station serviced both areas but served the unexposed area first. The following unexposed area attributes were used to describe the choice of the unexposed area.

Table A 10. Unexposed area selection for LPE 5

Unexposed area attributes	Reasoning
3. If in same pressure zone, served by pump or storage facility that floats on system.	True, close to pump station
4. If in same pressure zone, area served by larger diameter mains with routinely good steady state pressures.	True, close to 24” main that services both areas
6. Other, please describe	Upstream from the exposed area and closer to pump station; no alternative feed to exposed area, so confident unexposed area is upstream.

In addition to the study matching characteristics, several other factors were observed that might have impacted the quality of the exposed/unexposed area match for this event. The exposed area had not been flushed for several years because the blow-off valve was corroded, and there was a cross-connection between the abandoned main line and the in-service line that had been present for several years. It was not possible to know if the unexposed area had similar issues (i.e., the cross connection and inability to flush for several years).

LPE 6

Low pressure was caused by an area being valved-off and restored twice over a two day period to relocate a main to accommodate future installation of traffic light posts. For both event days, the utility study team assessed that there was low potential for contamination. On the first day, a small amount of dirt entered the pipe when it was cut, but the pipe was well flushed following the repair. On the second day, the utility study team did not go to the repair site, but a follow up inquiry with the utility inspector indicated that the repair went smoothly. An estimated 130 homes were exposed to low pressure when the operators valved off the area on the first day; a subset of these homes were also exposed on the second day. The two procedures were performed on the same main, and the approximate time of water loss was four hours on each day. The main was flushed extensively to drain air from pipe on the first day, and the main was also flushed following the procedure on the second day.

The selected exposed area was the area that the operators valved off to complete the first procedure to relocate the main. The exposed area was fed uni-directionally, and there were no alternate feeds to the area, so it was assumed that no additional areas outside of the repair area should have been affected by the event. The following exposed area attribute was selected:

Table A 11. Exposed area selection for LPE 6

Exposed area attributes	Reasoning
6. Other, please describe (for example, flow direction in surrounding areas changed as a result of the repair).	Exposed area valved off during repair; homes lost water service. There was no alternate feed to the area, so there was no additional exposed area.

The unexposed area was nearby but upstream of the valves that were closed to isolate the exposed area. Both exposed and unexposed areas were fed uni-directionally from the same main; 8” and 6” mains fed the areas. The flow patterns within the areas were slightly different. The exposed area was looped; the unexposed area had a looped section but also had several dead ends. The pipe sizes and materials were similar in both areas, and the water source was the same. The main housing types in the areas were similar (i.e., single family homes), but not an exact match. Most of the exposed area and all of the unexposed area had concrete block homes. Part of the exposed area had pre-fabricated homes. Both areas were in the same census block group, so it was reasonable to assume that the demographic characteristics of the populations in the exposed and unexposed areas were similar. The census housing occupancy was 87%. The following unexposed area attributes were used to describe the choice of the unexposed area.

Table A 12. Unexposed area selection for LPE 6

Unexposed area attributes	Reasoning
3. If in same pressure zone, served by pump or storage facility that floats on system.	True, served by water source before exposed area.
4. If in same pressure zone, area served by larger diameter mains with routinely good steady state pressures.	True, served by 48" to 12" to 8" mains from water source.
6. Other, please describe	Unexposed area is upstream of the valves that were shut off to isolate the exposed area. Both areas fed uni-directionally, so confident unexposed area was upstream.

REFERENCES

Kirmeyer, G.; Richards W.; Smith C.D. An assessment of water distribution systems and associated research needs. AWWARF, Denver, CO. 1994.

Nygard, K.; Wahl, E.; Krogh, T.; Tveit, O.A.; Bohleng, E.; Tverdal, A.; Aavitsland, P. Breaks and maintenance work in the water distribution systems and gastrointestinal illness: a cohort study. International Journal of Epidemiology. 2007 Aug;36(4):873-880.

