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Does intermittent supply result in hydraulic transients? Mixed evidence from two systems

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ABSTRACT

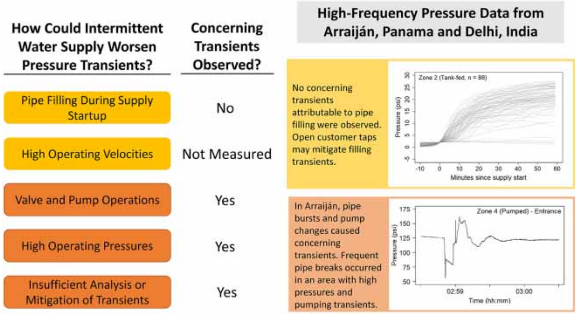
Pressure transients can cause severe damage in continuous water supply pipe networks, but little is known about pressure transients in intermittent networks. Published examples of high-frequency pressure monitoring in intermittent networks are lacking. Intermittent supply can be caused by poor network condition and is associated with delivering less water, less frequently, and with poorer quality than continuous supply. Given the frequency with which intermittent systems drain, fill, and change supply regimes, pressure transients have been hypothesized to be common and to be one mechanism by which intermittent supply further degrades network condition. We present supply start-up data from two very different intermittent systems: a low-pressure, intermittent network in Delhi, India, and a higher-pressure intermittent network in Arraiján, Panama. Across monitoring locations at both sites, we did not detect substantial pressure transients due to pipe filling. In Arraiján, pump start-ups, pump shutdowns, and pipe bursts were associated with potentially problematic transients. We conclude that pipe filling in intermittent supply does not always result in concerning pressure transients. The largest risks to pipe conditions we observed were due to pumping changes in close succession; hence, we recommend that utilities operating intermittent (and continuous) systems leave adequate dissipation time between changes in pump operation.

Key words: hydraulic transients, intermittent water supply, pipe damage, pipe filling, pressure monitoring

HIGHLIGHTS

- High-frequency pressure monitoring was conducted in two intermittent drinking water distribution networks.
- We found no evidence of substantial pressure transients due to pipe filling.
- In Arraiján, pump starts and stops were associated with transients.
- Pump starts and stops in rapid succession posed a greater risk to pipes than pipe filling did in the observed study zones and should be avoided in intermittent systems.

GRAPHICAL ABSTRACT



How Could Intermittent Water Supply Worsen Pressure Transients?	Concerning Transients Observed?
Pipe Filling During Supply Startup	No
High Operating Velocities	Not Measured
Valve and Pump Operations	Yes
High Operating Pressures	Yes
Insufficient Analysis or Mitigation of Transients	Yes

High-Frequency Pressure Data from Arraiján, Panama and Delhi, India

No concerning transients attributable to pipe filling were observed. Open customer taps may mitigate filling transients.

In Arraiján, pipe bursts and pump changes caused concerning transients. Frequent pipe breaks occurred in an area with high pressures and pumping transients.

1. INTRODUCTION

It is estimated that more than 1 billion people in low- and middle-income countries worldwide receive water from piped drinking water systems that are available to users for an average of less than 23 h/day (Bivins *et al.* 2017). Intermittent supply inconveniences users (Lee & Schwab 2005; Cook *et al.* 2016; Erickson *et al.* 2020), threatens water quality (Coelho *et al.* 2003; Lee & Schwab 2005; Klingel 2012; Kumpel & Nelson 2016), and leaves some users with insufficient volumes of water (Andey & Kelkar 2007; Kumpel *et al.* 2017; Taylor *et al.* 2019).

Intermittent water supply (IWS) can be caused by insufficient water resources, inadequate infrastructure, unplanned expansion of the distribution network, excessive water losses, ineffective operational strategies, or a combination of these factors (Yepes *et al.* 2001; Vairavamoorthy *et al.* 2007; Klingel 2012; Galaitsi *et al.* 2016; Kumpel & Nelson 2016). Many have argued that the hydraulics of IWS worsen an intermittent network's condition, causing a potentially vicious cycle (Yepes *et al.* 2001; Lee & Schwab 2005; Charalambous 2011; Christodoulou & Agathokleous 2012; Klingel 2012; Galaitsi *et al.* 2016) in which IWS causes pipe breaks and leaks, resulting in increased water losses and more severely intermittent supply. But due to the complexity of IWS, little rigorous evidence is available to evaluate if, where, or which specific IWS conditions cause pipe degradation.

Hydraulic transients, commonly known as a 'water hammer' (Boulos *et al.* 2005), are purported to be one component of the vicious cycle of intermittent supply (Lee & Schwab 2005; Klingel 2012). But to date, the influence of intermittent operations on the severity and/or frequency of hydraulic transients remains unknown. Hydraulic transients can result from any sudden disturbance in pressure or flow conditions, such as during pipe filling, pump start-up or shutdown, valve opening and closing, rapid changes in demand (such as opening or closing of large customer connections), entrapped air, or pipe breaks (Boulos *et al.* 2005). As such, the severity and/or frequency of hydraulic transients could be worsened by IWS because:

