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The Effects of Intermittent Drinking Water Supply in Arraiján, Panama

By

John Joseph Erickson

A dissertation submitted in partial satisfaction

of the requirements for the degree of

Doctor of Philosophy

in

Engineering – Civil and Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Dr. Kara L. Nelson, Chair
Dr. David Sedlak
Dr. Isha Ray
Dr. Charlotte D. Smith

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Abstract

The Effects of Intermittent Drinking Water Supply in Arraiján, Panama

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John Joseph Erickson

Doctorate of Philosophy in Civil and Environmental Engineering

University of California, Berkeley

Professor Kara L. Nelson, Chair

Over three hundred million people throughout the world receive supply from piped drinking water distribution networks that operate intermittently. This dissertation evaluates the effects of intermittent supply on water quality, pipe damage and service reliability in four study zones (one continuous and three intermittent) in a peri-urban drinking water distribution network in Arraiján, Panama. Normal water quality in all zones was good, with 97% of routine water quality grab samples from the distribution system and household taps having turbidity < 1 NTU, total coliform and *E. coli* bacteria concentrations < 1 MPN / 100 mL, and ≥ 0.3 mg/L free chlorine residual. However, negative pressures that represent a risk for contaminant intrusion and backflow were detected in three of the four study zones, and water quality during the first flush when supply resumed after an outage was sometimes degraded. High and transient pressures that could cause pipe damage were detected in study zones with intermittent pumping, but filling and emptying of distribution pipes due to intermittent supply was not associated with transient or extreme pressures. Operational challenges, including frequent infrastructure failures, difficulty monitoring the network, and a lack of system information, resulted in unreliable supply in the intermittent zones. Continuous pressure and flow monitoring methods used in this research could be helpful tools for operators of intermittent distribution networks to provide more reliable service and identify hydraulic conditions that could lead to contaminant intrusion or pipe breaks.

To my parents

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This dissertation would not have been possible without the generous support of many people and institutions.

I am grateful for my adviser Kara Nelson's constant support. Along the way, I have been inspired by her curiosity, thoughtfulness, high standards, and willingness to engage in interesting research topics even if they don't fit neatly within the traditional boundaries of an academic discipline.

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This research would not have been possible without the participation and permission of Panama's Institute of National Aqueducts and Sewers (IDAAN). Specifically, I thank Yamileth Quintero, the Regional Manager of IDAAN in Arraiján, for her constant support of this study even when many other urgent matters required her attention; Mauro Romero, Luis Navarro, Higinio Domínguez, Cesar Bustamante, and Alcibíades Muñoz for their explanations of the Arraiján distribution network and for coordinating all of the support IDAAN provided in the field; Teodora de Lezcano, Rosemary Quirós and Jessica Batista for inviting us to use IDAAN's laboratory in Panama Oeste and patiently sharing their experience in laboratory techniques; Agustin Miranda for making the metal boxes that protected the monitoring equipment; and the many other IDAAN personnel in Arraiján, La Chorrera and the central office who supported the project with their time and advice.

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Much of the laboratory analysis presented in this dissertation took place at the Institute for Scientific Investigation and High Technology Services (INDICASAT). Amador Goodridge generously allowed us to use space and equipment in INDICASAT's laboratory, and Dilcia Sambrano provided technical advice regarding microbiological analysis. Amador and his wife Colleen were also great friends during my time in Panama, helping me to bridge the gap between Berkeley and Panama, and inviting me to countless delicious meals at their house.

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Finally, I'm grateful to my parents, for always supporting me, believing in me, and wanting the best for me.

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CHAPTER 1. Introduction

1.1. Motivation

While piped water supply with a tap in every household is often seen as the gold standard of improved water supply, the quality of service offered by such systems varies significantly. The portion of the world's population with access to an improved drinking water source increased from 76% to 91% from 1990 to 2015, and the portion with access to piped water on their premises increased from 44% to 58% (WHO/UNICEF Joint Water Supply and Sanitation Monitoring Programme 2015). However, not all improved sources, even piped sources, necessarily provide safe water (Shaheed et al. 2014). By extrapolating data from the Rapid Assessment of Drinking Water Quality that the WHO and UNICEF conducted in five countries, Onda, LoBuglio, and Bartram (2012) estimated that 28% of the world's population used unsafe water in 2010, a much larger portion of the population than the 12% using unimproved sources in 2010. In addition to water quality problems, piped water systems often provide inadequate service due to operational inefficiency, high rates of water loss, and lack of cost recovery (Savedoff and Spiller 1999; McIntosh 2003).

Intermittent drinking water supply (IWS), defined as piped water supply service that is available to consumers less than 24 hours per day (International Water Association [IWA] 2016), is a common deficiency in piped water systems (Shaheed et al. 2014). Intermittent supply can be caused by insufficient water resources, inadequate infrastructure, unplanned expansion of the distribution network, excessive water losses, or a combination of those factors (Klingel 2012; Kumpel and Nelson 2016; Rosenberg, Talozi, and Lund 2008; Yepes, Ringskog, and Sarkar 2001). Available data suggest that IWS is common in low- and middle-income countries throughout the world. In the year 2000, it was estimated that 60% of households with connections to piped water supply in Latin America and the Caribbean had IWS (Pan American Health Organization and World Health Organization [WHO] 2001) and that over half of urban water supplies in Asia and over one-third of urban water supplies in Africa operated intermittently (WHO and UNICEF 2000). In a recent review of IWS, Kumpel and Nelson (2016) used data from the World Bank Water and Sanitation Program's International Benchmarking Network (IBNET) to estimate that at least 309 million people worldwide are supplied by utilities that provide intermittent supply. However, the actual population affected by IWS is likely much higher, since many utilities and countries do not report to IBNET.

IWS is an inconvenience for users (McIntosh 2003; Lee and Schwab 2005; Cook, Kimuyu, and Whittington 2016), can make it difficult for a utility to provide equitable supply to all customers in the distribution network (Klingel 2012; Fontanazza, Freni, and La Loggia 2007; Vairavamoorthy, Gorantiwar, and Mohan 2007), is thought to lead to pipe damage (Christodoulou and Agathokleous 2012; Batish 2003; Galaitsi et al. 2016), and is considered a risk to water quality (Gadgil 1998; Lee and Schwab 2005; Coelho et al. 2003; Tokajian and Hashwa 2003; Klingel 2012; Kumpel and Nelson 2016).

The nature and severity of IWS varies considerably throughout the world, between water systems, and often within water systems. Despite the prevalence of IWS and concerns about its effects on public health, pipe infrastructure and user satisfaction, very little research has been done to characterize the nature and the effects of different IWS conditions found throughout the world.

1.2. Research objectives

To improve understanding of the nature and effects of IWS in different situations, the intermittent distribution system of Arraiján, Panama is examined in this dissertation. Arraiján is a peri-urban area of 263,000 people located west of Panama City. The research had three main objectives:

1. Evaluate microbiological water quality in study zones representing continuous and a variety of intermittent supply situations.
2. Assess whether pressure conditions under IWS in Arraiján were likely to damage distribution system pipes.
3. Explore the challenges of monitoring and operating intermittent areas of the Arraiján network and how those challenges affected the reliability of service that users received.

1.3. Dissertation overview

After this introduction, Chapter 2 provides a description of the Arraiján distribution system and the four study zones chosen to examine continuous supply and three varieties of intermittent supply. The continuous hydraulic and water quality monitoring stations that were installed in the four study zones to collect data for different aspects of the research are also described in Chapter 2.

Chapter 3 focuses on water quality in the four study zones, and in an additional fifth study zone where water quality monitoring also took place. Water quality was characterized via random grab samples, intensive first-flush sampling during the first 2 hours of supply after an outage, and continuous monitoring of free chlorine and turbidity over 1 year. Results show that water quality was generally much better in the Arraiján network than in an intermittent network in Hubli-Dharwad, India, where previous research with similar methods was carried out. Although water quality was generally good in the Arraiján study zones, it was sometimes degraded during the first flush and after pipe breaks and repairs, suggesting that there were opportunities to reduce public health risks posed by IWS in Arraiján.

In Chapter 4, continuous pressure monitoring data and an analysis of pipe break rates in Arraiján are employed to assess whether IWS was associated with pressure conditions likely to damage pipes. Certain IWS situations involving intermittent pumping were associated with hydraulic transients and high rates of pipe breaks, but other zones with intermittent supply did not generally have hydraulic transients or high pipe break rates.

Lastly, Chapter 5 examines IWS from an operations perspective. Although this research was not designed to systematically study the operation of the Arraiján system, hundreds of hours spent interacting with system operators and utility customers, and being able to use continuous pressure and flow monitoring to track supply conditions in the study zones, provided a window into the challenging world of operating an intermittent system. Opportunities for using continuous monitoring and data analysis to improve service quality and reduce water losses are discussed.

Chapter 6 concludes with a summary of research contributions and discussion of their significance. The need for further research and innovation directed at improving our understanding of IWS systems and developing better methods to monitor, operate and improve them is also discussed.

CHAPTER 2. Description of study site and monitoring methods

The research described in this dissertation was conducted in Arraiján, Panamá from October 2013 to August 2015. Arraiján's drinking water network, operated by Panama's Institute of National Aqueducts and Sewers (IDAAN for initials in Spanish), was selected as a study site for technical and institutional reasons. From a technical perspective, the range of intermittent supply situations found in Arraiján, varying in severity and in how they were controlled, provided the opportunity to study the effects of different types of IWS. Also, water entering the Arraiján distribution network from three drinking water treatment plants was of consistently good quality, meaning that any contamination at customer taps could likely be attributed to contamination occurring in the distribution system. Institutionally, IDAAN showed interest in the project from the beginning and provided support with data collection. IDAAN had multiple projects underway to improve supply in Arraiján, so was interested in documenting supply conditions before those projects took effect.

Arraiján is a peri-urban area located directly west of Panama City and east of the district of La Chorrera. Arraiján's population grew rapidly over the last decades, from 60,000 inhabitants in 1990 to an estimated 263,000 in 2014 (National Institute of Census and Statistics, Panama 2010a; National Institute of Census and Statistics, Panama 2010b). Part of this growth was in the form of planned residential developments, and another part through informal development without legalization or planning (Figure 2.1). The rapid pace of residential expansion made it difficult for IDAAN to expand the distribution system accordingly. The majority of the development and demand for water in Arraiján at the time of this study was residential. In 2014, 96.4% of IDAAN's registered clients were residential, representing 79.6% of billed water consumption (IDAAN 2015).

Figure 2.1: Examples of planned (left) and informal (right) residential growth in Arraiján.

2.1. Arraiján's drinking water system

The Arraiján network was supplied by three treatment plants that extracted water from the Panama Canal or its watershed. All three plants were owned and operated by entities separate from IDAAN, and IDAAN purchased water in bulk from the plants. Arraiján's distribution network was quite complex due to the large area it covered, its supply from three different treatment plants, and its complex topography, particularly in the areas where this study focused. A 2010 survey identified 504 km of pipe in the network; of these, 431 km were PVC and 10" or smaller in diameter, and 73 km were ductile iron and 12" or larger in diameter (Louis Berger Group 2010). Utility personnel reported that there were also small quantities of cast iron pipes and old asbestos-cement pipes in the network. Due to recent rapid growth, over half of the pipe network was less than 25 years old, although some portions were over 35 years old, according to utility personnel. Additionally, there were 27 pump stations in the network with capacities between 2 and 300 horsepower. The network had 39 storage tanks between 38,000 and 5.7 million liters in capacity, for a total volume of 27.3 million liters; but three of those tanks, with a total volume of 12.3 million liters, were out of service (Louis Berger Group 2010). In 2014, the 15 million liters of useful storage represented only 10% of the daily production of 154 million liters per day, a quantity insufficient to supply the network for one third of normal daily demand, the storage capacity called for in IDAAN's standards. Combined, the three treatment plants also had approximately 5.7 million liters of storage capacity available for Arraiján.

According to utility statistics, average water production in 2014 was 154 million liters per day. That production, divided by the population of Arraiján served by the utility (262,517 people, according to IDAAN 2015), represented a daily production of 585 liters per person. Of those 585 liters, only an average of 275 were billed to customers, representing a non-revenue water rate of 53%, including both physical losses (leakage from the distribution system) and commercial losses (water that arrived to users but was not billed).

Despite the ample quantity of water entering the distribution network from the treatment plants, some utility customers in Arraiján received deficient service. According to utility records, 6,420 clients (13% of the total number of registered clients in 2014) received a monthly discount on their water bills due to deficient service. At times a much larger number of clients temporarily suffered from deficient service due to events such as large pipe breaks or treatment plant stoppages. Some areas had chronic supply deficiency caused by: 1) insufficient local distribution capacity (pipe diameter, storage capacity or pump capacity) to supply the water demand in the area; or 2) drawing supply from parts of the network that frequently lost pressure when the capacity of the entire network was surpassed by high demand (for example, a Sunday when many users were at home) or a pipe break. In addition to those with deficient service, some users did not receive piped water at all and were supplied by tanker trucks contracted by the utility. A 2010 census found that 443 users in Arraiján were supplied by tanker trucks (Louis Berger Group 2010), but the number at the time of this research was probably higher, given that ten trucks distributed water fulltime.

2.2. Study zones and monitoring locations

Four zones in the Arraiján distribution network were identified that represented four different supply situations, three intermittent and one continuous. The zones were chosen based on interviews with utility operations personnel, field visits, and interviews with customers in each zone. Zones were selected based on three criteria:

- Having only one or two hydraulic entrances and no hydraulic exit, so that the flowrate and quality of all of the water entering the zone could be monitored.
- Being as large as possible, while still maintaining a supply regime with similar characteristics within the zone.[1]
- The infrastructure investments that IDAAN was undertaking were expected to improve supply in the intermittent study zones, so that the impacts could be evaluated in a future study.

The four zones chosen (and abbreviations used for them) were:

- Zone 1 (Z1): Continuous supply ("continuous" or "cont.")
- Zone 2 (Z2): Intermittent supply controlled by the level in an upstream storage tank ("tank-fed" or "tank")
- Zone 3 (Z3): Intermittent supply controlled by a valve ("valve-controlled" or "valve")
- Zone 4 (Z4): Intermittent supply controlled by intermittent pumping ("pump")

The location of the four study zones in Arraiján are shown in Figure 2.2. Also shown are upstream monitoring points, marked "TA" and "TB" for transmission pipe A and transmission pipe B, where samples were collected to verify the quality of water from the two water treatment plants (referred to as WTP A and WTP B) that supply the study zones. A fifth study zone (Zone 5), where only water quality samples were collected (see Chapter 3) is also marked on the map.

[1] For purposes of estimating the quantity of water supplied to each zone, the zones functioned as district metering areas. When creating district metering areas, it is normally recommended that the areas have between 500 and 5,000 connections so that they be small enough for pipe breaks and changes of flow to be detectable, but large enough to avoid the excessive expense of making many small zones (Savić and Ferrari 2014). For the water-quality component of this project, larger zones would also have included a greater variety of contaminant sources and pipe conditions. However, to maintain one type of supply in each zone, it was only possible to find smaller zones.

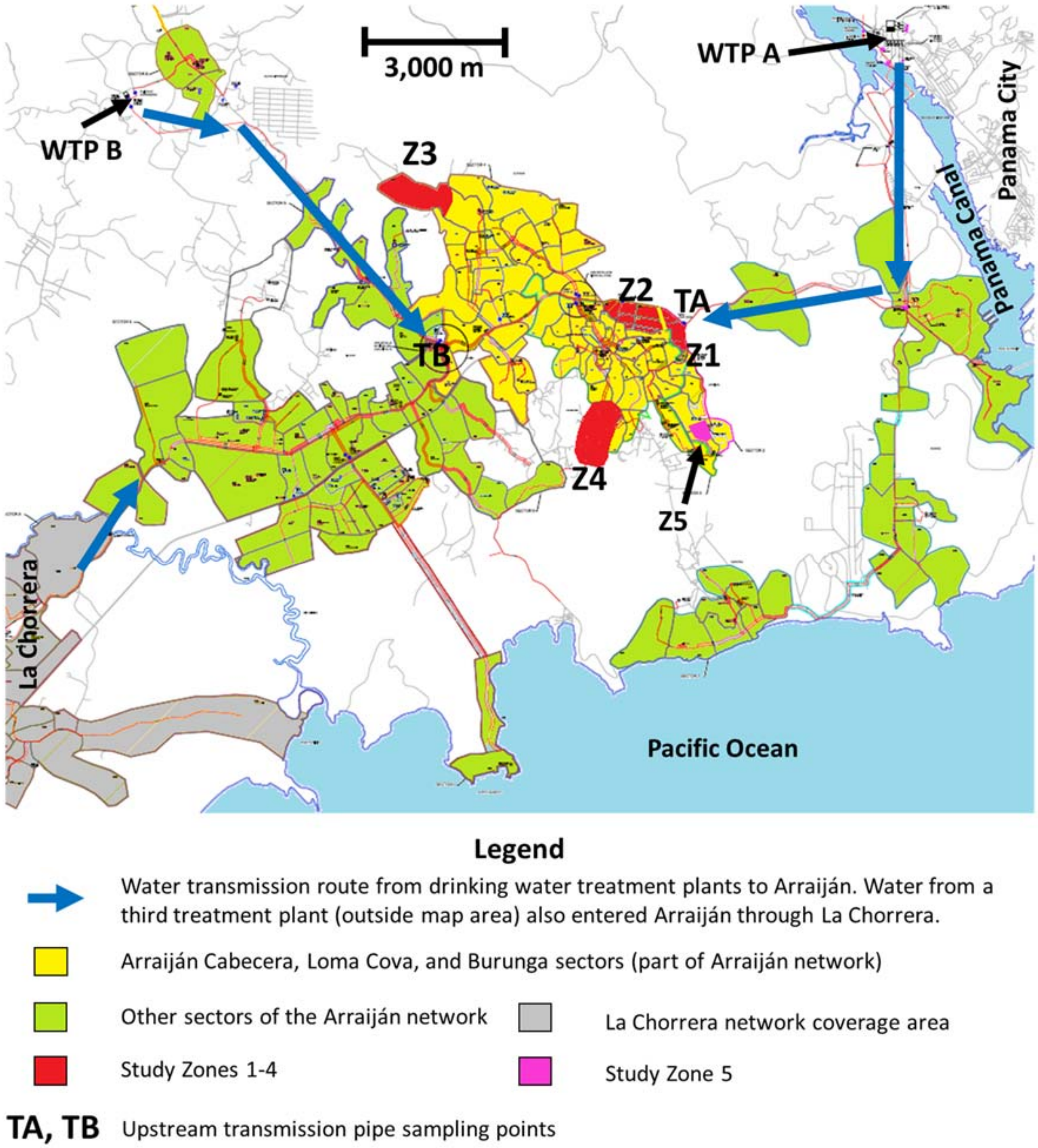

Figure 2.2: Location of the study zones and upstream monitoring points. Source: Modified from (Louis Berger Group 2010).

All four study zones were located in Burunga, Loma Cova and Arraiján Cabecera, contiguous sectors within the Arraiján network. Although the neighborhoods and housing developments in these three sectors varied in terms of urban development and water supply, many shared common characteristics that influenced water supply:

- The area's topography was complex, creating a need for pump stations.
- There were many informal housing settlements and a lot of unplanned and older (more than 30 years old) developments, factors which contributed to the complexity of the water network and often to a lack of data about its configuration.
- The network in this area depended on WTP A and WTP B, and did not receive water from the third treatment plant that supplied the western portion of Arraiján.

Below are satellite images of each zone with schematics showing zone boundaries, water pipes, and sampling points. Flowrate and pressure were continuously monitored at the entrance points (ENT) of each zone for one year. Additionally, pressure was monitored continuously at the downstream monitoring points (DS). Water quality (free chlorine residual and turbidity) was monitored continuously for periods of one to four weeks at a time, rotating monitoring equipment among the four zones. Routine grab samples and, at times, first flush samples, were collected at the ENT, DS and HT (household tap) locations. The entrance points for Zones 3 and 4 were outside the borders of the zones; the pipes that transmitted water to the zones from the entrance points did not connect to any houses or branching pipes outside the border of the zones.

Pressure and supply continuity varied spatially within each zone depending on elevation and distance from the entrance. The DS points were selected to represent a point far from the entrance, but the conditions there were not representative of the variety of conditions within the zone.

Zone 1: Continuous supply

- Source of supply: Direct from 24-inch (24”) transmission pipe from WTP A. Normally all of the water in Zone 1 was from WTP A. Water entered Zone 1 through two entrance locations, ENT1 and ENT2.
- Supply: Continuous.
- Number of buildings in the zone[2]: 348.

Figure 2.3: Schematic of Zone 1. (Sources for all satellite images and study zone schematics: Google Earth and IDAAN’s GIS database)

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[2] Includes houses and businesses, though the majority of the buildings in the study zones were houses. Buildings were counted using aerial photos of the area and the counts were verified with field surveys.

Zone 2: Intermittent supply controlled by the level of an upstream storage tank

- Source of supply: By gravity from a 7.6 million liter storage tank and a 6” pipe drawing water from a main transmission pipe. This zone normally received a mix of water from WTP A and WTP B.
- Supply: Depending on the elevation and the day, supply in Zone 2 varied between continuous and intermittent. The supply was controlled by the water level of the upstream storage tank, which changed depending on fluctuations in demand and pressure in the network. Even when the tank was empty, the lower elevations of the zone received water from the 6” pipe.
- Number of buildings in the zone: 650.

Figure 2.4: Schematic of Zone 2. Some differences between the network’s configuration in IDAAN’s GIS database and its actual configuration were found during field inspections to verify the isolation of this zone.

Zone 3: Intermittent supply controlled by the operation of a valve

- Source of supply: A local pump station that supplied water to Zone 3 and two other nearby sectors. This zone normally received water from WTP B.
- Supply: IDAAN's schedule called for supplying Zone 3 for three days and then closing a control valve for three days to stop supply to Zone 3 and fill a tank supplying another area. Even with the valve open, Zone 3 could lose supply if the pump station stopped.
- Number of buildings in the zone: 232.
- Note: Pressure and entrance flow were measured at ENT, directly downstream of the control valve for Zone 3. Since the pressure at ENT was routinely negative, water quality monitoring (grab samples and continuous chlorine and turbidity monitoring) was done at the pump station discharge (PD), where the pressure was positive.

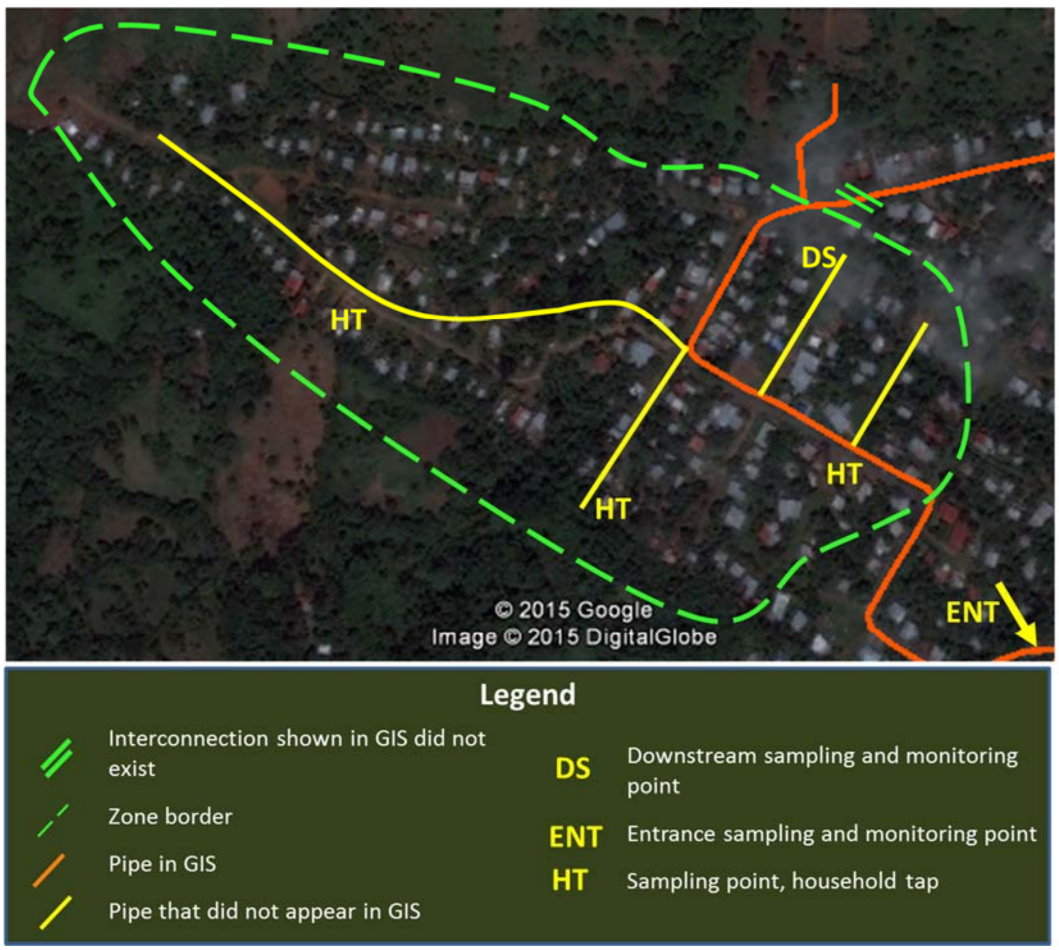

Figure 2.5: Schematic of Zone 3. The point where pressure and entrance flow were measured (ENT), was located outside the image, approximately 1 km to the southeast of the bottom right corner of the diagram. The pump station discharge (PD) where water quality grab samples were collected and continuous pressure, chlorine and turbidity monitoring took place, was located approximately 400 m to the south (upstream) of ENT.

Zone 4: Intermittent supply controlled by intermittent pumping

- Source of supply: Zone 4 normally received a mix of water from WTP A and WTP B via a 6” pipe from the Zone 4 pump station. A small quantity also entered via a 2” pipe near the DS monitoring station (with a check valve to prevent water from leaving Zone 4) coming from a different pump station. Initially, it was thought that these were the only entrances to the zone, and that they would be monitored by the ENT and DS stations. However, during the study it became apparent that the zone was not isolated as it was initially thought to be, since water also entered and left the zone through another interconnection.
- Supply: Intermittent according to the state of the Zone 4 pump station. Even when the Zone 4 pump station was off, some parts of Zone 4 received water through the 2” pipe from a different pump station or the interconnection with the adjacent sector. But, at times, even with the Zone 4 pump station on, the most distant parts of Zone 4 did not receive water.
- Number of buildings in the zone: 368.

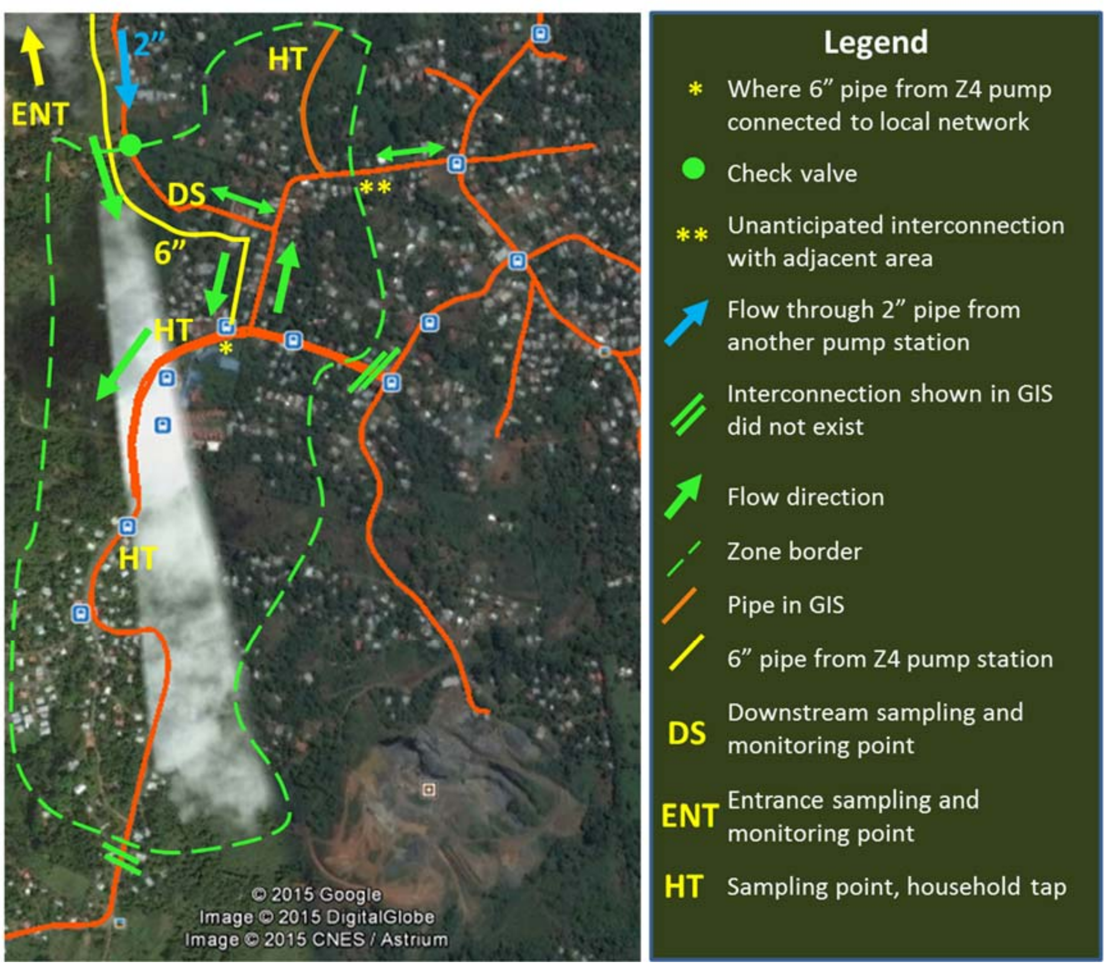

Figure 2.6: Schematic of Zone 4. The sampling and continuous monitoring point (ENT) was located at the discharge of the Zone 4 pump station, approximately 2 km north of the upper-right corner of this diagram.

