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Intermittent supply in the context of efforts to improve piped drinking water supply in Latin America and the Caribbean

Lessons from a case study in Arraiján, Panama

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Intermittent Supply

IN THE CONTEXT OF EFFORTS TO IMPROVE PIPED DRINKING WATER SUPPLY IN LATIN AMERICA AND THE CARIBBEAN

LESSONS FROM A CASE STUDY IN ARRAIJÁN, PANAMA

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Executive Summary

The characteristics and effects of intermittent piped drinking water supply (IWS), which is frequently present in Latin America and the Caribbean, are important to consider in efforts to provide safe, reliable and sustainable piped drinking water.

In addition to being an inconvenience for users, IWS is a threat to water quality, and often closely related to other drinking water distribution system deficiencies.

A case study was conducted in the intermittent drinking water distribution system in Arraiján, Panamá, a rapidly growing peri-urban area west of Panama City. Pressure, flow, turbidity and chlorine were monitored continuously in four study zones with a variety of supply conditions. Water quality grab samples were collected from the continuous monitoring stations and household taps, and analyzed for turbidity, chlorine, and indicator bacteria. In addition, 3 years of pipe repair records were analyzed to estimate break rates in different areas of the distribution system.

Pressure monitoring showed that supply schedules in intermittent areas were inconsistent and unpredictable, and identified negative pressures that represent a risk to water quality. Once supply was established, water quality in the study zones was consistently in compliance with Panamanian standards for turbidity and total coliform and *E. coli* bacteria and World Health Organization recommendations for free chlorine residual, but was sometimes degraded during the first flush when supply began after an outage. Overall, water quality was much better in the IWS zones of Arraiján compared to previously published water quality monitoring results from IWS areas in Hubli-Dharwad, India. Per-capita flows entering the study zones were high, and remained high during the middle of the night, suggesting high rates of leakage. Pipe break rates varied widely across different zones. Although there was no clear general association between intermittent supply and high break rates, intermittent pumping was associated with some of the highest break rates.

Results from the Arraiján case study, when compared to results from the study in Hubli-Dharwad (India), which used similar methodology, show that the nature and severity of IWS and its effects can vary substantially between and within distribution networks. Results from Arraiján also show that advanced monitoring techniques offer opportunities to diagnose problems in complex IWS systems and improve management of such systems.

Based on lessons learned from Arraiján and other research reported in the literature, a framework to consider IWS in efforts to improve drinking water service in Latin America and the Caribbean is proposed. IWS is inherently complex, and efforts to improve or avoid it should begin with efforts to understand it in the context of specific scenarios. Hydraulic and water quality monitoring methods specific to IWS can be used to diagnose intermittent systems and provide guidance on how best to improve service and water quality. In addition to best practices for continuous distribution systems (e.g., maintaining sufficient pressure and chlorine residual during supply periods), better management of water supply timing, pressure regimes, and first flush water have the potential to significantly improve service quality in IWS systems. Such management measures should be considered as complements to or replacements for more costly infrastructure investments to augment distribution system capacity and increase water production.

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The importance of considering intermittent supply

Intermittent drinking water supply (IWS) can be defined as piped water supply service that is available to consumers less than 24 hours per day seven days per week.[1]

IWS can be caused by insufficient water resources, inadequate infrastructure, excessive water consumption by users, excessive water losses in the distribution network, or a combination of those factors.[2] Unplanned urban growth and accompanying un-systematic expansion of drinking water distribution networks are also often underlying causes of IWS.[3] In this section we argue that understanding IWS is integral to improving piped drinking water supply in Latin American and the Caribbean, because of: i) the frequent presence of IWS in the region; ii) its inconvenience for users; iii) its potential effects on water quality; iv) its inter-relation with other factors that are critical to sustainable and efficient operation of a piped drinking water system. Next, in Section 2 we present lessons learned from a case study of an IWS system in Arraiján, Panamá and comparisons between that system and an IWS system in Hubli-Dharwad, Karnataka, India. Finally, in Section 3 we propose a framework for considering IWS in efforts to provide safe, reliable and sustainable piped drinking water supply in Latin America and the Caribbean.

1.1 IWS in Latin America and the Caribbean

Available data suggest that intermittent water supply is a widespread problem in Latin America and the Caribbean. According to statistics prepared by the Pan-American Health Organization and the World Health Organization, approximately 60% of households with piped water connections in Latin America and the Caribbean had intermittent supply in 2001.[4]

Data from a survey conducted by the National System of Sanitation Information (SNIS)[5] of Brazil in 2011 indicate that about 40% of households with connections to piped water supply countrywide suffered some kind of intermittency in their service during the year.

In a 2010 survey of households in nine large Mexican cities, 40 percent of respondents said their water was cut off sometimes or frequently.[6]

1.2 IWS is inconvenient and costly for users

An intermittent supply is inconvenient and can be costly for users, who have to adjust their water use to the supply schedule or invest in storage tanks.[7] These inconveniences could reduce users' willingness to pay for service. A study in Hubli-Dharwad, twin cities in India, found that users with intermittent supply spent significant amounts of money on tanks and containers to store water and pumps to extract water from the distribution network. They also spent significant amounts of time collecting water from other sources, waiting for water to arrive, and collecting the water when it arrived.[8] The results of that study indicate that when supply is intermittent users prefer that at least supply periods be predictable, longer, and more frequent[9] (average reported supply in Hubli-Dharwad was 5 hours every 6 days[10]). IWS also can make it difficult to supply users equitably. Often, customers at lower elevations are able to collect more water because they receive it earlier and with higher pressure than customers at higher elevations.[11]

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[1] International Water Association, "Intermittent Water Supply," accessed June 25, 2016, http://www.iwa-network.org/task/intermittent-water-supply-iws.

[2] Philipp Klingel, "Technical Causes and Impacts of Intermittent Water Distribution," Water Science & Technology: Water Supply 12, no. 4 (July 2012): 504, doi:10.2166/ws.2012.023.

[3] Ibid.

[4] Pan American Health Organization and World Health Organization, "Regional Report on the Evaluation 2000 in the Region of the Americas," 2001.

[5] http://www.snis.gov.br/

[6] IADB, "Complete Results (in Spanish) of Mexico Bottled Water Survey.," July 2012, http://www.iadb.org/document.cfm?id=36984661.

[7] Arthur C. McIntosh, Asian Development Bank, and International Water Association, Asian Water Supplies: Reaching the Urban Poor: A Guide and Sourcebook on Urban Water Supplies in Asia for Governments, Utilities, Consultants, Development Agencies, and Nongovernment Organizations (Manila, Philippines : London: Asian Development Bank ; International Water Association, 2003).

[8] Zachary Burt et al., "Costs and Benefits of an Upgrade to Continuous Water Service in Hubli-Dharwad, India" (2015 Water and Health Conference, University of North Carolina at Chapel Hill, October 26, 2015).

[9] Zachary Burt, M VanGordon, and A Vij, "Continuous Piped Water or Improved Intermittency? Willingness to Pay for Improved Piped Water Services in Hubli-Dharwad, India" (11th Annual Meeting of the International Water Resource Economics Consortium (IWREC), World Bank Headquarters, Washington, D.C., September 7, 2014).

[10] Emily Kumpel and Kara L. Nelson, "Mechanisms Affecting Water Quality in an Intermittent Piped Water Supply," Environmental Science & Technology 48, no. 5 (March 4, 2014): 2766–75, doi:10.1021/es405054u.

[11] C. M. Fontanazza, G. Freni, and G. La Loggia, "Analysis of Intermittent Supply Systems in Water Scarcity Conditions and Evaluation of the Resource Distribution Equity Indices," vol. I (WIT Press, 2007), 635–44, doi:10.2495/WRM070591; Kala Vairavamoorthy, Sunil Gorantiwar, and S. Mohan, "Intermittent Water Supply under Water Scarcity Situations," Water International 32, no. 1 (March 2007): 121–32, doi:10.1080/02508060708691969.

1.3 IWS can degrade water quality, and may reduce consumer confidence in piped water

Intermittent supply is considered to be a risk to microbiological water quality, due to:

i) intrusion of contaminated groundwater via leaks in underground pipes or backflow of contaminated water through customer connections during periods of low and negative pressure;[12]

ii) potential for regrowth of microorganisms in the water and in biofilms on pipe walls when the water is turned off and sits stagnant in pipes;[13]

and iii) recontamination and microbial regrowth during household storage.[14]

A recent critical review examined these mechanisms and results of previous research on microbial water quality in intermittent systems.[15] Studies in India,[16] Palestine,[17] and Lebanon[18] have found evidence of water quality deterioration in the distribution network or during household storage in intermittent networks, although, 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.

In Merida, Mexico, a study found **that 95% of 383 samples taken of water entering households complied with standards for bacteriological quality; but only 74% of samples from taps within the same households complied with the standards.**[19] This difference was attributed to water quality degradation in household storage tanks.

Intermittent supply has been linked to a typhoid outbreak in Tajikistan, a paratyphoid fever outbreak in India, and diarrhea rates in a city in Uzbekistan. A recent review and meta-analysis assessing the impact of distribution system deficiencies on endemic gastro-intestinal illness found that temporary water outages and chronic water outages under IWS were associated with gastro-intestinal illness.[23]

Another component of the research in Hubli-Dharwad mentioned above focused on the effects of IWS on water quality. It was found that samples from intermittent parts of the network were more frequently contaminated with fecal indicator bacteria (total coliform and *E. coli*) than samples from parts of the system where distribution pipes had been replaced and continuous supply had been implemented.[24] 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 was more contamination during the first flush when supply started and during periods of low pressure.[25]

In some cases, IWS may reduce consumer confidence in water quality.

In a 2010[26] survey of households in nine large Mexican cities, 58% of respondents said their tap water was not safe to drink. Of the 35% of respondents that rated the quality of their water a 7 or less on a scale of 1 to 10, 60% said that their water became contaminated in the trajectory from the treatment plant to the tap. Although it is not clear whether these users were thinking specifically of risks associated with IWS, it is clear that they did not trust the distribution system. Another 17% of respondents said that their water became contaminated in household storage tanks, which are closely associated with IWS.