1. Many intermittent networks regularly fill. Filling pipes can trap air pockets, which can induce transients when they collapse rapidly under increased pressure (Izquierdo *et al.* 1999); when the last of the air is expelled through an orifice (such as an open tap) and water begins to exit the orifice, suddenly increasing the hydraulic resistance and reducing the filling velocity (Li & Zhu 2018); and/or when air release valves close suddenly after expelling the air (Batish 2003; Lingireddy *et al.* 2004). Weston *et al.* (2022) measured significant hydraulic transients during the filling of a partially drained pipe in the laboratory designed to mimic many aspects of intermittent supply.
2. Many intermittent networks regularly change supply regimes. Changing supply regimes, at least in continuous water supplies, can cause transients due to pump shutdowns (Geldreich 1996) and valve operations (Batish 2003; De Marchis *et al.* 2010; Kumpel & Nelson 2014) – both of which are common under IWS.
3. Intermittent networks supply demand over shorter time intervals than continuous networks, which may result in higher flow velocities because most IWS networks were not built to operate intermittently (Ghorpade *et al.* 2021). All else being equal, higher flow velocities result in more severe transients (Karney & McInnis 1990).
4. Some intermittent networks have high pressures, especially near sources. Unplanned network expansion may necessitate the expansion of pumping capacity to force greater flows through undersized pipes, leading to excessive pressure near the pump station. Transient pressure increases superimpose on steady-state pressures, compounding the risk they pose to infrastructure.
5. Many intermittent systems are operated without accurate knowledge of the system (Klingel 2012). Uncertainty in operating and loading conditions prevents the effective analysis (and thereby mitigation) of transients (Karney & McInnis 1990).

Yet the severity and/or frequency of hydraulic transients could be mitigated by IWS because:

1. Intermittent systems tend to have high leakage rates when they are pressurized (Yepes *et al.* 2001; Klingel 2012; Galaitsi *et al.* 2016). Leaks act as pressure-dependent demand, helping to dissipate the energy from (and therefore severity of) hydraulic transients (Karney & Filion 2003). Furthermore, in some intermittent systems, users leave their taps open before and during supply, creating additional pressure-dependent demand (Vairavamoorthy *et al.* 2007) that can dissipate hydraulic transients.
2. Intermittent systems often have large pressure losses in the network, which reduce the average network pressure (Lee & Schwab 2005; Vairavamoorthy *et al.* 2007; Kumpel & Nelson 2016). As transient pressures are superimposed on network pressures, lower network pressures reduce the risk of over-pressurizing pipes (but increase the risk of contaminant intrusion (Taylor *et al.* 2018)).

Few studies have measured pressure in intermittent systems at a high enough frequency to characterize hydraulic transients. In one previous study, pressure was monitored during 16 supply cycles (at 4 Hz) in intermittent portions of a distribution network in Hubli-Dharwad, India, where system operators opened and closed valves during the supply cycles (Kumpel & Nelson 2014). One event was classified as a 'transient,' but as the observed pressures were between 0 and 15 psi, such an event would be very unlikely to damage pipes. Several other studies reporting pressure in IWS sampled too infrequently to detect transients, measuring every 5–30 min (Andey & Kelkar 2007; De Marchis *et al.* 2010; Al-Washali *et al.* 2018; Campisano *et al.* 2018; Meyer *et al.* 2021; Sánchez-Navarro *et al.* 2021).

Despite the prevalence of IWS and concerns about its effects on pipe infrastructure, there are critical knowledge gaps regarding the severity and mechanisms of pipe damage that occurs under IWS. Given the heterogeneity of intermittent networks, the goal of this study was to evaluate the prevalence of extreme pressures and pressure transients in five contexts: (i) a normally high-pressure continuous supply that experienced 11 unplanned outages over a year; (ii) a high-pressure, tank-fed IWS; (iii) a high-pressure, valve-controlled IWS; (iv) a high-pressure, pump-controlled IWS; and (v) a low-pressure, pump-controlled IWS. Although any change in pressure or flow can be considered a transient, we focus on and define transients as short-term pressure peaks or valleys that are outside of the range of steady-state pressures observed before and after the pressure change occurred. The study primarily focused on pressure conditions during supply start-up when transients due to pipe filling could occur.

2. METHODS

2.1. Study sites

Data were collected in five study zones experiencing a variety of IWS conditions, including four zones in Arraiján, Panama, and one zone in Delhi, India. Characteristics of each study zone, including supply continuity and how supply was controlled, are summarized in Table 1.

Table 1 | Summary of study zones

Zone (supply type)	Water system	Customer connections	Supply source	Average fraction of time supply was on[a]	Supply continuity
1 (continuous, high-pressure)	Arraiján, Panama	348	Main transmission pipe from the treatment plant via two entrances to the zone	99.1%	Continuous except for 11 outages during the year of monitoring and several users at high elevation
2 (tank-fed, high-pressure)	Arraiján, Panama	650	Mostly via gravity from two storage tanks and some supply directly from main transmission pipes	83%	Users at high elevations lost supply when storage tanks drained, which was most common during afternoons and weekends
3 (valve-controlled, high-pressure)	Arraiján, Panama	232	Local pump station pumping directly into the distribution network, with a control valve used to direct supply to Zone 3 or other sectors	57%	Scheduled to have 3 days with supply and 3 days without, but the actual supply varied due to irregular valve operation, pipe breaks, and pump station failures
4 (pumped, high-pressure)	Arraiján, Panama	368	Mostly from the local pump station pumping directly to the distribution network, with small amounts of supply through small diameter pipes from other parts of the network	87%	The pump station stopped frequently (an average of approximately once per day, but often a few times per day) due to insufficient supply or power failures, causing most of the zone to lose supply
5 (pumped, low-pressure)	Delhi, India	181	From transmission main fed by a pump station	22%	Supply provided for 2–3 h in the morning and 2–4 h in the evening, regulated by turning pumps on and off at the distribution reservoir

Information on Arraiján, Panama study zones was previously reported by Erickson *et al.* (2020).