2.3. Continuous monitoring methods

Nine monitoring stations were installed at the entrance(s) and a downstream point in each study zone to monitor hydraulic and water quality parameters. Figure 2.7 shows one of the monitoring stations and the sensors.

2.3.1. Monitoring stations

The monitoring equipment was installed in above-ground metal boxes. Each set of equipment was powered by a 12-volt battery charged with a solar panel installed on the top of the box. Each monitoring station was connected to the distribution pipe via a saddle installed on the pipe, a ½” PVC pipe, and a 3/8” PVC hose. Through this connection, pressure and water quality were monitored. At the entrance stations, insertion flow meters were installed on the buried pipe and connected to the monitoring equipment via a cable.

2.3.2. Pressure sensor and remote telemetry unit

Pressure was monitored with an ECO-3 RTU (remote telemetry unit, AQUAS Inc., Taipei, Taiwan). The pressure monitor normally recorded a measurement every 30 seconds (s). It also was programmed to record measurements more frequently when a pressure transient was detected. In addition to measuring pressure, the RTU received the signals from the other sensors, recorded the data, and sent them periodically to an internet server. The RTU also had the capacity to send text messages to the operator when pressure or other parameters went out of a programmed range.

At the Zone 3 entrance monitoring point (where sustained negative pressures were common), pressure was monitored by a LPR-31i pressure monitor (Telog Instruments Inc., Victor, NY). Data were downloaded from that sensor each week to a laptop computer.

2.3.3. Chlorine and turbidity sensors

Four sets of Q46/76 free chlorine and Q45H/62 turbidity sensors (Analytical Technology Inc., Collegeville, PA) were rotated among monitoring stations. These sensors were chosen for their low energy consumption and because they could function with low supply pressures. A check valve was installed upstream of the flow cells so that the cells would not empty when the supply pressure dropped below zero.

2.3.4. Flow meters

IP80 Paddle-wheel insertion flow meters (Seametrics Inc., Kent, WA) were installed at the entrance(s) of each zone. These sent an electrical pulse signal to the RTU.

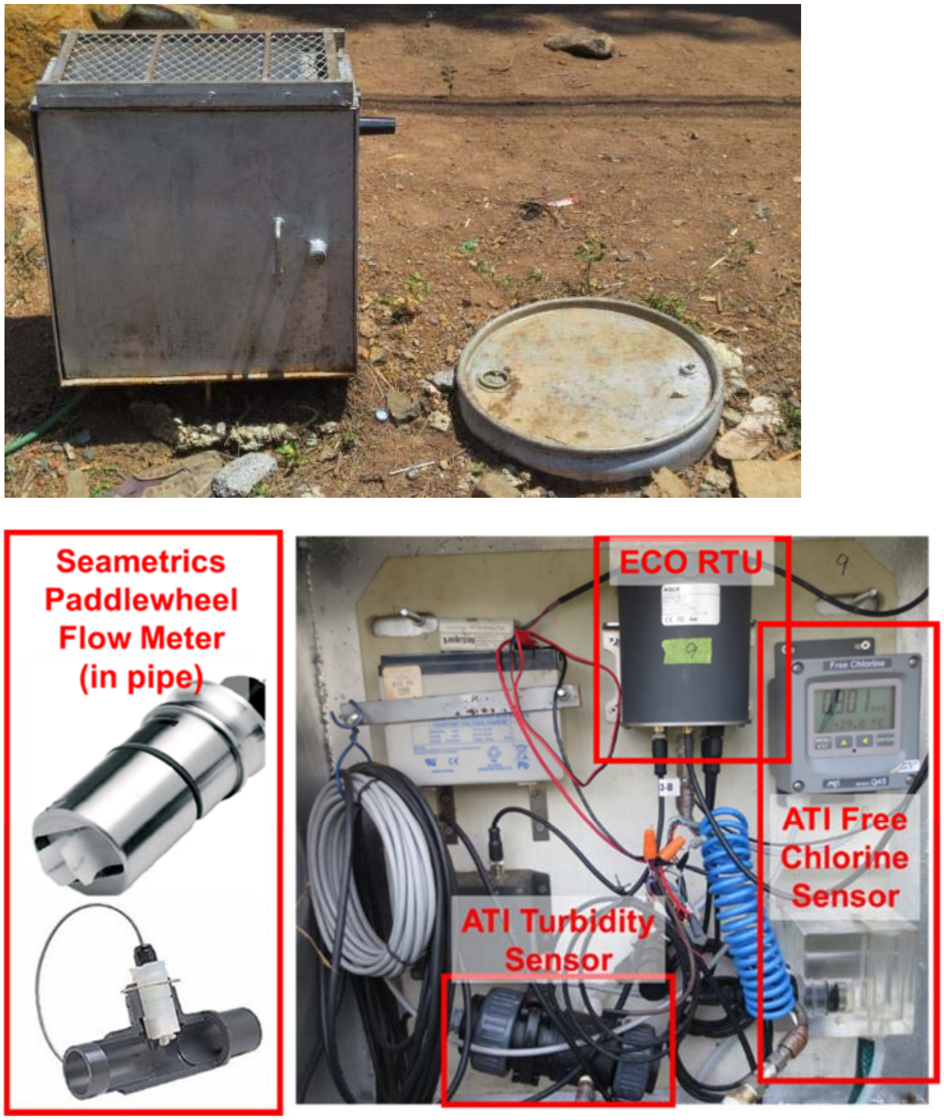

Figure 2.7: Continuous monitoring station (top) and sensors (bottom).

CHAPTER 3. Water quality effects of intermittent water supply

3.1. Introduction

This chapter focuses on the water quality effects of intermittent water supply (IWS) in the drinking water distribution system in Arraiján, Panama. Intermittent supply is considered a risk to microbiological water quality due to: 1) intrusion of contaminated groundwater via leaks in underground pipes or backflow of contaminated water through customer connections during periods of negative pressure (Besner, Prévost, and Regli 2011; Gadgil 1998; Lee and Schwab 2005; Vairavamoorthy, Gorantiwar, and Mohan 2007); 2) potential for microbial regrowth in bulk water, pipe-wall biofilm, and loose deposits while water is stagnant, and subsequent flushing and detachment of this regrowth when supply resumes (Coelho et al. 2003); and 3) recontamination and microbial regrowth during household storage (Coelho et al. 2003; Lee and Schwab 2005). Kumpel and Nelson (Kumpel and Nelson 2016) provided a comprehensive review of these mechanisms. In addition to these risks inherent to IWS, distribution systems in low and middle income countries often have additional deficiencies that can affect water quality, such as frequent pipe leaks and breaks (Lee and Schwab 2005), poor control of water quality entering the distribution network from treatment plants (Lee and Schwab 2005; Besner et al. 2002), and repair practices that do not adequately prevent contamination of the pipes being repaired (Besner et al. 2002).

Researchers conducting studies in India (Kelkar et al. 2001; Elala, Labhasetwar, and Tyrrel 2011; Kumpel and Nelson 2013), Palestine (Coelho et al. 2003) and Lebanon (Tokajian and Hashwa 2003) have found evidence of water quality deterioration in the distribution network or during household storage in intermittent networks; however, some of these studies were based on a small number of water samples and/or only showed an increase in the concentration of heterotrophic plate count (HPC) bacteria, which do not necessarily represent a health risk. Intermittent supply has been linked to a typhoid outbreak in Tajikistan (Mermin et al. 1999), a paratyphoid fever outbreak in India (Kapil et al. 1997), and diarrhea rates in a city in Uzbekistan (Semenza et al. 1998). In a recent review and meta-analysis assessing the impact of distribution system deficiencies on endemic gastro-intestinal illness, Ercumen, Gruber, and Colford (2014) found that temporary and chronic water outages under IWS were associated with gastro-intestinal illness.

Kumpel and Nelson (Kumpel and Nelson 2013) compared intermittent and continuously operated portions of the drinking water distribution system in Hubli-Dharwad, India and found that samples from intermittent parts of the network were positive for fecal indicator bacteria (*E. coli*) more frequently than samples from parts of the network where distribution pipes had been replaced and continuous supply had been implemented. In the intermittent areas, more contamination was found in water from household taps than in water from upstream storage reservoirs, with a higher incidence of contamination during the rainy season. In the intermittent zones there also was more contamination during the first flush after the supply re-started and during periods of low pressure (Kumpel and Nelson 2014).

Despite the high prevalence of intermittent supply globally, the variety of forms it takes, and concerns regarding its effects on water quality, few studies have characterized hydraulic and water quality conditions in these systems. Therefore, we monitored conditions in four zones of the distribution network in Arraiján, Panama, each one with different supply conditions, with the goal of better understanding relationships between intermittent supply and water quality. We also implemented continuous monitoring of pressure, turbidity and free chlorine residual, and compared continuous monitors versus grab samples for their usefulness as research tools and for utilities that operate intermittent distribution systems.

3.2. Materials and Methods

3.2.1. Study site

The research was conducted in the piped drinking water distribution network serving Arraiján, Panama, which is described in detail in Chapter 2. The Arraiján network was supplied by three treatment plants that extract water from Lake Gatun or other bodies of water connected to the Panama Canal. Treatment at all three plants included coagulation, sedimentation (or dissolved air flotation), rapid sand filtration, and disinfection with free chlorine. Free chlorine was also used as a residual disinfectant. The portion of the distribution system evaluated in this study received water from two of the water treatment plants (WTPs), referred to here as WTP A and WTP B.

As described in Chapter 2, five study zones within the Arraiján distribution network were chosen to examine the effects of different supply situations. Zones 1 through 4, and water supply conditions within them, are described in Chapter 2. An additional zone, referred to here as Zone 5, was selected for water quality monitoring. Water was normally supplied to Zone 5 every other day when a valve was opened to release water from a storage tank uphill of the zone. Supply periods ended when the tank emptied after one to several hours. Only first-flush sampling (see Section 3.2.4) was conducted in Zone 5.

Normally, Zones 1 and 5 received water exclusively from WTP A, Zone 3 received water exclusively from WTP B, and Zones 2 and 4 received a mix of water from the two plants. All zones had approximately 200 to 650 connections (not all legally registered with the utility), and pipe within the zones was ½”- to 6”-diameter PVC. None of the study zones had piped sewerage. Sanitation consisted of flush toilets connected to on-site septic systems, or pit latrines. In intermittent zones, most users stored water for drinking in small-neck plastic bottles or pitchers and water for other household uses in buckets or 55-gallon plastic barrels (often covered). Some users, particularly in Zone 3, stored water for drinking in buckets or barrels. A few houses had larger plastic ground-level or elevated storage tanks. At least one household in Arraiján was observed to pump water directly from the distribution network, but that practice was not the norm and no other houses in the study zones were observed pumping from the network.

3.2.2. Continuous turbidity, chlorine and pressure monitoring

Continuous monitoring stations were installed at entrance and downstream locations in Zones 1 – 4 as shown in Chapter 2. From August 2014 to August 2015 pressure was monitored with the Telog LPR-31i sensor at the entrance to Zone 3 and the ECO-3 RTU sensors at all other monitoring stations. All pressure sensors were programmed to normally record a measurement every 30 seconds (s). They were also programmed to record measurements more frequently when a pressure transient was detected. The Telog sensor recorded measurements every 0.05 s for a period of 40 s whenever pressure changed by > 10 psi within 10 s, and the ECO-3 recorded measurements every 0.1 s for a period of 2 minutes (min) when pressure changed more than 5% during 1 s. The Telog LPR-31i sensor was rated to measure pressure to -15 psi. The ECO-3 pressure sensor was not rated to detect negative pressures, but it registered negative pressures that appeared to be approximately accurate based on observation of transient waveforms following pump start-ups.

Four sets of Analytical Technology Inc. Q46/76 turbidity sensors and Q45H/62 chlorine sensors were rotated approximately every 2 weeks among the study zones so that each zone was monitored (entrance and downstream station[s] simultaneously) for a total of approximately 100 days. Pressure, turbidity and chlorine measurements were made every 30 s. Chlorine sensors were calibrated approximately every 2 weeks and before and after they were moved to a different station. The sensors were calibrated to the chlorine concentration in the flow leaving the sensor, measured with the Hach Pocket Colorimeter II used to analyze chlorine grab samples (see Section 3.2.5). Average absolute error was estimated to be 0.10 mg/L, with a very small bias (average over-registration of 0.003 mg/L), assuming sensor drift was linear between calibrations (Figure 3.1). Turbidity sensors were not calibrated, but at the end of the study the measurements of each sensor were confirmed to be within 20% of measurements made by the portable turbidimeter used to analyze grab samples.

Rainfall was also monitored at a location near the study zones to assess whether water quality varied according to rainfall, which would affect soil moisture and perhaps potential for intrusion.

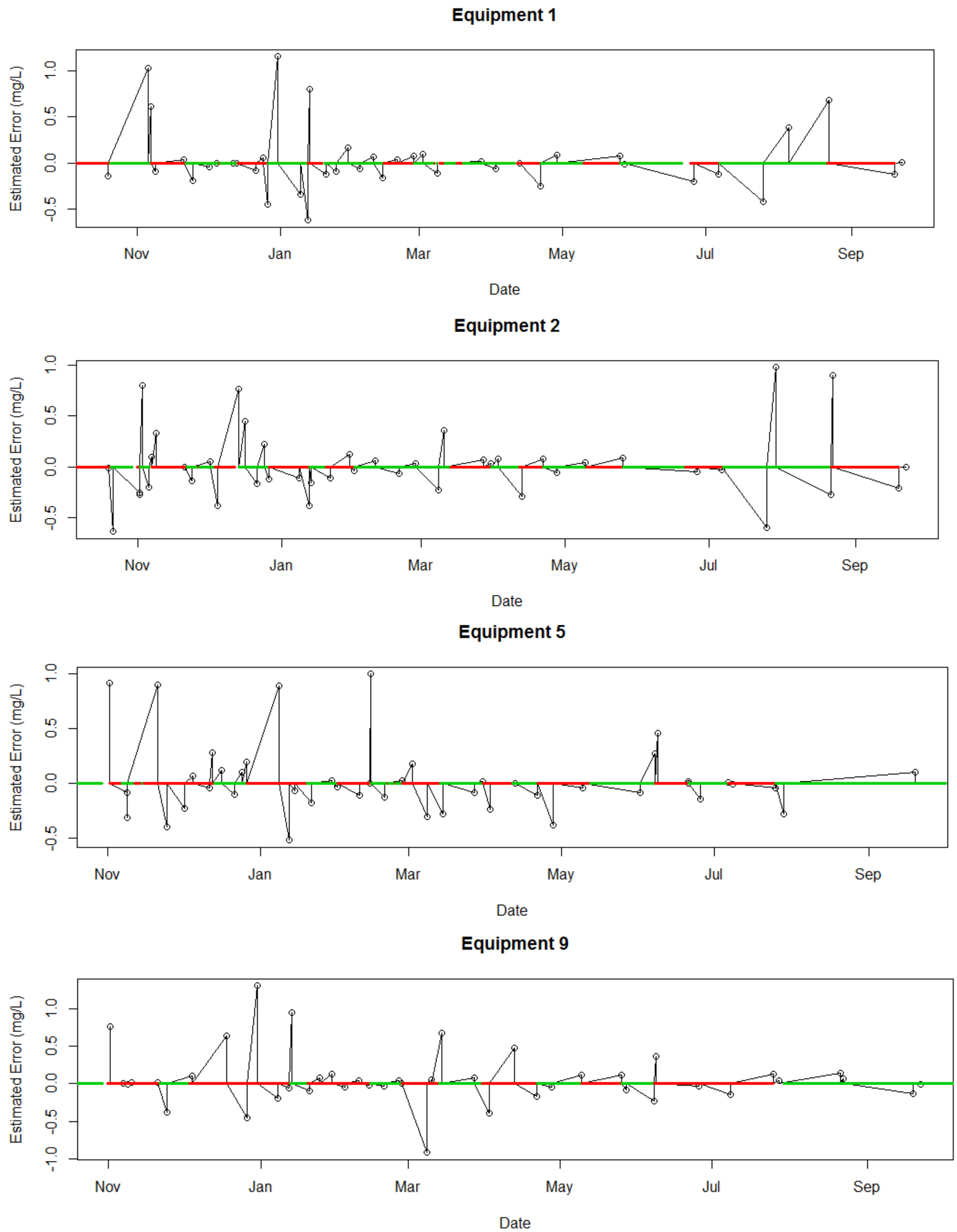

Figure 3.1: Estimated error for each of the four continuous chlorine sensors during the course of the study. At times where the thick line switches from red to green, a sensor was moved to a different location. Round points mark times when sensor was calibrated and error at that time.

3.2.3. Collection of routine grab samples

Water quality grab samples were collected from sampling taps in transmission pipes coming from each of the two treatment plants and from sample taps and household taps in Zones 1 – 4 (see maps of sampling locations in Chapter 2). On each day of sampling, samples were first collected from transmission pipes from each of the two treatment plants. Next, samples were collected from one to three study zones. For each study zone, samples were collected from the entrance continuous monitoring station, the downstream continuous monitoring station, and from taps in three houses. Samples were collected from household taps receiving water that came directly from the utility's network without passing through household storage tanks. When possible, the same three houses were sampled each time a zone was sampled; if no one was home in one of these houses, the sample was taken from another house as nearby as possible. All samples were collected between 7 am and 4 pm. When possible (58% of samples), the amount of time the water had been on at the time the sample was taken was estimated based on the customer's memory or continuous pressure monitoring data. The estimated time water had been on ranged from 15 min to over 1 week and was greater than 2 hours for 93% of samples for which a time could be estimated. When applicable, samples were collected in an upstream-to-downstream order. Since sample households within a zone were normally on different pipe branches, and not noticeably up- or downstream of one another, they were sampled in a random order. The order in which study zones were sampled was also randomized when possible.

Sample taps were disinfected with a 0.5% sodium hypochlorite spray and flushed for at least 1.5 min before sampling. Grab samples were analyzed for turbidity, free chlorine, and total coliform and *E. coli* bacteria, parameters typically used to monitor distribution system water quality (Ainsworth 2004). Some samples were also analyzed for aerobic spore-forming bacteria, which have been proposed in other studies (Cartier et al. 2009) as potential indicators for intrusion, and HPC bacteria, which, though not a public health concern themselves, are commonly used to assess distribution system water quality (Ainsworth 2004; WHO, NSF International, and IWA 2003).

3.2.4. First-flush sampling

Series of grab samples were collected to evaluate water quality during first-flush events (the first 2 hours of supply after an interruption) in the zones with intermittent service (Zones 2 - 5). When possible, samples for total coliform, *E. coli*, and HPC bacteria were collected from the first water that came out of the tap and after 1, 5, 10, 20, 30, 45, 60, 80, 100 and 120 min of supply. Samples for aerobic spore-forming bacteria were collected after 1, 5, 20, 60 and 120 min of supply. In addition to the programmed samples, extra bacteria samples were collected if high turbidity was noticed. Turbidity and free chlorine samples were collected and analyzed approximately every 5 min during the first 2 hours of supply. In addition to grab samples, during the majority of the first-flush events, pressure, turbidity and free chlorine residual were monitored continuously with the same sensors used for long-term monitoring.

Although first-flush sampling was intended to detect degradation of water quality occurring in the distribution pipes, bacterial regrowth in the monitoring stations' service lines (1/2" PVC pipe) and the sample hoses (3/8" flexible PVC hose) while supply was off could also have contributed to water quality degradation detected during first-flush sampling at the continuous monitoring stations. To test for this effect, six "mock" first-flush events were conducted at the downstream continuous monitoring stations in Zones 2 and 3. Before these mock events, sample taps were left closed and flow through continuous sensors was stopped for a time period similar to the stagnation period before the actual first-flush events, even though supply was on in the distribution pipe the monitoring station was connected to. After this period of simulated stagnation, samples were collected in the same way they would be during a normal first-flush event and analyzed for all water quality parameters except total coliform and *E. coli*.

3.2.5. Analysis of grab samples

Free chlorine residual (Pocket Colorimeter II and DPD, Hach Company, Loveland, CO) and turbidity (MicroTPW, HF Scientific Inc., Fort Myers, FL) were measured in the field. Chlorine samples were analyzed within 5 min of collection.

All bacteria samples were collected in sterile bottles with sodium thiosulfate to quench residual free chlorine. Samples were stored on ice or in a refrigerator after collection. Total coliform, *E. coli* and HPC samples were analyzed within 22 hours of collection (98% of samples within 18 hours and 92% within 12 hours). Spore samples were analyzed within 28 hours of collection.

One hundred mL samples were analyzed for total coliform and *E. coli* using Colilert reagents (IDEXX Laboratories, Inc., Westbrook, ME) and quantified using the most probable number method with Quantitray 2000 trays (IDEXX Laboratories, Inc.). Samples were incubated at approximately 35° C (incubation temperatures ranged from 31° to 38.5° C, with 92% of samples incubated between 33° and 37° C) for 22 to 39 hours (92% of samples were incubated between 22 and 28 hours, and all samples incubated more than 28 hours were negative). All but one of the 143 lab and field blanks analyzed for total coliform and *E. coli* were negative. The positive blank was positive for total coliform but not *E. coli,* and was collected during a first-flush event when none of the other samples were positive for total coliform or *E. coli*.

Some HPC samples were diluted with sterile water by up to a factor of 100 (according to the expected HPC concentration based on previous results) for a final volume of 100 mL and then analyzed for HPC with an IDEXX reagent and Quantitray 2000 trays. The HPC samples were incubated at between 34° and 38.5° C for 45 to 75 hours (92% of samples between 64 and 76 hours). Samples of 2.0 liters were analyzed for spore-forming bacteria according to the membrane filtration method detailed by Cartier et al. (2009), with some differences: trypticase soy broth was used instead of trisaline buffer; the samples were sealed in plastic bags and pasteurized in an air oven for 17 min instead of a water bath for 15 min; and the plates were incubated at 37° C instead of 35° C. Incubation times ranged from 20 to 26 hours. HPC and spore concentrations measured in field blanks are shown in Figure 3.5 and Figure 3.7 in the Results section.

3.2.6. Water quality standards and data analysis

Panama's water quality standards (Ministry of Commerce and Industry, Panama 1999) stipulate that piped drinking water should have turbidity ≤ 1.0 NTU, free chlorine residual of 0.8 – 1.5 mg/L, 0 CFU/100 mL *E. coli* and ≤ 3 CFU/100 mL total coliform bacteria. We used these standards for comparative analysis, with two exceptions: we mainly use the World Health Organization (WHO) standard of ≥ 0.2 mg/L free chlorine residual (WHO 2011) and, because incidence of total coliform bacteria was low, we report all samples with ≥ 1 MPN/100 mL total coliform.

Data analysis methods were similar to those reported by Kumpel and Nelson (2013). Microbial detection limits varied depending on the sample volume collected and the dilution factor. Values of one half the lower detection limit were substituted for values below the lower detection limit and the upper detection limit was substituted for values above the upper detection limit. As in (Kumpel and Nelson 2013), statistical tests of significance were performed on ranked values of water quality parameters using permutation tests. These methods were chosen because the use of ranked values accounts for censoring of indicator bacteria at lower and upper detection limits, and permutation tests do not require any assumptions about the distribution of the data. The statistical package R (R Core Team 2012) was used for graphing and data analysis and the coin package (Hothorn et al. 2015) was used for permutation tests. Values were considered significant at $p < 0.05$ level.

3.3. Results

3.3.1. Continuous pressure monitoring

Low pressures in distribution pipes are inherent to intermittent supply (during non-supply periods). Pressure was monitored for 269 to 355 days at the continuous monitoring stations in each study zone. Pressure was < 2 psi at ground level (low enough so that a tap 0.7 meters above the ground will not have supply) at the downstream station for 0.9% of the time in continuous zone (Zone 1), 17% in the tank-fed zone (Zone 2), 43% in the valve-controlled zone (Zone 3) and 5.8% in the pumped zone (Zone 4). Average pressure at the downstream continuous monitoring station when supply was on (≥ 2 psi at ground level) was 21.9 psi in Zone 1, 37.9 psi in Zone 2, 35.5 psi in Zone 3 and 47.2 psi in Zone 4.

Negative pressures were observed in some instances. At the entrance to the valve-controlled zone (Zone 3), located at the crest of a hill, steady-state negative pressures were routinely measured as water was siphoned over the hill (Figure 3.2). Over 269 days of total monitoring, pressure at the level of the pipe was < -1 psi 40% of the time and < -5 psi 18% of the time. For some of these times, the valve controlling Zone 3 was closed and water was not flowing into the zone. During the 184 days of pressure monitoring when water was flowing into Zone 3, pressure at the level of the pipe was < -1 psi 36% of the time and < -5 psi 18% of the time, and the minimum pressure recorded was -14 psi.

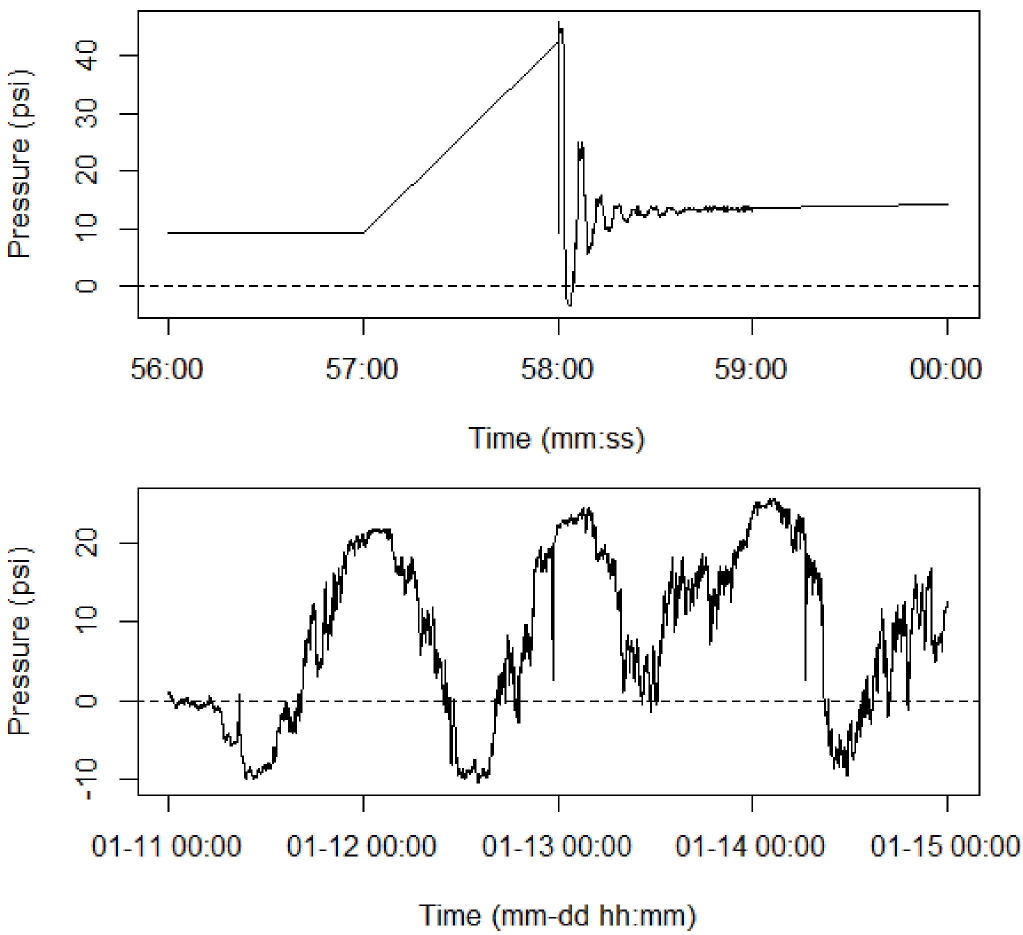

Figure 3.2: Examples of negative pressure events. Top: Negative transient pressure during startup of Zone 4 pump. Bottom: Sustained negative pressures at the entrance to Zone 3 (valve-controlled).

Transient negative pressures were registered at the entrance to Zone 4, located at the discharge of the pump station that operated intermittently (Figure 3.2). During 351 days of monitoring, pressures < -1 psi (at pipe level) were recorded 83 times for a total duration of 107.1 s, with each event lasting 0.1 to 5.1 s. Pressures < -5 psi were recorded 18 times for a total duration of 24.9 s, with each event lasting 0.1 to 3.4 s. Events that occurred within 2 s of one another were grouped together, but total duration only includes the time that pressure was actually below the pressure threshold. The lowest pressure recorded from a transient at the pump station discharge was -10.6 psi.

During occasional supply outages in the continuous zone (Zone 1), negative pressures were also measured at the monitoring stations at the entrance to the zone, including a brief transient down to -5.6 psi on one occasion.

Pressure monitoring was not conducted in Zone 5; however, during first-flush sampling there it was noted that at the end of most supply cycles air was heard and felt being sucked into the household taps used for sampling, indicating negative pressures as the pipes drained at the end of the supply cycle. These negative pressures could be particularly problematic, since many customers in Zone 5 used hoses to fill storage tanks and the ends of the hoses were sometimes submerged in the tanks, creating an opportunity for backflow.