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[12] Marie-Claude Besner et al., “Pressure Monitoring and Characterization of External Sources of Contamination at the Site of the Payment Drinking Water Epidemiological Studies,” Environmental Science & Technology 44, no. 1 (January 2010): 269–77, doi:10.1021/es901988y; Ashok Gadgil, “Drinking Water in Developing Countries,” Annual Review of Energy and the Environment 23, no. 1 (1998): 253–86, doi:10.1146/annurev.energy.23.1.253; Ellen J. Lee and Kellog J. Schwab, “Deficiencies in Drinking Water Distribution Systems in Developing Countries,” Journal of Water and Health 3, no. 2 (2005): 109–27.

[13] S.T. Coelho et al., “Controlling Water Quality in Intermittent Supply Systems,” Water Supply 3, no. 1–2 (2003): 119–25.

[14] Ibid.; Lee and Schwab, “Deficiencies in Drinking Water Distribution Systems in Developing Countries.”

[15] Emily Kumpel and Kara L. Nelson, “Intermittent Water Supply: Prevalence, Practice, and Microbial Water Quality,” Environmental Science & Technology 50, no. 2 (January 19, 2016): 542–53, doi:10.1021/acs.est.5b03973.

[16] P.S. Kelkar et al., “Water Quality Assessment in Distribution System under Intermittent and Continuous Modes of Water Supply,” Journal of Indian Water Works Association, March 2001, 39–43; Daniel Elala, Pawan Labhasetwar, and Sean F. Tyrrel, “Deterioration in Water Quality from Supply Chain to Household and Appropriate Storage in the Context of Intermittent Water Supplies,” Water Science & Technology: Water Supply 11 (September 2011): 400, doi:10.2166/ws.2011.064.

[17] Coelho et al., “Controlling Water Quality in Intermittent Supply Systems.”

[18] S. Tokajian and F. Hashwa, “Water Quality Problems Associated with Intermittent Water Supply,” Water Science and Technology 47, no. 3 (2003): 229–34.

[19] Javier J. Flores-Abuxapqui et al., “Calidad Bacteriológica Del Agua Potable En La Ciudad de Mérida, Yucatán,” Revista Biomédica 6, no. 3 (1995): 127–34.

[20] Jonathan H. Mermin et al., “A Massive Epidemic of Multidrug-Resistant Typhoid Fever in Tajikistan Associated with Consumption of Municipal Water,” The Journal of Infectious Diseases 179, no. 6 (June 1999): 1416–22, doi:10.1086/314766.

[21] Arti Kapil et al., “Letter to the Editor,” Emerging Infectious Diseases 3 (1997): 407.

[22] J.C. Semenza et al., “Water Distribution System and Diarrheal Disease Transmission: A Case Study in Uzbekistan,” American Journal of Tropical Medicine and Hygiene 59, no. 6 (1998): 941–46.

[23] Ayse Ercumen, Joshua S. Gruber, and John M. Colford, “Water Distribution System Deficiencies and Gastrointestinal Illness: A Systematic Review and Meta-Analysis,” Environmental Health Perspectives, March 21, 2014, doi:10.1289/ehp.1306912.

[24] Emily Kumpel and Kara L. Nelson, “Comparing Microbial Water Quality in an Intermittent and Continuous Piped Water Supply,” Water Research 47, no. 14 (September 2013): 5176–88, doi:10.1016/j.watres.2013.05.058.

[25] Kumpel and Nelson, “Mechanisms Affecting Water Quality in an Intermittent Piped Water Supply.”

[26] IADB, “Complete Results (in Spanish) of Mexico Bottled Water Survey.”

1.4 IWS is often closely related to other drinking water distribution system deficiencies

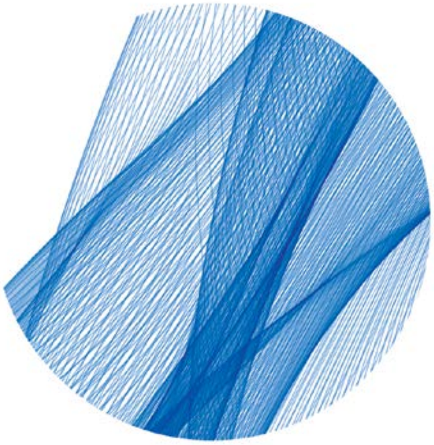
IWS can be a cause and/or a symptom of other important problems in drinking water distribution systems.[27] At times a vicious cycle is created, where a deficiency that contributes to IWS is also exacerbated by IWS.

For example, high rates of water loss are often a principal cause of IWS,[28] and, at the same time, IWS can make it difficult to measure and manage water losses effectively. In intermittent systems, traditional leak detection strategies are difficult to apply[29] and customer metering can be less accurate.[30]

IWS can also be a cause and effect of damage to pipe infrastructure. It has been proposed that pressure transients (temporary spikes of high or low pressure) under IWS cause additional stress on distribution system pipes and lead to higher rates of leakage and pipe breaks.[31] In a distribution network in Cyprus, pipe burst rates increased when IWS was instituted temporarily to cope with drought conditions.[32] Water hammers caused by pump startup or shutdown or valve operations, events that can be more common in intermittent systems, can lead to excessively high pressures or negative pressures that burst pipes.[33] Air pockets that develop in pipes when water is turned off also can cause extreme pressures when supply returns.[34] Conversely, pipe breaks in the distribution network cause supply interruptions that contribute to IWS.

Lack of system knowledge, such as the location of pipes, contributes to ineffective operation and IWS.[35] Conversely, IWS often makes it difficult to generate system knowledge and operate a distribution system rationally. Hydraulic modeling methods used for continuous supply systems do not capture some of the complexities of intermittent supply.[36] Without hydraulic models it is difficult to make informed operational and planning decisions. Also, efforts to improve service and equitably distribute water in an IWS system may result in a more complex network that lacks an overarching design concept and becomes even more difficult to manage.[37] Additionally, the operational crises associated with IWS can monopolize the time and resources of system operators, preventing them from improving service quality by addressing the original causes of IWS.

IWS can also be tied to institutional problems. It reduces service quality and can erode consumers' willingness to pay and their confidence in the utility as an institution and in the quality of the water they are receiving. Because of this, IWS can contribute to the "low level equilibria" described in Savedoff and Spiller's "Spilled Water."[38] The low level equilibrium described by Savedoff and Spiller is a political-economic equilibrium, where users don't have sufficient confidence in service providers to pay sustainable water rates and service providers don't have the political incentive to charge sustainable rates. Nevertheless, through the mechanisms detailed above, IWS could be considered to be part of a different, more technical low level equilibrium, in which it is difficult to properly control an intermittent system, but it is difficult to provide continuous supply with a system that isn't properly controlled.



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[27] Galaitsi, S., Robert Russell, Amahl Bishara, John Durant, Jennifer Bogle, and Annette Huber-Lee. 2016. "Intermittent Domestic Water Supply: A Critical Review and Analysis of Causal-Consequential Pathways." Water 8 (7): 274. doi:10.3390/w8070274. [28] G. Yepes, K. Ringskog, and S. Sarkar, "The High Cost of Intermittent Water Supplies," Journal of Indian Water Works Association 33, no. 2 (2001). [29] Avadhesh Kumar, "Management of Intermittent Supplies," 18th WEDC Conference, Water, Environment and Management, Kathmandu, Nepal, 1992. [30] A. Criminisi et al., "Evaluation of the Apparent Losses Caused by Water Meter under-Registration in Intermittent Water Supply," Water Science & Technology 60, no. 9 (November 2009): 2373, doi:10.2166/wst.2009.423. [31] Bambos Charalambous, "The Hidden Costs of Resorting to Intermittent Supplies," Water21, IWA, December 2011. [32] S. Christodoulou and A. Agathokleous, "A Study on the Effects of Intermittent Water Supply on the Vulnerability of Urban Water Distribution Networks," Water Science & Technology: Water Supply 12, no. 4 (July 2012): 523, doi:10.2166/ws.2012.025. [33] Paul F. Boulos et al., "Hydraulic Transient Guidelines for Protecting Water Distribution Systems," Journal AWWA 97, no. 5 (May 2005): 111–24. [34] Rajiv Batish, "A New Approach to the Design of Intermittent Water Supply Networks" (ASCE, World Water Congress, 2003). [35] Klingel, "Technical Causes and Impacts of Intermittent Water Distribution." [36] N. Sashikumar, M.S. Mohankumar, and K. Sridharan, "Modelling an Intermittent Water Supply" (ASCE, World Water Congress, 2003). [37] Klingel, "Technical Causes and Impacts of Intermittent Water Distribution." [38] William D. Savedoff, Pablo T. Spiller, and Inter-American Development Bank, eds., Spilled Water: Institutional Commitment in the Provision of Water Services (Washington, D.C: Inter-American Development Bank, 1999).

02

Lessons from an IWS case study in Arraiján, Panama

To better understand the nature and effects of IWS in one Latin American drinking water distribution system, and to develop techniques for monitoring and evaluating IWS systems, a detailed study 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), 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 the way that IDAAN controls supply, provided the opportunity to study the effects of different types of IWS. Institutionally, IDAAN showed interest in the project from the beginning and provided support with data collection.

2.1 Description of the study area: Arraiján, Panama

Arraiján is a peri-urban area located directly west of Panama City and east of the district of La Chorrera. **Arraiján's population has grown rapidly over the last decades, from 60 thousand inhabitants in 1990 to an estimated 263 thousand in 2014.**[39]

Part of this growth has been in the form of planned residential developments, and another part through informal development without legalization or planning. The majority of the development and demand for water in Arraiján is residential. In 2014, 96.4% of IDAAN's registered clients were residential, representing 79.6% of billed water consumption.[40]

2.1.1 Arraiján's drinking water system

The vast majority Arraiján's residents is supplied with drinking water from the IDAAN network.