[a] Depending on the zone, this fraction was calculated based on the portion of monitoring time that pressure at the downstream monitoring station was $\geq$2 psi at the ground level (Zones 1–3), the fraction of monitoring time that the pump station serving the zone was on (Zone 4), or the fraction of time pressure was higher than its value when supply was off (Zone 5).

2.1.1. Arraiján, Panama (Zones 1–4)

Arraiján is a rapidly growing peri-urban area west of Panama City, Panama. Arraiján's population grew from 60,000 inhabitants in 1990 to an estimated 263,000 in 2014 (National Institute of Census and Statistics Panama 2010a, 2010b), increasing demand for drinking water. At the time of the study, the Arraiján drinking water distribution network was supplied with an average of 585 liters per person per day, and most of the network normally had a continuous supply. Yet some areas routinely received intermittent supply due to high rates of leakage (according to utility data, only 47% of 2014 production was billed to customers, i.e., 53% non-revenue water) and because pumps, storage tanks, and/or pipes did not provide sufficient local distribution capacity. All areas of the network were subject to occasional loss of supply due to infrastructure failures such as pipe breaks, treatment plant shutdowns, and power outages affecting pump stations.

Arraiján's distribution system mainly has a branched topology, spans a large area with complex topography, and is supplied from three treatment plants. The elevation difference between the highest point and the lowest point in each of the Arraiján study zones ranged from approximately 26 to 82 m. 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.

Study Zones 1–4 in Arraiján (mapped in Supplementary Figure S2) were estimated to have between 232 and 650 connections each (not all legally registered with the utility). Pipes within these zones were PVC with diameters between 15 and 150 mm. The majority of households in intermittent areas (Zones 2, 3, and 4) stored water in their homes. A few households had larger storage tanks that filled automatically from the distribution network, but most households manually filled storage containers directly or through a flexible hose. A more detailed description of the Arraiján distribution network and supply in the Arraiján study zones is provided in Erickson *et al.* (2020).

2.1.2. Delhi, India (Zone 5)

Delhi is India's capital and its water utility, the *Delhi Jal Board* (DJB), serves treated piped water to 75.2% and untreated water to 6.1% of Delhi's 18 million inhabitants (3.3 million households) (Government of NCT of Delhi 2017). The DJB's water treatment capacity equates to 229 liters per inhabitant per day (Government of NCT of Delhi 2017). The DJB officially estimates their 'total distribution losses' to be on the 'order of' 40% (Government of NCT of Delhi 2017).

Study Zone 5 in Delhi covered one neighborhood (unspecified for privacy reasons) with 60 multi-story residential structures and 181 service connections. All customers had some form of water storage and most used private suction pumps to fill roof tanks (Meyer *et al.* 2021), some of which were automatically controlled. Zone 5 contained approximately 800 m of a 100–150 mm diameter cast iron pipe supplied from a 450 mm diameter cast iron trunk main, which remained at least partially full between supply cycles. The distribution network within Zone 5 had a looped topology.

2.2. Monitoring methods

2.2.1. Zones 1–4 (Arraiján, Panama)

From August 2014 to August 2015, pressure was monitored at the entrance(s) and a downstream location in each of the four Arraiján study zones (Zone 2 configuration shown in Figure 1(a) as an example), collecting between 273 and 354 days of pressure data. ECO-3 RTUs (remote telemetry units, Aquas Inc., Taipei, Taiwan) were used to monitor pressure at all locations except for the entrance to Zone 3, where pressure was monitored by an LPR-31i-200 pressure impulse recorder (Telog Instruments Inc., Victor, NY). The pressure sensors were installed in above-ground metal boxes and powered by 12-volt batteries charged with solar panels. Sensors were connected to the distribution pipe via a saddle installed on the pipe, a 15 mm PVC pipe, and a 12 mm PVC hose. Turbidity, free chlorine, and flowrate were also measured at some stations for related research (Erickson *et al.* 2017).

The ECO-3 pressure monitors normally recorded measurements every 30 s and recorded measurements every 0.1 s for a period of 2 min whenever the pressure changed more than 5% during 1 s. Specifications in the manual for the ECO-3 sensors indicated that they were rated to measure pressure down to 0 psi. However, personal communication with Aquas indicated that the sensors were capable of measuring negative pressures. Negative measurements registered by the ECO-3 sensors appeared to be qualitatively accurate based on the inspection of transient waveforms during pump start-ups. The LPR-31i-200 recorder was rated to measure pressure from −15 to 200 psi and was configured to sample pressure at 20 Hz and record the average, maximum, and minimum every 30 s. The recorder was also configured to record at 20 Hz for a period of 40 s whenever pressure changed by >10 psi within 10 s.