3.3.2. Routine grab samples

A total of 500 grab samples was collected between October 2013 and March 2015. The number of samples taken from each type of sampling point that was analyzed for each parameter is shown in Table 3-1. Not all samples were analyzed for all parameters, because the 65 samples collected before February 2014 were not analyzed for coliform and *E. coli*, and a few samples were not analyzed for chlorine or turbidity due to malfunctioning equipment.

Table 3-1: Number of samples collected by location and analysis type.

Sample location type	Free chlorine	Turbidity	Total coli. and *E. coli*
Transmission pipe	93	93	91
Zone entrance station	94	95	88
Zone downstream station	82	81	79
Household tap	229	227	165
Total samples	498	496	423

Of 419 samples analyzed for all parameters, only 12 (2.8%) had turbidity > 1 NTU or coliform bacteria present, and all had ≥ 3 mg/L chlorine residual. A total of four samples (0.9%) were positive for total coliform, and one of those was positive for *E. coli*. Nine samples (1.8%) had turbidity > 1.0 NTU. Those samples are discussed at the end of this section. Median turbidity was 0.18 NTU from the WTP A transmission pipe, 0.26 NTU from the WTP B transmission pipe, 0.25 NTU from zone entrance stations, 0.25 NTU from zone downstream stations and 0.22 NTU from household taps. The distribution of turbidity measurements for samples with turbidity ≤ 1 NTU is shown in Figure 3.3.

The distribution of free chlorine residual measurements is shown in Figure 3.4. The minimum chlorine residual measured was 0.3 mg/L; 17 samples (3.4% of all samples), all of them in Zones 2 and 4, were below 0.5 mg/L; and 186 samples (37%) were below the Panamanian standard of 0.8 mg/L. The free chlorine concentrations from the transmission pipe from WTP B were significantly higher than that of WTP A (two-tailed permutation test for independence), contributing to chlorine concentrations in Zone 3, which received water only from WTP B, that were significantly higher than chlorine concentrations in the other three zones (two-tailed permutation test for independence).

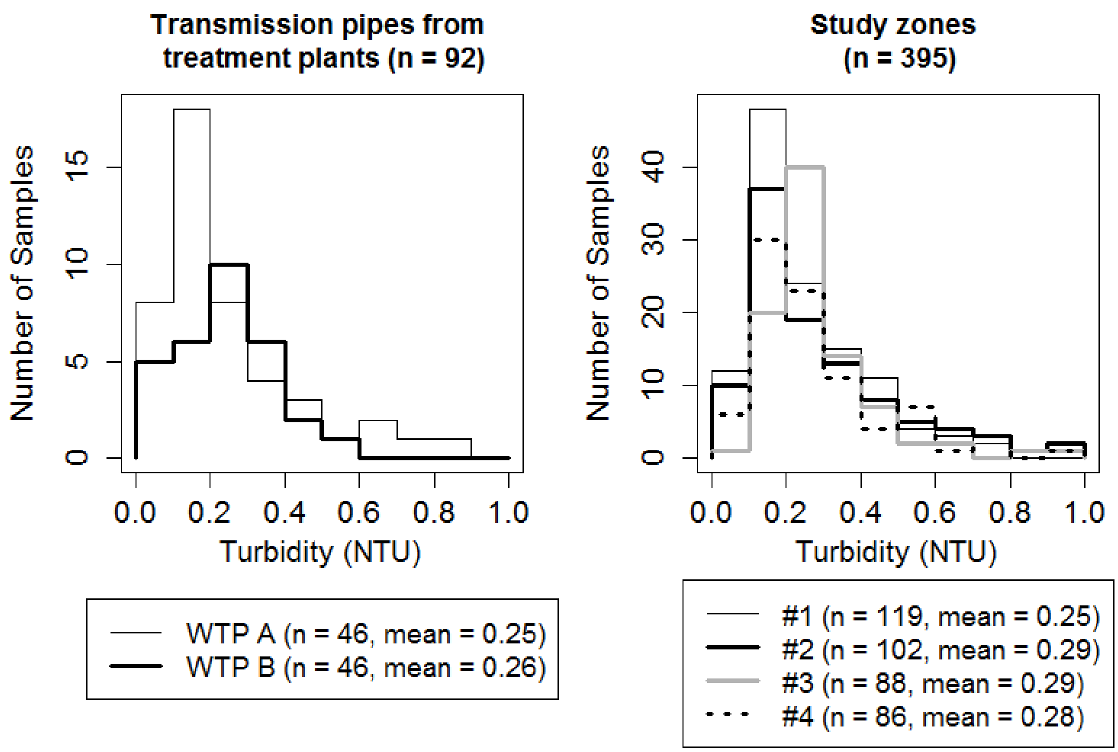

Figure 3.3: Distribution of turbidity measurements by sampling location. Samples with turbidity > 1 NTU are excluded from the histograms, sample counts, and means.

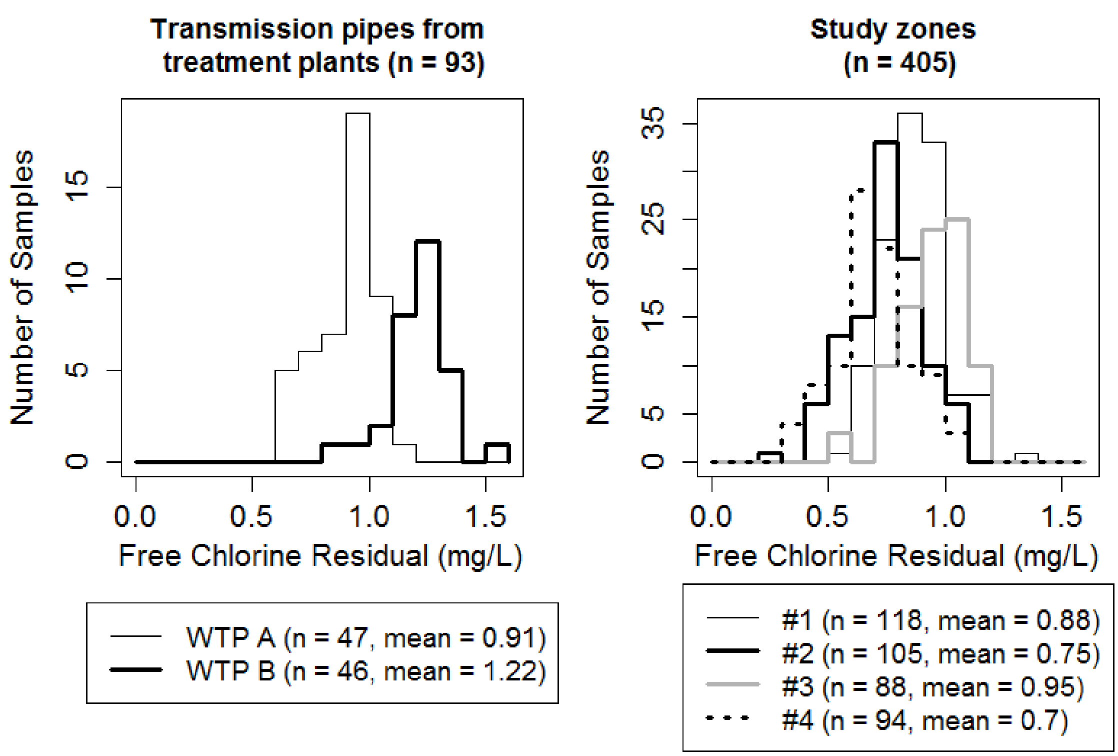

Figure 3.4: Distribution of free chlorine measurements by sampling location.

The HPC concentrations ranged from non-detect (< 1 CFU/100 mL) to 479 CFU/100 mL. Aerobic spore-forming bacteria concentrations ranged from non-detect (< 0.05 CFU/100 mL) to 16 CFU/100 mL (Figure 3.5). The HPC and spore concentrations were significantly greater in samples from the transmission pipe from WTP B than from WTP A (two-tailed permutation test for independence, $p = 0.02$ for HPC and $p = 0.002$ for spores). Nine of 30 field blanks were positive for HPC and one of nine was positive for spores; however, HPC concentrations from each of the transmission pipes and study areas were significantly greater (one-tailed permutation test for independence) than concentrations in field blanks, and spore concentrations were significantly greater than field blanks for all areas except the WTP A transmission pipe.

In Zones 1 and 3, the only two zones that received supply from just one treatment plant, HPC concentrations were significantly higher than in the treated source water (TA and TB respectively in Figure 3.5, two-tailed permutation test for independence), which suggests that regrowth or intrusion occurred in distribution system and/or premise plumbing. Spore concentrations in Zones 1 and 3 were not significantly different from concentrations in the treated source water. Some countries recommend that HPC levels in piped drinking water be < 500 CFU/mL, over 100 times greater than concentrations in the routine Arraiján samples, though that recommendation was originally made based not on the health effects of HPC, but because high HPC levels can interfere with some methods for total coliform testing (WHO, NSF International, and IWA 2003; Ainsworth 2004). Spore concentrations similar to those found in Arraiján have been found in treatment plant effluent in other municipal drinking water systems (Cartier et al. 2009). The HPC and spore concentrations in the routine Arraiján samples provide an estimate of background levels to which concentrations during first-flush events can be compared.

Samples positive for total coliform or with turbidity > 1 NTU are detailed in Table 3-2. The high turbidities on 2014-04-23 were because of contamination in the transmission pipe from WTP A, due to construction to reroute the pipe. The high turbidities and presence of total coliform and *E. coli* in Zone 4 on 2014-10-20 were associated with the repair of a break in the pipe that transmits water to the zone. High turbidity from the transmission pipe from WTP A on 2014-10-09 was associated with higher than normal turbidity (0.92 NTU) at the WTP A effluent on that day, according to plant operator data. Since only one plant effluent turbidity measurement was available per day, plant effluent turbidity could have been higher at a different time that day. The causes of the other high turbidities and coliform positives are unknown, but all but one of them were from household taps and thus could be from contamination in domestic plumbing. Three of the samples with coliform bacteria or high turbidity were collected within 1 hour of the start of supply, which could have contributed to contamination.

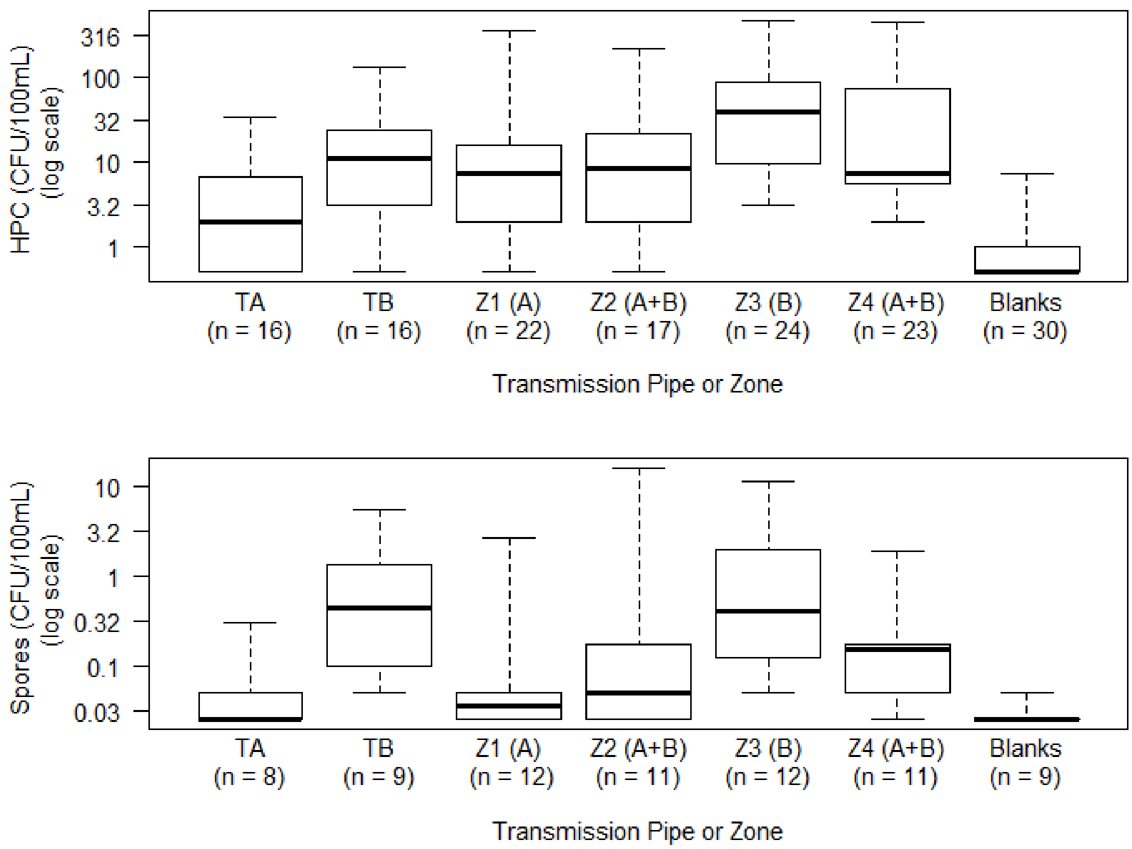

Figure 3.5: HPC and aerobic spore-forming bacteria concentrations in grab samples. A, B or A+B after zone number denotes which WTP(s) the zone received water from. Non-detects are plotted as 0.025 CFU/100mL, half the detection limit. Blanks include only those collected during routine grab sampling. First-flush blanks are reported with first-flush results.

Table 3-2: Samples with turbidity > 1.0 NTU or positive for total coliform. Abbreviations: BDL = Below Detection Limit; NA = Not Available; TA = Transmission pipe from WTP A; HT = Household Tap; CM-DS = Downstream Continuous Monitoring Station; CM-ENT = Entrance Continuous Monitoring Station.

Date (yyyy-mm-dd)	Zone / WTP	Sample point	Turb. (NTU)	Free chlorine residual (mg/L)	Total Coliform (MPN / 100 mL)	*E. coli* (MPN / 100 mL)	Hours since start of supply	Cause
2014-04-23	2	HT	7.3	0.77	BDL	BDL	NA	Construction
2014-04-23	2	CM-DS	6.16	0.50	BDL	BDL	NA	Construction
2014-04-23	2	HT	6.52	0.53	BDL	BDL	16	Construction
2014-06-03	1	CM-ENT	0.14	1.04	2.0	BDL	>168	Unknown
2014-06-03	4	HT	1.37	0.31	BDL	BDL	1	Unknown
2014-10-09	WTP A	TA	1.03	0.87	BDL	BDL	NA	WTP effluent
2014-10-09	2	HT	0.50	0.53	45.7	BDL	NA	Unknown
2014-10-20	2	HT	0.50	0.53	8.5	BDL	15	Unknown
2014-10-20	4	CM-DS	83.45	0.31	4.1	1.0	0.75	Pipe break/repair
2014-10-20	4	HT	3.43	0.47	BDL	BDL	0.5	Pipe break/repair
2014-12-18	4	HT	2.67	0.58	BDL	BDL	NA	Unknown
2015-02-02	4	HT	2.76	1.00	BDL	BDL	NA	Unknown

3.3.3. First-flush sampling

Between June 2014 and March 2015, samples were collected during 33 first-flush events (13 events at a downstream continuous monitoring station and 20 events from household taps). In some first-flush events, very little variation in water quality was detected (example, Figure 3.6a). For 11 of the 33 events, all samples were negative for total coliform and *E. coli*, and had turbidity ≤ 1.0 NTU and chlorine > 0.2 mg/L. In other events, water quality was degraded during the first minutes of supply, with elevated turbidity, elevated concentrations of HPC and aerobic spore-forming bacteria, and low free chlorine (example, Figure 3.6b). Total coliform and *E. coli* were detected in some of those events.

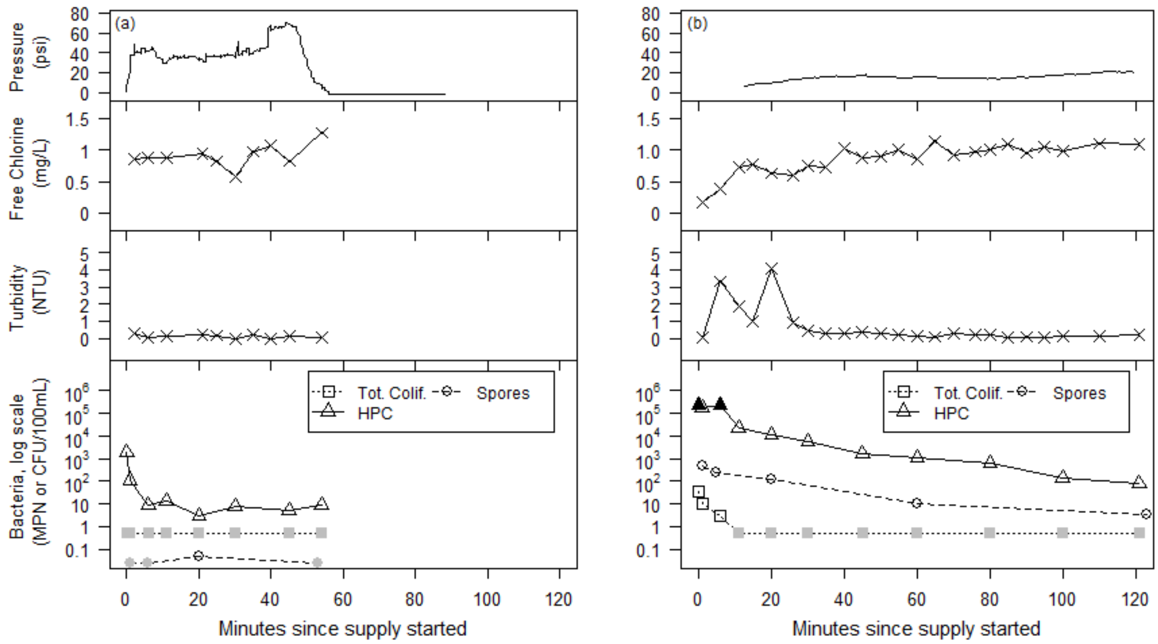

Figure 3.6: Examples of first-flush events (a) where little variation in water quality was detected (Zone 5, household tap, after 47-hour supply interruption during the dry season) and (b) where considerable water quality variation was detected (Zone 3, household tap, after 3-day supply interruption during the rainy season). Pressure is reported at ground level. Some pressure variations in (a) are due to other household taps being opened and closed during monitoring. In the bacteria graphs, black symbols mark samples above the detection limit (plotted at detection limit) and grey symbols mark samples below the detection limit (plotted at ½ the detection limit).

For each first-flush event, the average of the three highest values for each water quality parameter (or, for chlorine, the average of the three lowest values) is shown in Figure 3.7 (by sample location) and Figure 3.8 (by the amount of time supply had been off). For seven of the 33 events, one or more samples collected were positive for total coliform. Across all events, four samples were positive for *E. coli* (data not shown). The four samples positive for *E. coli* were from four different sampling events in Zone 3 and were all during the first 11 min of supply. In two of the events with *E. coli* and total coliform, only the sample of the first water to come out of the tap was positive for *E. coli* or coliform. Although the outside of the tap was disinfected with sodium hypochlorite, bacteria within the tap could have been the source of this contamination. The other two samples positive for *E. coli* were from simultaneous sampling events at two different Zone 3 locations at beginning of the same supply period.

Many events without coliform bacteria had elevated HPC and spore concentrations (Figure 3.7) as compared to the concentrations in routine grab samples shown in Figure 3.5, indicating that water quality was altered even without the presence of coliform and *E. coli*. Of 29 events where free chlorine was measured, nine had samples with chlorine < 0.5 mg/L and five had samples with chlorine < 0.2 mg/L.

In 20 events, at least one sample had turbidity > 1 NTU and in six events at least one sample had turbidity > 5 NTU. Turbidities > 100 NTU were detected in three events associated with pipe breaks. Figure 3.9 shows water quality results for pipe break events in Zones 4 and 5. Intrusion from the pipe breaks was associated with notably higher turbidity, spore and HPC concentrations. In the case of the break in Zone 5 (Figure 3.9b), high turbidity was measured during the last minutes of the supply period shown in the figure and the first minutes of the next supply period two days later. The pipe probably broke at approximately 60 min into the first supply period, where a pressure drop is visible, and turbid water entered the network when the pressure dropped during the last minutes of supply.

Factors that could potentially influence water quality during first flush include amount of time supply had been off, rainfall, and local conditions (contaminant sources, pipe leaks, water table, etc.). Samples from rainy and dry seasons are shown separately in Figure 3.7 and Figure 3.8. It is difficult to determine which factors were most associated with water quality degradation. For instance, first-flush water quality was most degraded in Zone 3 (the valve-controlled zone), where all total coliform positives after ≥ 1 minute of supply, all chlorine residuals below 0.2 mg/L, and the highest HPC concentrations occurred (Figure 3.7). However, supply interruptions tended to be longer in Zone 3 and water quality tended to be more degraded when supply had been off for a long time (Figure 3.8). Thus, it is difficult to know whether degraded water quality in Zone 3 was due to supply being off for a long time or other factors associated with Zone 3. Three of four events with *E. coli* positives and five of seven events with total coliform positives were after rainy weather, but no other clear qualitative associations between rainy weather and extreme values of water quality parameters are observed.

The percent of samples meeting water quality criteria as a function of time since supply started is shown in Figure 3.10 (two events associated with pipe breaks and one event where a pump stopped during the sampling period were excluded because these circumstances affected the water quality during first flush). After ≥ 20 min of supply all but one of the events (97%) were free of total coliform and after ≥ 60 min of supply all events were free of total coliform. After ≥ 20 min of supply, 73% of events remained below 1000 MPN/100 mL HPC, 83% of events remained below 10 CFU/100 mL spore concentration, 80% of events remained below 1 NTU turbidity, and 89% of events remained above 0.5 mg/L free chlorine. A larger portion of dry-weather events were below 1 NTU and 10 CFU/100 mL spore concentration by 20 min of supply, as compared to rainy-weather events, but given the small sample size and that other covariates could affect the results, this difference may not indicate an actual effect of rainfall. Comparing among study zones, Zone 3 started with the lowest portion of events within thresholds for all water quality parameters and took the longest time for all events to be within limits for bacteriological parameters.

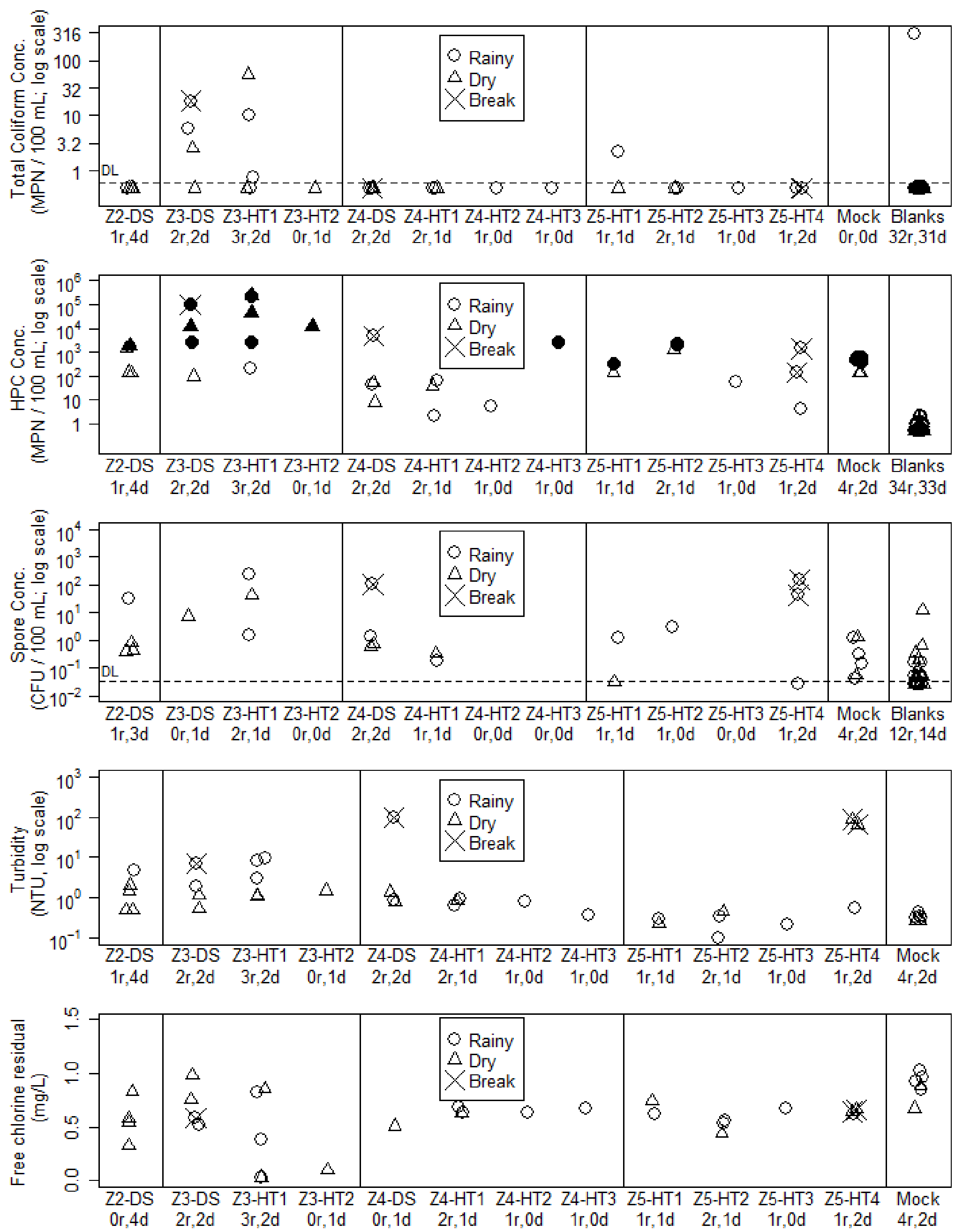

Figure 3.7: Extreme values of water quality parameters during first-flush events, by sampling location ("DS" = downstream continuous monitoring station and "HT" = household tap). Reported values are the average (arithmetic for turbidity and chlorine and geometric for bacteria) of the three highest (lowest for chlorine) samples for that event. The number of dry- ("d") and rainy-weather ("r") samples collected is shown below each location. ≥ 1.0 cm rainfall during the last seven days was considered rainy weather. "Blanks" include only field blanks collected during first-flush sampling. Events associated with a pipe break are marked by an X in addition to the normal Rainy/Dry symbol. The horizontal dotted line in the bacteria graphs, represents the lower detection limit (DL). No detection limit is shown for HPC, because it varied from 1 to 100 MPN/100 mL depending on dilution. Points filled with black represent events where at least one of the three samples was above the detection limit.

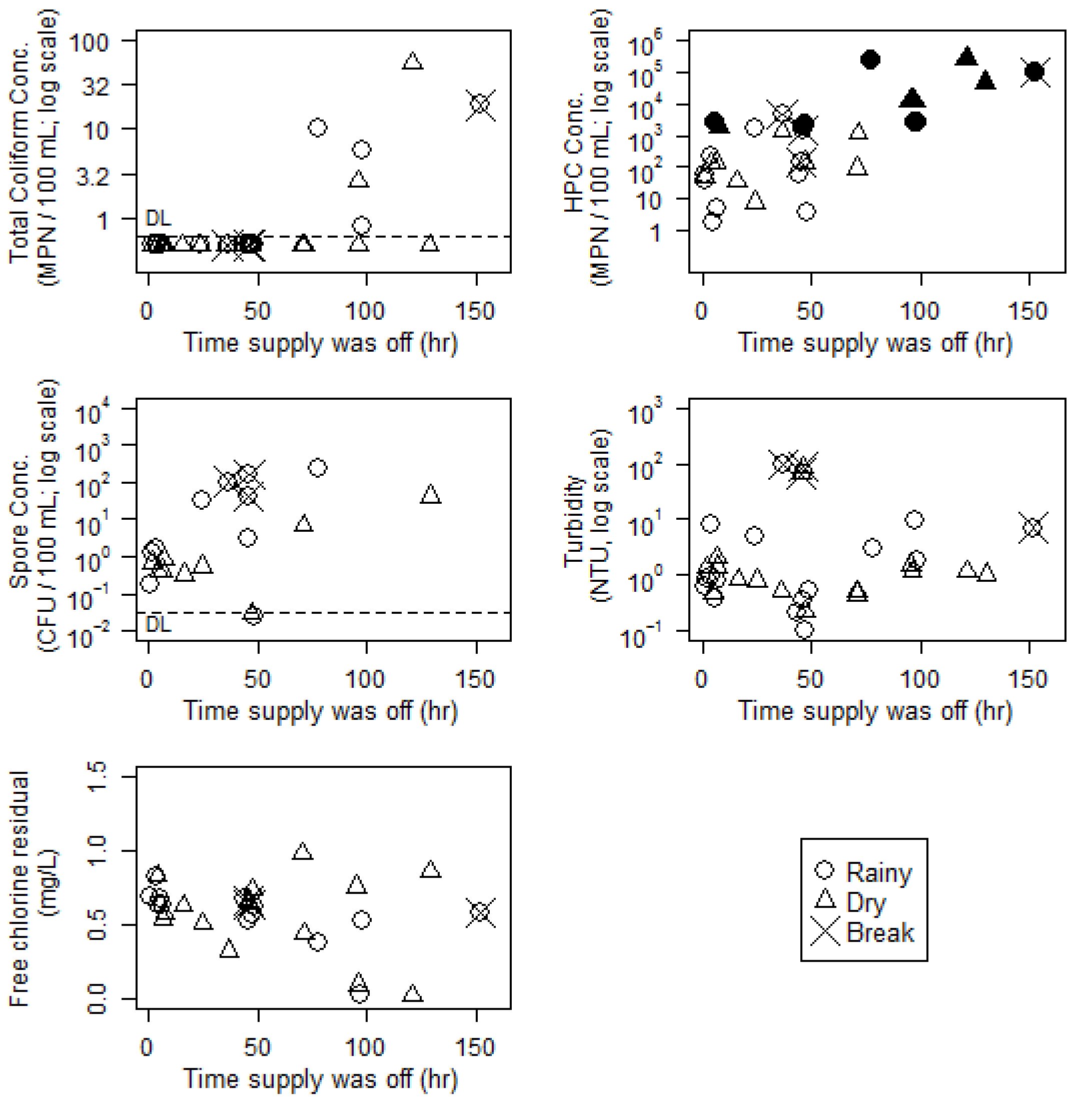

Figure 3.8: Extreme values of water quality parameters during first-flush events vs. hours supply had been off. Reported values are the average (arithmetic for turbidity and chlorine and geometric for bacteria) of the three highest (or lowest for chlorine) samples for that event. Events associated with a pipe break are marked by an X in addition to the normally Rainy/Dry symbol. The horizontal dotted line in the bacteria graphs represents the lower detection limit (DL). No lower detection limit is shown for HPC, because it varied from 1 to 100 MPN/100 mL depending on dilution. Points filled with black represent samples above the detection limit.