Apart from the production of eight small wells owned by IDAAN that supply only 0.35% of the water entering Arraiján's network, the network is supplied by three treatment plants that extract water from the Panama Canal or its watershed.[41] IDAAN purchases water in bulk from the Panama Canal Authority, which operates the Miraflores and Mendoza treatment plants, and the private consortium Aguas de Panamá S.A., which operates the Laguna Alta plant. The Mendoza and Miraflores plants also supply most of La Chorrera and part of Panama City respectively, and the La Chorrera and Arraiján distribution networks are interconnected, but the Arraiján network is operated as a separate entity by a separate regional office of IDAAN.

Arraiján's distribution network is complex due to the large area it covers, its supply from three different treatment plants, and its topography, which is particularly complex in the areas where this study focused. **A 2010 survey identified 504 km of pipe in Arraiján's network;** of these, 431 km were PVC and 10" or smaller in diameter, and the other 73 km were ductile iron and 12" or larger in diameter.[42] IDAAN personnel report that there are also small quantities of cast iron pipe and old asbestos-cement pipe in the network. Additionally, the network has 27 pump stations and 39 storage tanks, though three of the larger storage tanks are out of service.[43]

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[39] Instituto Nacional de Estadística y Censo. "Cuadro 11: Superficie, población y densidad de población en la República, según provincia, comarca indígena, distrito y corregimiento: Censos de 1990 a 2010" and "Cuadro 44: Estimación y proyección de la población del distrito de Arraiján, por corregimiento, según sexo y edad: Años 2010-20." [40] IDAAN. Boletín Estadístico No. 28, 2012-2014. http://www.idaan.gob.pa/sites/default/files/transparencia/BOLET%C3%8DN%20ESTADISTICO-No.%2028_0.pdf [41] Ibid. [42] Louis Berger Group, "Fortalecimiento Institucional Del IDAAN a Través de Acciones de Optimización Para La Ciudad de Panamá," 2010. [43] Ibid.

2.1.2 Deficient service despite high production volume

Average water production in 2014 for the Arraiján network was 40.6 MGD, representing a daily production of 155 gallons per person.[44]

Of those 155 gallons, only an average of 73 were billed to customers, representing a non-revenue water rate of 53%, which includes both physical and commercial losses.[45]

Despite the high level of water production, some of IDAAN's clients in Arraiján have deficient service. At the time of the study, 6,420 clients (13% of the total number of registered clients in 2014) receive a monthly discount on their water bills due to deficient service.[46] Although this is a relatively small portion of IDAAN's clients, at times a larger number of clients suffer from deficient service. For example, between August 2014 and July 2015 users in a large portion of Arraiján were without supply on approximately 13 occasions (eight unexpected and five planned), due to pipe breaks, treatment plant stoppages, or other operational problems.[47] Two of these events were when the supply from one of the three treatment plants was suspended for more than 24 hours.[48]

Some areas have chronic supply deficiencies caused by:

1) insufficient local distribution capacity (pipe diameter or pump capacity) to satisfy water demand in the area; or

2) their dependence on portions of the network that frequently lose pressure when the capacity of the entire network is surpassed by high demand (for example, a Sunday when many users are at home) or a pipe break.

In addition to those with deficient service, some users do not receive piped water and are supplied by tanker trucks contracted by IDAAN.

2.1.3 Operational challenges

Even though Arraiján's distribution network is quite complex, IDAAN's regional office operates it with little information about its current state. Some of the 27 pump stations frequently malfunction unexpectedly, causing supply interruptions. Apart from the monitoring equipment installed for this project, only one of the pump stations can be monitored by telemetry; to check on the others IDAAN personnel must do a daily inspection by driving around in a truck. As a consequence of the lack of storage capacity in the network, the supply deficit, and unexpected infrastructure failures, sometimes large areas of the network lose supply. If such outages persist, operators manipulate valves to send water, in shifts, to different sectors of the network.

As part of a 2010 project, the Arraiján network was divided into eight sectors, with 15 monitoring stations for pressure and flowrate located in the points where each sector connects to the rest of the network.[49] At the end of that project, all of the bulk metering stations were working and water balances for the different sectors were calculated. At the time of this study, however, only some of the sensors were working and the original telemetry equipment to upload the data to the internet was not working. Consequently, IDAAN has not been able to update the water balances for the eight sectors.[50]

Arraiján's network experiences frequent pipe breaks. During 2014, IDAAN's operations crews repaired 604 breaks in pipes of diameter 2" or larger (1.46 breaks per km per year).[51] Although this break rate puts IDAAN's Arraiján system near the average of 13 Latin American utilities that participated in a regional benchmarking report,[52] it is much higher than the average of 0.068 breaks per km per year from a study of 188 utilities in the U.S. and Canada.[53] Often the repair of breaks is complicated by a lack of information about the configuration of the distribution network and a lack of control valves. The repair crew can lose time trying to determine how to depressurize the sector where a break is. At times, due to a lack of control valves, IDAAN has to cut off service to a large sector to depressurize the area near a break.

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[44] Production data from IDAAN, Department of Distribution and Loss Control, Bulk Metering Section. The population served in 2014 was 262,517, according to IDAAN, Boletín Estadístico No. 28, 2012-2014. [45] Billed volume comes from: IDAAN. Boletín Estadístico No. 28, 2012-2014. The same document estimates a non-revenue water rate of 42.2%, but it appears that the calculations do not account for the 9.3 MGD that Arraiján receives from the Mendoza treatment plant. [46] This number is according to IDAAN's client list. A survey of users as part of the institutional strengthening project in 2010 (Louis Berger Group. Fortalecimiento institucional del IDAAN a través de acciones de optimización para la ciudad de Panamá.) found that 443 clients (0.8%) were supplied by tanker trucks and only 1,285 (2.6% of those with piped supply) had intermittent service, but the report did not explain what criteria were used to define which users had intermittent service. [47] Personal communication with IDAAN's regional management in Arraiján. [48] According to a log kept by IDAAN's regional management in Arraiján.

Operations personnel keep a log of valve operations, pump operations and repairs, and other operations events, and fill out a form each time a pipe is repaired. They also make some summaries of this information, for instance, the number of repairs for each pipe diameter by month. The information also could be useful for more detailed analyses, for example, to understand what zones have the highest rates of pipe breaks and what the high break rates might be caused by. To carry out such analyses it would be necessary to have personnel dedicated to such work. Currently, management and operations personnel do not have the capacity to do it; a large fraction of their time is spent fixing pipe breaks and dealing with supply outages.

2.1.4 Water quality monitoring

IDAAN collects water quality samples from different points in the distribution network, following the Authority of Public Services (Panama's utility regulator, ASEP, for its initials in Spanish) guidelines for the number of samples and parameters to monitor. The majority of the sampling points are taps of commercial and governmental clients. The entities that operate the treatment plants are in charge of water quality monitoring at the plant exits. Before this study began, many of the areas with intermittent service were not included in IDAAN's sampling points, perhaps because there were no convenient monitoring points in these areas or because these areas do not always have water to sample.

Now, with the incorporation of the sampling taps used in this project, IDAAN has increased its monitoring in sectors with intermittent supply.

2.1.5 Planned and ongoing improvements

IDAAN has implemented or is the process of implementing many changes intended to improve operations in Arraiján. These improvements include construction of storage tanks, an increase in capacity to convey water to portions of the network with deficient service, and efforts to reduce non-revenue water, including the installation of 14,000 new customer meters and 26 pressure control valves to reduce excessive pressures in some areas.[54]

IDAAN's Arraiján regional office is also planning improvements in its technical and operational capacity, contracting more operations personnel and planning a telemetry system for Arraiján's network.[55] IDAAN is also planning to increase treatment capacity in the area.[56]

2.2 Research methods

2.2.1 Study zones

To study the effects of different types of intermittent supply, four study zones with different supply situations were selected in Arraiján: El Cristal (CR) with continuous service, 7 de Septiembre (7S) with occasional supply interruptions due to the emptying of a storage tank, La Alameda (AL) with intermittent supply controlled by a valve that was scheduled to be open for 3 days and closed for 3 days, and Vista Bella (VB) with intermittent supply controlled by the startup and shutdown of a pump station.

The zones, consisting of 230 to 650 households each, were chosen based on interviews with IDAAN operations personnel, field visits, and interviews with customers in each zone. Zones were chosen to have only one or two hydraulic entrances and no hydraulic exits, so the quantity and quality of water entering the zone could be accounted for, and were chosen to be as large as possible, while still maintaining a supply regime with similar characteristics within each zone.[57]