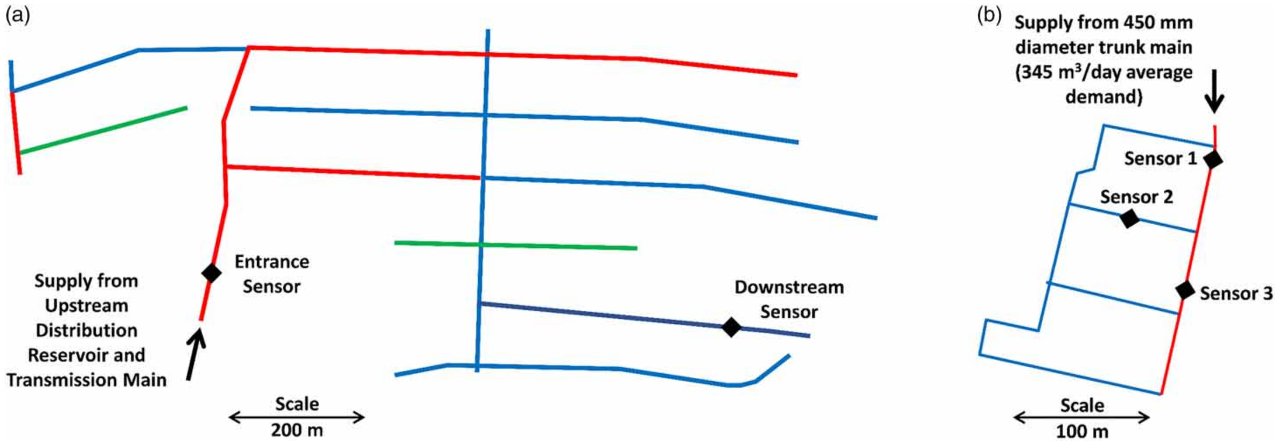


Figure 1 | Monitoring setups in Arraiján, Panama (a; Zone 2 shown as an example) and Delhi, India (b; Zone 5). Pipe diameters were 150 mm (red), 100 mm (blue), and 75 mm (green). (a) Zone 2 (Arraiján). (b) Zone 5 (Delhi). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/aqua.2022.206.

2.2.2. Delhi, India

To observe filling pattern dynamics, three LPR-31i-100 pressure impulse recorders (same as in Arraiján, but with a maximum range of 100 psi) were installed in the neighborhood's distribution pipes (Figure 1(b)) for 2 weeks (28 filling cycles) from April 2 to 16, 2016 and configured to sample at 50 Hz and record the minimum, average, and maximum pressure every 2 min. To distinguish between full and empty pipes, pressure sensors were installed at the pipe invert (bottom of pipe).

2.3. Data analysis

Both datasets were analyzed and graphed in R (R Core Team 2021). For analysis of Arraiján data, transient data and periodic data (the data collected continuously every 30 s regardless of whether a transient was occurring) were combined into one time series for each monitoring location. All pressure data were adjusted to the level of the buried pipe at the monitoring location. Occasional errors in the ECO-3 sensors produced nonphysical readings, which were filtered out (filtering details in Supplementary Text S1). An algorithm was used to identify supply start-up events in the 60 min following a transition from pressure <2 psi to pressure >2 psi at ground level at the downstream monitoring station. Plots of pressure during these start-up events were then manually reviewed for patterns indicating the occurrence of hydraulic transients. Concerning transients not associated with supply start-up were identified by the manual review of pressures when the ECO-3 sensors recorded high-frequency data due to a sudden pressure change or when abnormally high or negative pressures were observed.

In Delhi, differential (gauge) pressure sensors were installed at the pipe invert, and soil saturation occasionally induced negative-pressure readings at times when customers were known to have open taps (e.g., between midnight and 2 AM). The average recorded gauge pressure (range -1, 0.4 psi) between midnight and 2 AM was used to re-zero sensors daily in postprocessing. Supply start-up events were identified based on the time the pressure became >2 psi during either the morning or the afternoon (times when the pumps were scheduled to supply the study zone). As was done with the Arraiján data, plots of pressure during these start-up events were manually reviewed for patterns indicating the occurrence of hydraulic transients.

3. RESULTS AND DISCUSSION

3.1. Downstream pressures during supply start-up

Supply start-up is a time of particular concern for transient events in IWS systems, since, if pipes have drained while the supply is off, the expulsion or collapse of entrained air pockets, and the subsequent deceleration of water columns as they run into the end of dead-end pipes (or into one another), can cause hydraulic transients. To identify potential pipe-filling transients during supply start-up, as opposed to transients from pump or valve operations, we focus our analysis on monitoring locations far downstream from pump and valve operations and close to where pipe emptying and filling were likely to be occurring. In Figure 2, pressure traces are shown from the downstream monitoring stations of Zones 1–4 (in Arraiján,