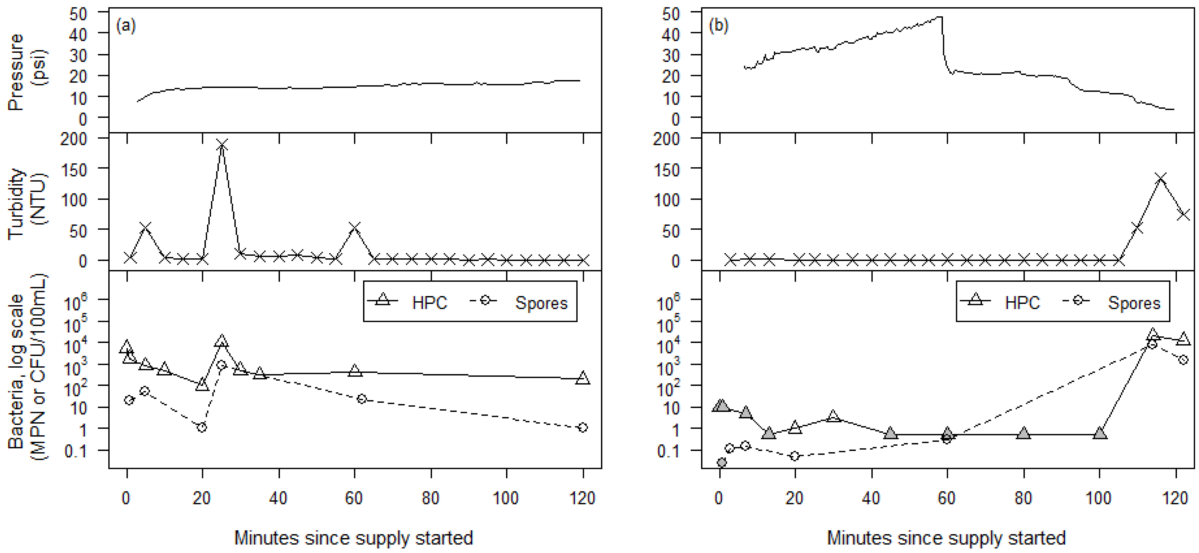

Figure 3.9: Two first-flush events related to pipe breaks in Zones 4 (a) and 5 (b). Pressure is adjusted to ground level. All total coliform samples during these events (not shown) were negative. Free chlorine was only measured during the Zone 5 event (not shown), during which it was consistently approximately 0.7 mg/L, except for the two high-turbidity samples near the end of the supply when it dropped to 0.65 and 0.57 mg/L. In the bacteria graphs, symbols shaded grey mark samples below the detection limit. The detection limit was higher for some samples than for others because they were diluted more.

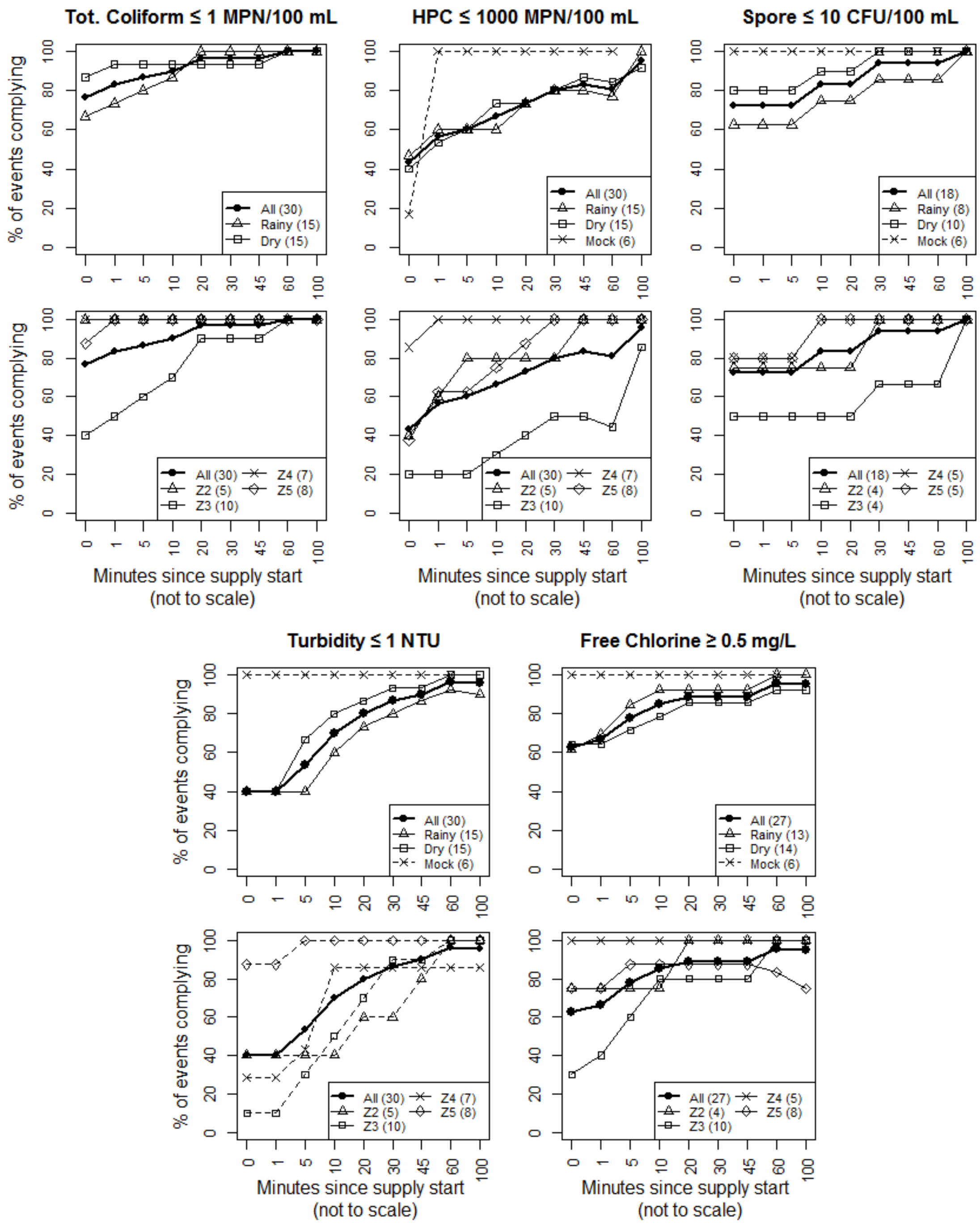

Figure 3.10: Portion of first-flush events where water quality parameters were within a given threshold for all samples after a given time. For example, for 9 of 10 events (90%) in Zone 3, all samples taken after ≥20 min of supply were negative for total coliform. Numbers of events in each category are shown in parentheses in legends. For some events sampling for some or all parameters ended before 100 min of supply, either for logistical reasons (running out of sample bottles for instance) or because supply ended. In those cases, for later times those events were removed from both the numerator and denominator used to calculate the portion of events within the threshold. For Z5 chlorine and Rainy turbidity this resulted in a decrease in the portion of events within the threshold after a given time.

Turbidity and chlorine were also measured continuously during most of the first flush events where grab samples were collected. Apart from discrepancies during the first few minutes of supply (likely due to challenges detailed in 3.3.4), continuous monitoring data were generally in agreement with chlorine and turbidity grab sample data and did not show high turbidities or low chlorine residuals that were not already captured in grab sample data.

3.3.4. Effect of regrowth in monitoring station pipes and hoses on first-flush results

As explained in Section 3.2.4, "mock" first-flush events were sampled to evaluate the extent to which altered water quality during the first flush was due to bacterial regrowth in sample pipes and hoses. Extreme parameter values from the mock first-flush trials are shown in Figure 3.7. Maximum spore concentration (overall maximum of 3.3 CFU/100 mL) and turbidity (overall max of 0.56 NTU) and minimum free chlorine residual (overall minimum of 0.61 mg/L) during the mock events were not noticeably different from background values during routine grab sampling (see Section 3.3.2; mock flushes were conducted in Zones 2 and 3), indicating that regrowth in the service pipe and sample hose did not significantly affect first-flush measurements of those parameters. However, maximum HPC concentrations after ≥ 1 min of mock supply ranged from 129 to 488 MPN/100 mL, higher than typical HPC concentrations for routine grab samples and higher than maximum HPC concentrations for some of the real first-flush events, but still more than 100 times lower than maximum HPC concentrations for a few of the first-flush events. These results indicate that first-flush HPC concentrations below approximately 1000 MPN/100 mL may be background concentrations due to regrowth in the sample apparatus, but that concentrations above that level are likely the result of high HPC concentrations in water coming from the distribution pipes. Figure 3.10 also includes mock first-flush results. All mock samples were above 0.5 mg/L free chlorine and below 1 NTU, 10 CFU/100 mL spore concentration and 1,000 MPN/100 mL HPC concentration (with the exception of mock first-flush HPC samples taken at 0 min, immediately when the mock event began), indicating that the effect of regrowth in sample pipes and hoses did not have an important effect on samples after 1 min of supply.

3.3.5. Continuous turbidity and chlorine monitoring

Continuous turbidity and chlorine monitoring was used to evaluate water quality over a larger cross-section of times and conditions than was possible with grab sampling. For instance, grab sampling captured only 33 first flush events, but continuous turbidity and chlorine monitoring at the downstream stations captured 400 events. Similarly, while only 500 routine grab samples were collected, continuous monitoring included approximately 2.4 million turbidity and free chlorine measurements, taken every 30 s over approximately 20,000 hours (counting monitoring time at each station separately).

Although it characterized water quality over a longer cross-section of time, continuous monitoring had important limitations. Continuous monitoring took place only at the downstream monitoring stations connected directly to the distribution network, so did not capture any effects premise plumbing may have had on water quality. Additionally, the ability of the continuous sensors to accurately capture water quality during the first flush was limited. Although mock first flush data (see Section 3.3.4) showed that regrowth in continuous monitoring station hoses and pipes did not have an important effect on chlorine and turbidity, the potential for air from pipes to be expelled through sensor flow cells during the first-flush events made measurements during the first minutes of supply unreliable (see Figure 3.11). To remove unreliable data, continuous turbidity and chlorine data from the first 10 min of each first-flush event were discarded. A first-flush event was considered to begin when pressure first increased to 1.5 psi at the level of the water quality sensor flow cells, which was enough pressure to produce sufficient flow through the sensors. The 10-min threshold was chosen because, after that time, continuous first-flush turbidity and chlorine data appeared to be free of interference from air expulsion and were in approximate agreement with grab samples when grab samples were collected.

Despite limitations, continuous monitoring allowed for comparisons of water quality between different times in the supply cycle and between different monitoring locations. Even after discarding the first 10 min of first-flush data, Figure 3.12 shows that high turbidities were more frequent when supply had recently begun, particularly in Zone 2. This trend was not as evident in Zone 1, but there were only four supply interruptions during continuous water quality monitoring in that zone, so very few first-flush data were available. With the exception of Zone 2, chlorine did not follow a clear trend of being lower when supply had recently begun (Figure 3.13). In the case of Zone 3, the trend was the opposite for chlorine, with lower chlorine concentrations more frequent when supply had been on longer. That reverse trend could be due to a tendency for water age to be lower, and thus chlorine decay to be less, when supply began and pipes were filling. Figure 3.12 and Figure 3.13 show that first-flush grab sample data were similar to continuous data, with all samples after 10 min < 1 NTU and > 0.5 mg/L except for in Zone 2.

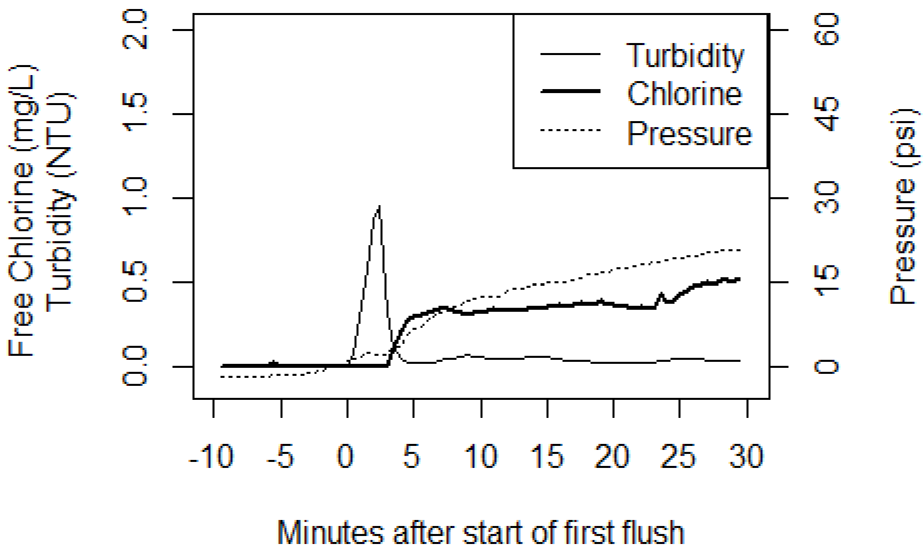

Figure 3.11: Example of continuous monitoring data with inaccurate water quality measurements during the first minutes of supply. The initial peak in turbidity while the free chlorine measurement was 0 appears to be due to air being expelled through the water quality sensors.

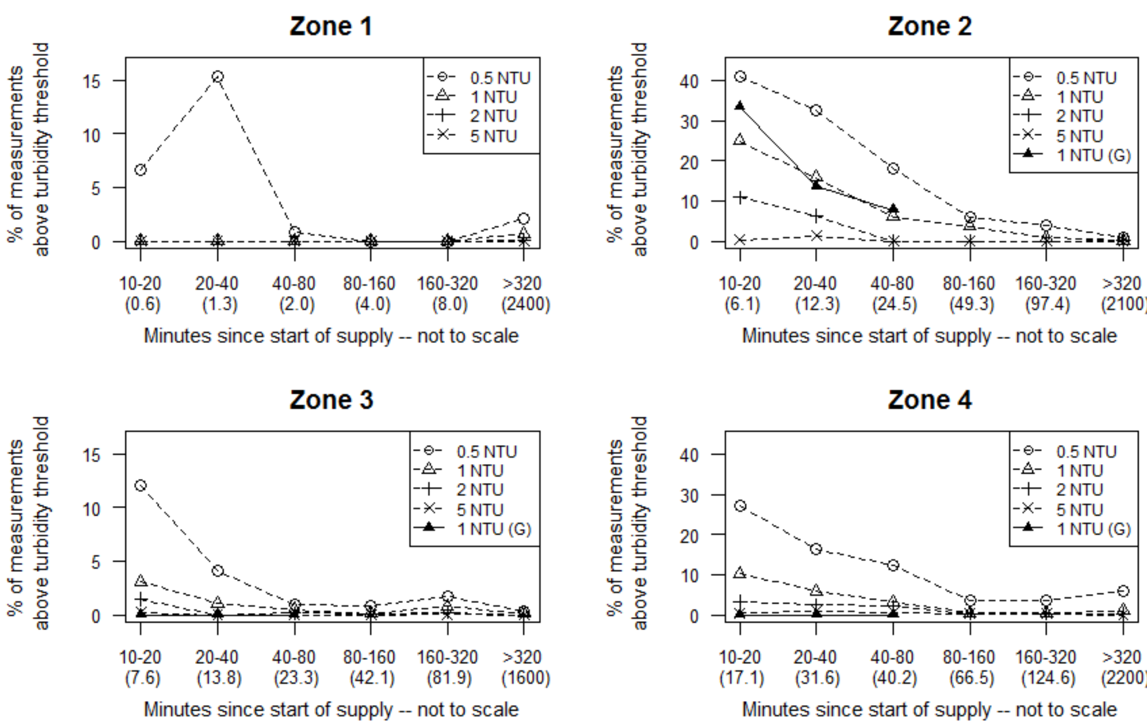

Figure 3.12: Portion of time during continuous monitoring when measurements were above different turbidity thresholds for ranges of time since supply started. Measurements were normally made every 30 s. Hours of data in each time category are shown in parentheses below the x axis labels. Note that the y-axis scale varies between graphs. For Zones 2-4, solid lines with filled triangles show the portion of first-flush grab samples (G) from the downstream continuous monitoring stations that had turbidity > 1 NTU.

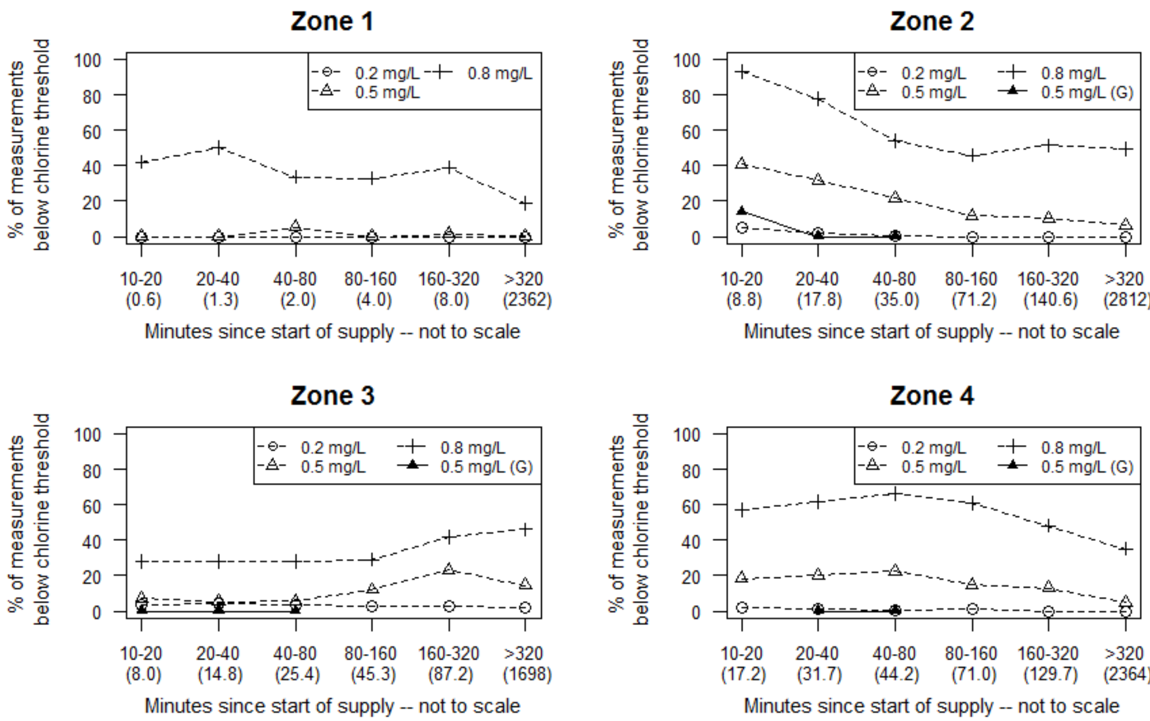

Figure 3.13: Portion of time during continuous monitoring when measurements were below different chlorine thresholds for ranges of time since supply started. Measurements were normally made every 30 s. Measurements during the first 10 min of supply are not shown because they were unreliable. Hours of data in each time category are presented in parentheses below the x axis labels. For Zones 2-4, solid lines with filled triangles show the portion of first-flush grab samples (G) from the downstream continuous monitoring stations that had < 0.5 mg/L chlorine.

Some events with turbidity > 1.0 NTU were detected by continuous sensors at the downstream monitoring locations when supply had already been on for 2 hours or more (Table 3-3). Any instance with turbidity > 1.0 NTU for at least two consecutive measurements was considered a high turbidity event. Only data where pressure was at least 1.5 psi at the level of the water quality sensor flow cells were analyzed. Sometimes multiple events occurred within a short amount of time. Any group of events where less than 1 hour passed between neighboring events was considered to be one event cluster, but the duration only includes time when the turbidity was > 1.0 NTU. For each event cluster detected by a computer algorithm, a graph of pressure and turbidity at the zone's downstream and entrance monitoring locations was visually inspected to try to determine the likely cause.

Table 3-3: Summary of events at downstream continuous monitoring locations with turbidity > 1.0 NTU for at least two consecutive measurements. To exclude the effects of first flush, only events occurring after supply had been on for 2 hours are included. *Causes of "Other" events: 46 events in Zone 4 were associated with the startup or shutdown of one or both of the two pumps at the entrance to the zone; two events in Zone 4 were associated with pipe breaks; one event in Zone 2 was associated with decreasing pressure as supply ended. †Events where cause was "Unknown": in some cases no turbidity data were available at the zone entrance, so it was unclear whether the event was an isolated spike or associated with high upstream turbidity; in other cases upstream turbidity was higher than normal, but < 1 NTU, and it appeared that an additional isolated spike caused the downstream turbidity to be > 1 NTU.

Study Zone	Days of data		# of events > 1 NTU							Total duration > 1 NTU (hours)	# of events with max turbidity > 5 NTU
						Caused by:					
	Total	With water on	Total	Total lasting > 10 min	Total duration (hours)	High turbidity at zone entrance	Isolated spike	Other*	Unknown†		
Zone 1	102	101	22	9	15.4	12	6	0	4	15.4	0
Zone 2	117	94	23	5	3.5	3	13	1	6	3.5	0
Zone 3	132	73	4	3	2.2	2	2	0	0	2.2	1
Zone 4	108	102	60	24	21.9	4	3	48	5	21.9	10

Figure 3.14 shows examples of non-first-flush events with downstream turbidity > 1 NTU. Zone 4 had the largest number (60) of high turbidity events. Forty six event clusters were associated with the startup or shutdown of one or both of the pumps in the pump station that pumps water to Zone 4. These pump changes caused abrupt changes in velocity and likely in the direction of flow in some pipes, which could have suspended loose deposits. Negative pressures were also measured during pump startup and shutdown and could have caused intrusion of turbid water into distribution network pipes. In 18 of the startup or shutdown event clusters, the first pump or both pumps started, which amounted to a first flush leaving the pump station. However, since water could enter Zone 4 from other portions of the network, pressure was often still positive at the downstream monitoring station, meaning that some of these events were not first-flush events at the downstream location. The highest turbidities were also measured at the downstream location in Zone 4, with peak turbidities of > 22 NTU during 6 events, all of them associated with pump starts or stops.

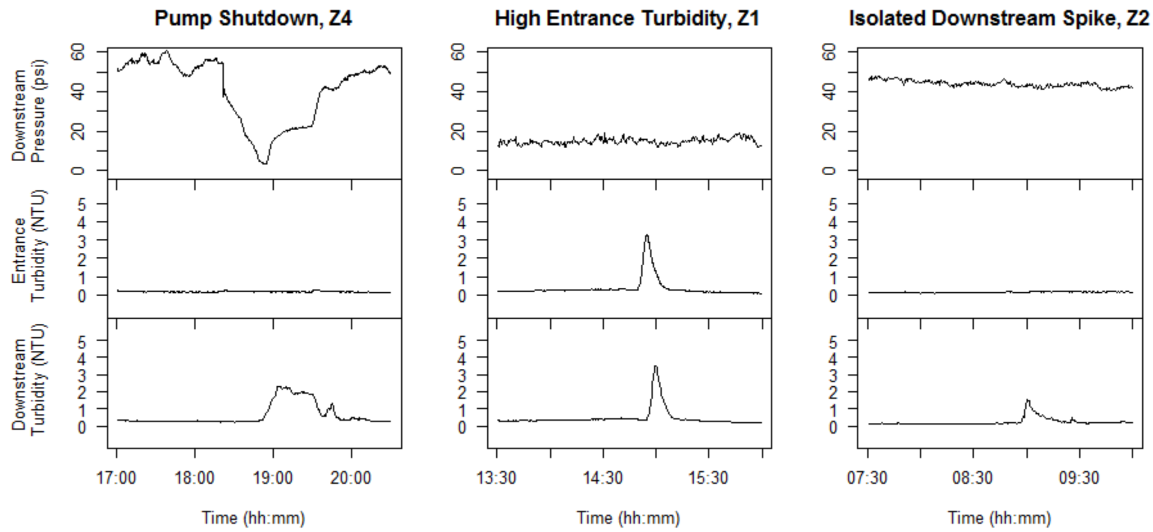

Figure 3.14: Examples of different types of events where turbidity reached > 1 NTU. In the "Pump Shutdown" event, the pump stopped at approximately 18:20.

Most of the high turbidity events in Zone 1 were associated with high upstream turbidity, and most in Zone 2 were isolated spikes. All zones had isolated turbidity spikes. Such spikes, which lasted from 0.5 to 17.5 min and reached peak turbidities of up 3.7 NTU, could be due to biofilm detachment, suspension of loose deposits, or intrusion of turbid water in distribution network pipes. However, intrusion does not appear to be a likely cause, since they occurred at times when pressure was stable and not low. Most of the turbidity spikes were probably not related to expulsion of air from distribution pipes, since chlorine measurements, which would likely also be affected by air, were normally stable during the turbidity spikes. Zones 3 and 4 had fewer isolated spikes, perhaps because more frequent emptying of pipes and velocity changes in these zones prevented loose deposits that caused such spikes from building up.

All zones also had turbidity events associated with high turbidity at the zone entrance. These events lasted from 1 min to 6.5 hours, reached peak turbidities of up to 3.5 NTU, and could have been caused by high turbidity at the treatment plant effluent or contamination upstream in the distribution system. The turbidity events associated with high entrance turbidity in Zone 1, which is directly connected to a large transmission pipe from WTP A, must have been due to high turbidity at the plant effluent or contamination in the transmission.

An identical analysis was carried out with the continuous free chlorine data at the downstream monitoring locations to identify events with chlorine residual < 0.2 mg/L after at least 2 hours of supply. No credible events with chlorine < 0.2 mg/L were identified. Chlorine measurements dropped below 0.2 mg/L on six occasions at the downstream location in Zone 3 and two occasions at the downstream location in Zone 4, and these measurements were associated with lower than normal and/or unsteady chlorine concentrations at the entry point to the zone, but it also appeared that the downstream chlorine sensors were not accurately calibrated at the time and, had they been accurately calibrated, the measurements would not have dropped below 0.2 mg/L. Similarly, it is possible that at some times sensors were miscalibrated in the other direction and chlorine concentrations that were actually below 0.2 mg/L were not detected. Nevertheless, the data are accurate and complete enough to show that chlorine residuals were almost always above 0.2 mg/L at the downstream monitoring locations.

3.4. Discussion

Pressure monitoring in the intermittent study zones detected low and negative pressures that were a risk for intrusion and backflow. In addition to extended periods of low and zero pressures between supply periods, pressure sensors and qualitative observation uncovered transient and sustained negative pressures during supply periods that created a hydraulic gradient for backflow and intrusion. Despite low and negative pressures, water quality monitoring showed little evidence of contaminant intrusion in the study zones, with the exception of some first-flush events and pipe breaks and repairs.

3.4.1. Potential reasons for less contamination in Arraiján

Routine and first-flush water quality was much better in Arraiján than in intermittent areas of the distribution system in Hubli-Dharwad, India that was studied using similar methods (Kumpel and Nelson 2014; Kumpel and Nelson 2013). In Hubli-Dharwad, 32% of grab samples from taps in intermittent supply areas were positive for *E. coli* and 56% had turbidity > 5 NTU. Several factors could explain low turbidity and low incidence of coliform and *E. coli* bacteria in the intermittent Arraiján study zones:

1. Supply was less intermittent in Arraiján than in Hubli-Dharwad where, on average, households in intermittent areas reported receiving water for only 5 hours once every 6 days. Supply pressure was also higher in the Arraiján study zones than in Hubli-Dharwad, where, of 21 supply cycles where pressure was monitored, mean pressure was below 10 psi for 5 cycles and below 20 psi for 17 (Kumpel and Nelson 2014). Additionally, the use of household pumps to extract water directly from distribution pipes, which can lead to negative pressures in the pipes, was not as common in Arraiján as in some parts of Hubli-Dharwad.

2. Few contaminant sources in Arraiján may have been in proximity to leaks in drinking water pipes. None of the study zones had piped sanitary sewerage, such that no sanitary sewer pipes were in proximity to drinking water pipes. Development was not very dense in the study zones, and most septic tanks and latrines were located behind houses, at a considerable distance from drinking water pipes running in front of the house. Open concrete storm sewer gutters or unlined ditches were often in proximity to drinking water pipes, but given that almost all households had access to latrines or septic tanks, fecal contamination levels were likely low in these ditches and gutters.