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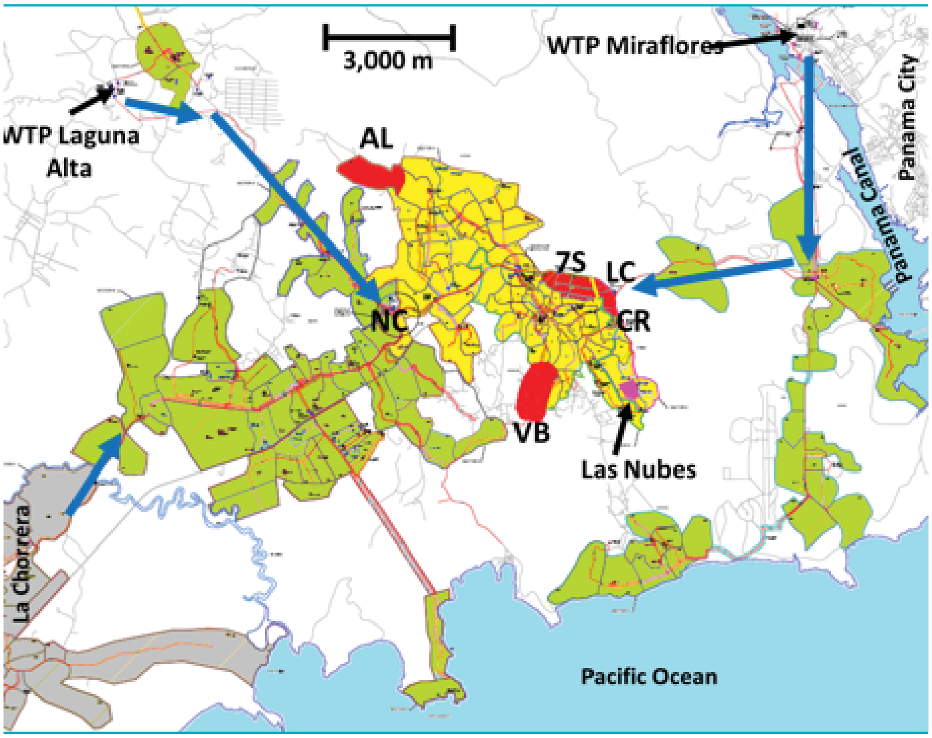
[49] Louis Berger Group, "Fortalecimiento Institucional Del IDAAN a Través de Acciones de Optimización Para La Ciudad de Panamá." [50] Personal communication with personnel in charge of the bulk metering division in IDAAN's Department of Distribution and Loss Control. [51] This rate does not include small-diameter breaks, breaks in customer connections, or some areas of Arraiján where pipe length and pipe repair data were not available. [52] Annual Report – 2013 of the Regional Benchmarking Working Group of the Association of Water Supply and Sanitation Regulatory Entities of the Americas. [53] Folkman, Steven. "Water main break rates in the USA and Canada: A comprehensive study." Utah State University Buried Structures Laboratory. April, 2012. [54] Personal communication with IDAAN's regional management in Arraiján. [55] Ibid. [56] Eric Ariel Montenegro and Aminta Bustamante, "Saneamiento de La Bahía Se Extenderá a Panamá Oeste," La Prensa, September 16, 2015. [57] It is normally recommended that district metering areas have between 500 and 5,000 connections so that they are 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, D., and G. Ferrari. 2014. Design and Performance of District Metering Areas in Water Distribution Systems. Procedia Engineering 89: 1136–1143). 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 1 shows the location of the four study zones in Arraiján. It also shows upstream monitoring points, where samples were collected to verify the quality of water from the two treatment plants that supply the study zones. The upstream sampling locations were at Loma Cova (LC, water from the Miraflores plant) and the entrance to Nuevo Chorrillo (NC, water from the Laguna Alta Plant).

The four study zones were in the same portion of the Arraiján network, in the sectors of Loma Cova, Arraiján Cabecera and Burunga. This part of Arraiján received water from two treatment plants: Laguna Alta and Miraflores. Although the neighborhoods and housing developments in these three sectors varied in terms of urban development and water supply, many shared common characteristics that can affect water supply. The area's topography was complex, creating a need for pump stations. Also, many housing developments were informal, unplanned, or older (more than 30 years old), factors that contributed to the complexity of the water distribution network and often to a lack of data about its configuration.

FIGURE 1



🟦 Water conveyance route from drinking water treatment plants to Arraiján. Water from the Mendoza plant (outside area covered by map) also enters Arraiján through La Chorrera.

🟨 Arraiján Cabecera, Loma Cova, and Burunga sectors (part of Arraiján network)

🟩 Other sectors of the Arraiján network

🟥 Study zones (CR, 7S, AL and VB)

▨ La Chorrera network coverage area

🟪 Las Nubes

LC NC Upstream sampling points

Figure 1. Location of the study zones and upstream monitoring points. Although it is not one of the four study zones, Las Nubes, an area where water quality samples were taken during first flush events, is also marked on the map. (Source: Modified from Louis Berger Group. 2010. Fortalecimiento institucional del IDAAN a través de acciones de optimización para la ciudad de Panama, Anexo O, "Plano de Macromedidores").

2.2.2 Hydraulic and water quality monitoring

As an example, **Figure 2** shows the monitoring locations in 7S. Flowrate[58] and pressure[59] were continuously monitored at the entrance (ENT) of each zone. Additionally, pressure was monitored continuously at a downstream monitoring point (DS). Pressure data were used to characterize supply schedules and any negative or high pressures occurring at the monitoring locations. Entrance flowrate data, counts of the number of households in each study zone, available metering data, and household surveys were used to approximately characterize water consumption and loss patterns in CR, 7S and AL.

Water quality (free chlorine residual and turbidity[60]) was monitored continuously for periods of one to four weeks at a time simultaneously at the ENT and DS locations, rotating monitoring equipment among the four zones. Routine grab samples were collected at ENT and DS monitoring stations and household taps (HH).

Series of first flush samples were collected from DS monitoring stations and HH taps during the first two hours of supply after some outages. Samples were collected from household taps receiving water that came directly from the utility's network without passing through household storage tanks. Routine grab samples were collected between 7 am and 4 pm when water was on. Routine and first flush grab samples were analyzed for turbidity, free chlorine residual, and total coliform and *E. coli* bacteria. First flush grab samples were also analyzed for heterotrophic plate count (HPC) and spore-forming bacteria.

In addition to the four study zones, first flush sampling was conducted in Las Nubes, another zone with intermittent service where water normally was supplied every other day for about 2 hours in the afternoon, when a valve was opened to release water from a storage tank.

Grab samples were also collected from stored drinking water in households randomly selected from the study zones.

FIGURE 2

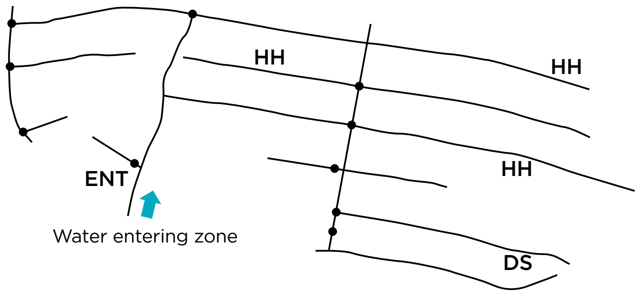


Figure 2. Schematic of 7S. "ENT" = Entrance continuous monitoring and grab sampling location. "DS" = Downstream continuous monitoring and grab sample location. "HH" = Household tap grab sampling location

2.2.3 Pipe break rate analysis

IDAAN's 2012-2014 pipe repair logs were analyzed, along with pipe lengths from IDAAN's GIS database, to calculate pipe break rates for 142 zones covering most of the Arraiján distribution network.

2.3 Results

2.3.1 Intermittent supply schedule

Using the continuous pressure monitoring results, the supply schedule in each of the four study zones was characterized from August 2014 to August 2015. During the study period, water was being pumped to VB 87% of the time, the higher elevations of 7S had supply 83% of the time, AL had supply 57% of the time and CR had supply 99% of the time. The supply interruptions did not normally follow a predictable or reliable schedule, creating an inconvenient situation for users. In 7S and VB, the supply schedule was irregular because it was controlled by the level of the storage tank supplying 7S and the amount of supply arriving to the pump station serving VB, factors that depended on the hydraulic state of the network as a whole and were not directly controlled by operators. In AL, the programmed supply schedule of 3 days with supply and 3 days without supply was not strictly followed and there were three supply interruptions that lasted longer than 6 days due to pipe breaks (**Figure 3**). AL also was affected by additional shorter outages caused

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[58] Flow was measured with an inexpensive Seametrics IP80 paddlewheel flow meter. [59] A Telog LPR-31i pressure monitor was used at the entrance to Zone 3 and ECO-3 (Aquas Inc.) monitors were used at all other stations to record pressure every 30 seconds. Both devices had the ability to detect pressure transient events and record measurements every 0.1 seconds when they occurred. [60] Q46/76 and Q45H/62 (Analytical Technology Inc.) sensors measured free chlorine residual and turbidity respectively every 30 seconds.

by stoppages of the pump station supplying the area. Even portions of the network with normally continuous service were affected by unexpected interruptions due to large pipe breaks and treatment plant shutdowns. For example, in CR, during the study year there were four interruptions lasting more than 9 hours each.

FIGURE 3

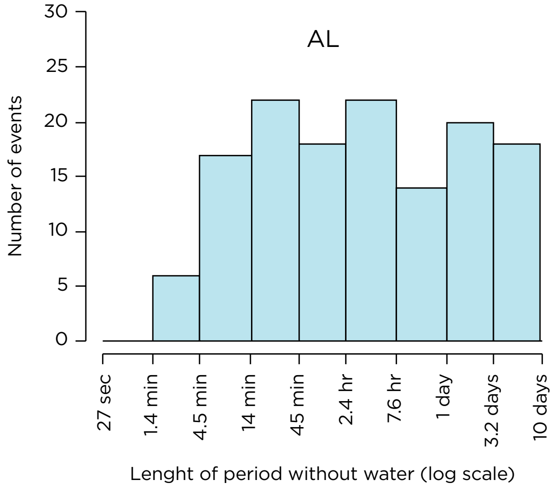

Figure 3. Distribution of the duration of periods without water in AL, based on 316 days of pressure data collected between August 2014 and August 2015. AL was considered to have been without supply when pressure at the DS monitoring station was below 2 psi at ground level.

Often, lack of system information and insufficient monitoring capacity contributed to long or unplanned supply outages. For example, during the study period the capacity of a pump station near the VB pump station was increased, which reduced flow to the VB pump station and reduced service quality in VB. IDAAN did not anticipate these effects, and changes were only made to resolve the situation after VB residents blocked a lane of Panama's largest highway to protest the decline in service quality.[61]

In a second situation several months later, one of two pumps at the VB pump station stopped working, again reducing supply to the area. Because this pump only was intended to operate intermittently, it was difficult for operators passing for a daily inspection to realize that it was malfunctioning, and the problem was only detected after two weeks when users arrived to IDAAN's office to complain. Days after the second pump was repaired, the pump station malfunctioned again due to an electric problem, and the problem was not detected until VB residents again closed a portion of the highway.[62]

All three of these malfunctions were later found to be apparent in continuous pressure and flow data collected at the VB pump station discharge as part of this project. If IDAAN operators collected such data and monitored it routinely (or set up alarms to alert them of problems), these situations might be avoided.