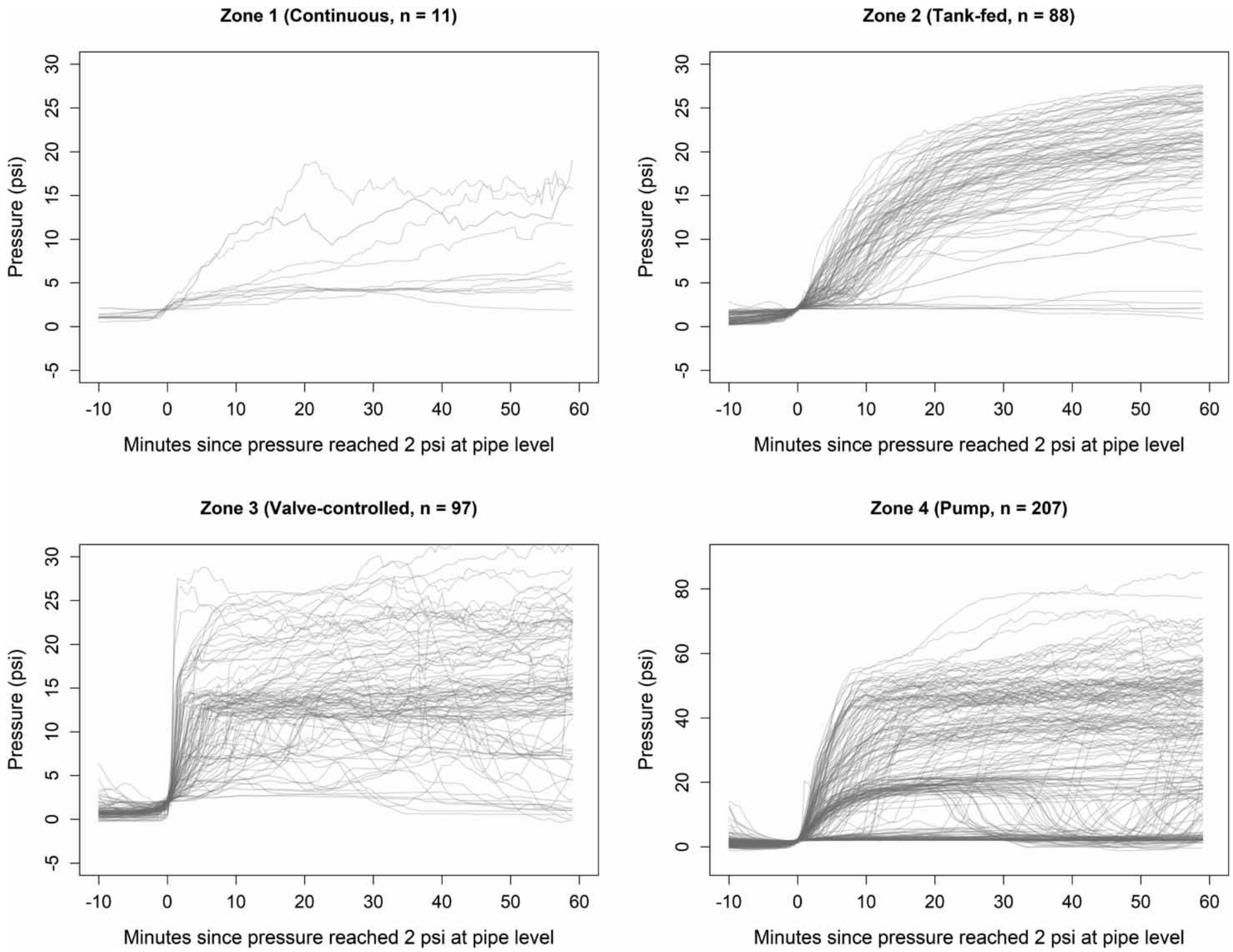


Figure 2 | Pressure during pipe filling at downstream monitoring stations in Zones 1–4 in Arraiján, Panama. Zone 4 pressure is depicted with an expanded vertical axis.

Panama) during all supply start-up events that occurred during the year of monitoring. Each trace includes 10 min of data before and 60 min of data after pressure reached 2 psi at the pipe level.

Despite the theoretical potential for filling-induced transients, no negative or extremely high pressures were observed during the 403 supply start-up events monitored at the downstream stations. At the downstream stations in Zones 1–3, no pressures >35 psi were observed during the start-up events. The 11 filling events in Zone 1, where supply was normally continuous, were after supply outages caused by pipe breaks or maintenance. While pressures as high as 105 psi were recorded at the Zone 4 downstream monitoring station, which was supplied by intermittent pumping, these high pressures were caused by high steady-state pressures, not transients.

The downstream pressure sensors' transient detection feature was triggered for only five start-up events, all in Zone 4 (Supplementary Figure S3). While all five events were characterized by an increase in pressure when the Zone 4 pump turned on, none included the subsequent pressure oscillations typical of hydraulic transients. Pressure did oscillate during some Zone 3 and 4 start-up events (examples in Supplementary Figure S4), but the nature of these pressure changes suggests that they were not filling-induced transients.

In Zone 5 in Delhi, India, no pressure transients were observed during supply start-up (Figure 3) during the 15 morning and 15 evening filling cycles. Furthermore, for both morning and evening supply, the system appeared to reach its steady-state pressure without any substantial overshoot (Figure 3). The recorded maximum and minimum pressures during the 2-min recording intervals show trends (Supplementary Figure S5) similar to the 2-min average pressures plotted in Figure 3.