3. Adequate free chlorine residual likely suppressed regrowth of coliform bacteria in the Arraiján distribution system and, in the event of intrusion, could have inactivated total coliform and *E. coli* as long as the chlorine demand in the intruding water did not deplete the chlorine residual. A microbial risk assessment for virus infection due to intrusion in drinking water distribution systems found that 0.2 mg/L free chlorine residual provided significant protection from virus infection (LeChevallier et al. 2011), and *E. coli* is more susceptible to chlorine than typical viruses (LeChevallier, Au, and World Health Organization 2004). In contrast to the Arraiján results, free chlorine residual at customer taps in Hubli-Dharwad was below 0.2 mg/L for 31.7% of samples in continuous supply areas and 61.1% of samples in IWS areas.

Consistent chlorine dosing at treatment plants and low water age in the study zones likely contributed to consistently adequate chlorine residual at customer taps in Arraiján. Approximate calculations based on flows from the treatment plants and transmission pipe and storage tank volumes indicate that water age was normally between 2 and 24 hours in the study zones. Low water age may be common in intermittent systems, since they generally suffer from inadequate distribution system storage capacity, in contrast to distribution systems in high-income countries that are designed to provide adequate capacity for future demand and fire flows (AWWA 2002b). Although Panama's relatively high standard of 0.8 mg/L free chlorine residual was not always met, attempts to meet it may have helped keep residual above 0.2 mg/L. While striving for high levels of disinfectant residual may provide a safety factor, operators should carefully consider whether they could result in problematic levels of disinfection byproducts (DBPs) (USEPA 1999). Assessment of DBPs was beyond the scope of this study.

Many bacteria, enteric viruses and protozoa are more resistant to inactivation with chlorine than *E. coli* (LeChevallier, Au, and World Health Organization 2004). If fecal contamination entered the distribution system, some pathogens could have persisted even though coliform bacteria were inactivated. Further research should investigate the prevalence of relevant chlorine-resistant pathogens, such as *Cryptosporidium*, *Giardia lamblia* and Coxsackie virus (35), in chlorinated intermittent distribution systems.

4. High-quality drinking water treatment plant effluent in Arraiján almost certainly contributed to better water quality at the tap in comparison to Hubli-Dharwad. Fourteen samples taken from the Hubli-Dharwad treatment plants had turbidity between approximately 2 to 10 NTU and 5 of them were positive for total coliform bacteria.

5. The size and number of study zones may have limited detection of contamination from intrusion events. Each study zone contained only approximately 2 to 6 km of pipe. Had the study zones been larger or more numerous, the probability of there being a contaminant source in close proximity to pipe with a leak would have been greater. The small size of the study zones was a limitation of the study, but also was a result of the fact that supply areas affected by IWS in Arraiján tend to be small, a factor that may reduce actual risk of contaminant intrusion. Contaminant intrusion may be more likely in systems where larger areas experience IWS, even if hydraulic conditions and contaminant source prevalence are the same. With larger IWS areas, water will pass through a greater length of pipe affected by IWS and will be more likely to pass a point of contaminant intrusion.

3.4.2. Opportunities for improvement

Although typical water quality met Panama's national standards (apart from free chlorine residual, which met WHO recommendations), opportunities for improvement were identified:

1. Water quality was most degraded during the first 20 min of supply after an outage, particularly in the valve-controlled zone (Zone 3), were supply outages were longest. Reducing the duration of outages and/or avoiding consumption of first-flush water may reduce public health risks associated with IWS. Feasibility of avoiding the consumption of first-flush water will depend on users' household storage practices and infrastructure. In the intermittent Arraiján study zones, most users filled drinking and cooking water storage containers manually, which would allow them to control when the containers are filled. However, in cases where users store drinking and cooking water in automatically filled tanks, it will be more difficult to avoid consuming first-flush water. Although it would result in wasting water, it may also be possible for system operators to open purge valves when supply is first turned on so that first-flush water does not reach customer taps. However, this would only protect from contamination originating from principal water mains, because it would be more difficult to purge all small-diameter branches and customer service lines.

2. Pressure monitoring detected negative pressures, the most severe of which were at the entrance to Zone 3, that are a clear risk factor for intrusion and could perhaps be avoided by making changes to the configuration of the distribution network.

3. Pipe breaks and repairs were associated with high turbidities and the only routine sample positive for *E. coli*. The utility could reduce contamination from breaks and repairs by following best practices for pipe repairs (Kirmeyer et al. 2014) and installing additional valves to be able to better isolate pipes for repair.

This research provided an opportunity to test non-conventional water quality and hydraulic monitoring methods in an intermittent system and evaluate their usefulness as tools for research and operation. Continuous pressure monitoring proved useful for identifying negative pressures that were a risk for water quality. Though not reported in this paper, continuous pressure monitoring data were analyzed to determine the actual supply schedule that users were receiving, which sometimes differed substantially from the intended supply schedule. Such monitoring could allow the utility to provide a more reliable supply schedule, which, in turn, might make it easier for users to avoid consumption of first-flush water and better plan their household water storage. Continuous turbidity and free chlorine monitoring was an effective tool for this research, but would not necessarily be useful for routine monitoring of the Arraiján study zones, since, apart from the first flush, when the accuracy of continuous water quality monitoring was less reliable, high turbidity and low chlorine residual events were very infrequent. However, in other networks, or other portions of the Arraiján network, where consistently adequate free chlorine residual is not maintained, continuous monitoring may be effective for identifying risks to water quality.

Intensive first-flush grab sampling and continuous monitoring revealed first-flush water quality problems that would not have been detected with random grab sampling. While first-flush grab sampling was more reliable than continuous monitoring, and allowed for detection of indicator bacteria, it is logistically more challenging than continuous monitoring, since the person collecting samples must arrive at the sample tap when the water is off and wait for supply to begin. Automatic grab sampling devices, and improved continuous monitoring techniques, such as the use of an air release valve to avoid interference from air being expelled from pipes, could make first-flush monitoring easier and more effective. Operators, regulators and researchers should include first-flush sampling in their efforts to characterize water quality risks associated with intermittent supply in different parts of their systems. Higher concentrations of HPC and spore-forming bacteria during many first-flush events indicated that water quality was altered even when total coliform and *E. coli*, more traditional indicators, were not present. More research is needed on methods to distinguish regrowth from intrusion, and to characterize risks from actual waterborne pathogens and not just indicators.

In addition to enhanced monitoring, Water Safety Plans (World Health Organization 2005) may provide a useful framework for identifying hazards in IWS systems. Above, several hazards (e.g. household pumps, overflowing sewers, inadequate disinfectant residual) were identified that were present in the Hubli-Dharwad system but not in the Arraiján system.

3.5. Conclusions

The stark contrast between water quality conditions in Arraiján and the distribution network previously studied in Hubli-Dharwad, India shows that the nature of intermittent supply and its effects on water quality vary widely among systems labeled as intermittent. For operators and policy makers to evaluate and reduce the water quality risks associated with different intermittent supply situations, it will be important to continue to characterize the different characteristics of intermittent supply (topology, water quality, duration of outage, etc.) found around the world and develop tools to effectively and efficiently characterize and diagnose individual systems and specific supply zones within those systems.

CHAPTER 4. Evaluation of whether pressure conditions under intermittent supply damage pipes

4.1. Introduction

4.1.1. Motivation

Intermittent water supply (IWS) has been proposed to cause additional stress on water distribution system pipes and lead to higher rates of leakage and breaks (Charalambous 2011; Lee and Schwab 2005; Klingel 2012; Yepes, Ringskog, and Sarkar 2001). Hydraulic transients, also known as pressure surges or water hammers, may be an important source of this additional stress on intermittent systems (Lee and Schwab 2005). Increased pipe damage would be an important disadvantage to intermittent operation, because it would further degrade infrastructure in systems where it is often already in poor condition. Because high rates of water loss, normally associated with poor pipe condition, can be a cause of IWS (Yepes, Ringskog, and Sarkar 2001; Klingel 2012; Galaitsi et al. 2016), a vicious cycle could develop, where IWS causes pipe breaks and leaks, resulting in increased water losses and even more intermittent supply.

We have only identified one previously published field study on the relationship between IWS and pipe damage. In that study, two distribution networks in Cyprus were examined that had always been operated continuously until drought conditions caused IWS to be implemented temporarily for 2 years (Christodoulou and Agathokleous 2012). The incidence of service calls related to water loss or pipe inspections increased in both systems once IWS was implemented. The authors found that the increase in failure rates caused by IWS was particularly severe for pipes that were already deteriorated (four or more previously observed breaks) and for small-diameter pipes. No pressure monitoring data were published and the authors did not comment on what specific hydraulic aspects of IWS might be causing pipe bursts. There are critical knowledge gaps regarding the extent to which different varieties of IWS cause pipe damage and the different mechanisms of pipe damage that may occur under IWS.

Few studies have measured pressure in intermittent systems at a high enough frequency to detect hydraulic transients. In one previous study that included such monitoring (Kumpel and Nelson 2014), pressure was monitored during 16 supply cycles in intermittent portions of a distribution network in Hubli-Dharwad, India. Pressure was measured every 250 milliseconds and the average, minimum and maximum pressures were recorded for every 2-second (s) period. Transient events were identified during only one supply cycle, where they were associated with expulsion of air near the end of a pipe with few outlets. Though these events fit the authors' definition of a transient (when the maximum pressure during a 2-s period exceeded the highest 2-s mean pressure recorded during the supply period by > 10%), they did not result in pressures > 15 psi or < 0 psi, so would be unlikely to damage pipes. Although operators opened and closed valves during the supply cycles monitored in Hubli-Dharwad, no pressure transients were detected due to the valve operations.

Andey and Kelkar (2007) monitored pressure under IWS in four cities in India, and De Marchis et al. (2010) monitored pressure during charge-up of intermittent sectors of a distribution system in Palermo, Italy, but measurements were made every 30 minutes (min) and every 5 min in the respective studies, which is not frequent enough to detect transient pressures.

4.1.2. Background

Numerous models have been developed to explain pipe deterioration and failure rates based on a variety of factors, such as pipe age, pipe material, internal pressure loading, number of previous repairs, and soil and water corrosivity (Wang, Moselhi, and Zayed 2009; Rajani and Kleiner 2001). Rajani and Kleiner (2001) divide physical failure mechanisms into three categories: 1) pipe structural properties, 2) internal loads due to pressure and external loads, and 3) material deterioration. Here we will focus on failure due to internal pressure loading, and how it might be influenced by IWS. The focus is on PVC pipe, since most distribution pipes in the Arraiján network and all pipes in the study zones were PVC. Wetting and drying of pipes under IWS could also affect material deterioration of metal pipes via corrosion, but that mechanism is not considered here.

Pressurized PVC drinking water pipes are normally designed to withstand maximum long-term pressures, maximum anticipated surge or transient pressures, and fatigue due to cyclic loading (AWWA 2002a; Williams 2011). Thin-walled or reinforced concrete pipes can also fail due to negative pressures (Boulos et al. 2005). Although fatigue failure from cyclic loading could also be a concern in intermittent systems, we will limit our scope to how IWS might cause extreme pressures that damage pipes, categorizing potential mechanisms between those acting via steady state pressures and those acting via transient pressures.

Steady state operating pressures

IWS is normally associated with inadequate operating pressure, rather than high pressure, (Lee and Schwab 2005; Kumpel and Nelson 2016; Vairavamoorthy, Gorantiwar, and Mohan 2007). However, IWS networks often are not designed based on technical criteria and expand without careful planning, so may also have excessive pressures (Klingel 2012). For instance, expansion of pumping capacity to force greater flows through a small-diameter pipe may lead to excessive pressure at the pump station discharge. This phenomenon, as shown later in 4.3.1, was the case in the Arraiján study zone supplied by intermittent pumping (Zone 4). Since IWS networks are often under-designed, and tend to experience low pressures, they may sometimes also operate under negative pressures. As shown in 4.3.1, sustained negative pressures occurred in the valve-controlled study zone (Zone 3) in Arraiján.

Transient pressures

Hydraulic transients can occur in both intermittent and continuous distribution networks. A considerable body of literature has reviewed risks posed by transients in continuous networks. We first review that literature, and then examine how specific aspects of IWS may affect the potential for damaging transients.

When pipes are full and pressurized, hydraulic transients can result from any disturbance in pressure or flow conditions. Although transient conditions have historically been analyzed more often in long transmission pipes, they also can be important in looped and branched water distribution networks (Karney and McInnis 1990). In distribution networks, hydraulic disturbances can be caused by pump startup or shutdown, valve opening and closing, rapid changes in demand (such as opening or closing of large customer connections), entrapped air, or pipe breaks (Boulos et al. 2005; AWWA 2002a). Consider, for instance, the instantaneous closure of a valve at the downstream end of a pipeline, as described by Karney and McInnis (1990). When the valve closes, water is no longer leaving the end of the pipe, but, for an instant, is still entering the upstream end of the pipe. This creates a mass imbalance, which must be compensated for by compression of the water column and deformation of the pipe.Since water is relatively incompressible and the pipe is relatively inelastic, large pressures are required to compress and deform them, which result in a fast-moving pressure wave that propagates up and down the pipeline. This phenomenon is commonly known as a “water hammer” (Boulos et al. 2005).

Transients can result in water column separation or cavitation when negative pressures below the vapor pressure of water cause the water column to separate and a vapor cavity to form (Boulos et al. 2005; Wylie and Streeter 1978). When pressure increases again, the vapor cavity collapses, and the surrounding water collides with either another column of water or the end of the pipe, causing rapid deceleration and a pressure surge.

While hydraulic transients can occur in both continuous and intermittent networks, several factors unique to intermittent supply could make them more frequent or severe in intermittent systems:

1. Air pockets that develop in pipes when water is turned off can cause extreme pressures when supply returns. The air pockets can collapse rapidly under increased pressure, causing high transient pressures to develop when the water columns decelerate after the collapse (Izquierdo et al. 1999); or they can be expelled through available outlets, also causing high pressures to develop once the air has been expelled and the water column runs into the end of the pipe and rapidly decelerates because the water is not expelled through the outlets as fast as the air (Batish 2003; Lingireddy, Wood, and Zloczower 2004; Liou and Hunt 1996).
2. Many of the disturbances that cause transients in continuous networks, such as pump shutdowns and valve operations, may be more common in intermittent networks. In many intermittent networks (Kumpel and Nelson 2014; De Marchis et al. 2010; Batish 2003), valves are opened and closed to ration water between

different supply sectors. In the case of some intermittent sectors of Arraiján (see Chapter 2), pumps started and stopped frequently due to supply limitations and power outages. Geldreich (1996) also reported daily pump stoppages in Lima, Peru.

3. Flow velocities are likely higher in many intermittent networks than in continuous networks, since demand is distributed over fewer hours of supply. Flow velocities will also likely be higher under IWS because many intermittent networks are not as over-designed as continuous networks in high-income countries, which are sized to deliver flows sufficient for firefighting (AWWA 2002b). In simple cases, all else being equal, high flow velocities will normally result in more severe transients, because higher initial velocities provide potential for a greater change in velocity if flow is stopped, although this is not necessarily the case for more complex situations (Karney and McInnis 1990). According to the (AWWA 2002a) manual for PVC pipe design, specific surge calculations are difficult to do in distribution networks, but safety factors built into design standards are sufficient to protect against surges in typical distribution pipes with velocities ≤ 2 feet per second (0.61 m/s). However, typical velocities at the entrances to the Arraiján study zones ranged from 0.96 to 1.45 m/s, and seven of eleven monitoring locations in a study of an intermittent network in Bangalore, India had peak velocities ≥ 1 m/s (Sashikumar, Mohankumar, and Sridharan 2003).
4. Lack of systems knowledge in intermittent systems (Klingel 2012) could make effective anticipation and mitigation of transient events much more difficult. Transient analyses are complex and often very sensitive to operating and loading conditions (Karney and McInnis 1990). Hydraulic conditions can be highly variable in IWS networks, and system operators are often not aware of them. Boulos et al. (2005) propose a strategy for controlling transients by i) understanding system configuration, ii) predicting transient loadings, iii) setting criteria for how much load the system can withstand, and iv) considering mitigation measures for cases where predicted transient loadings are greater than what is acceptable. This strategy will be difficult to employ in networks where there is little understanding of system configuration.

Despite the above reasons why transients may be more frequent under IWS, some aspects of IWS may reduce the severity of transients. Intermittent systems tend to have high rates of leakage (Klingel 2012; Yepes, Ringskog, and Sarkar 2001; Galaitsi et al. 2016) and pressure-sensitive demand from leaks will tend to reduce the severity of transients (Jung, Boulos, and Wood 2009). Leaks exposed to the atmosphere can also reduce the severity of downsurges by allowing air to enter, serving a purpose similar to that of vacuum-breaking valves (Boulos et al. 2005), but also representing a risk for contaminant intrusion if they are in contact with contaminated water (Gadgil 1998). In addition to leaks, in intermittent systems where supply durations are short and infrequent, a high portion of customers will have their taps open before and during supply, as they attempt to collect as much water as they can (Vairavamoorthy, Gorantiwar, and Mohan 2007). These open taps also function as pressure-sensitive demand and air inlets. Karney and Filion (2003) show that both leaks and pressure-dependent demand are effective mechanisms for dissipating the energy from a transient disturbance.

4.1.3. Chapter overview

The objective of the research presented in this chapter was to assess whether the different IWS situations studied in Arraiján resulted in steady-state operating pressures and transient pressures that could lead to pipe failure from extreme pressures. Additional analysis, beyond the scope of this dissertation, is planned to assess whether pressure conditions in Arraiján could have led to fatigue failure due to cyclic loading, which may also be a concern in intermittent systems.

To investigate possible relations between IWS, extreme pressures, and pipe damage, steady-state and transient pressures were monitored in the Arraiján study zones (described in Chapter 2) for one year, and pipe break rates between intermittent and continuous zones of the broader Arraiján network were compared. The pressure-monitoring and pipe-break-analysis methods used in the study are presented in Section 4.2, results and discussion are presented in Section 4.3, and final conclusions are made in Section 4.4.

4.2. Methods

4.2.1. Pressure monitoring and data analysis

From August 2014 to August 2015 pressure was monitored at the entrance(s) and a downstream location in each of the four Arraiján study zones (study zones described and monitoring locations shown in Section 2.2; Telog LPR-31i at the entrance to Zone 3; Aquas ECO-3 at all other stations). The LPR-31i sensor was rated to measure pressure down to -15 psi, normally recorded measurements every 30 seconds (s), and recorded measurements every 0.05 s for a period of 40 s whenever pressure changed by > 10 psi within 10 s. The ECO-3 pressure monitors normally recorded measurements every 30 s, and recorded measurements every 0.1 s for a period of 2 minutes (min) whenever the pressure changed more than 5% during 1 s. Specifications in the manual for the ECO-3 sensors indicated that they were rated to measure pressure down to 0 psi. However, personal communication with Aquas indicated that the sensors were indeed capable of measuring negative pressures. Negative measurements registered by the ECO-3 sensors appeared to be accurate based on inspection of transient wave-forms during pump start-ups.

During the course of the study it became apparent that the ECO sensors sometimes reported rapid pressure changes that did not correspond to known actions that could cause transients. These events were identified as spurious because they occurred in rapid succession when the sensor battery was low, often were from one particular sensor (regardless of the monitoring location), and the sudden pressure changes did not have the waveform that transients normally have (example shown in Figure 4.1). The Telog sensor did not report such events. While one ECO sensor recorded more of these false transients than the others, multiple ECO sensors recorded transients that appeared to be spurious.

Despite detection of spurious transients, some of the transients that were detected clearly corresponded to the startup or shutdown of pump stations and had waveforms typical of hydraulic transients. It is unlikely that real transients went undetected by the sensors, because, when events occurred that were known to cause transients, such as pump starts and stops or the opening or closing of a sample tap, we confirmed that transients were detected by the sensors.

Pressure data were analyzed and graphed in R (R Core Team 2012). An algorithm was used to remove events from the dataset for which pressure changes were too abrupt and isolated, or too small in magnitude, to correspond to actual hydraulic transients. Graphs of included and discarded transients were also inspected visually to make sure that the real transients that had been captured were included and that the spurious ones were discarded. Opening monitoring station sample taps for research or maintenance activities sometimes affected pressure data. These activities were logged and data affected by them were discarded before analysis. For analysis, transient data and periodic data (the data collected continuously every 30 s regardless of whether a transient was occurring) were combined into one time series for each monitoring location. All pressure data presented in this chapter are adjusted to the level of the buried pipe at the monitoring location.

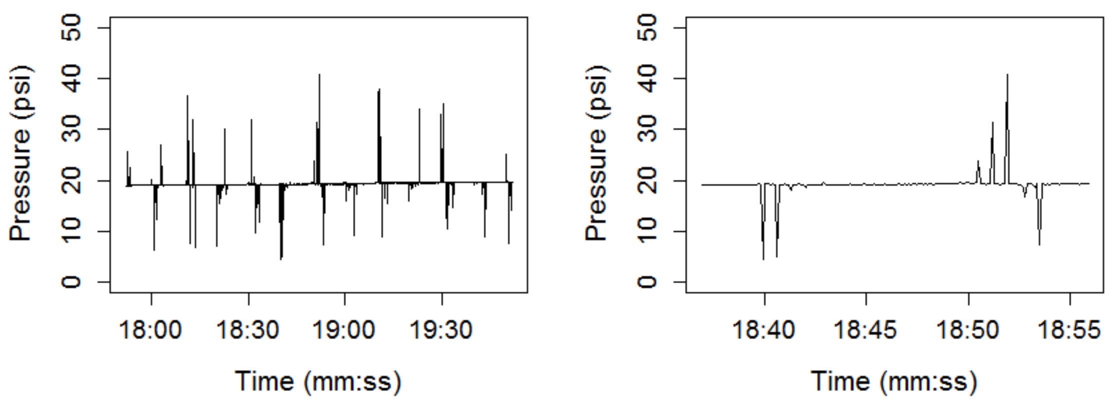

Figure 4.1: Pressure transient recorded at the Zone 2 downstream location that was deemed to be false and discarded. The right plot is an up-close version of the left plot.

4.2.2. Pipe-break analysis

Pipe break repair records for the entire Arraiján network during 2012-2014 were analyzed to investigate whether there was an association between the frequency of pipe breaks and intermittent supply. Although these records represented repairs instead of breaks, for this analysis each repair is referred to as a break. Based on the location written on the form filled out by the repair crew, each break was assigned to a zone (a neighborhood or housing development). The length of pipe in each zone was calculated using the utility's GIS database. Pipes with diameter < 2" or > 12" were excluded from the analysis (The small-diameter pipes were not in the GIS database, so could not be included. The large-diameter pipes were normally transmission pipes and the pressure regime in those pipes was not normally related to the supply regime in the zones they passed through.) Some zones of Arraiján where pipe information was not available in the GIS database were excluded from the analysis.

To categorize supply continuity and the approximate age of the pipes in each zone, the utility's field supervisor, who had more than 30 years' experience working for the utility in Arraiján, was consulted. Pipe break data were analyzed in R (R Core Team 2012). Statistical tests for independence were done with permutation tests using the coin package (Hothorn et al. 2015), because these do not require assumptions regarding the distribution of the data. The threshold for statistical significance was $p < 0.05$.

4.3. Results and Discussion

4.3.1. Pressure monitoring

At each monitoring location, 273 to 354 days of pressure data were collected. Extreme high and negative pressure events at each monitoring location are summarized in Table 4-1 and the distributions of pressures recorded at each location are shown in Figure 4.2. No pressures > 75 psi or < -1 psi were measured at the Zone 2 monitoring stations, where supply was intermittent and controlled by the level in large upstream storage tanks. Extreme pressures measured in the other three zones are detailed and discussed below.

High pressures

Pressures > 100 psi were recorded at three locations:

- Z3-PD, the discharge of the pump station serving the valve-controlled zone (although Z3-PD is also an entrance to Zone 3, it is called PD [for pump discharge] to differentiate it from Z3-ENT, the second entrance monitoring station located farther downstream of the pump station [see Figure 2.5]);
- Z4-ENT, the entrance to the zone supplied by intermittent pumping, which was also located at a pump station discharge;
- and Z4-DS, the Zone 4 downstream station.

The highest pressures were recorded at the pump discharges. The highest pressure recorded was > 284 psi (the maximum pressure that could be recorded by the ECO sensors was 284 psi) for 3.6 s at Z3-PD (Figure 4.3a). This event was after a period of several days when the pump was out of service, so was likely associated with repair or testing of the pump. The second-highest pressure at Z3-PD was 178 psi and lasted for 7 s (Figure 4.3b). This peak occurred less than 2 min after a brief drop in pressure, so could have been due to the pump restarting after a stoppage. A pressure surge was also recorded at Z3-PD a few minutes after the closure of the Zone 3 control valve downstream of the pump station (Figure 4.4a). The cause of the delayed surge is unclear, but it might have occurred after the pipe to a storage tank at higher elevation filled and a sticky level-control valve at the tank failed to open immediately.

Maximum pressure at Z4-ENT was 162 psi, recorded at 3 am when operating pressure was high and one of the pumps shut down for less than a minute and then restarted (Figure 4.3c). Less severe transients occurred frequently at Z4-ENT due to pump startups and shutdowns, and sometimes provoked high pressures. High steady-state pressures were common at Z4-ENT, particularly because a second pump was added to the pump station to improve supply in the sector just before this study began. On four occasions during the year of monitoring, steady-state pressure rose above 135 psi. Z4-DS also experienced 18 min of pressures > 100 psi.

Design limits for common classes of PVC pipe, according to American Water Works Association Standard C900-07, are shown in Table 4-2. As called for in the standard, the ratings have been adjusted for a temperature of 29° C, Panama's average temperature during the hottest month of the year (Weatherbase 2016). The pressure ratings and quality of PVC pipe installed in the study zones were not investigated thoroughly. We will assume that all pipe had a dimension ratio (DR, the ratio of the outside diameter to the wall thickness) of 25, meaning that at 29° C it was rated to withstand constant working pressures up to 132 psi and occasional surge pressures up to 212 psi. As seen in Table 4-1, pressures measured in the Arraiján study zones exceeded the 132 psi pressure rating only at the Zone 3 pump discharge (on eight occasions for a total duration of 3.8 min) and the Zone 4 entrance (on 40 occasions with a total duration of 53 min). Pressure only exceeded 212 psi one time at the Zone 3 pump discharge during the 3.6-s event mentioned above.

High and oscillating pressures may still contribute to pipe breaks even if they do not exceed design limits. Studies have found that, even when working pressures are well below initial design pressures, reducing them through pressure management can reduce break rates, suggesting that, as pipes age, pressures below design pressures can contribute to breaks (Thornton and Lambert 2007).

Negative pressures

Pressures < -1 psi were recorded at all stations in Zones 3 and 4 and at the entrances to Zone 1. Sustained negative pressures, at times reaching -14 psi (approximately a full vacuum), were recorded for long periods of time at the Zone 3 entrance station (Z3-ENT; downstream of Z3-PD), where water was siphoned over the crest of a hill (Figure 4.3d). Negative pressures were recorded both while the Zone 3 control valve was open and water was flowing through the pipe, and while it was closed. Negative transient pressures were also recorded at Z3-PD (minimum -6.7 psi) and Z4-ENT (minimum -10.6 psi). The vast majority of the negative pressures at Z4-ENT were due to the startup of the first of two pumps in the Zone 4 pump station (example Figure 4.3e).

Four negative pressure events occurred when the pipe downstream of Z4-ENT broke or when the Zone 4 pump station stopped while the discharge pressure was low due to a downstream break. Negative pressures at Z3-PD were normally due to pump shutdowns, and also caused transients downstream at Z3-ENT (Figure 4.4b). Although supply was normally continuous in Zone 1, negative pressures occurred at the entrance stations there during supply outages and breaks in the 24” transmission pipe from WTP A. Pressure transients associated with one such pipe break caused a minimum pressure of -5.6 psi at Z1-ENT2 (Figure 4.3f).

While they present a risk to water quality, the negative pressures measured likely do not present a risk for damage to the PVC pipe found in the Arraiján study zones, because PVC pipe is normally resistant to vacuum pressures (Diamond Plastics Corp. 2014). However, in other situations, negative pressures may cause failure of thin-walled or reinforced concrete pipes (Boulos et al. 2005).

Table 4-1: Summary of extreme high and negative pressure events at each monitoring location.