2.3.2 Low, negative and high pressures

Continuous monitoring detected low and negative pressures representing risks for intrusion or backflow, as well as high pressures due to pressure transients. Low and zero pressures are inherent to the supply outages associated with intermittent supply. Pressure was below 2 psi at ground level 0.9%, 17%, 43% and 5.8% of the time at the downstream monitoring locations in CR, 7S, AL and VB respectively. Average pressure at the downstream continuous monitoring station when supply was on (above 2 psi at ground level) was 21.9 psi in CR, 37.9 psi in 7S, 35.5 psi in AL and 47.2 psi in VB.[63]

Pressure transients were recorded at the discharge of the VB pump station due to startup or shutdown of the pump (**Figure 4**). While pump start and stop transients also occur in continuous systems,[64] they were likely more frequent in this case because of frequent power failures and the pump station often not having sufficient water supply to run continuously. During 351 days of monitoring at the VB pump station discharge, pressures below -1 psi (at pipe level) were recorded 46 times for a total duration of 107 seconds and pressures below -5 psi were recorded 18 times for a total duration of 25 seconds.

Nine events with pressure above 135 psi were detected. The minimum pressure measured at the VB pump station discharge was -10.6 psi and the maximum pressure was 162 psi.

At the ENT monitoring station in AL, which was located at the crest of a hill, sustained negative pressures were recorded even when there was flow entering the study zone, indicating that the pipe at that location was working like a siphon. During 269 total days of monitoring, the pressure was below -1

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[61] Castillo, Pablo. "Moradores de Vista Bella de Arraiján protestan por agua." La Crítica. July 22, 2014.
[62] "Dispersan a manifestantes que tenían cerrada vía en Arraiján." La Crítica. May 11, 2015; Montenegro, Eric Arial. "Moradores de Vista Bella de Arraiján protestan por la falta de agua." La Prensa. May 11, 2015.
[63] Note that the VB downstream monitoring station was located at an alternate entrance to the zone, so was not very far downstream. Other portions of the zone experienced much lower pressure. There were also many portions of AL that experienced pressure lower than at the downstream monitoring station.
[64] Boulos et al., "Hydraulic Transient Guidelines for Protecting Water Distribution Systems."
[65] Events that occurred within 2 seconds of one another were grouped together, but total duration only counts for time when pressure was actually below the pressure threshold. Four of the < -1 psi events and two of the < -5 psi events events lasted for only one of the measurements taken every 0.1 seconds.

psi (at pipe level) 40% of the time, and below -5 psi 18% of the time. During the 184 days of monitoring when water was passing through the pipe, the pressure was below -1 psi 36% and below -5 psi 18% of the time, with a minimum pressure of -14 psi, approximately a complete vacuum. During first flush sampling in Las Nubes, negative pressures were observed in household taps immediately after supply ended. Given that many users in Las Nubes used a hose connected to their tap to fill storage containers, these negative pressures presented a risk of backflow when the hose was submerged in a storage container or other body of contaminated water.

FIGURE 4

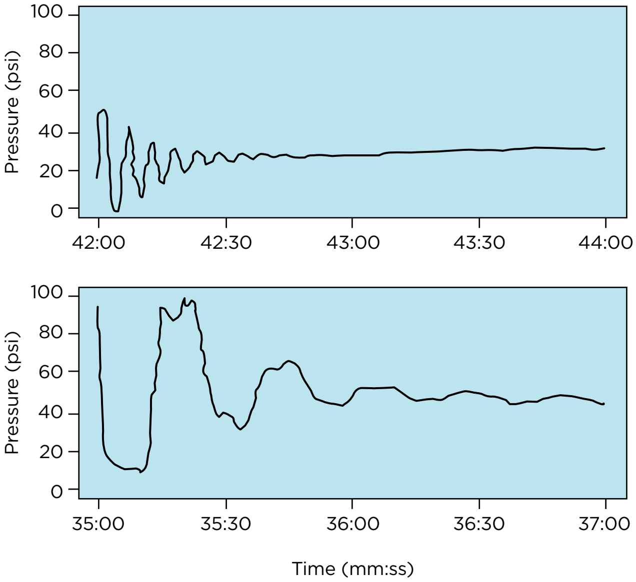

Figura 4. Ejemplos de oscilaciones de presión por transitorios hidráulicos en el arranque (superior) y apagado (inferior) de la estación de bombeo VB.

2.3.3 Water quality

With very few exceptions, the routine grab samples collected during normal conditions in the four zones were within Panama's COPANIT standards for turbidity, total coliforms and *E. coli*.[66] The low incidence of coliform bacteria was likely related to maintenance of a consistent free chlorine residual in the distribution system. Both continuous monitoring and routine grab sampling results indicated that, except for the first flush, IDAAN maintained a consistent free chlorine residual in the study zones. Thirty eight percent of routine samples had free chlorine residual concentrations below the COPANIT standard of 0.8 mg/L, but all had at least 0.3 mg/L and thus were in compliance with the World Health Organization's recommendation that water in the distribution network have at least 0.2 mg/L.[67]

A higher incidence of high turbidity and coliform bacteria was found during first flush events. In some first flush events no notable variation in water quality was detected (example, **Figure 5a**). All samples collected during 13 of the 33 events sampled were negative for total coliforms and *E. coli* and turbidity ≤ 1.0 NTU. In other events, water quality was degraded during the first minutes of supply as indicated by elevated turbidity, elevated concentrations of HPC bacteria and aerobic spore-forming bacteria, low free chlorine levels and, less frequently, the presence of total coliforms and *E. coli* (example, **Figure 5b**).

During 20 of the 33 events one or more samples had turbidity above the Panamanian standard of 1.0 NTU; during six events one or more samples were above the Panamanian norm for total coliforms of 3 MPN (most probable number) per 100 mL; and during four events one or more samples were positive for *E. coli*. All of the events with *E. coli* positives and all but one of the events with total coliform positives were in AL, the zone where supply was most intermittent. For two of the events with total coliform and *E. coli* positives, only the first sample, collected at the moment supply started, was positive. Although the mouth of the tap was always disinfected with sodium hypochlorite, in those two cases it is possible that the contamination came from the tap itself. In six of the 29 events where samples were analyzed for chlorine (all of them in AL), one or more samples had a free chlorine con-

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[66] Reglamento Técnico DGNTI-COPANIT 23-395-99. "Agua Potable. Definiciones y Requisitos Generales." [67] World Health Organization. 2011. "Guidelines for drinking water quality, fourth edition."

centration below 0.2 mg/L. With the exception of one first flush event where a sample collected after 45 minutes of supply was positive for total coliforms, coliforms and *E. coli* were only detected during the first 20 minutes of supply, probably because after that time contamination that could have intruded or grown within the pipes during the supply interruption was already flushed from the network. On some occasions after pipe breaks and repairs, high turbidity water was found during routine and first flush sampling, indicating that reducing the incidence of pipe breaks or improving repair practices would likely reduce the incidence of contamination. Three first flush events associated with pipe breaks and repairs had samples with turbidity >100 NTU, and one routine sample associated with a pipe repair had a turbidity of 83 NTU.

FIGURE 5

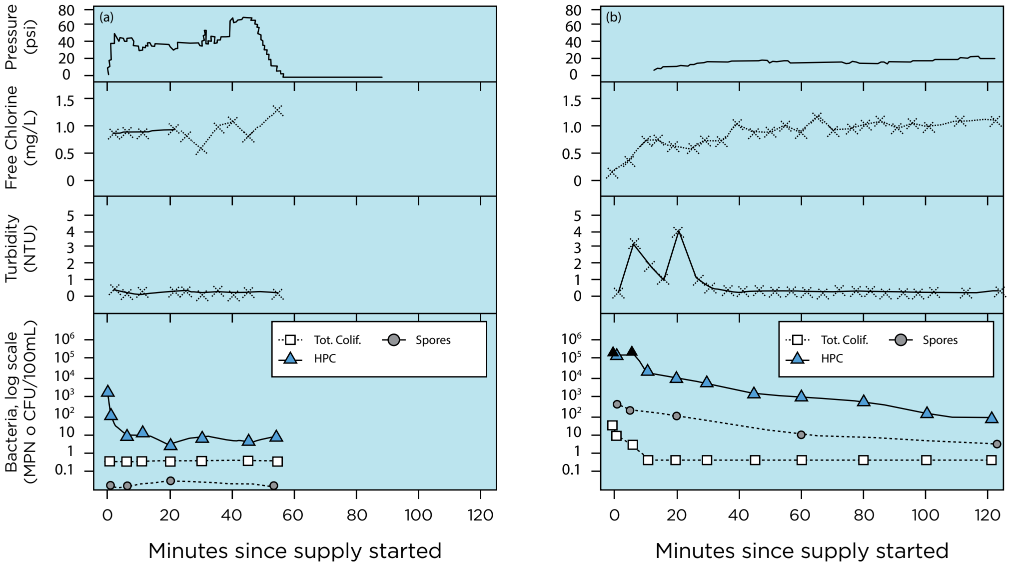

Figure 5. Example first flush events: **(a)** where very little variation in water quality was detected (Las Nubes, household tap, after 47-hour supply interruption during the dry season) and **(b)** where considerable water quality variation was detected (AL, household tap, after 3-day supply interruption during the rainy season). In the bacteria graphs, black symbols mark samples above the detection limit (plotted at detection limit) and symbols shaded grey mark samples below the detection limit (plotted at half of the detection limit).

With respect to household storage, 9 of 93 (10%) stored water samples were positive for *E. coli* and 24 (26%) had a total coliform concentration above 10 MPN per 100 mL, the maximum value established by Panama's standard for un-piped water.[68] Seven of the 9 samples positive for *E. coli* were from AL, and 8 of them were from buckets or barrels where users dipped water from the container.

Considering that only approximately 5% of all first flush samples were positive for total coliform bacteria, contamination must be occurring during the household storage process. **Promoting safe storage, where water is poured from a narrow-neck storage container, would likely reduce contamination of water stored in the household.**

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[68] Reglamento Técnico DGNTI-COPANIT 23-395-99. "Agua Potable. Definiciones y Requisitos Generales".