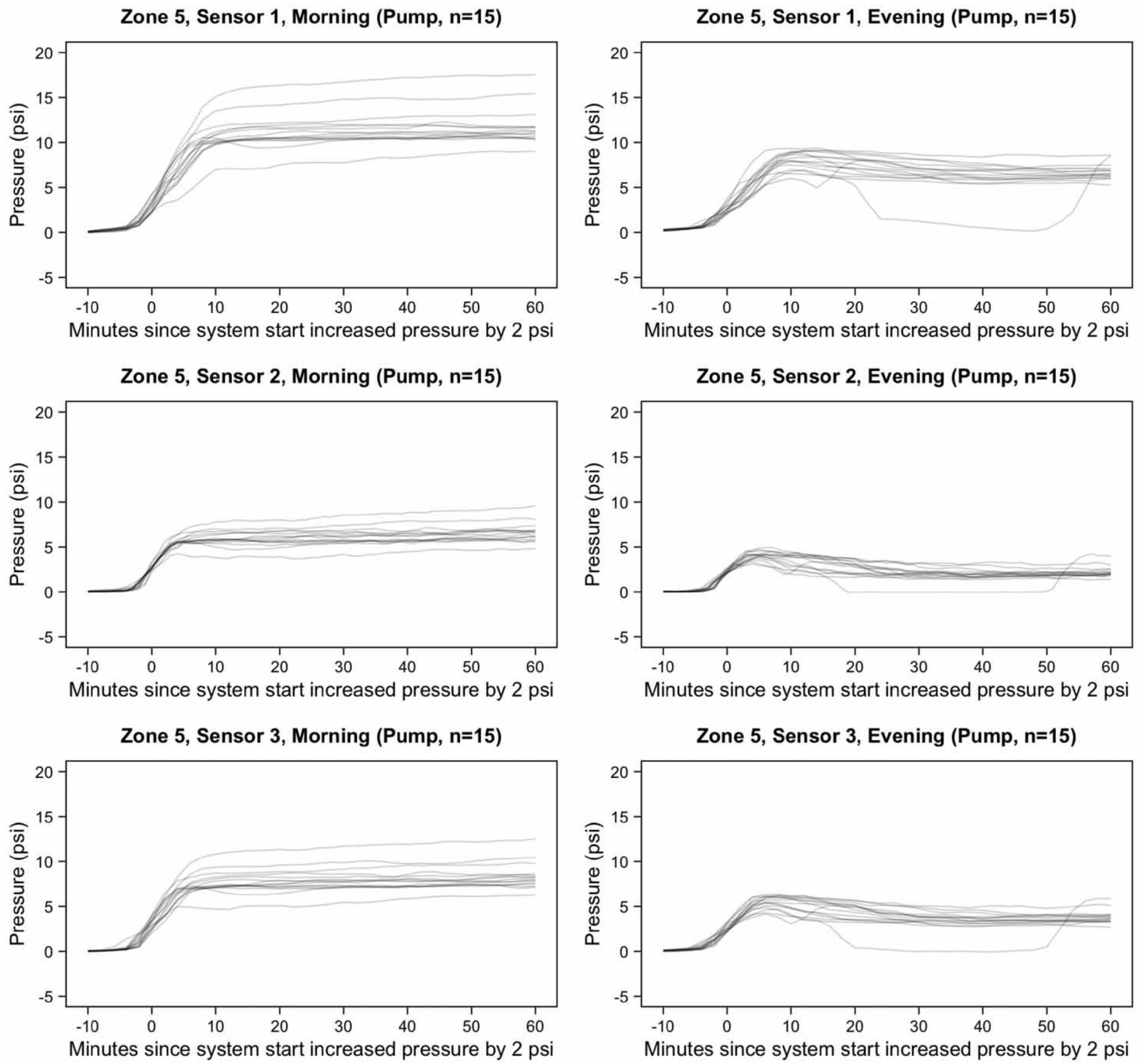


Figure 3 | Supply start-up profiles (15 mornings and 15 evenings, measured at three sensors) in Zone 5 in Delhi, India. Pressures were recorded at 50 Hz and averaged into the 2-min recording intervals plotted. Observed max and min pressures in each recording interval are summarized in Supplementary Figure S5.

Across all five (highly varied) study zones, no substantial start-up-induced transients were observed at downstream monitoring locations, indicating that either pipes did not empty while the supply was off or that pipe filling did not result in substantial hydraulic transients.

The extent to which pipes empty while the water supply is off could affect the severity of start-up transients since there is no filling if pipes remain full during an outage. However, according to utility pipe maps, in Zones 1, 2, and 3, the downstream monitoring location was on a downhill dead-end pipe, which would presumably have been drained by customer taps further downhill on the pipe. Air was sometimes observed being expelled from customer or water quality sampling taps before supply began, suggesting that pipe draining and filling did sometimes occur.

Assuming that pipes did empty and fill, the lack of transients may be explained by the absence of a sudden transition between filling the network and the network's 'steady-state' operation. As a pipe with a downstream orifice fills, the hydraulic resistance increases when water begins to exit the orifice (instead of air), which can reduce the filling velocity and induce a pressure transient. Li & Zhu (2018) found that when the diameter of the downstream orifice was at least 17% of the pipe diameter, increasing the orifice diameter reduced the magnitude of the filling-induced pressure transient. Mimicking such downstream orifices, many customers in IWS leave taps open when the supply is off so that, when the supply returns, they will be alerted by the sound of water coming out of the tap and/or so a tank located under the tap will fill automatically when supply returns. The absence of the expected filling-associated transients in Zones 1–5 may, therefore, be explained by consumers who left their taps open during supply.

3.2. Concerning pressures observed in Arraiján not associated with filling

While no pipe-filling transients were observed at the downstream monitoring locations in the four Arraiján study zones, both high positive and negative transient pressures associated with other causes were observed in Arraiján, mainly at the upstream monitoring locations. These transients were associated with the irregular and complex operation that is common in intermittent systems. Uncontrolled pump starts and stops (e.g., Figure 4(a)–4(e)) and occasional pipe breaks (e.g., Figure 4(f)) caused severe pressure transients.