	Diam. (in.)	< -1 psi		< -5 psi		< -10 psi		> 100 psi		> 132 psi		> 212 psi	
		# Events	Total Time (s)	# Events	Total Time (s)	# Events	Total Time (s)	# Events	Total Time (s)	# Events	Total Time (s)	# Events	Total Time (s)
Z1-ENT1	**2**	19	5790	1	30	-	-	-	-	-	-	-	-
Z1-ENT2	**3**	9	2.7	3	0.5	-	-	-	-	-	-	-	-
Z1-DS	**1**	-	-	-	-	-	-	-	-	-	-	-	-
Z2-ENT	**6**	-	-	-	-	-	-	-	-	-	-	-	-
Z2-DS	**4**	-	-	-	-	-	-	-	-	-	-	-	-
Z3-PD	**4**	126	296	10	4.0	-	-	48	1.9E+04	8	228	1	3.6
Z3-ENT	**4**	1753	1.3E+07	1262	5.1E+06	229	1.1E+06	-	-	-	-	-	-
Z3-DS	**2**	6	1110	-	-	-	-	-	-	-	-	-	-
Z4-ENT	**6**	83	107	18	25	1	1	3746	4.3E+06	40	3.2E+03	-	-
Z4-DS	**3**	8	1167	-	-	-	-	11	1110	-	-	-	-

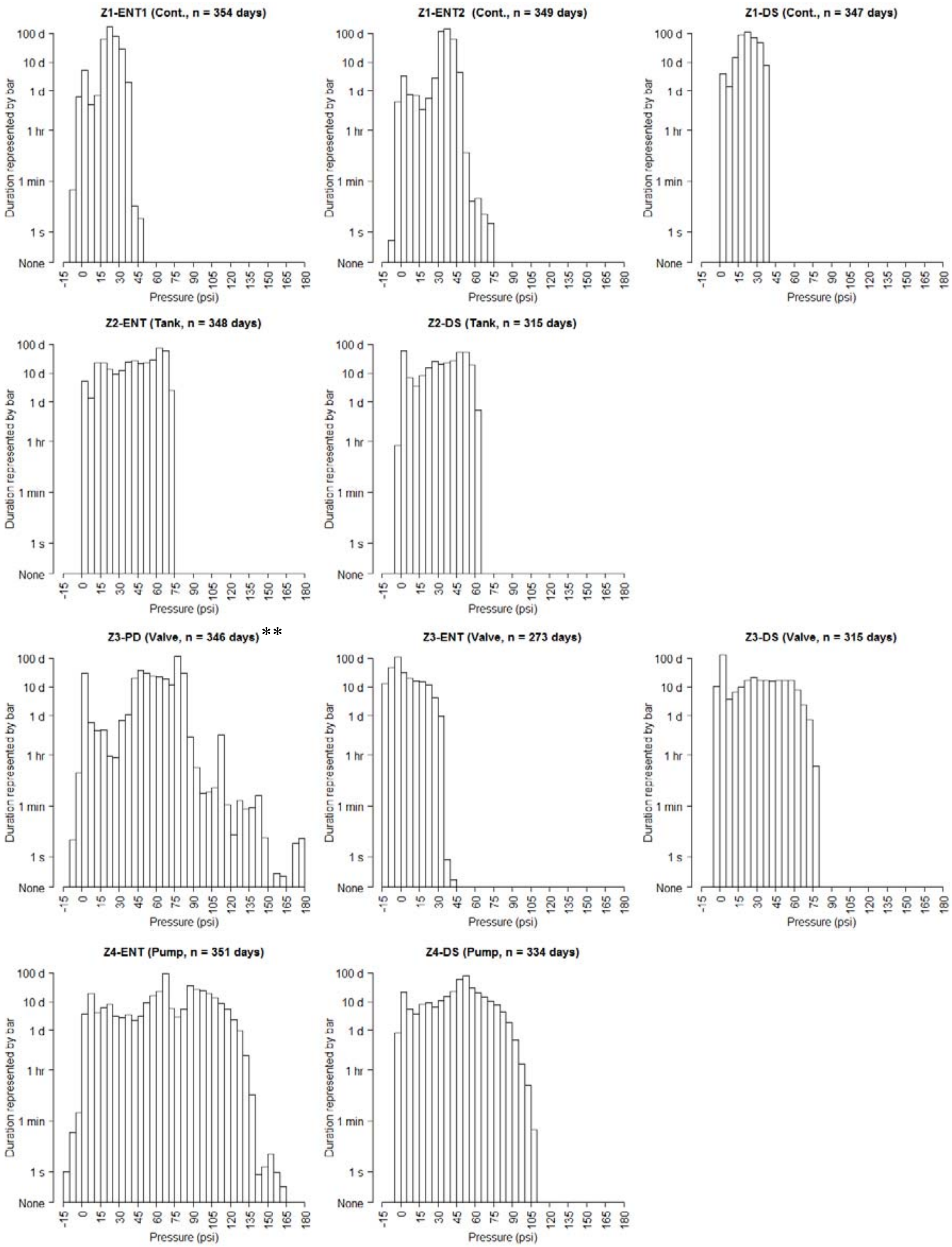

Figure 4.2: Histograms of pressure at each monitoring location. Note that the y-axis scale is logarithmic, so the area of each bar is not proportional to the amount of time that pressure was in that category. The way supply was controlled in each zone and the amount of data at each location are shown in the plot titles. **Not included on the Z3-PD plot is one event with pressure > 284 psi for 3.6 s.

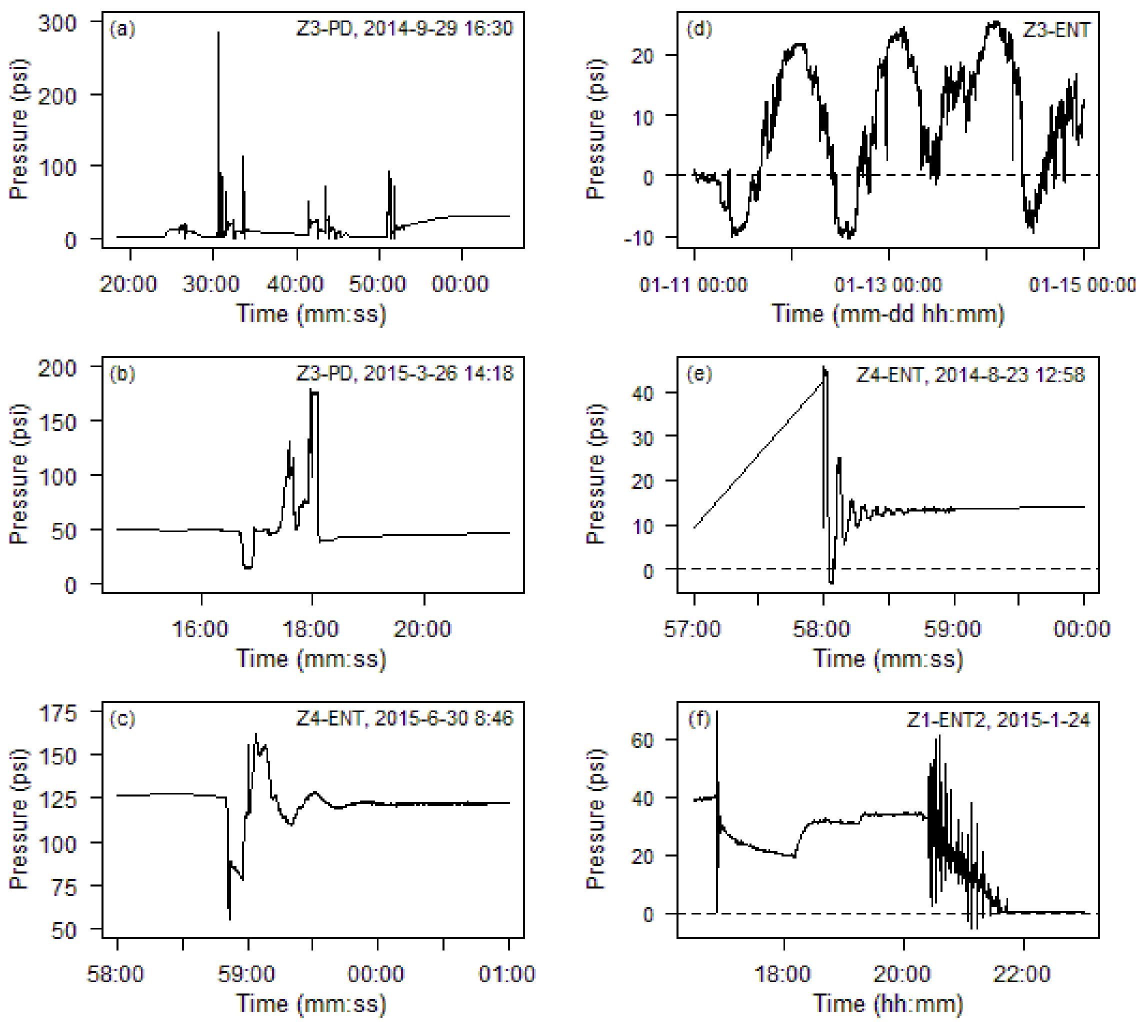

Figure 4.3: Examples of high (a: possible Zone 3 pump testing or repair; b: Zone 3 pump stop and start; c: Zone 4 pump stop and start) and negative (d: sustained negative pressures at Zone 3 entrance; e: Zone 4 pump startup; f: transients at Zone 1 entrance from break in 24" transmission pipe) pressure events.

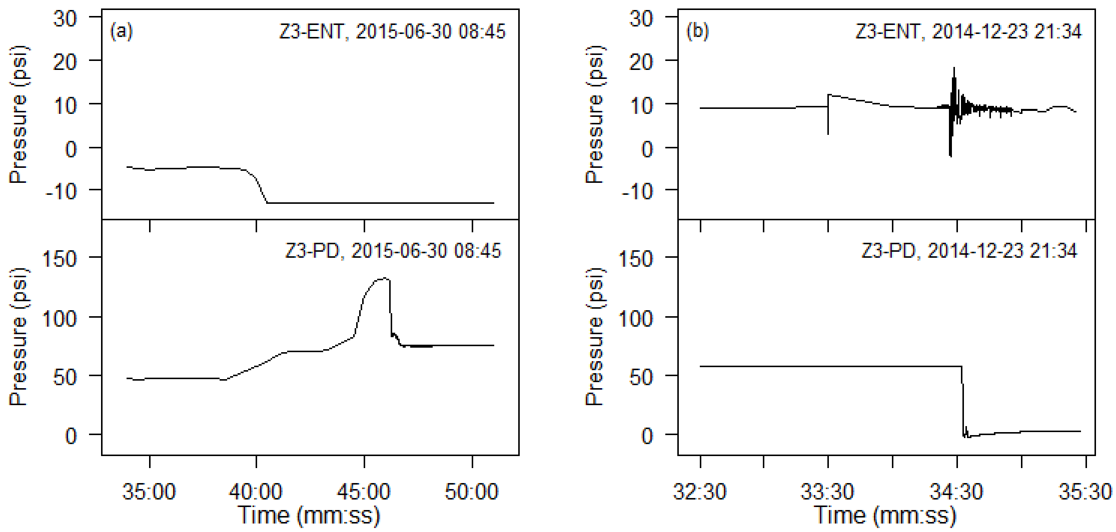

Figure 4.4: Pressure data at Z3-ENT and Z3-PD during two extreme pressure events: (a) closure of the Zone 3 control valve, causing high pressure a few minutes later at Z3-PD, and (b) pump shutdown causing negative transient pressure (minimum -2.4 psi) at Z3-PD. The Z3-ENT data are shifted forward 90 s compared to what was recorded by the LPR-31i monitor. Based on data from this and other events, the ECO and LPR-31i loggers appeared to be out of synch, likely because the ECO loggers all set their clocks to the same website, but the LPR-31i set its clock to the laptop computer that was used to download data.

Table 4-2: Pressure classes and allowable occasional surge pressures for PVC pipe according to AWWA standard C900 (AWWA and ANSI 2007).

DR (dimension ratio = outside diameter / wall thickness	Pressure Class (psi) For 23° C	Pressure Class (psi) Adjusted to 29° C	Occasional Surge Pressure Capacity (psi) Adjusted to 29° C
25	165	132	212
18	235	188	302
14	305	245	391

Pipe filling

Pipe filling is a time of particular concern for transient events in IWS systems, since the expulsion or collapse of entrained air pockets, and the subsequent deceleration of water columns as they run into one another or into the end of dead-end pipes, may cause hydraulic transients. Figure 4.5 to Figure 4.8 show pressure traces during all pipe-filling events that occurred at the four downstream monitoring stations during the year of monitoring. Each trace includes 10 min of data before and 60 min of data after pressure reached 2 psi at pipe level. Despite the theoretical potential for transients, no extreme high or negative pressures were observed during the 403 filling events monitored at the downstream stations. At the downstream stations in Zones 1-3, no pressures > 35 psi were observed during the filling events. In the zone supplied by intermittent pumping (Zone 4), pressure was sometimes as high as 85 psi 1 hour after the pipe began to pressurize (normally due to the Zone 4 pump starting), but this was simply because steady-state pressure was high at that location.

The transient detection feature was triggered for only five of the filling events, all of them in Zone 4. While all five events showed a rapid increase in pressure (because of the pump turning on), none included pressure oscillations. Pressure did oscillate during some Zone 3 and 4 filling events (examples in Figure 4.9), but with periods of several minutes or more. In the case of Zone 3, these oscillations were likely due to users opening and closing their taps. In Zone 4, the oscillations were due to the Zone 4 pump station turning on and off or the intermittent operation of a pump station serving an adjacent zone that Zone 4 was connected to (see Section 2.2).

The lack of transients during filling could be due to energy dissipation through leaks and open customer taps, as discussed at the end of Section 4.1.2. While this may be the case in Arraiján, other systems with less leakage, or where customers are not accustomed to IWS and don't leave their taps open, may be more prone to transients from filling. Such may have been the case in the Cyprus systems where more pipe breaks were observed after implementation of IWS (Christodoulou and Agathokleous 2012). Lieb, Rycroft, and Wilkening (2016) used hydraulic modeling to show that inflow patterns could be optimized to reduce pressure fluctuations in a filling pipe, which indicates that different filling patterns may also explain why transients are more severe in some situations than others.

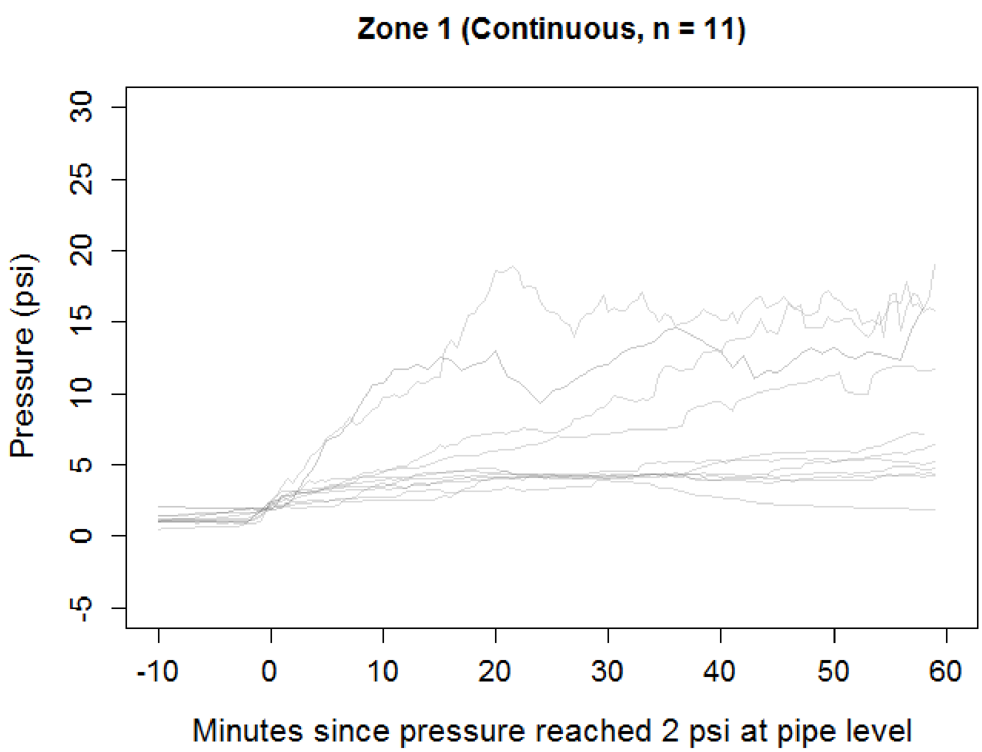

Figure 4.5: Pressure during pipe filling at Zone 1 downstream monitoring station.

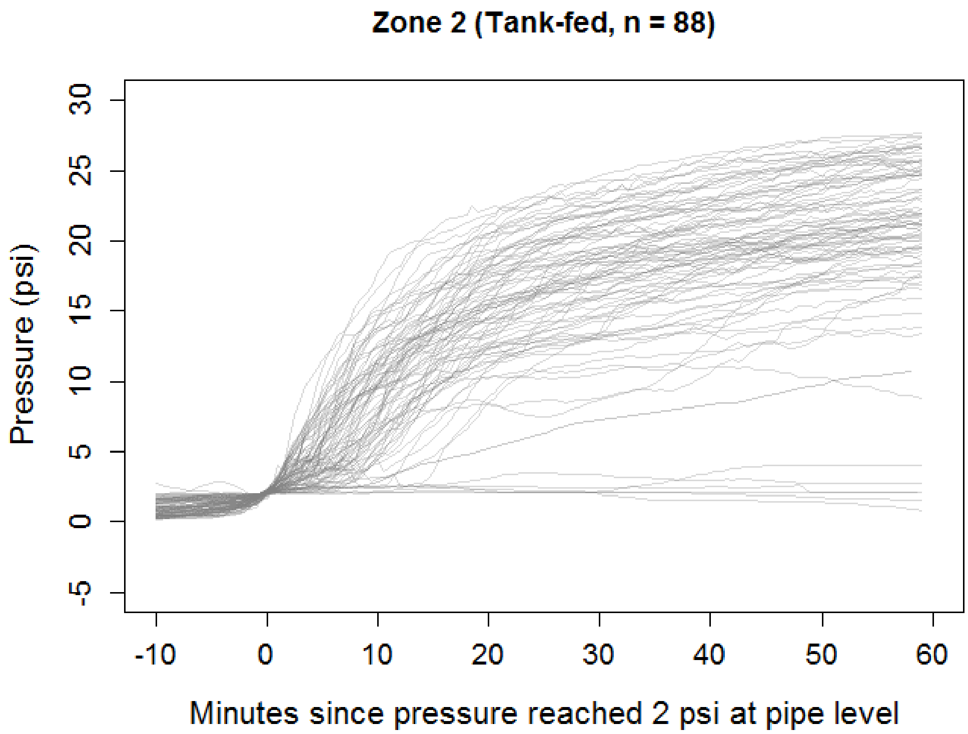

Figure 4.6: Pressure during pipe filling at Zone 2 downstream monitoring station.

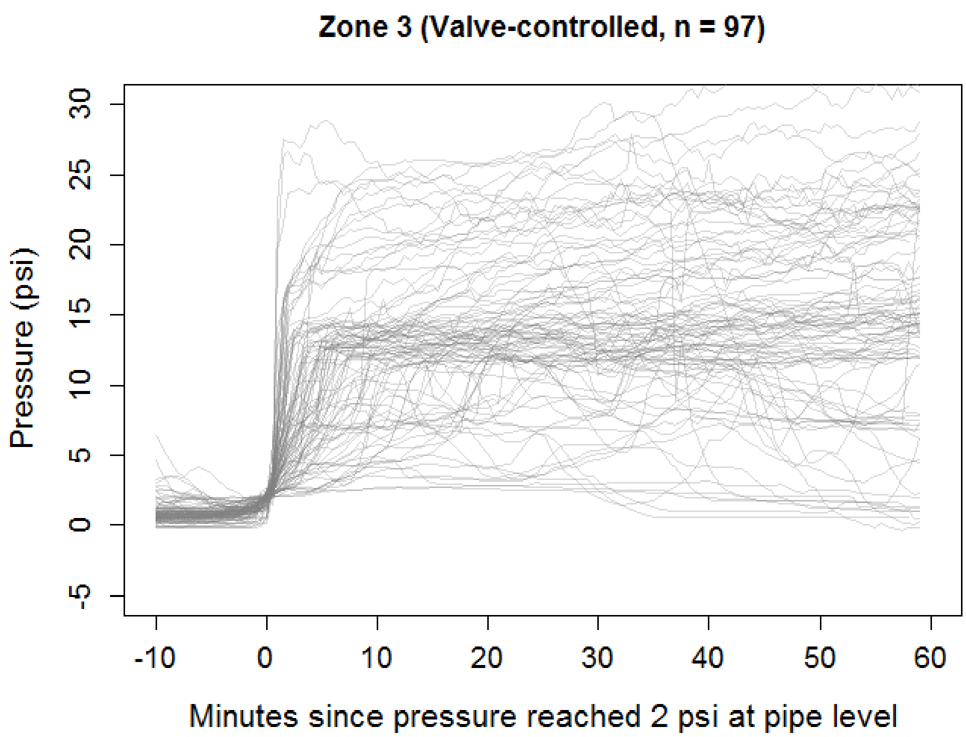

Figure 4.7: Pressure during pipe filling at Zone 3 downstream monitoring station.

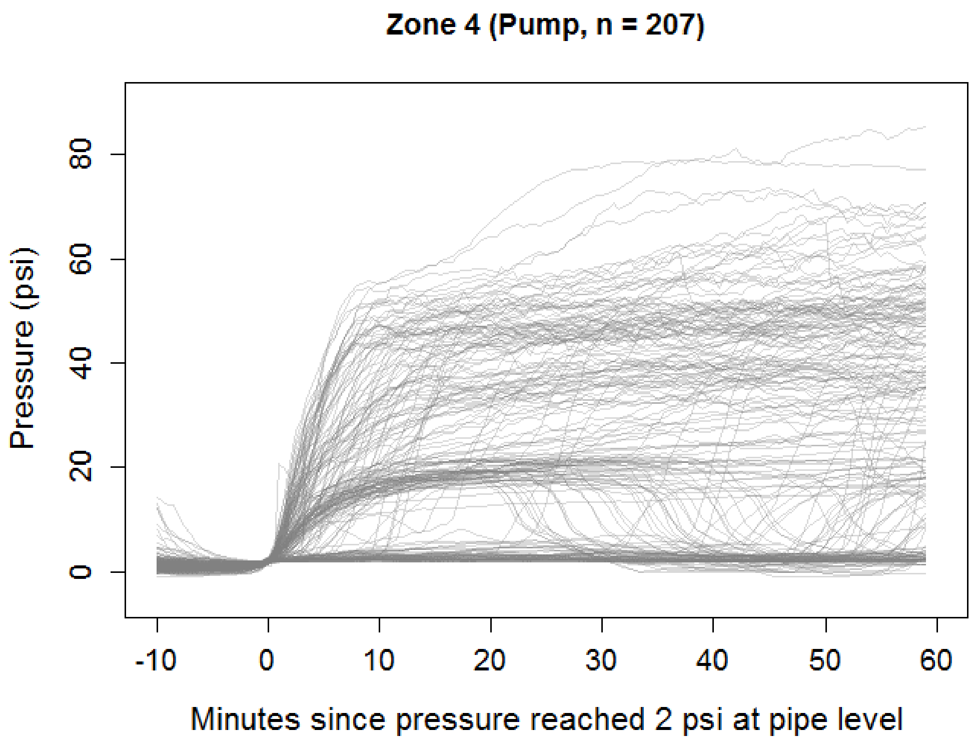

Figure 4.8: Pressure during pipe filling at Zone 4 downstream monitoring station.

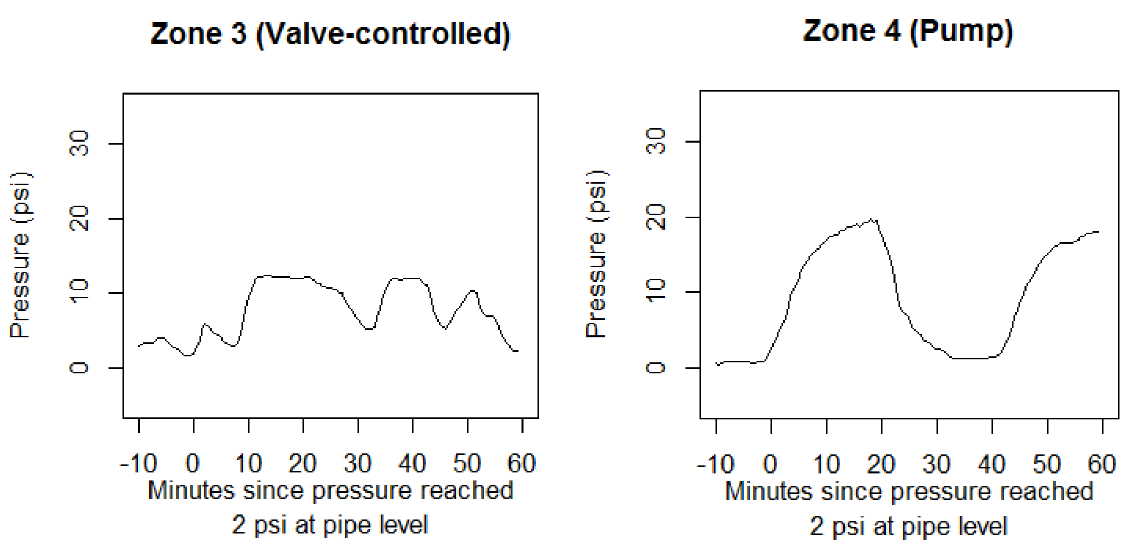

Figure 4.9: Examples of low-frequency pressure oscillations during filling in Zone 3 (likely due to fluctuating user demand) and Zone 4 (likely due to pump station turning off and on).

4.3.2. Pipe-break analysis

The average pipe break rate across the 142 zones analyzed was 1.42 breaks per km per year. Some breaks were fractioned between multiple zones when the recorded location was not specific enough to know in which of the zones the break occurred. Also, some breaks where the diameter of the break was unknown (and may have been < 2" and thus should have been excluded) were counted as only 0.61 breaks, the portion of all breaks that had diameter ≥ 2".

Break rates varied widely by zone (Figure 4.10a). In 54 zones there were no recorded pipe breaks during the 3 years. Supply was classified into three categories: "Continuous" supply meant that the zone only lost supply when a large portion of Arraiján was without water; "Intermittent" supply mean that the zone regularly was without water; and "Intermediate" supply meant that the zone normally had continuous supply, but was vulnerable to losing supply when pressure was low in the main network. Break rates and break rate ranks are compared by supply type in Figure 4.10b and c. In one-way permutation tests for independence (two-tailed tests, classifying supply and age categories as ordered factors, and using break-rate ranks) higher break rates were significantly associated with more intermittent supply ($p = 0.042$) and higher pipe age ($p = 0.030$). In a permutation test for independence where both supply and pipe age categories were considered simultaneously, the association almost met the threshold for significance ($p = 0.058$).

Table 4-3 shows the ten zones with the highest break rates. Twenty three percent of all of the breaks occurred in these ten zones, even though they only had 2.9% of the pipes. Some small zones (such as the zones ranked 1st and 7th) probably had artificially high pipe break rates either because some pipes in these zones were not registered in the GIS database or because some breaks in nearby zones were classified as within these zones. The second-ranked zone included the 6" transmission pipe between the Zone 4 pump station and Zone 4. Thirty nine of the 51 breaks in that zone were in the 6" pipe going to Zone 4. Zone 4 itself does not appear in the top-ten list, but also had 20 breaks registered on same 6" pipe. The frequent breaks in that pipe are probably due to high transient pressures from the intermittent pumping. The zone with the third-highest break rate also had a pump station that stopped frequently and had a known problem with pressure surges. The fifth-ranked zone was Study Zone 3, controlled by intermittent valve operations. Study Zone 1 (continuous) ranked 45th, with a break rate of 1.08 breaks per km per year, and Study Zone 2 (tank-fed) ranked 29th, with a rate of 2.16.

While the permutation test showed a marginally significant association between more intermittent supply and high break rates, that association might have been driven mainly by a few zones affected by intermittent pumping and not indicate a general effect of IWS. As seen in Figure 4.10, some intermittent zones had very low break rates, and some continuous zones had high break rates. Also, in some cases, other factors associated with IWS may be the actual cause of high break rates instead of the hydraulics of intermittent supply. For example, in Study Zone 3 many breaks occurred in a location were the main pipe transmitting water to the zone was suspended in the air to cross a stream, an installation made by the local residents. Intermittent areas may tend to have more such situations, due to their informal development, and such situations may lead to more pipe breaks.