Dillman, D.A. Mail and Internet Surveys: The Tailored Design Method. 2nd ed. New Jersey: John Wiley & Sons, Inc; 2007.

CDC. Ten great public health achievements – United States, 1990 – 1999 Morbidity and Mortality Weekly Reports. 1999a;48: 241-243.

CDC. Achievements in public health, 1990 – 1999: control of infectious diseases. Morbidity and Mortality Weekly Reports 1999b; 48: 621-629.

Cutler, D.; Miller, G. The role of public health improvements in health advances: the twentieth-century United States. Demography. 2005;42: 1-22.

Borchardt, M.A.; Haas, N.L.; Hunt, R.J. Vulnerability of drinking-water wells in La Crosse, Wisconsin, to enteric-virus contamination from surface water contributions. Applied and Environmental Microbiology. 2004 Oct;70(10):5937-5946.

LeChevallier, M.W.; Gullick, R.W.; Karim, M.R.; Friedman, M.; Funk, J.E. The potential for health risks from intrusion of contaminants into the distribution system from pressure transients. J Water Health. 2003 Mar;1(1):3-14.

Swerdlow, D.L.; Woodruff, B.A.; Brady, R.C.; Griffin, P.M.; Tippen, S.; Donnell, H.D., Jr.; Geldreich, E.; Payne, B.J.; Meyer, A., Jr.; Wells, J.G.; et al. A waterborne outbreak in Missouri of Escherichia coli O157:H7 associated with bloody diarrhea and death. Ann Intern Med. 1992 Nov 15;117(10):812-819.

Lambertini, E.; Spencer, S.K.; Kieke, B.A., Jr.; Loge, F.J.; Borchardt, M.A. Virus contamination from operation and maintenance events in small drinking water distribution systems. Journal of Water and Health. 2011 Dec;9(4):799-812.

Craun, G.F.; Brunkard, J.M.; Yoder, J.S.; Roberts, V.A.; Carpenter, J.; Wade, T.; Calderon, R.L.; Roberts, J.M.; Beach, M.J.; Roy, S.L. Causes of outbreaks associated with drinking water in the United States from 1971 to 2006. Clinical Microbiology Reviews. 2010 Jul;23(3):507-528.

Colford, J.M.; Wade, T.J.; Sandhu, S.K.; Wright, C.C.; Lee, S.; Shaw, S.; Fox, K.; Burns, S.; Benker, A.; Brookhart, M.A.; van der Laan, M.; Levy, D.A. A randomized, controlled trial of in-home drinking water intervention to reduce gastrointestinal illness. American Journal of Epidemiology. 2005 Mar 1;161(5):472-482.

Payment, P.; Richardson, L.; Siemiatycki, J.; Dewar, R.; Edwardes, M.; Franco, E. A randomized trial to evaluate the risk of gastrointestinal disease due to consumption of drinking water meeting current microbiological standards. Am J Public Health. 1991 Jun;81(6):703-708.

Hellard, M.E.; Sinclair, M.I.; Forbes, A.B.; Fairley, C.K. A randomized, blinded, controlled trial investigating the gastrointestinal health effects of drinking water quality. Environ Health Perspect. 2001 Aug;109(8):773-778.

Payment, P.; Siemiatycki, J.; Richardson, L.; Renaud, G.; Franco, E.; Prevost, M. A prospective epidemiological study of gastrointestinal health effects due to the consumption of drinking water. International Journal of Environmental Health Research. 1997 Mar;7(1):5-31.

Colford, J.M., Jr.; Roy, S.; Beach, M.J.; Hightower, A.; Shaw, S.E.; Wade, T.J. A review of household drinking water intervention trials and an approach to the estimation of endemic waterborne gastroenteritis in the United States. J Water Health. 2006;4 Suppl 2:71-88.

Ercumen, A.; Gruber, J.S.; Colford, J.M., Jr. Water Distribution System Deficiencies and Gastrointestinal Illness: A Systematic Review and Meta-Analysis. Environmental Health Perspectives. 2014 Mar 21.