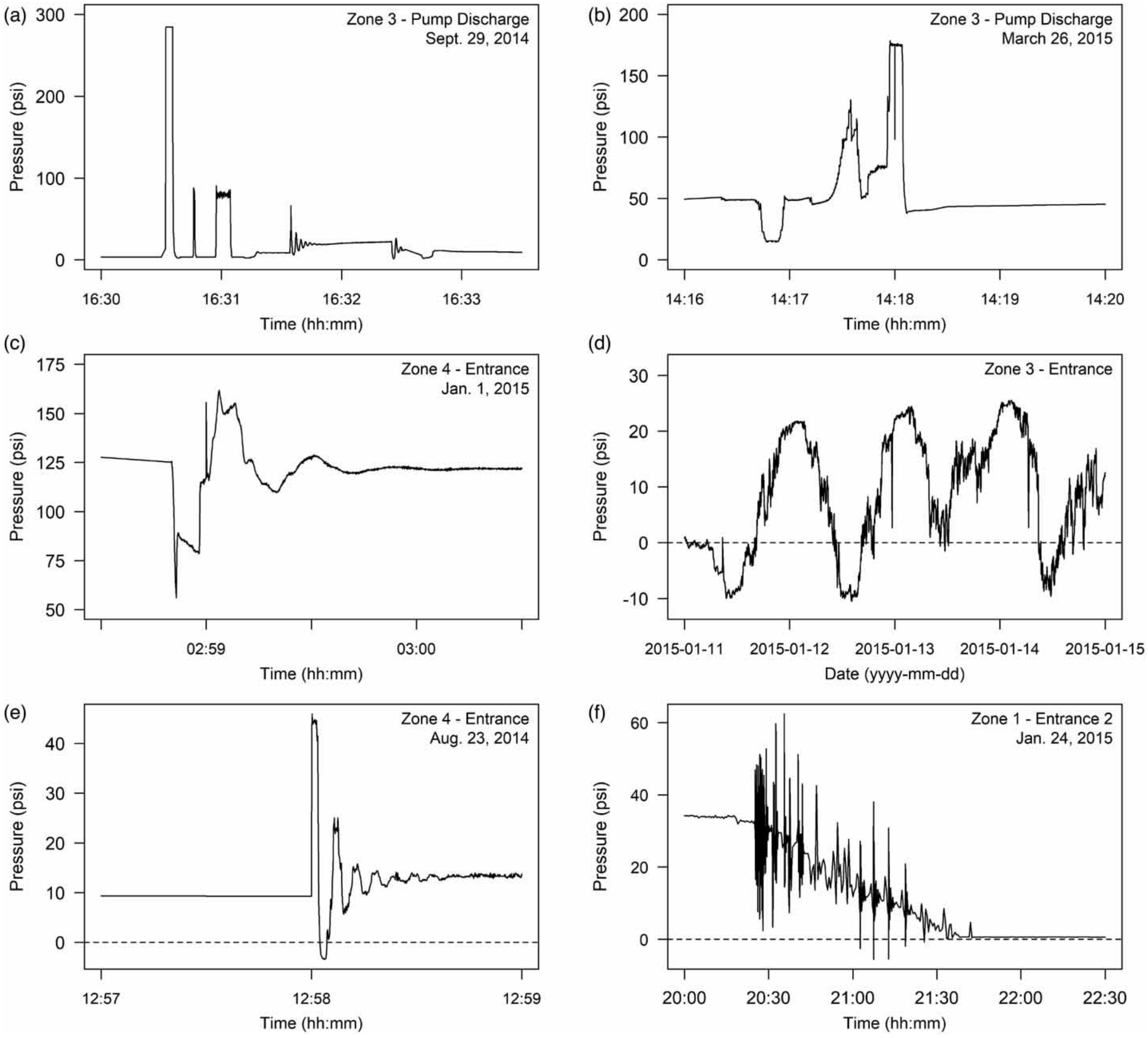


Figure 4 | Examples of high-pressure events: (a) possible Zone 3 pump testing or repair, (b) Zone 3 pump stop and start, (c) Zone 4 pump stop and start when steady-state pressure was already high. Examples of negative-pressure events: (d) sustained negative pressures at the Zone 3 entrance, (e) Zone 4 pump start-up, and (f) transients at Zone 1 entrance from the break in a 600 mm transmission pipe.

In addition to transients, high and severely negative steady-state pressures were observed in Zones 3 and 4 (Figures 4(d) and 5(d)–5(f)). Figure 5 shows the distribution of pressures (steady-state and transient) measured at all upstream monitoring stations, where high positive and severely negative pressures were most common. Steady-state pressure at the discharge of the pump station supplying Zone 4 exceeded 132 psi during steady-state transient conditions for 0.011% of all readings, equivalent to 56 min per year (Figure 5(f)). Pressures >132 psi are above the recommended pressure limit for the DR-25 150 mm PVC pipe (AWWA 2016, based on an operating temperature of 29°C; the actual pipe class was unknown). At times, such as the pump stop and start shown in Figure 4(c), pressure transients were superimposed on already high steady-state pressures, causing further concern for pipe integrity. The pressures measured at the entrances to Zones 1 and 2 (Figure 5(a)–5(c)) and the downstream monitoring stations (see pressure distributions in Supplementary Figure S6) were more moderate.

In the zone where high steady-state pressures were most prevalent, Zone 4, the utility logged 59 breaks (Erickson *et al.* 2020) in the approximately 3 km of 150 mm PVC pipe downstream of the pump station over a 3-year period (2012–2014). While transient pressures from pump starts and stops likely played a role in the pipe breaks in this zone, the large elevation differences in the zone also contributed to extreme pressures. The Zone 4 pump station supplied areas approximately 50 m above the pump station, requiring high pumping pressures, and passed through an area approximately 30 m below the pump station, which likely experienced pressures significantly higher than those experienced at the pump station.