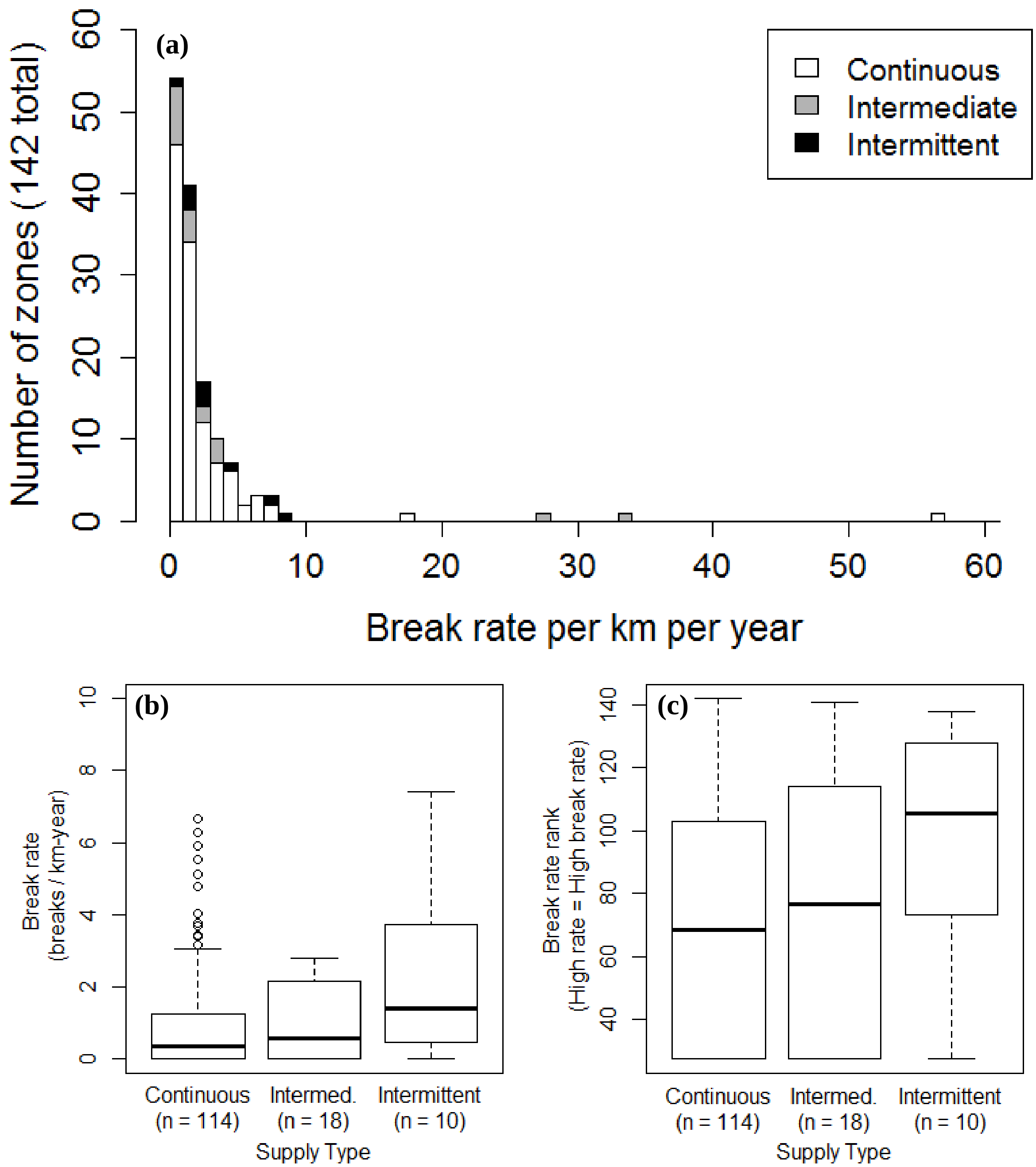

Figure 4.10: Distribution of break rates for each zone during 2012-2014 by supply type (a) and boxplots of break rate (b) and break rate rank (c) by supply type. In plot (a), the bar to the far left represents the quantity of zones with no breaks. Four zones with break rates > 10 breaks/km-year are excluded from plot (b). Note that the minimum rank in (c) is 27.5 because 54 zones had no breaks and were each assigned an average rank.

Table 4-3: The ten zones with the highest break rates. *The second-ranked zone was downstream of the Study Zone 4 pump station. †The fifth-ranked zone was Study Zone 3.

Zone Rank (by break rate)	Pipe length (km)	Number of breaks	Breaks per km per year	Age (years)	Supply
1	0.07	12	55.57	10 to 25	Continuous
2*	0.52	51	32.69	10 to 25	Intermediate
3	1.50	119	26.36	< 10	Intermediate
4	0.44	22	16.77	> 25	Continuous
5†	1.35	30	7.41	< 10	Intermittent
6	0.88	18	6.85	10 to 25	Intermittent
7	0.20	4	6.68	> 25	Continuous
8	2.64	49.8	6.28	10 to 25	Continuous
9	3.08	54.6	5.91	10 to 25	Continuous
10	0.42	7	5.52	< 10	Continuous

4.4. Conclusions

At the beginning of the chapter, potential mechanisms through which IWS might cause (or in some cases prevent) high and negative pressures were proposed. Later, results from long-term pressure monitoring under a variety of supply conditions in the Arraiján system were presented. While high and transient pressures were observed at pump station discharges, and negative pressures were observed in various cases, pipe filling did not produce transients or extreme pressures at downstream monitoring locations. Finally, pipe break rates throughout the Arraiján network were analyzed. While some intermittent zones, particularly those with intermittent pumping, had high break rates, evidence did not indicate that IWS causes high break rates in all cases.

This chapter presents only an initial analysis of the Arraiján dataset. Future work with the same dataset or similar datasets could include analysis of whether cyclic loading under intermittent conditions is likely to cause failure due to fatigue. Hydraulic transient modeling of the Arraiján study zones and intermittent supply situations in other systems could also be used to better understand why hydraulic transients do or do not occur, and what distribution network topologies (looped vs. branched, for example) are most vulnerable to transients under intermittent conditions. As understanding of the relationship between IWS and damaging transients improves, practical approaches for avoiding such conditions might be developed. For instance, pump station designs or network topologies could be developed to better dissipate the types of pressure surges found to be most damaging in intermittent systems.

CHAPTER 5. Challenges of operating an intermittent distribution network

5.1. Introduction

All intermittent supply situations are not the same, and various factors affect user satisfaction under intermittent water supply (IWS). Burt and Ray (2014) argue that customers' satisfaction with water supply is affected by quantity, quality, convenience and reliability. Reliability is a particular concern in intermittent systems, since supply often comes at irregular times (Kumpel et al. 2012). In an intermittent system in Hubli-Dharwad, India, users who had never experienced continuous supply placed more value on punctual supply, increased frequency and duration of supply, and water quality than they did on receiving continuous supply (Burt, VanGordon, and Vij 2014). Adequate supply pressure when water is on is also likely an important factor for user satisfaction under IWS. In cases of inadequate pressure, households have been reported to use pumps to extract more water from the distribution network or lift it to elevated tanks (Kumpel and Nelson 2016; Gadgil 1998).

While reliable supply is important for customer satisfaction in intermittent systems, many factors make it difficult for water utilities to operate intermittent distribution networks reliably and equitably. Common operations challenges in intermittent networks include lack of system knowledge, inapplicability of hydraulic modeling methods designed for continuous systems, inadequate monitoring of dynamic hydraulic conditions, and high rates of water loss.

Knowledge of system infrastructure is critical for optimally planning, expanding, and operating a water distribution system, but such data are often lacking for intermittent systems in low- and middle-income countries (Klingel 2012). Without knowing the state of system infrastructure, it is difficult, if not impossible, to understand or model the hydraulic behavior of the distribution network.

Even if adequate data are available, important differences between intermittent and continuous systems make modeling approaches developed for continuous systems unfit for intermittent systems. Traditional distribution system modeling is demand-driven, with customers' extractions from the network based on how much water they want to consume at a given time. But demand in intermittent systems is often supply-driven, with users extracting as much water as they can based on available supply pressure (Batish 2003; Ingeduld et al. 2006). High peak demands in intermittent networks often result in excessive pressure loss, as large flows are forced through small-diameter pipes, which leads to supply inequities between users at upstream and downstream ends of a pipe (Vairavamoorthy, Gorantiwar, and Mohan 2007). In addition to problems modeling demand, hydraulic models for continuous systems do not account for emptying and filling of pipes (Lieb, Rycroft, and Wilkening 2016). Methods for modeling unique aspects of IWS have been developed (Batish 2003; Ingeduld et al. 2006; Cabrera Bejar and Tzatchkov 2009; Lieb, Rycroft, and Wilkening 2016), but, to our knowledge, no model capturing all of unique aspects of IWS has been applied at the scale of a full network.

Real-time monitoring of intermittent networks also tends to be inadequate. The number of possible states of an intermittent network is larger than that of a continuous network, since pipes may be full or empty during intermittent supply; but operators of intermittent networks often do not have the resources to invest in SCADA (Supervisory Control And Data Acquisition) systems to monitor their networks (Kumpel et al. 2012). In the network in Hubli-Dharwad, India, > 800 valves were operated during a supply cycle, and the state of the system was communicated between employees via phone calls and field visits, with some data recorded in logbooks (Kumpel et al. 2012).

Intermittent supply is frequently associated with high rates of leakage, and efforts to improve supply conditions in intermittent systems will normally need to include management of water losses. However IWS can impede effective measurement and management of water losses. Traditional leak detection strategies can be difficult to apply in intermittent systems (Kumar et al. 2010) and customer metering, if it even exists, can be less accurate (Criminisi et al. 2009). As noted in Chapter 2, non-revenue water in the Arraiján network as a whole was estimated at 53%.

The goal of the work presented in this chapter was to use continuous pressure monitoring to assess the reliability of supply in the intermittent study zones of the Arraiján network. We found the supply schedule to be largely unreliable, and, based on qualitative observations of the network operation, we point out some of the operational challenges that led to unreliable supply. A second objective of the research was to estimate water losses in the study zones. We found water loss rates to be high, based on flow monitoring at the study zone entrances and estimates of water consumption. In light of these findings, we discuss how the hydraulic monitoring methods employed in this research, and better management of operations data, could lead to more reliable and efficient drinking water service in Arraiján.

5.2. Methods

We evaluate supply reliability based on quantitative continuous pressure and flow monitoring data and describe operational challenges that became apparent from qualitative observations of how the Arraiján network was operated. Water consumption and losses are characterized based on flow entering each study zone, limited customer metering data, and the number and characteristics of customers in each zone.

5.2.1. Continuous pressure and flow monitoring

Continuous pressure and flow monitoring (described in Sections 2.3.2 and 2.3.4) at the entrance(s) and a downstream location in each study zone allowed us to detect when supply was on and off at the monitoring locations. Pressure and supply schedule varied within the study zones depending on elevation and location in the pipe network; nonetheless, the monitoring characterized the supply schedule a user connected at the location of the monitoring station would receive, and approximated the supply schedule received by users in the general area.

Pressure data were smoothed (running average of five nearest data points) before analysis. Zones 1-3 were considered to be without supply when pressure (at ground level) was < 2 psi at the downstream monitoring station. Zone 4 was considered to be without supply when the Zone 4 pump station was stopped (with both pumps off), because the Zone 4 downstream monitoring station received supply from interconnections with adjacent areas of the network and often had supply even though the pump station was off and much of Zone 4 was without supply. Outages with less than 10 minutes (min) between them were grouped together and considered single outages for analysis purposes, but reported durations only include time when water was actually off. Outage groups with total duration < 10 min are not reported.

5.2.2. Qualitative observations of network operation

Hundreds of hours were spent informally observing and interacting with Arraiján system operators, which offered an up-close view of the operation of the Arraiján network. While this study was not intended to be a systematic analysis of the operation of the network, those informal observations, when coupled with continuous monitoring data, provided insight into the challenges of operating a complex intermittent distribution network. Following hydraulic events captured by continuous monitoring, system operators were interviewed informally to understand what had happened. Also, when operators mentioned problems in the study zones, the relevant continuous monitoring data were reviewed. This back and forth between operators' observations and hydraulic monitoring data also allowed us to assess whether and how such monitoring might be useful to operators.

5.2.3. Analysis of water consumption and losses

Paddle-wheel insertion flow meters (IP80, Seametrics) were installed at the study zone entrances to quantify entrance flow. According to manufacturer specifications, flow measurements were accurate to within 15% of average flow for all study zones. Ideally, authorized consumption based on customer metering data would be subtracted from the quantity of water that entered each zone to calculate water losses (Lambert 2002), but only approximately 50% of connections in Zones 1 and 2, and no connections in Zone 3, had meters that were read. Given this limited data, water losses were estimated in two ways: 1) using per-capita consumption estimates based on available household metering data and a household survey to estimate the number of people per household, and 2) an analysis of minimum night flows (Alkasseh et al. 2013), which, in Zones 1 and 2, where supply was normally continuous, were assumed to mainly represent leakage. Consumption and water-loss analysis could not be done for Zone 4, due to unforeseen interconnections between that zone and surrounding portions of the network.

Very few households in Zone 3 were registered in the utility's client database, and some households in Zones 1 and 2 were likely also unregistered. To attain more accurate counts of consumers, buildings in the study zones (mainly single-family households, with some small apartment buildings and businesses) were counted using aerial photos from Google Earth and counts were verified with field surveys. A survey was conducted to estimate the number of people and flush toilets per household, and a second survey (part of stored water quality research not included in this dissertation) was used to estimate total water storage capacity per household. Only residential households (including small apartment buildings) were surveyed, because they made up the vast majority of customers in the study zones. Survey households were selected randomly, but the sample was not completely representative, because only households where someone was home at the time of the survey could be included.

For the first lost-estimation method, per-capita consumption in Zones 1 and 2 was estimated by dividing total metered consumption for each zone by the number of metered clients multiplied by the estimated number of people per household (based on the survey). Zone 3 per-capita consumption was assumed to be equal to that in Zone 1, because both had fewer flush toilets per household than Zone 2 had.

The second method, based on minimum night flows, was only applied to Zones 1 and 2, as flowrates did not vary diurnally in Zone 3. (Lack of diurnal variation in Zone 3 can be partly explained by some users at high elevations collecting water during the middle of the night, the only time they had supply.) First, the hour of the day with minimum average flow was selected (2-3am in Zone 1 and 1-2am in Zone 2) and leakage at that time was estimated by subtracting an estimate of legitimate night-time consumption. In Zone 1, legitimate night-time consumption was estimated as 6% of average consumption, estimated based on household metering, assuming only 6% of population was active during that time (Alkasseh et al. 2013). In Zone 2, legitimate nighttime consumption was estimated as 12% of average consumption, to account for users collecting water at night at times when supply outages occurred during the day.

Leakage during the hour of minimum night flow was adjusted, according to pressure and the portion of time that water was on (based on Taylor 2015), to estimate leakage for each hour of the day. Leakage scales with the portion of the time that water is on, since no leakage occurs when water is off, and also varies with pressure. Leakage rates have been found to be proportional to pressure to the N_{th} power, where N may range from roughly 0.5 to 2.5 (Lambert 2002). We assumed that leakage was directly proportional to pressure ($N = 1$). Equation 5-1 shows the combined effects on leakage of pressure and the fraction of time supply is on. Adjusted leakage rates for each hour were averaged to estimate total leakage for each zone. The same relationship between pressure, supply continuity, and leakage was also used to estimate how improvements to supply continuity and pressure would affect leakage.

$$\frac{L_1}{L_0} = \left(\frac{F_1}{F_0}\right) \cdot \left(\frac{P_1}{P_0}\right)^N$$

Equation 5-1: Relationship showing how leakage will compare in two different situations (0 and 1) based on pressure (P) and fraction (F) of time supply is on (based on Lambert 2002).

5.3. Results and discussion

5.3.1. Supply schedule in study zones

Supply in the intermittent study zones was sporadic and unpredictable, with the length of outages varying widely. Supply during each day, week and month was different, varying according to demand, pipe breaks and pump failures within the study zones and in other parts of the network. Supply statistics for each zone are summarized in Table 5-2. Zone 3 was without water for the highest fraction of monitoring time, as would be expected given the utility's plan for supply to be on there for 3 days and then off for 3 days. Although Zone 1 normally had continuous service, 12 outages occurred in that sector, with the longest lasting 22 hours. At least two of these outages were due to breaks in the 24" conduction line that conducts water from WTP A to Arraiján. Another two interruptions were due to large-scale shutdowns for construction work on large transmission pipes in nearby parts of the Arraiján network.

Table 5-1: Summary statistics of supply in each zone. *This is the average pressure at the Zone 4 downstream monitoring station when the Zone 4 pump station was on.

Study Zone	Zone 1 (Cont.)	Zone 2 (Tank-fed)	Zone 3 (Valve)	Zone 4 (Pumped)
Monitoring time (days)	350	318	317	349
Time without supply (days)	3.2	54.5	137	47
Fraction of monitoring time without supply	0.9%	17%	43%	13%
Average pressure when there was supply (psi)	22	38	36	47*
Number of supply outages	11	107	114	336

The distributions of outage durations at each of the downstream monitoring stations are shown in Figure 5.1. The tank-fed zone (Zone 2) had 107 outages lasting up to 3 days. A typical outage occurred when supply stopped during the afternoon, because the upstream storage tanks serving Zone 2 drained, and resumed around midnight once the level in the tanks rose again. Longer interruptions occurred when the upstream storage tanks were without water for longer because of a supply deficit in the overall network caused by a pipe break or pump or treatment plant shutdown.

According to the operation plan for the valve-controlled zone (Zone 3), the outages there should have lasted 3 days; but many measured interruptions were much longer or shorter than 3 days. Eight interruptions of > 4 days occurred. The three longest, lasting 6.3, 6.6 and 8.2 days, were associated with breaks in the main 4" pipe conveying water to Zone 3. Many shorter interruptions occurred when the Zone 3 pump station stopped temporarily or when the control valve at the entrance to the zone was partially closed and supply was interrupted during periods of high demand. (Sometimes operators partially closed the valve at the entrance to Zone 3, instead of closing it completely, so that some, but not all, of the flow went to the storage tank in an adjacent sector. With the valve completely open the storage tank sometimes overflowed.)

Outage durations in the pumped zone (Zone 4) varied widely, since the pump station was not run according to a schedule, and stopped whenever the suction tank it pumped from emptied or electricity supply was interrupted. Seventy percent of the 336 outages, representing 24% of the time that the pump station was off, lasted between 30 and 120 min, likely because this was the approximate length of time it took for the suction tank to fill from the level at which the pump was set to shut off to the level at which it was set to turn back on again. Ten outages lasted more than 24 hours, with the longest one lasting 48 hours. Between April 29 and May 7, 2015, the Zone 4 pump station stopped daily at 8:50 pm and started again at 4:52 am, causing complaints from customers (see Section 5.3.2). During that time one of the pumps was damaged without operators being aware of it and the other was programmed to stop during the night.

The percentage of time, during each hour of the day and each day of the week, that each zone was without supply is shown in Figure 5.2. A high percentage means that that zone was without water more frequently during that hour of the day or day of the week. Service continuity did not vary noticeably by hour of the day or day of the week in Zones 1 and 3. In Zone 1, this lack of variation is explained by the zone hardly ever being without water, making the percentage of time that water was off low at all times. In Zone 3, the lack of variation is explained by the service being controlled by a valve that was scheduled to be opened or closed in the morning every 3 days, which meant that there were no specific hours or days during which the zone would more frequently be with or without service. On the other hand, supply in Zones 2 and 4 varied noticeably by hour of the day. In Zone 2 it also appeared to vary by day of the week. In Zone 2 supply was off more often between 3 pm and 10 pm, when it was more likely for the upstream storage tanks supplying the zone to be empty after being depleted by daytime demand. In Zone 4 supply was off more often between 8 am and 5 pm, probably because during those hours demand was higher in other parts of the network and less supply reached the Zone 4 pump station. Zone 2 was without water more often on Saturdays and Sundays, when many people were at home consuming water, which depleted the upstream storage tanks.

Variation in the percent of time that each zone was without supply throughout the year is shown in Figure 5.3. On some occasions supply problems occurred in one zone and the other zones were unaffected. For example, at the end of October and beginning of November, Zone 3 was affected by two long outages (8.2 and 6.4 days) associated with breaks in the 4” pipe supplying that zone, but supply remained normal in the other zones. On other occasions, large-scale supply problems affected all four zones at once. For example, during the beginning of September and end of January, all four zones were affected by breaks in the 24” transmission pipe from WTP A.

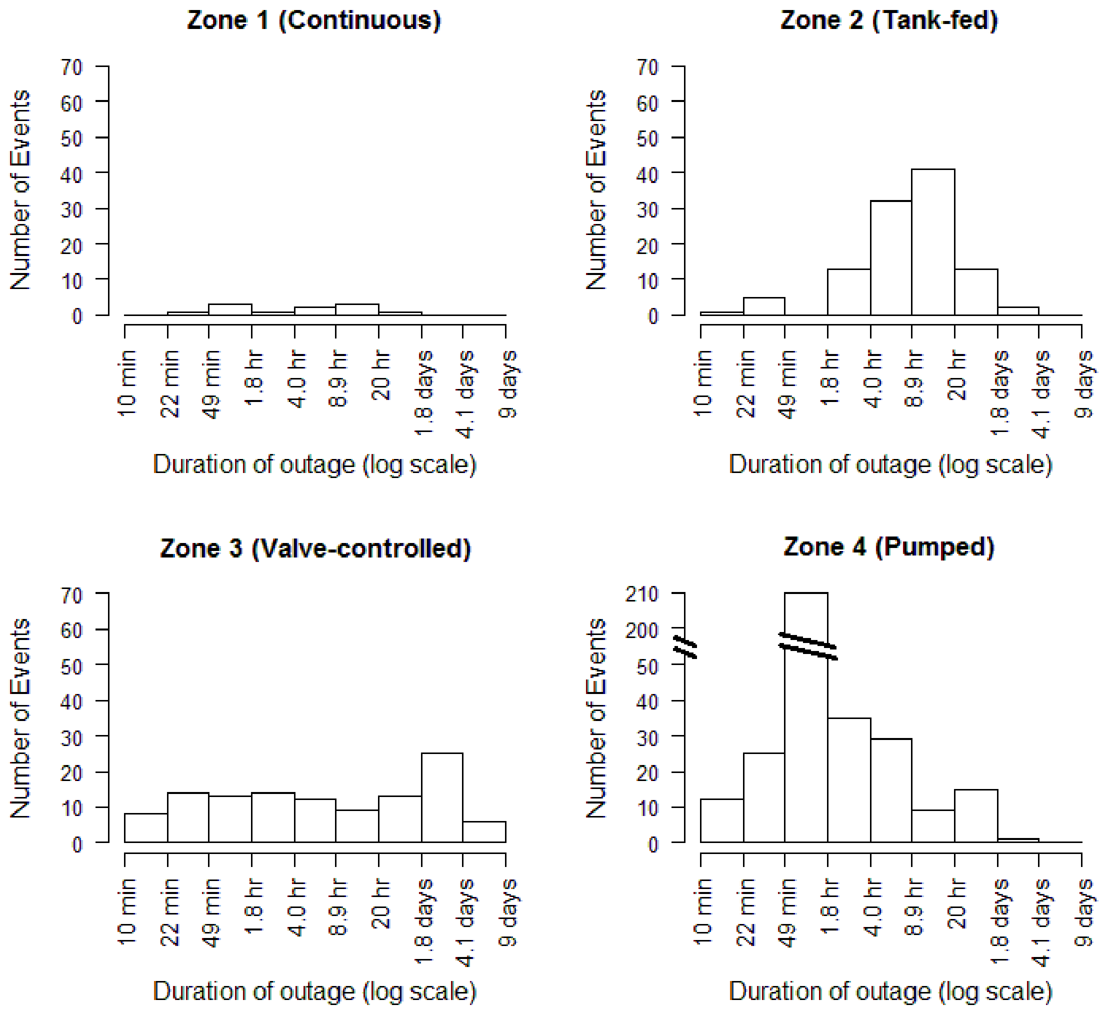

Figure 5.1: Distribution of outage durations for each study zone. Note: y axis for Zone 4 graph is cut.

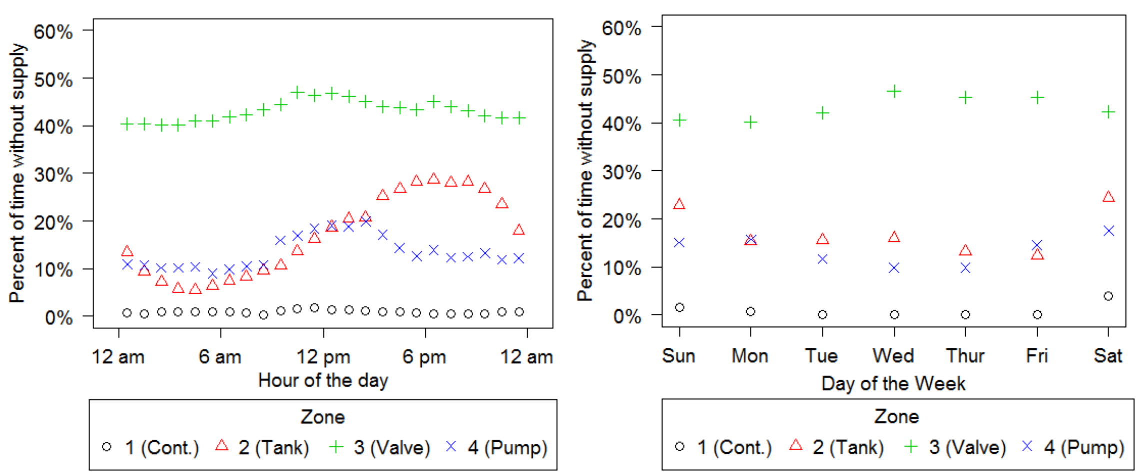

Figure 5.2: Percent of time each study zone was without supply by hour of the day and day of the week.

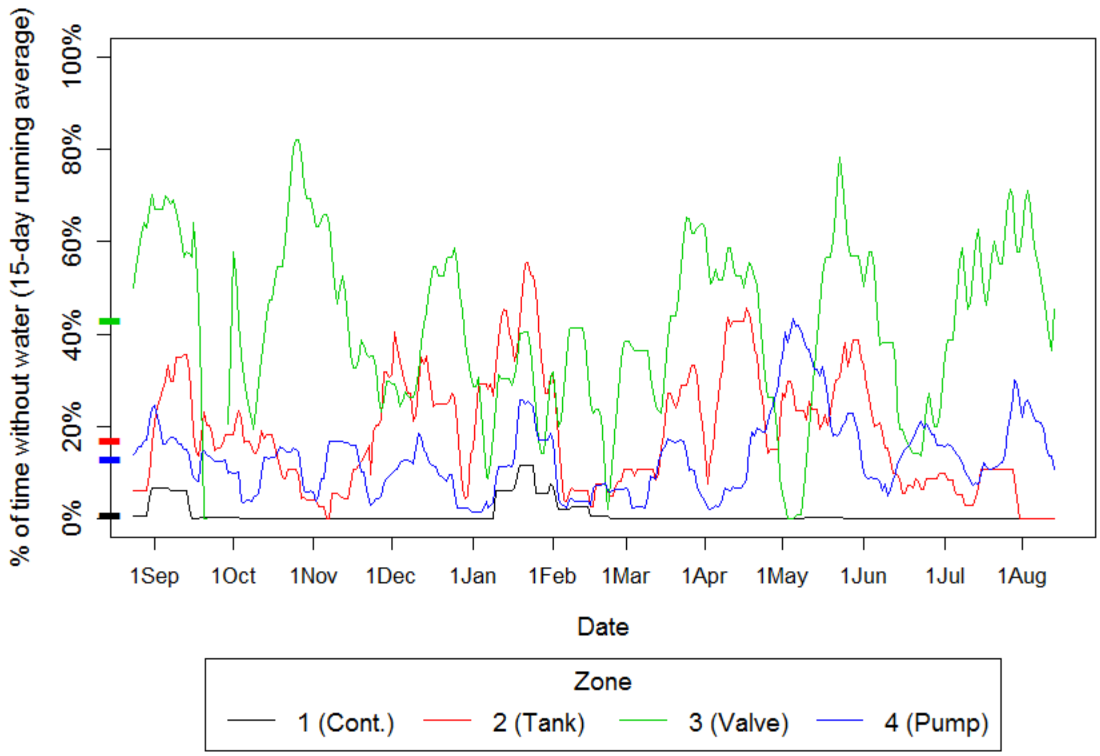

Figure 5.3: Fifteen-day running average of the percent of time that supply was off in each zone. For each day, the average of the percent of time water was off during the 15 nearest days is graphed. Dashes on the y axis mark the average percent of time water was off in each zone. Note: The break in the line for Zone 3 during September is because of an interruption in data collection.

5.3.2. Operational challenges contributing to unreliable supply

Operational challenges contributed to unreliable supply in the Arraiján network. The network was vulnerable to infrastructure failures, such as treatment plant stoppages, pump shutdowns, and frequent pipe breaks. These events often indirectly affected large portions of the network, since no surplus supply was available to compensate for them. Operators' inability to monitor the network meant that smaller infrastructure failures, such as breaks in distribution pipes or pump malfunctions, often were not detected for days, at which point users had already been severely affected. In some cases, a lack of system information made it difficult for operators to shut off a sector of the system to repair a pipe break or prevented the utility from anticipating unintended consequences of infrastructure changes.

During 2014, the utility repaired 604 breaks in pipes of diameter ≥ 2", a rate of 1.46 breaks per km per year (small-diameter and customer connection breaks are excluded, as well as some areas of Arraiján where pipe length and repair data were not available). Although that break rate puts the Arraiján system near the average of 13 Latin American utilities that participated in a regional benchmarking report (Grupo Regional de Trabajo de Benchmarking de ADERASA 2013), it is much higher than the average of 0.068 breaks per km per year from a study of 188 utilities in the United States and Canada (Folkman

2012). Often the repair of breaks was complicated by a lack of information about the configuration of the distribution network and a lack of control valves. Repair crews lost time trying to determine how to depressurize the sector where a break was, and, due to a lack of control valves, sometimes had to cut off service to a large portion of the network in order to depressurize the area near a break.

According to a log kept by utility managers, between August 2014 and July 2015 users in a large portion of Arraiján were without supply on 13 occasions (eight unexpected and five planned), due to pipe breaks, treatment plant stoppages, maintenance, or other operational problems. Two of these events were when the supply from one of the three treatment plants was suspended for more than 24 hours. The effects of infrastructure failures were exacerbated because the network did not have additional supply capacity to compensate. For instance, on two occasions when the 24" transmission pipe from WTP A broke (mentioned in Section 5.3.1), supply from the other two treatment plants was insufficient to compensate, a large portion of the Arraiján network lost pressure, and all four study zones were affected. Although the quantity of water supplied by the treatment plants should have been enough to supply all of Arraiján and still have surplus capacity for emergencies, high rates of water loss drained that surplus away.

While operators usually quickly noticed treatment plant stoppages and large transmission main breaks, smaller pipe breaks or pump station failures often went undetected until users had already been severely affected. Even though Arraiján's distribution network was quite complex, the utility operated it with little information about its current state. Some of the 27 pump stations frequently malfunctioned. Apart from the monitoring equipment installed for this project, only one of the pump stations could be monitored by telemetry; to monitor the others, operators had to do daily field inspections driving around in a truck.