2.3.4 Quantity of supply and water losses

The average flowrate entering each zone was high in comparison to billed consumption and in comparison to metered consumption where there were customer meters. The estimated entrance flowrate of 948 gallons per building (house or business) per day for 7S was particularly high compared to 586 and 467 gallons in CR and AL respectively. Based on a survey of a selection of 34 to 48 households in each zone, the average number of people per house was 4.7 in 7S, 5.6 in AL and 8.7 in CR, resulting in estimated daily per-capita inflows of 202 gallons in 7S, 82 gallons in AL, and 67 gallons in CR.[69] These average inflows are high, and in some cases translate into much higher hourly flows when it is considered that water was not always on. Despite CR having continuous supply, it still had the lowest per-capita inflow of the three zones. This suggests that leakage rates were likely higher in the two intermittent zones analyzed, particularly in 7S. The conclusion that leakage rates were high in 7S is also supported by the fact that metered clients in 7S consumed less water per client than those in CR.

In each of the three study zones, average entrance flow during the hour with minimum flow (during the middle of the night) was equal to 73% or more of the average entrance flow during the hour with maximum flow (**Figure 6**). In AL some clients only had supply during the middle of the night and, for that reason, they could be collecting water to store during those hours; but in CR and the vast majority of 7S, users normally had water 24 hours per day. In those zones, the majority of flow entering during the middle of the night must have been lost, either to leaks in the network or in household plumbing. During July 2015, billed consumption in 7S and CR was 25% and 61% of the quantity of water that entered the respective zone. The difference between the two zones in fraction of water billed was probably due to a higher rate of physical losses in 7S, not because more consumption was billed in CR.

Consumption and water loss analysis was not possible in VB, because after the study was underway interconnections were discovered that meant that VB was not hydraulically isolated in the way it was previously thought to be.

FIGURE 6

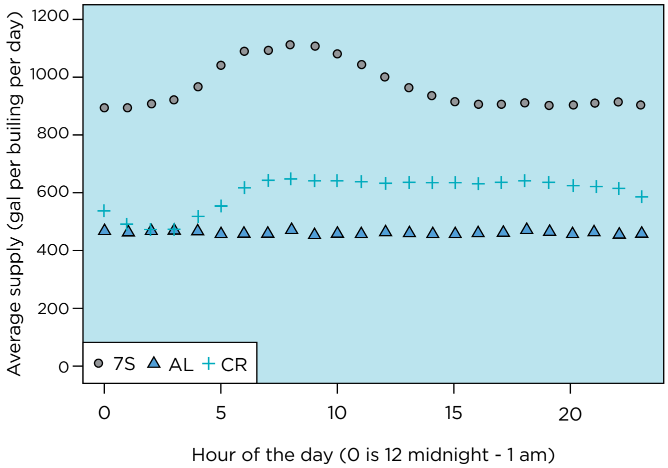

Figure 6. Average entrance flow per building by hour of the day.

2.3.5 Intermittent supply and pipe breaks

According to IDAAN's 2012-2014 pipe repair records, break rates varied widely across Arraiján (**Figure 7**).[70] **The break rate in 13 of the 142 zones analyzed in Arraiján was greater than 4 breaks per km of pipe per year, much higher than the network average of 1.42 breaks per km per year.** Twenty six percent of the breaks occurred in these 13 zones, even though they only had 3.8% of the pipes.

Each zone was classified as having continuous (normally no interruptions), intermediate (un-planned interruptions are common), or intermittent supply (routine interruptions), according to interviews with an experienced IDAAN operator. No general relationship was observed between intermittent supply and pipe breaks, since zones with all three types of supply continuity were found among those with high and low break rates. However, in some zones, like VB, a high break rate was associated with extreme pressures caused by intermittent pumping. Four of the eight zones with the highest break rates were affected by intermittent pumping. Due to likely errors in pipe length and break location data, break rates for some individual zones are likely inaccurate. For instance, some pipes in the zone with > 50 breaks per km per year were probably not

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[69] The households surveyed were selected at random and distributed geographically throughout the study zone, but the sample was not completely representative, since only households where someone was home during the day could be included.

[70] Only pipes from 2 inches to 12 inches in diameter were included in this analysis. Several parts of the Arraiján network where pipe length data were not available were excluded from the analysis.

registered in IDAAN's GIS database, which would have contributed to an artificially high break rate.

Despite potential inaccuracies in break rates for individual zones, the overall quality of the data is good enough to support the general trends observed.

FIGURE 7

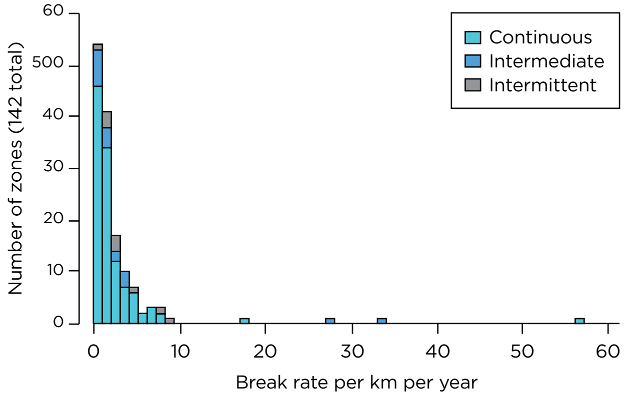

Figure 7. Distribution of break rates for each zone during 2012-2014 according to supply continuity. The bar to the far left represents the quantity of zones with no breaks. The following bar represents the quantity of zones with between zero and one breaks per km per year.

2.4 Lessons learned from Arraiján study and comparison to Hubli-Dharwad

2.4.1 The nature and severity of IWS and its effects vary substantially within and between distribution networks.

Comparison between the different Arraiján study zones and between Arraiján and Hubli-Dharwad, India, where detailed research on the water quality effects of IWS was conducted previously using similar methods, shows that the nature and severity of IWS and its effects vary widely. In continuous water supply (CWS) systems, the entire distribution network is supplied at all times. In intermittent systems, different portions of the network can be supplied anywhere between none or almost all of the time, and the frequency, duration, and predictability of supply periods can vary widely, resulting in a large and complex space of different supply possibilities. In Arraiján, supply ranged from nearly continuous in most of the network to hardly any supply at all in some areas that had piped connections but rarely received water from them. In Hubli-Dharwad, on average, households in intermittent areas reported receiving water for only 5 hours once every 6 days, a supply schedule that was worse than everywhere in Arraiján except for areas that received no supply at all.

IWS varies not only according to supply schedule, but also according to how intermittency is controlled.

In Hubli-Dharwad and in the case of the AL and Las Nubes sectors of Arraiján, operators manipulated valves to ration water between different sectors of the network according to a predetermined schedule, which, in the case of AL, was not always closely followed. In 7S and other portions of Arraiján, supply was always "on" but did not arrive to higher elevations or distant portions of the network when pressure was low due to high demand or pipe breaks elsewhere. In VB and other zones in Arraiján, intermittent pumping controlled IWS. In VB, the pump station was always programmed to be on, but stopped pumping when it did not receive enough supply to maintain the water level in its suction tank.

Different supply schedules and IWS control methods likely can have different effects on water quality, infrastructure degradation, operational complexity, and user satisfaction. In addition to the nature of IWS itself, different contextual factors can also interact with the effects of IWS on these outcomes.

For instance, the presence of fecal contaminant sources, a higher groundwater table, frequent pipe leaks, inadequate or inconsistent disinfectant residual concentration, and unsanitary household storage practices could all exacerbate the negative effects of IWS on water quality.

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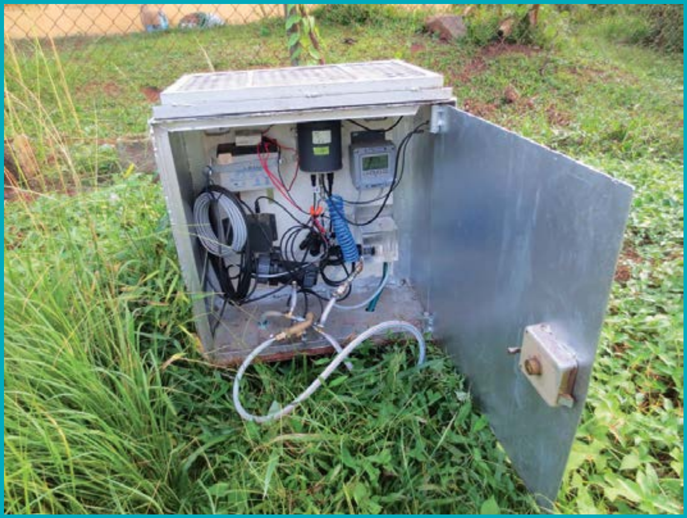
[71] Kumpel and Nelson, "Comparing Microbial Water Quality in an Intermittent and Continuous Piped Water Supply"; Kumpel and Nelson, "Mechanisms Affecting Water Quality in an Intermittent Piped Water Supply." [72] Kumpel and Nelson, "Mechanisms Affecting Water Quality in an Intermittent Piped Water Supply."

Monitoring point 7 de septiembre (7S).

Monitoring point in La Alameda (AL) with negative pressures.

Development of informal urban structures and irregular topography within the sector "Las Nubes".



Continuous monitoring station with pressure, turbidity and free chlorine sensors.

Although sustained low and negative pressures were detected in the Arraiján study zones, **water quality monitoring detected little evidence of contaminant intrusion, with the exception of some first flush events and pipe breaks and repairs. Table 1** shows that routine, first flush, and stored water quality was better in the intermittent Arraiján study zones than in intermittent areas of Hubli-Dharwad.

TABLE 1

Location	% of routine samples (n)				First flush events having at least one sample with *E. coli* ≥1 MPN/ 100 mL	% of stored samples with *E. coli* ≥1 MPN/ 100 mL (n)
	E. coli ≥1 MPN/ 100 mL	Total coliform ≥1 MPN/ 100 mL	Turbidity ≥ 5 NTU	Free chlorine residual ≤ 0,2 mg/L		
Arraiján IWS*	0.5% (182)	1.6% (182)	1.8% (223)	0% (226)	4 de 33	11% (71)
Hubli-Dharwad IWS	31.7% (589)	64.9% (589)	55.6% (586)	61.1% (557)	12 of 15	34% (266)
Hubli-Dharwad CWS	0.7% (587)	17.7% (586)	55.5% (618)	31.7% (575)	NA	12% (332)

Table 1. Comparison of water quality between IWS zones in Arraiján and Hubli-Dharwad.[73]
*"Arraiján IWS" statistics include routine and stored water samples from 7S, AL and VB, and first flush samples from those three zones and Las Nubes. Arraiján routine samples only include those collected from downstream monitoring stations and household taps. Total number of samples in each category is shown in parentheses.