In Zone 3, extended, steady-state periods of negative pressure were observed (less than −2 psi for 40% of the monitoring time) at the entrance monitoring location (see Figures 4(d) and 5(e)). This location was approximately 500 m downstream of the pump station supplying the zone and at a higher elevation than the pump station on the crest of a hill over which water

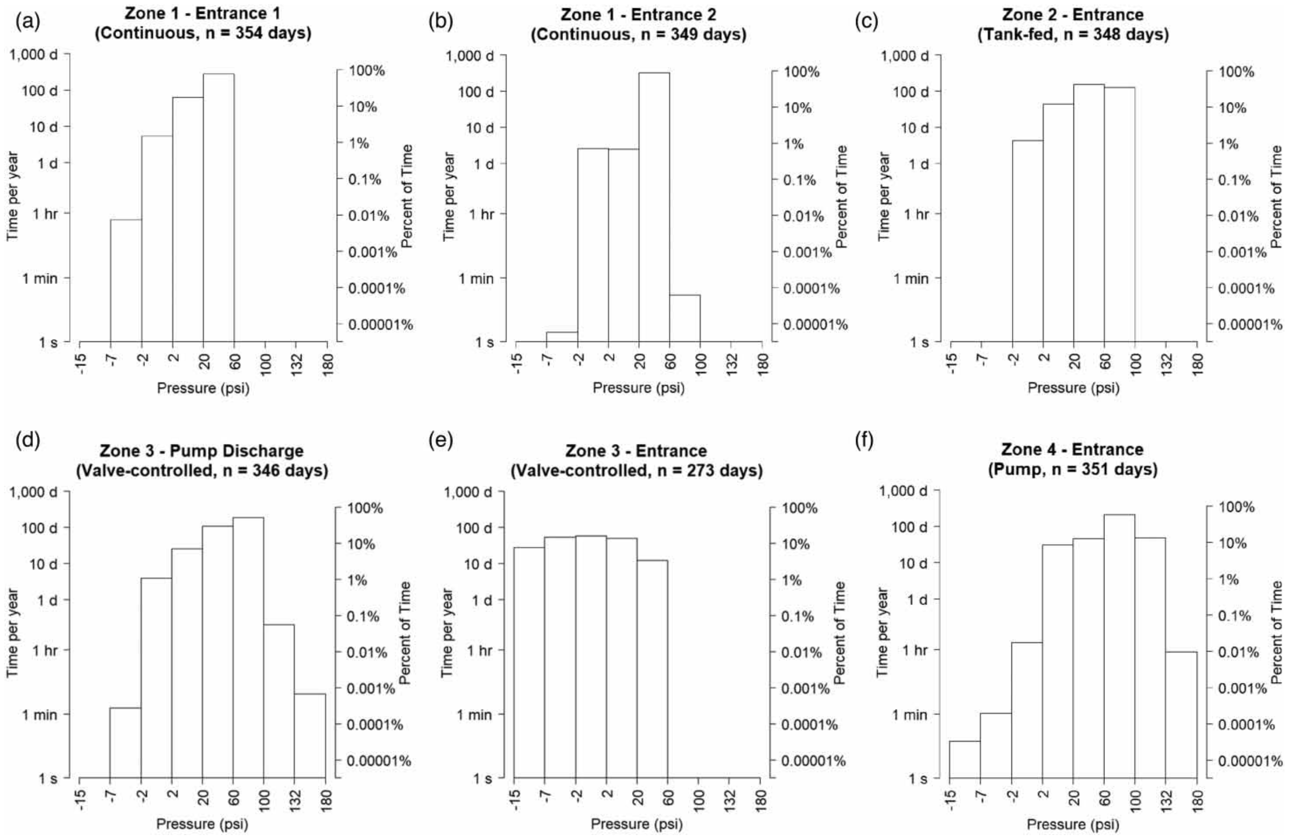


Figure 5 | Distribution of the pressures measured at each Arraiján upstream monitoring location (Zones 1–4), including high pump station discharge pressures in Zone 3 (d) and Zone 4 (f), very negative steady-state pressures at the entrance to Zone 3 (e), and more moderate pressures at the entrances to Zones 1 and 2 (a-c). Two upstream locations are shown (a and b) for Zone 1, because water entered Zone 1 at two locations. Zone 3 upstream pressure was monitored both at the discharge of the pump station serving Zone 3 (d) and adjacent areas, and approximately 500 m downstream of the pump station, just downstream of the valve used to control supply into Zone 3 (e). The data presented include both steady-state and transient pressures. Because the number of days of data collected at each site varied, data have been normalized to the equivalent duration per year of monitoring.

was being siphoned. While PVC pipe is normally resistant to vacuum pressures (Diamond Plastics Corp 2014), negative pressures can cause contaminants to be drawn into the system (Kumpel & Nelson 2016).

Transients associated with pump operations and pipe breaks were observed in Zones 1, 3, and 4, and negative and extremely high transient and steady-state pressures were observed in Zones 3 and 4 (>100 psi for 5.6 h per year and 52 days per year at the respective discharges of Zone 3 and Zone 4 pump stations; Figure 5(d) and 5(f)). While we found no evidence of filling-induced transients, our results indicate that transients and extreme pressures can be a problem in IWS. We recommend that utilities operating intermittent (and continuous) systems leave adequate dissipation time between changes in pump operation to avoid potentially damaging transients. Monitoring for transients and analyzing pipe break data could help utilities identify and avoid operations that result in damaging pressure conditions.

4. CONCLUSIONS

Some aspects of IWS may aggravate hydraulic transients, while others may mitigate them. No significant pressure transients were observed at downstream monitoring locations during supply start-up in any of the five study zones in Arraiján and Delhi. However, high and negative pressures were detected in Zones 3 and 4 in Arraiján both during steady-state operation and due to or exacerbated by pump start-up and shutdown transients. Results from these field studies indicate that pipe filling in IWS does not always result in concerning pressure transients. Further research is needed to investigate why such transients do not occur in some systems and whether they do occur in other systems. We encourage future researchers working in other IWS networks to sample pressures at a high enough frequency (e.g., the methods employed in this research) to document the existence of any transient pressure conditions and to develop methods to quantify the extent to which pipes empty when supply is off. If damaging transients are more prevalent in some systems than in others, it would be beneficial to understand why so that strategies could be developed to prevent them.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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