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Water quality effects of intermittent water supply in Arraiján, Panama

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A B S T R A C T

Intermittent drinking water supply is common in low- and middle-income countries throughout the world and can cause water quality to degrade in the distribution system. In this study, we characterized water quality in one study zone with continuous supply and three zones with intermittent supply in the drinking water distribution network in Arraiján, Panama. Low or zero pressures occurred in all zones, and negative pressures occurred in the continuous zone and two of the intermittent zones. Despite hydraulic conditions that created risks for backflow and contaminant intrusion, only four of 423 (0.9%) grab samples collected at random times were positive for total coliform bacteria and only one was positive for *E. coli.* Only nine of 496 (1.8%) samples had turbidity >1.0 NTU and all samples had ≥0.2 mg/L free chlorine residual. In contrast, water quality was often degraded during the first-flush period (when supply first returned after an outage). Still, routine and first-flush water quality under intermittent supply was much better in Arraiján than that reported in a previous study conducted in India. Better water quality in Arraiján could be due to better water quality leaving the treatment plant, shorter supply outages, higher supply pressures, a more consistent and higher chlorine residual, and fewer contaminant sources near pipes. The results illustrate that intermittent supply and its effects on water quality can vary greatly between and within distribution networks. The study also demonstrated that monitoring techniques designed specifically for intermittent supply, such as continuous pressure monitoring and sampling the first flush, can detect water quality threats and degradation that would not likely be detected with conventional monitoring.

1. Introduction

Intermittent water supply (IWS) occurs when a water utility is unable to continuously maintain positive pressure in the entire piped drinking water distribution network. IWS can be caused by insufficient water resources, inadequate infrastructure, unplanned expansion of the distribution network, excessive water losses, or a combination of these factors (Galaitsi et al., 2016; Klingel, 2012; Kumpel and Nelson, 2016; Rosenberg et al., 2008; Yepes et al., 2001). IWS is common in low- and middle-income countries throughout the world. In 2000, it was estimated that 60% of households with piped water connections in Latin America and the Caribbean had IWS (PAHO and WHO, 2001) and over half of urban water supplies in Asia and over one-third of urban water supplies in Africa operated intermittently (WHO and UNICEF, 2000). A recent review estimated that at least 309 million people worldwide are supplied by utilities that provide intermittent supply (Kumpel and Nelson, 2016).

Intermittent water supply is an inconvenience for users (Lee and Schwab, 2005; McIntosh, 2003), can make it difficult for a utility to provide equitable supply to all customers in the distribution network (Fontanazza et al., 2007; Klingel, 2012; Vairavamoorthy et al., 2007), is thought to cause pressure transients that cause damage to pipes (Batish, 2003; Christodoulou and Agathokleous, 2012), and is a risk to water quality (Coelho et al., 2003; Gadgil, 1998; Klingel, 2012; Kumpel and Nelson, 2016; Lee and Schwab, 2005; Tokajian and Hashwa, 2003). Risks to microbiological water quality are due to: 1) intrusion of contaminated groundwater via leaks in underground pipes or backflow of contaminated water through customer connections during periods of low or negative pressure (Besner et al., 2011; Gadgil, 1998; Lee and Schwab, 2005; Vairavamoorthy et al., 2007); 2) microbial regrowth in bulk water,

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in pipe-wall biofilm, and attached to 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 (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 such as frequent pipe leaks and breaks (Lee and Schwab, 2005), poor control of water quality entering the distribution network from treatment plants (Besner et al., 2002; Lee and Schwab, 2005), and repair practices that do not adequately prevent contamination (Besner et al., 2002; Kelkar et al., 2001). These deficiencies have the potential to degrade water quality (Besner et al., 2002).

Studies in India (Elala et al., 2011; Kelkar et al., 2001; 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. A recent review and meta-analysis assessing the impact of distribution system deficiencies on endemic gastro-intestinal illness found that temporary and chronic water outages under IWS were associated with gastro-intestinal illness (Ercumen et al., 2014).

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 total coliform and *E. coli* bacteria 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. Concentrations of indicator bacteria in intermittent areas were higher during the rainy season and after specific rain events, when intrusion would have been more likely due to saturated soil and overflowing sewers. In the intermittent zones there 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 these data with grab samples analyzed for turbidity, free chlorine and indicator bacteria to evaluate the usefulness of continuous monitoring as a research tool and for utilities that operate intermittent distribution systems.

2. Materials and methods

2.1. Study site

The research was conducted in the piped drinking water distribution network serving Arraiján, a rapidly growing peri-urban area west of Panama City, Panama. Arraiján's population grew from 60 thousand inhabitants in 1990 to an estimated 263 thousand in 2014 (National Institute of Census and Statistics, Panama, 2010a; 2010b), increasing demand for drinking water. The drinking water system 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. 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. Arraiján's distribution system was complex due to the large area it covered, its supply from three treatment plants, and its complex topography. Smaller diameter ($\leq$25 cm) distribution pipes were mostly PVC and larger diameter ($\geq$30 cm) transmission pipes were mostly ductile iron. Over half of the pipe network was <25 years old, although some portions were >35 years old.

Although a sufficient quantity of water (585 L per person per day) entered the Arraiján network and most of the network normally had continuous supply, some areas routinely received intermittent supply due to high rates of leakage and because pumps, storage tanks and/or pipes did not provide sufficient local distribution capacity.

Five study zones within the Arraiján distribution network were chosen to examine the effects of different supply situations (Fig. 1). Zones were selected: 1) to represent a variety of supply situations; 2) to be hydraulically isolated, with only one or two connections to the rest of the network so that the quality of the water entering the zone could be monitored; and 3) to be as large as possible while still maintaining a similar supply regime within the study zone. Zone 1 (abbreviated as "continuous") received water directly from the main transmission pipe coming from WTP A and had continuous supply throughout the study, aside from eight outages lasting between 45 min and 22 h, which were mostly related to breaks of the transmission pipe or intentional shutdowns due to construction. Zone 2 (abbreviated as "tank") received most of its supply by gravity from two 1 million gallon storage tanks that normally received water from both WTP A and WTP B. Zone 2 also received some supply directly from a main transmission pipe that did not depend on the tanks. The tanks often drained when the overall system had a supply deficit, particularly on weekends and in the afternoon hours, causing higher elevations in Zone 2 to lose supply. Supply to Zone 3 (abbreviated as "valve") was rationed by the utility with a valve at the entrance to the zone, because of insufficient distribution capacity in the area. The utility's schedule called for leaving the valve open for three days to supply Zone 3 and closed for three days to send more supply to another nearby sector; however, actual supply often deviated greatly from this schedule. Zone 4 (abbreviated as "pump") was supplied principally by a pump station that pumped directly into the zone's local distribution network. This pump station stopped frequently because of insufficient water or power failures, causing most of the zone to lose supply. In Zone 5 (abbreviated as "tank + valve"), water was normally supplied for a few hours every other day when a valve was opened to empty water from an uphill storage tank. Only first-flush sampling (see Section 2.2.3) was conducted in Zone 5. A summary of the study zones is provided in Supporting Information Table S1.

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. Zones had between 200 and 650 connections each (not all legally registered with the utility), and pipe within the zones was ½″- to 6″-diameter PVC. At least one household in Arraiján was observed to extract water directly from the distribution network with a household booster pump, a practice that is common in some intermittent systems and can cause negative pressures in the distribution network (Kumpel and Nelson, 2016). However, pumping from the network was not common in Arraiján and no houses in the study zones were