DeSilva, M. EIS Conference Presentation. 2014.

American Public Health Association (2005). Standard Methods for the Examination of Water and Wastewater (21st ed.): American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF).

Smith, C.M.; Hill, V.R. Dead-end hollow-fiber ultrafiltration for recovery of diverse microbes from water. Applied and Environmental Microbiology. 2009 Aug;75(16):5284-5289.

United States Geological Survey, Ohio Water Science Center (2007). Analysis of Clostridium perfringens in Environmental Water Samples. Retrieved from http://oh.water.usgs.gov/micro_methods_clostridium_perfringens.htm

United States Environmental Protection Agency (2001). Method 1602: Male-specific (F+) and Somatic Coliphage in Water by Single Agar Layer (SAL) Procedure. (EPA 821-R-01-029). Washington, D.C.: Retrieved from http://www.epa.gov/microbes/documents/1602ap01.pdf.

Hill, V.R.; Mull, B.; Jothikumar, N.; Ferdinand, K.; Vinje, J. Detection of GI and GII Noroviruses in Ground Water Using Ultrafiltration and TaqMan Real-time RT-PCR. Food Environ. Virol. 2010; 2:218-224.

Haugland, R.A.; Varma, M.; Sivaganesan, M.; Kelty, C.; Peed, L.; Shanks, O.C. Evaluation of genetic markers from the 16S rRNA gene V2 region for use in quantitative detection of selected Bacteroidales species and human fecal waste by qPCR. Systematic and Applied Microbiology. 2010 Oct;33(6):348-357.

Hornung, R.W.; Reed, L.D. Estimation of average concentration in the presence of nondetectable values. Appl Occup Environ Hyg. 1990; 5: 46-51.

Van Belle, G.M., Steven P. STRUTS: Statistical Rules of Thumb. Seattle, WA: University of Washington; 1998.

Ailes, E.; Budge, P.; Shankar, M.; Collier, S.; Brinton, W.; Cronquist, A.; Chen, M.; Thornton, A.; Beach, M.J.; Brunkard, J.M. Economic and health impacts associated with a Salmonella Typhimurium drinking water outbreak-Alamosa, CO, 2008. PloS One. 2013;8(3):e57439.

Rajasingham A.; Ayers T.; Derado G.; Stockman L.J.; Larsen G.; Higgins C.; Beach M.J.; Roy S.L., CDC Report (2013). Yellowstone National Park Backcountry Study: Study of Illness and Injury among Backcountry Users.

Jones, A.Q.; Majowicz, S.E.; Edge, V.L.; Thomas, M.K.; MacDougall, L.; Fyfe, M.; Atashband, S.; Kovacs, S.J. Drinking water consumption patterns in British Columbia: an investigation of associations with demographic factors and acute gastrointestinal illness. The Science of the Total Environment. 2007 Dec 15;388(1-3):54-65.

Thomas, M.K.; Majowicz, S.E.; MacDougall, L.; Sockett, P.N.; Kovacs, S.J.; Fyfe, M.; Edge, V.L.; Dore, K.; Flint, J.A.; Henson, S.; Jones, A.Q. Population distribution and burden of acute gastrointestinal illness in British Columbia, Canada. BMC Public Health. 2006;6:307.

Arnold, B.F.; Schiff, K.C.; Griffith, J.F.; Gruber, J.S.; Yau, V.; Wright, C.C.; Wade, T.J.; Burns, S.; Hayes, J.M.; McGee, C.; Gold, M.; Cao, Y.P.; Weisberg, S.B.; Colford, J.M. Swimmer Illness Associated with Marine Water Exposure and Water Quality Indicators Impact of Widely Used Assumptions. Epidemiology. 2013 Nov;24(6):845-853.

EPA. SDWIS Envirofacts http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=FL6521405&state=FL&source=Purch_surface_water&population=426877&sys_num=0; [modified February 10, 2014May 22, 2014]