Examples from the study zones illustrate how a lack of system information and delays in detecting infrastructure failures made supply less reliable. In one case, the capacity of a pump station near the Zone 4 pump station was increased, which reduced flow to the Zone 4 station and reduced supply to Zone 4. IDAAN did not anticipate these effects, and changes were only made to resolve the situation after Zone 4 residents blocked a lane of Panama's largest highway to protest the decline in service quality.

In a second situation several months later, one of the two pumps in the Zone 4 pump station stopped working (see Section 5.3.1), again reducing supply to the area. Because the other pump was often working and making noise, operators did not realize that the first pump was malfunctioning when they passed for a daily inspection and listened to see whether the pumps were running, and the problem was only detected after two weeks when users came to the utility's office to complain. The second pump was quickly repaired, but days later the pump station malfunctioned again due to an electrical problem, and the problem was not detected until Zone 4 residents again closed a portion of the highway.

All three of these problems with the Zone 4 pump station were apparent when continuous pressure and flow data collected at the pump station discharge as part of this study were reviewed afterward. If operators had access to such data and monitored it routinely (or set up relevant alarms to alert them of problems), situations like these might be avoided.

Inconsistent operation and monitoring difficulties caused actual supply to deviate substantially from the utility's schedule (3 days on, 3 days off) for the valve-controlled zone (Zone 3). The control valve was sometimes not operated according to schedule, because operators were not available to open or close it due to another crisis or commitment, or because weekend operators were unaware of the schedule. Delay in detecting and repairing breaks in the 4" pipe supplying Zone 3 caused the three longest outages. Zone 3 valve operations and pipe breaks were also visible in continuous monitoring data and such data could help the utility operate the valve more consistently and respond faster to pipe breaks. Continuous pressure and flow data from the Zone 3 entrance during a pipe break are shown in Figure 5.4. Flow increased and pressure decreased to a negative value at the time of the break. Approximately 8 hours later, flow stopped and pressure increased to zero when an operator closed the control valve located just upstream of the entrance monitoring station.

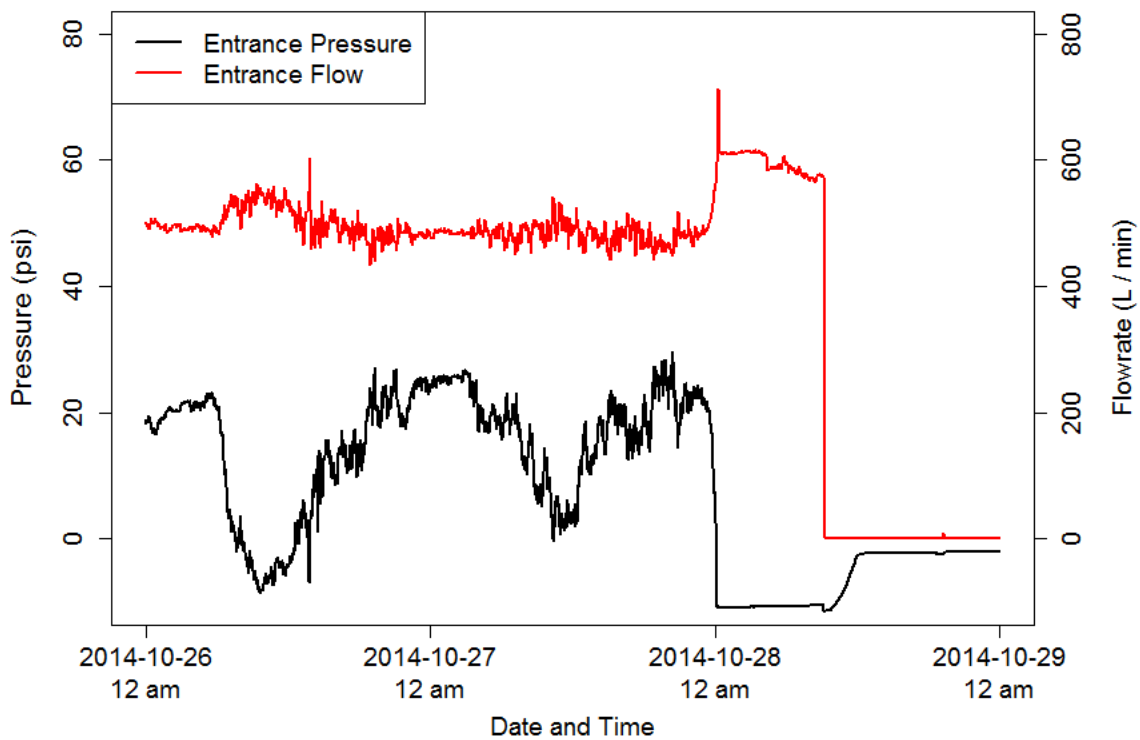

Figure 5.4: Continuous pressure and flow monitoring data from Zone 3 (valve-controlled) entrance monitoring station during a break in the 4" pipe supplying Zone 3 (downstream of the entrance) at approximately 12am 2014-10-28.

5.3.3. Water losses

Entrance flows and metered consumption

Entrance flows, the number of buildings per study zone, and household characteristics based on survey data are presented in Table 5-2. The average entrance flow of 3,587 liters per building day (764 liters per capita per day [LPCD]) in the tank-fed zone (Zone 2) was much higher than that of the other zones. The data indicate that the higher entrance flowrate in Zone 2 was due to a higher rate of water loss in that zone. Although houses in Zone 2 tended to be larger house and have more flush toilets (Table 5-2), July 2015 metered and estimated consumption in Zone 2 (Table 5-3) was lower than that in the continuous zone (Zone 1), suggesting that higher entrance flows were not related to higher water consumption. Even though most households in Zone 2 appeared to have accounts with the utility (559 accounts for 650 buildings) 71% of the entering water was not billed. Field investigation suggested that Zone 2 had some (un-monitored) small-diameter (< 2") interconnections with the adjacent network, but the adjacent network was at a higher pressure, so these would most likely have caused additional water to enter Zone 2 rather than leave.

Flow supplied per building was 25% higher in Zone 1 than in Zone 3, but that difference is easily explained by Zone 1 receiving a much more continuous supply (Table 5-1:) and the higher number of people and toilets per household in Zone 1 (Table 5-2). Since the vast majority of users in Zone 3 did not have formal contracts with IDAAN, no metering or billing data from there were available for comparison with Zone 1.

Table 5-2: Supply statistics and household characteristics. Numbers in parentheses are the number of households surveyed in each zone to arrive at the average. Abbreviations: LPCD = liters per capita per day. *Includes capacity to store water for all uses.

Zone	Days of data	Average entrance flow (L/min)	Number of buildings	Average flow per building (L / building-day)	Average number of people per house	Average flow per person (LPCD)	Average number of toilets per house	Average storage capacity* (L / house)
1	346	536	348	2,216	8.7 (34)	255	0.65 (34)	380 (18)
2	345	1,619	650	3,587	4.7 (43)	764	1.3 (43)	252 (19)
3	343	285	232	1,769	5.6 (48)	316	0.19 (48)	985 (17)

Table 5-3: Customer metering and supply data. The customer metering data are from the last billed month that was in the utility's database on August 7, 2015, and are assumed to roughly represent consumption for July 2015. These data are compared with entrance flow data for that month. The volume billed for clients whose meters were not read is based on an average consumption that the utility assigned to each area and type of client, or on previous metering data available for the same client. *Customers that consumed less than the minimum consumption (8,000 or 6,000 gallons per month for residential customers) were billed for the minimum, so it is only known that their consumption was below the minimum. For those cusomters, consumption was assumed to be 75% of the minimum. **Metered consumption per customer was calculated by dividing total metered consumption by the number of customers with meters read.

Zone	Total accounts in zone	Accounts with meter read	Entrance Flow (L/day)	Volume billed (L/day)	% of entrance flow that was billed	Billed volume per account (L/day)	Total metered consumption (L/day)*	Metered consumption per account (L/day)**
1	317	149	772,000	522,000	68%	1,646	265,000	1,776
2	559	318	2,332,000	670,000	29%	2,098	439,000	1,380

Minimum night flows were high, indicating high rates of leakage in the distribution network or premise plumbing. As shown in Figure 5.5, the average entrance flow per building increased a small amount during the morning hours in Zone 2 (tank-fed) and decreased a small amount during the middle of the night in Zone 1 (continuous). However, diurnal variation in entrance flow was very small in comparison to how much rates of consumption would be expected to vary. In Zone 2, the entrance flow during the hour of minimum average flow (in the middle of the night), was 81% of the flow during the hour of peak average flow. Similarly, in Zone 1, the flow during the hour of minimum average flow was 73% of the flow during the hour of peak average flow. Actual water consumption from 12 am to 4 am was almost certainly low in those zones, since in Zone 1 and most of Zone 2 clients normally had water 24 hours per day. In Zone 3 (valve-controlled), average entering flow was almost constant for all 24 hours of the day. There, some clients probably only had supply during the middle of the night, and could have been collecting water during those hours. Users interviewed in Zone 3 had more household water storage capacity than users interviewed in Zones 1 and 2 (Table 5-2).

The entrance flow for each zone did not vary noticeably by day of the week, but in Zones 2 and 3 it did appear to vary by month (Figure 5.6). The months with low flow approximately corresponded to months when the downstream monitoring point was more frequently without water (Figure 5.3).

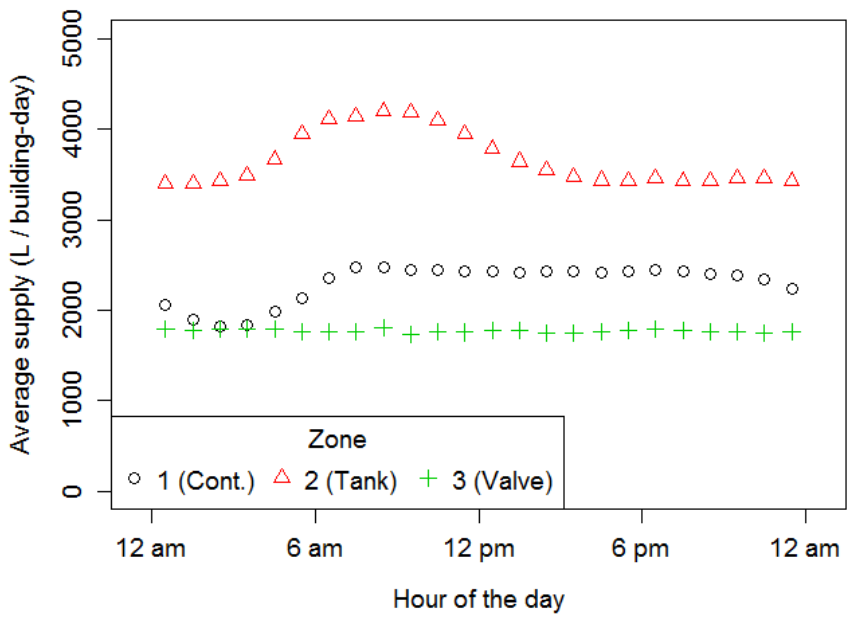

Figure 5.5: Average entrance flow per building by hour of the day.

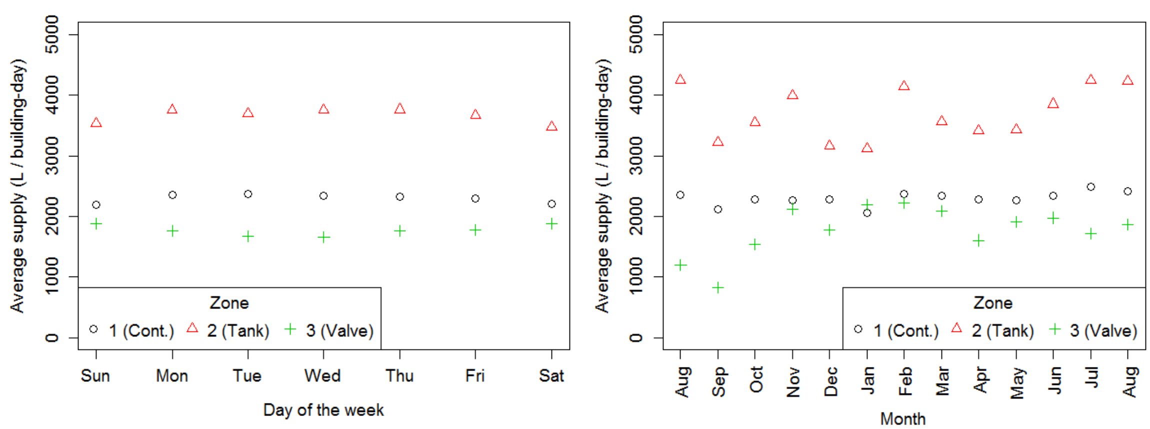

Figure 5.6: Average entrance flow per building by day of the week and by month.

Water loss estimates

Water losses estimated by subtracting per-capita consumption (estimated based on customer metering data) from per-capita entrance flows are shown in Table 5-4 (20% for Zone 1, 62% for Zone 2 and 35% for Zone 3). As expected, given high entrance flows, estimated losses are highest in Zone 2. This estimation method assumes that un-metered customers had similar consumption to metered customers, and that customers in Zone 3 had similar consumption to those in Zone 1 (since no metering data were available for Zone 3). In fact, since fewer households had flush toilets in Zone 3 than in Zone 1 (Table 5-2), and supply was more intermittent in Zone 3, consumption there may have actually been lower, which would have caused us to underestimate losses.

In Table 5-5 we present water loss estimates based on minimum night flows (56% in Zone 1 and 77% in Zone 2). For both zones, the estimates using this method are much higher than estimates based on per-capita consumption. Much of this difference could be explained by leakage within premise plumbing, which would have been included in consumption measured by household meters and thus not counted in the water losses calculated in the first method. Since the utility bills customers for such losses, they are not normally considered losses from the utility's perspective, but it may be in the utility's best interest to reduce them if rates do not cover the utility's true costs or if, due to water resources limitations, the utility would prefer to reduce water production.

Table 5-4: Water loss estimated based on per-capita metered consumption.

Zone	Per-capita entrance flow (LPCD)	Estimated consumption based on meter data (LPCD)	Estimated per-capita losses (LPCD)	Losses as % of entrance flow
1	255	204	51	20%
2	764	294	470	62%
3	316	204	112	35%

Table 5-5: Water loss estimated based on minimum night flows.

Zone	Minimum avg. hourly flow (LPCD)	Estimated minimum consumption (LPCD)	Estimated leakage rate at hour of minimum flow (LPCD)	Estimated avg. overall leakage rate, adjusted for pressure and outages (LPCD)	Losses as % of entrance flow
1	255	12 (6% of avg.)	197	144	56%
2	764	35 (12% of avg.)	687	591	77%

Discussion of water loss results

Large per-capita volumes of water entering the study zones, high rates of unbilled water in Zones 1 and 2, and high minimum night flows, as well as both water loss estimation methods we used, suggest that rates of water loss are high in the study zones, particularly in Zone 2. These high loss rates are not surprising, given that non-revenue water was estimated at 53% for the Arraiján system as a whole.

High rates of water loss in the study zones underscore the importance of including water loss reduction in efforts to make intermittent systems more continuous. First, reducing water losses is an opportunity to make additional supply available without increasing pumping and treatment costs. Additionally, if supply is made more continuous and pressures are increased without reducing leakage, water loss rates will increase (Taylor 2015). As discussed in the Methods section, leakage will scale with supply pressure and the portion of the time that water is on.

As an example, assume that actual consumption in Zone 3 was 150 LPCD, not including leakage in premise plumbing. Then 166 LPCD (53%) of the 316 LPCD entering the zone would have been lost to leakage in the network or in premise plumbing. Now assume that supply is improved in Zone 3, so that average pressure increases from 35 psi to 55 psi and supply is on 100% of the time rather than 57% of the time. If consumption stays the same, leakage will increase by 276% according to Equation 5-1 from 166 LPCD to 458 LPCD, and entrance flow will increase 96% from 310 LPCD to 608 LPCD. The percentage of water lost to leakage will increase from 53% to 75%.

5.4. Opportunities to improve service quality

Continuous pressure and flow monitoring methods applied in this research could also be used by system operators to monitor supply conditions, improve supply reliability, and monitor and reduce water losses. For example, pressure monitoring showed that supply in Zone 3 did not follow the utility's programmed schedule, a situation utility managers would likely be unaware of otherwise. With such data in hand, utility operators and managers could identify the causes of deviations from the programmed schedule and take corrective actions. Hydraulic monitoring also identified acute problems, such as pipe breaks and pump station failures. Rather than having to make frequent field visits or wait for customer dissatisfaction to boil over, continuous monitoring with telemetry would allow system operators to detect problems from the office. Analysis of other operations data, such as valve operation logs and pipe repair records, and more complete information about the distribution network's configuration could also lead to more systematic operation and improved service quality.

Division of the network into district metered areas (DMAs) (Savić and Ferrari 2014), with flow monitoring at the entrance to each area, is a promising tool for water loss reduction, allowing operators to identify areas with high loss rates (e.g. Zone 2) and track progress of water loss reduction efforts. Increasing coverage of customer meters is also critical for accurately estimating water losses and encouraging customers to use water rationally. While 79% of customers in Arraiján had meters in 2014, only 74% of those meters were read (IDAAN 2015) and metering coverage was much lower in some informally developed areas with intermittent supply, such as Zone 3, where practically no customers were registered with the utility or had meters.

We are not the first to propose using sensor networks to monitor drinking water systems in developing countries. In India, a social enterprise called NextDrop developed a human sensor network in which operators reported valve operations through their mobile phones and that information was used to relay water delivery times to customers (Kumpel et al. 2012). In Nairobi, Kenya slums, where pipe breaks, intermittent supply, and contamination events are common, Heland et al. 2015 proposed installing sensor networks to alert trained local residents, called "citizen field engineers", of needed maintenance. Sensor networks installed and managed by utilities, like those proposed here, will offer advantages in some situations.

We were also not the first to install online monitoring stations in Arraiján. As part of a 2010 project, the network was divided into eight DMAs, and 15 pressure and flowrate monitoring stations, not altogether different from the ones we propose, were installed at the boundaries of each DMA (Louis Berger Group 2010). At the time of our research, however, only some of the sensors were working, the original telemetry equipment to upload the data to the internet was not working, and water balances for the DMAs had not recently been calculated. Several factors could explain why the previously installed sensors were not maintained. A specialized division of the utility, located 20 km away in Panama City, was in charge of maintaining and collecting data from the Arraiján monitoring stations and many others throughout the country, but had few resources to dedicate to the task. The stations were set up by a private contractor, and capacity building to teach utility personnel how to use and maintain them may have been inadequate. Also, with few personnel available to analyze and use the monitoring data, and local operators not involved in that process or able to use the data as an operational tool, the data's value, and thus the value of maintaining the monitoring stations, may have been seen as low.

As seen from previous experience in Arraiján, monitoring will only be useful if the utility has the human and logistical resources required to maintain sensors, analyze and interpret the data they produce, and take corrective actions based on the data. Promptly detecting a pipe break will be of little value if a repair crew is not available to fix it.

5.5. Conclusions

We identified many opportunities to improve supply reliability in the intermittent Arraiján study zones, even if continuous supply is not attained. Pressure monitoring indicated that supply was irregular and unpredictable in the intermittent study zones, and sometimes interrupted by infrastructure failures that the utility did not correct for several days. Operational challenges, such as inadequate information about infrastructure configuration and the inability to monitor the state of the network, were often root causes of unreliable supply. In the long term, reduction of water losses is critical to achieving continuous supply or more reliable intermittent supply. Estimates of water losses based on available household metering data and minimum night flows indicated that large quantities of water were being lost to leakage in the study zones, particularly Zone 2. High estimated loss rates are not surprising, given that 53% of water entering the Arraiján network as a whole was not billed to customers.

Continuous pressure and flow monitoring are promising tools for operating intermittent distribution networks more reliably and tracking and reducing water losses. While such "high-tech" solutions are currently more common in continuous drinking water networks in high-income countries, they may be even more useful in complex and dynamic intermittent networks that are prone to frequent infrastructure failures. However, such monitoring techniques will only be effective if the utility using them has the capacity (human and logistical) to maintain the monitoring equipment, analyze the data it produces and take corrective action based upon those data.

CHAPTER 6. Conclusions

Despite the widespread prevalence of intermittent water supply (IWS) and important concerns regarding its effects on water quality, infrastructure deterioration, and users' access to a reliable water supply, our understanding of its nature and effects is quite limited. Given its obvious disadvantages, it may be tempting to conclude that there is little point to understanding the intricacies of IWS, and that all efforts should be focused on converting intermittent systems to continuous ones. However, given that such conversion is unlikely to happen in the short term, and that a better understanding of intermittent systems would likely help generate strategies to make them more continuous, I believe that it is important to improve our understanding of IWS. Research on intermittent systems may also help us to better operate continuous networks, because IWS is closely linked to other distribution system deficiencies, such as contaminant intrusion, hydraulic transients, and water loss, that are also concerns in continuous systems. It may be possible to study such deficiencies in intermittent systems, where they are more common and thus easier to observe, and then extrapolate the results to continuous systems.

The objective of the research presented in this dissertation was to evaluate the effects of intermittent supply on water quality, pipe damage and service reliability in four study zones in the Arraiján distribution network, each of them with a different supply situation (continuous, tank-fed intermittent, valve-controlled intermittent, and pump-controlled intermittent). I was fortunate to be able to use methods and results from previous work in intermittent and continuous distribution networks—particularly from Kumpel and Nelson (2013 and 2014) —as a foundation. However, at the outset, I still knew little about how the Arraiján network functioned or how well the monitoring methods we planned to use would capture water quality and hydraulic conditions there, so it was difficult to formulate detailed hypotheses. In essence, this research was an effort to collect as much relevant data as possible and then use that data to begin to answer the initial general research questions. Just as this work built on previous experience, I hope that others can use the methods and results presented here to generate hypotheses and develop new methods to further our understanding of the variety of intermittent networks throughout the world that supply hundreds of millions of people.

In this last chapter, principal findings from the three main chapters are summarized, opportunities for improving operation and management of IWS in Arraiján and similar systems are identified, and directions for future research are proposed.

6.1. Principal findings

CHAPTER 3: Water quality effects of intermittent supply

To evaluate water quality and contamination risks in the Arraiján study zones, pressure was monitored continuously for a year to detect negative pressures that could cause backflow or intrusion, water quality grab samples were collected at random times during supply and intensively during first-flush events, and turbidity and free chlorine residual were monitored continuously.

Despite the occurrence of negative pressures, water quality grab samples collected from household taps and distribution system pipes at random times almost always met water quality criteria (turbidity ≤ 1 NTU, total coliform and *E. coli* bacteria < 1 MPN / 100 mL, free chlorine residual ≥ 2 mg/L). Consistently good routine water quality in Arraiján was particularly remarkable when compared to water quality in intermittent areas of a distribution network previously studied in Hubli-Dharwad, India (Kumpel and Nelson 2013). Several factors—better treatment plant effluent water quality, supply being on a greater portion of the time, fewer contaminant sources, and consistently adequate chlorine residual—could have contributed to better water quality under IWS in Arraiján. In contrast to routine sampling results, water quality was sometimes degraded during the first 20 minutes of first-flush events, particularly in Zone 3, where supply was controlled by a valve and supply outages were longest. High turbidities (> 100 NTU) were also measured after some pipe breaks and repairs. Continuous monitoring showed that turbidity tended to be higher during the first hours of supply and confirmed that chlorine residual was consistently adequate.

CHAPTER 4: Evaluation of whether pressure conditions under intermittent supply damage pipes

Pressure was monitored at study zone entrances and downstream locations to investigate whether extreme pressures (transient or steady-state) occurred that could damage distribution system pipes. Three years of pipe break data for the Arraiján system as a whole were also analyzed to assess whether high pipe break rates were associated with intermittent supply. No extreme or transient pressures were observed due to filling of distribution pipes in the intermittent study zones. However, intermittent pumping caused extreme and transient pressures and was associated with high pipe break rates in some parts of the Arraiján network. There was a marginally significant association between intermittent supply and high pipe break rates, but that association may have been mainly driven by the zones with intermittent pumping, and it was not clear that break rates were higher in intermittent zones without pumping. Other factors associated with IWS, such as installation of pipes by users, may have also been related to high pipe break rates.

CHAPTER 5: Challenges of operating an intermittent distribution network

Continuous pressure and flow monitoring were used to evaluate the reliability of supply in the four study zones. Informal observation of network operation and conversations with operators shed light on the challenges of operating and monitoring a complex and dynamic intermittent distribution network like Arraiján's. Flow measurements at the entrances to the study zones, along with household surveys and limited customer metering data, were used to estimate water losses within three of the study zones.

Supply in the intermittent study zones was generally unreliable, with supply outages not conforming to a defined schedule and sometimes lasting longer than expected. Operational challenges, such as lack of system information and the inability to detect supply problems and infrastructure failures, contributed to the unreliability of supply. Average per-capita flows and minimum night flows entering the study zones were high, indicating that large quantities of water were leaking from either distribution pipes or premise plumbing. Results and experience from this research suggest that continuous pressure and flow monitoring, and better management of operations data, could be effective tools for improving supply reliability and reducing water losses.

6.2. Opportunities for improving intermittent supply

By comparing different parts of the Arraiján network to one another, and comparing the Arraiján network to previously studied networks, we saw that there is a great deal of variation within the category of water systems classified as "intermittent." This variation suggests that, even when continuous supply is not achievable in the short term, intermittent supply can still be improved.

Several opportunities to improve water quality conditions, prevent infrastructure damage and improve supply reliability in intermittent areas of the Arraiján network were identified. Similar strategies might also be applicable to other intermittent networks.

- **Continuous pressure and flow monitoring** at key locations of the network can detect negative pressures that threaten water quality, detect extreme pressures that may cause pipe breaks, evaluate and improve supply reliability, and identify areas with high rates of leakage.
- Preventative measures, such as maintaining a consistent free chlorine residual, using best practices to avoid contamination during pipe repairs, and educating users to avoid consuming first-flush water, can **reduce water quality risks** in intermittent systems.
- Maintaining and analyzing **operational and infrastructure data** can allow for a more rational operation of complex intermittent networks.
- Investing in **water loss reduction** has potential to make supply more reliable and continuous without the additional expense of treating or pumping more water.

All of the measures proposed above involve building the utility's capacity to manage the distribution network and will require human and logistical resources. While infrastructure investments will surely be necessary in some cases to improve service provided by intermittent systems, the long-term process of improving distribution system management is even more important than short-term investment projects.

6.3. Directions for future work

The results of this research suggest directions for future work to investigate the mechanisms through which IWS affects water quality and pipe condition; develop technologies specific to IWS; and develop methods to improve management of intermittent systems.

6.3.1. Mechanisms affecting water quality and pipe damage

A better understanding of the mechanisms through which IWS affects microbiological water quality could help operators protect water quality in intermittent systems. More research is needed on the protection provided by a disinfectant residual, the risks posed by chlorine-resistant pathogens, the effects of IWS on the distribution system microbiome, and the relative importance of regrowth vs. intrusion as contamination mechanisms. Likewise, a more mechanistic understanding of the hydraulics of intermittent supply is needed to develop strategies for protecting valuable pipe infrastructure. Study of how intermittent supply affects corrosion rates is also needed to evaluate how it may affect water quality and pipe deterioration in networks with metal pipes.

6.3.2. Engineering innovation to develop technologies specific to intermittent supply

Most drinking water distribution system technologies (e.g. pumps, hydraulic surge protection devices, hydraulic modeling software, and distribution network topologies) have been developed for continuous systems. Technologies specifically designed for intermittent systems could alleviate some of the problems associated with IWS. Potential areas for IWS-specific design include:

- robust and inexpensive backflow preventers to reduce risk of backflow through customer connections,
- pumping systems and/or network topologies designed to operate intermittently without causing damaging transients,
- and hydraulic and water quality monitoring equipment designed to monitor intermittent systems.

6.3.3. Management and improvement of intermittent systems

Practical research is needed to develop effective strategies for reducing the problematic effects of IWS and, when possible, making intermittent systems continuous. Monitoring and operation strategies specific to the challenges of IWS have the potential to protect water quality and pipe infrastructure and make supply more reliable in intermittent systems. Effective strategies must also be developed to rehabilitate failing intermittent drinking water distribution networks by reducing water losses and making infrastructure improvements. In some cases, the immediate goal will be to make supply continuous, while in other cases the goal will be to provide a better intermittent supply.

A first step to developing management and rehabilitation strategies is characterizing the variety of intermittent supply situations found throughout the world. The World Bank Water and Sanitation Program's International Benchmarking Network (IBNET) already collects data by utility for average hours of service per day and percent of customers with discontinuous service. While such metrics are an efficient way to track supply continuity at a high level, they miss many important details of IWS, such as supply reliability. More detailed characterization of a sample of systems around the world would be helpful. International development organizations and water utilities themselves may be better suited to this large task than academic researchers are. Academic researchers, in collaboration with practitioners, could develop standardized methods for characterizing individual systems, which would then be applied by utilities and on-the-ground practitioners. Longitudinal tracking (on the scale of decades) of supply conditions and efforts to improve them would be particularly helpful for evaluating management and rehabilitation strategies. International development organizations and utilities would be well suited for doing this long-term tracking.

Finally, technical research must be coupled with policy research on how to promote and implement effective management and rehabilitation strategies in the real world, where water networks are planned, built, financed, operated, maintained and used by institutions and people.

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