THE LOW INCIDENCE OF CONTAMINATION IN ARRAIJÁN COMPARED TO HUBLI-DHARWAD COULD BE RELATED TO SEVERAL FACTORS:

Contaminant sources: *Hubli-Dharwad had a higher population density and inadequate sanitation (open, unlined sanitary drains, latrines and drains near drinking water pipes). The study zones in Arraiján did not have sanitary sewers and the majority of the latrines, septic tanks and storm water drains were located behind the houses, far from drinking water pipes.*

Treatment plant effluent quality: *The fourteen samples taken from the Hubli-Dharwad treatment plants had turbidity between approximately 2 to 10 NTU and five of them were positive for total coliform bacteria.*[74] *No samples were collected directly from the Arraiján treatment plants, but of 93 turbidity samples collected from the conveyance pipes coming from the plants only one had turbidity >1 NTU (1.03 NTU). None of the 91 bacteria samples collected from the conveyance pipes were positive for total coliforms.*

Free chlorine residual: *Consistent chlorine residual in the Arraiján study zones likely suppressed regrowth of coliform bacteria in the distribution system and, in the event of intrusion, would likely have inactivated coliform bacteria, which are highly susceptible to chlorine. Consistent chlorine dosing at treatment plants and low water age in the study zones were likely important factors for maintaining adequate chlorine residual at customer taps. Approximate calculations based on flows from the treatment plants and volumes of the conveyance pipes 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 capacity, in contrast to distribution networks in high-income countries that are normally over-sized to provide adequate fire flows.*[75] *In contrast to the Arraiján results, free chlorine residual at customer taps in Hubli-Dharwad was below 0.2 mg/L for 61.1% of samples in IWS areas and 31.7% of samples in CWS areas.*

Household storage practices: *The lower incidence of E. coli bacteria in Arraiján stored water as compared to Hubli-Dharwad could have been partly due to more sanitary storage practices. In Hubli-Dharwad, 74% of*

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[73] Kumpel y Nelson, "Comparing Microbial Water Quality in an Intermittent and Continuous Piped Water Supply."[74] Ibid. [75] AAWWA, "Effects of Water Age on Distribution System Water Quality" (U.S. Environmental Protection Agency, August 15, 2002), https://www.epa.gov/sites/production/files/2015-09/documents/2007_05_18_disinfection_tcr_whitepaper_tcr_waterdistribution.pdf.

households where stored water was sampled dipped water out of their storage containers,[76] *as compared to 20% of houses sampled in Arraiján. Stored water quality results from the two studies were also likely affected by different sampling methods*[77] *and the quality of the tap water being stored.*

Severity of intermittency: *All of the Arraiján study zones normally received supply more frequently and for longer duration than the IWS areas in Hubli-Dharwad. Of the four Arraiján study zones, AL had the most intermittent supply and also had the most degraded water quality during first flush.*

Supply pressure: *When supply was on in Arraiján, pressures tended to be higher than in the IWS zones in Hubli-Dharwad, where mean pressure during supply was below 10 psi for 5 of 21 supply cycles monitored and below 20 psi for 17 of 21 supply cycles.*[78]

Power of study to detect contamination: *While the results from Arraiján provide convincing evidence that distribution system water quality was much better there than in Hubli-Dharwad, it is important to note that the low and negative pressure conditions detected in Arraiján are a real and concerning risk for water quality. The fact that incidence of contamination in four study zones of limited size was low does not mean that it would always be low in similar study zones with the same supply conditions. For instance, sustained negative pressures at the entrance to AL were an obvious risk to water quality, but no water quality effects were detected, likely because there were no pipe leaks next to contaminant sources in the section of pipe with negative pressure. It is also important to note that some pathogens are more resistant to inactivation with chlorine than total coliforms and E. coli are. If fecal contamination did enter the Arraiján distribution system, some pathogens could have persisted even though coliform bacteria were inactivated.*

Given the many important differences between Hubli-Dharwad and Arraiján in terms of supply and conditions, it is no surprise that water quality also differed greatly between the two systems. Hubli-Dharwad was not selected as a point of comparison because it was similar to Arraiján, but simply because it was the only place where comparable data were available. The examples of Arraiján and Hubli-Dharwad show that conditions can vary greatly within the category we call "*intermittent supply*".

The incidence of negative pressures, extreme pressures, and pipe breaks varied across IWS zones. The highest pressures measured were associated with pump startup and shutdown transients in VB and AL. No significant pressure transients or extreme high pressures were detected under intermittent supply in 7S. While some IWS areas in Arraiján, particularly zones affected by intermittent pumping, had high pipe break rates, not all IWS zones had high pipe break rates. These results suggest that certain cases of IWS result in more pipe wear and tear than others.

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[76] Kumpel and Nelson, "Comparing Microbial Water Quality in an Intermittent and Continuous Piped Water Supply." [77] In Arraiján samples were transferred directly from the storage container to a sterile sample bottle, while in Hubli-Dharwad, to simulate the quality of water that the user would actually be drinking, the sample was transferred via a glass provided by the user. [78] Kumpel and Nelson, "Mechanisms Affecting Water Quality in an Intermittent Piped Water Supply."

2.4.2 High rates of water loss are associated with IWS

IWS is considered to often be associated with high rates of water loss.[79] Flow monitoring in three of the Arraiján study zones, and IDAAN's production and billing data show that Arraiján's situation fits that trend. Despite a high per-capita production of 155 gallons per person per day, service is deficient in much of the Arraiján network. High measured flows entering the study zones and high flows during nighttime hours suggest that significant water losses were occurring within the study zones, either in distribution pipes or household plumbing.

2.4.3 Advanced monitoring techniques offer opportunities to diagnose problems in complex IWS systems and improve management of such systems.

The project provided the opportunity to evaluate the usefulness of several different monitoring methods in an intermittent distribution system and consider whether they could be used by operators to improve service quality in intermittent systems. Continuous pressure and flow monitoring proved useful for quantifying the schedule of supply that users receive, detecting pump station shutdowns, identifying extreme pressures (high and low/negative) that can damage pipes and are a risk for water quality, detecting pipe breaks, and identifying areas of the distribution network where the entering flowrate is higher than expected.

Pressure monitoring in Arraiján, along with conversations with and observations of system operators, showed that the pattern of supply outages in an IWS zone was often the result of a combination of causes. When superimposed upon one another, these failure patterns resulted in a complex supply pattern in which conditions in the Arraiján network were unique almost every week. While some outages were caused by inadequate distribution capacity or the unfavorable water balance in the system due to high demand and excessive water losses, other outages were caused by other failures that could be avoided or shortened by improving monitoring capabilities and response times. For instance, in AL the duration of pump outages and operators' response time to pipe breaks could be reduced by installing a pressure monitor in the zone with telemetry to alert operators of outages. Of course, this enhanced monitoring would only be effective if operators were available to respond to sensor alerts and make needed repairs in a timely manner.

Inconsistent operation also sometimes affected the supply schedule in AL, for example when a weekend operator was not aware that the control valve should be opened or closed. Pressure monitoring would also address this problem, since it would allow weekend operators to see whether the water was on or off in the zone and when it had last been turned on or off, without having to visit the valve itself. Monitoring data would also help supervisors assure that operators are following the proper valve operation schedule.

All areas of the system, including CR, were vulnerable to occasional interruptions due to treatment plant shutdowns, construction or repairs on major water mains, or large unexpected pipe breaks. While some such failures may be unavoidable, pipe break records identified certain problem areas where breaks are frequent. In some cases these problem areas were affected by intermittent pumping. Monitoring for pressure transients, or hydraulic modeling and analysis, could be used to determine the cause of breaks in these areas so operational changes or surge protection devices could be put in place to avoid them.

Interruptions in power supply also caused local failures, such as the shutdown of the VB pump station, and more widespread failures, such as the shutdown of a treatment plant or larger pump station. While fluctuations in the power grid are beyond the water system operators' control, monitoring and logging of these failures might allow system operators to better adapt the water network to them or coordinate with power grid operators to avoid outages that are particularly problematic.

Advanced monitoring techniques could also allow operators to improve water quality. Pressure monitoring in Arraiján identified problematic negative pressures in specific locations in the network. Prior to installation of the pressure monitors, system operators were not aware of those negative pressures. As expected, grab sampling of first flush and stored water revealed water quality problems not apparent from routine grab sampling. First flush and stored water sampling identified AL as an area where the water quality effects of IWS are greatest. As long as supply in AL is intermittent, it may be hard to improve tap water quality there during the first flush. However, it may be feasible to reduce the negative

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[79] Klingel, "Technical Causes and Impacts of Intermittent Water Distribution."

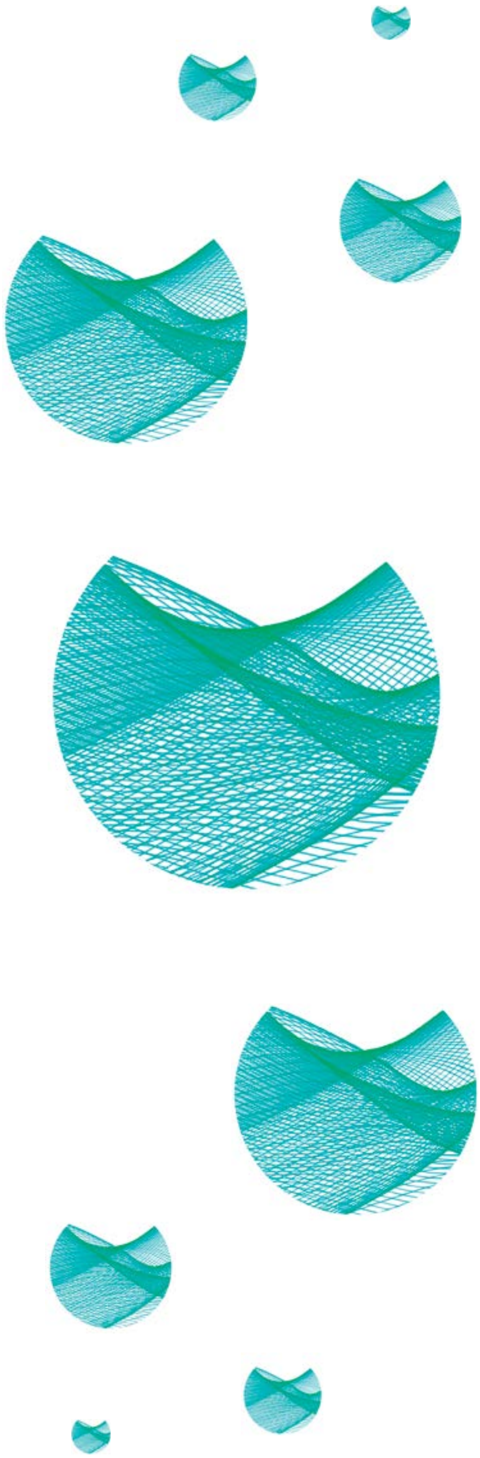
impacts of IWS there by developing strategies to avoid consumption of water from the first flush and practicing more hygienic drinking water storage.

Both routine and first flush sampling indicated that pipe breaks and repairs are an important cause of contamination in Arraiján. This contamination could be avoided or reduced by improving repair practices. Specifically, the need for installing more hydrants or flushing valves in the network to facilitate flushing of pipes after repairs should be evaluated.

Although continuous monitoring of turbidity and free chlorine was useful for this research project, it is not recommended for routine monitoring of the study zones, given that these zones do not present turbidity and chlorine problems. However, continuous monitoring might be useful in other portions of the Arraiján network where low chlorine concentrations are a problem. Continuous turbidity and chlorine monitoring was not reliable during the first several minutes of supply, due, at least in part, to air being expelled from the pipes and through the sensors. However, online monitoring techniques could perhaps be improved, with the addition of an air release valve upstream of the water quality sensors for instance, to allow for more reliable monitoring of the first flush, since it is a critical time for water quality.

In the context of excessive water losses and unplanned system growth, IWS may appear to be an uncontrollable problem from the perspective of a water provider.

However, results from this case study in Arraiján suggest that advanced monitoring techniques provide opportunities to make incremental improvements to service quality in IWS systems.



03

Framework for considering IWS in efforts to improve drinking water service in Latin America and the Caribbean

Drawing on lessons from the case study in Arraiján and other IWS research in available literature, in this section we propose a framework for considering IWS in broader efforts to provide safe, reliable and sustainable piped drinking water supply in Latin America and the Caribbean. As detailed in Section 1, IWS presents many problems and should be avoided when feasible, but if it cannot be avoided, measures should be taken to monitor and mitigate its problematic effects.

IWS is inherently complex, and efforts to improve or avoid it should begin with efforts to understand it in the context of specific scenarios. As seen in the comparison between Arraiján and Hubli-Dharwad, the nature and effects of IWS can vary drastically between different distribution systems. Comparison of different study zones within the Arraiján distribution system shows that IWS can also vary substantially across different areas within one distribution system. Experience from Arraiján demonstrated that advanced monitoring methods can be useful for diagnosing the effects of a specific case of IWS and also for improving operation of an intermittent system.

3.1 Monitoring methods to diagnose and improve IWS

Water quality monitoring methods in intermittent distribution systems should be tailored to the specific concerns that IWS presents.

In addition to the routine grab sampling normally required as part of drinking water quality regulations, potentially useful techniques for diagnosing water quality in IWS systems include:

- water quality grab sampling during the first flush,

- sampling of stored drinking water,

- pressure monitoring to identify negative pressures that increase risk for intrusion and backflow,

- and continuous turbidity and chlorine monitoring.

The optimal monitoring strategy for a specific IWS system will depend on that system's specific situation. For example, if routine grab sampling shows that chlorine residual is consistently sufficient, as was the case in the study zones in Arraiján, then continuous chlorine monitoring is probably not necessary. However, if grab sample data identify that chlorine residual is sometimes deficient in a certain area, continuous monitoring may be warranted. Initial intensive monitoring could be used to diagnose areas of concern in a distribution network, so that a future monitoring program and the design of operational improvements can focus on those areas.

Improved water quality monitoring in IWS systems can contribute to efforts to reduce public health risks by changing utility practices (e.g. avoiding negative pressures, using pipe repair practices accompanied by appropriate flushing and disinfection procedures) and educating customers to change their practices (e.g. avoiding consumption of the first flush when possible, reducing risk of backflow, or practicing safer storage).

Design of solutions to reduce risk, especially solutions involving customer practices, will be very context-specific and will require careful evaluation of what solutions will be effective in a specific situation. In addition, water quality monitoring appropriate for intermittent systems can help determine whether a specific system is providing water of acceptable quality (thus increasing consumer confidence) or is providing water of unacceptable quality (thus alerting consumers that they need to practice household treatment and alerting the water utility that water quality must be improved).

Advanced monitoring techniques can also help improve service continuity and operational efficiency in IWS systems. Pressure and flow monitoring can characterize supply conditions and detect problems in the system in order to reduce operator response time, determine the causes of outages, identify areas where water losses are particularly high, and track the effects of efforts to improve supply continuity. Monitoring need not only focus on sensors and water quality sampling. Tracking pipe repairs can identify areas where poor pipe condition or problematic hydraulic conditions are leading to high rates of pipe breaks. Logging valve operations and other operational events, and the analysis of these logs, can lead to more systematic operation of IWS systems.

By making monitoring results, particularly those related to water quality and supply continuity, publicly available, utilities can show customers that they are making serious efforts to address supply problems, which should increase customers'

support for the utility as an institution and their willingness to pay for service.

3.2 Opportunities to improve service quality in IWS systems

In addition to the monitoring techniques discussed above, many best practices for operating continuous distribution systems also apply to intermittent systems and often are even more important under IWS.

These practices include:

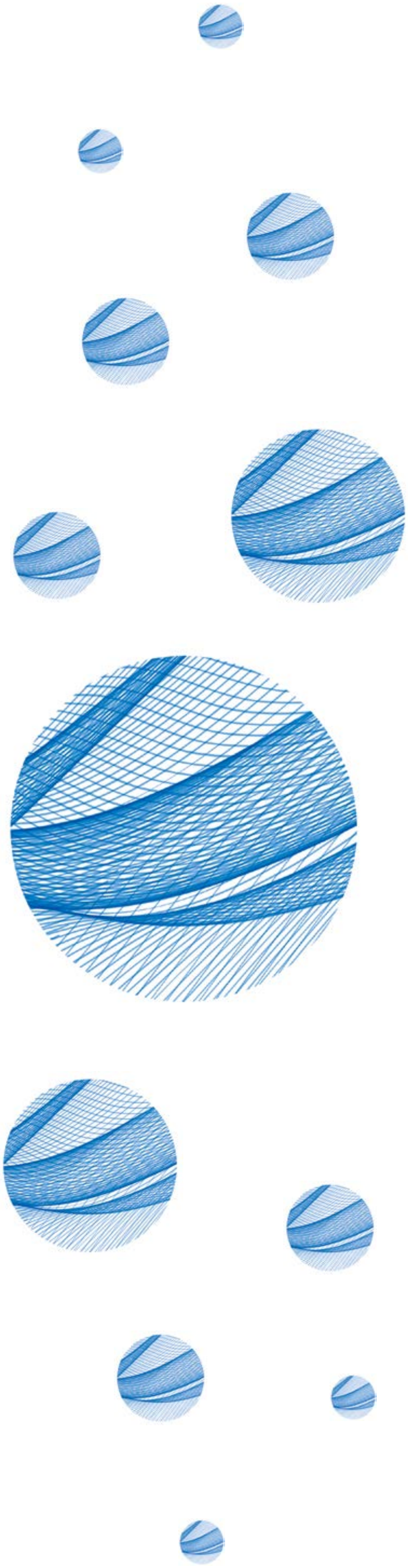
- measuring and reducing water losses,

- communicating effectively with customers,

- avoiding potential for water quality contamination due to backflow and cross-connections by maintaining sufficient pressure and chlorine residual when water is on,

- collecting and managing operations data,

- and managing distribution system assets with a GIS database.



04

Conclusions

In light of the importance of IWS within the context of efforts to improve drinking water supply, a study was carried out in four zones (three with intermittent supply and one with continuous supply) of the drinking water network in Arraiján, Panama.

Through continuous pressure monitoring it was seen that supply in the intermittent zones was irregular and unpredictable, sometimes because operators lacked adequate capacity to monitor conditions in the network. Despite low and negative pressures in the intermittent zones, except for some pipe repairs and first-flush events, water quality was consistently within Panamanian standards for turbidity, total coliform and *E. coli*, and WHO standards for free chlorine residual. Per-capita entrance flows and nighttime flows were high in the three zones where entrance flows were measured, indicating high levels of water loss, particularly in the intermittent zones. Although a general relationship between pipe breaks and IWS was not observed, high transient pressures and high pipe break rates were observed in situations of intermittent pumping.

Comparison between conditions in the different Arraiján study zones and another network previously studied in Hubli-Dharwad, India confirms that conditions under IWS can vary greatly between different intermittent systems and among different parts of the same intermittent system. Additionally, various monitoring methods were identified that operators can use to better understand and control conditions in intermittent networks.

There are many opportunities to improve service in intermittent systems by monitoring the distribution system and its operation, improving utility operation practices, and reducing water losses. Such management measures should be considered as complements to or replacements for more costly investments to augment distribution system capacity and increase water production. For these measures to be effective and sustainable, they must involve capacity building among water utility personnel and be implemented with maximum involvement from these personnel.

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