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RESEARCH ARTICLE

Short-term impacts of the filling transition across elevations in intermittent water supply systems

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ABSTRACT

Intermittent Water Supply (IWS) is characterised as drinking water distribution systems that are supplied with water for less than 24 hours/day on average. The filling transition from non-supply to pressurised supply is a period of hydraulic instability that negatively impacts water quality, deteriorates infrastructure integrity and intensifies social inequalities. Understanding the factors contributing to the severity of impact from filling is vital to develop effective management strategies. This paper investigates the hydraulic phenomena induced during the short-term IWS filling period and how this behaviour can be exacerbated by elevation and other hydraulic system factors, such as velocity and pressure. Controlled laboratory experiments conducted in the UK and field studies performed in operational networks across South Africa are presented. Results demonstrate the crucial role elevation plays in the network response during the filling transition, emphasising the need for greater consideration of elevation in IWS and well-maintained air relief valves in strategic locations.

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KEYWORDS
Intermittent water supply; filling; inequity; water distribution; transients

Introduction

Intermittent Water Supply (IWS) is the practice of supplying water in piped networks for limited periods, less than 24 hours per day on average. IWS is adopted by drinking water management authorities worldwide in an effort to control consumption, reduce leakage and/or cope with scarcity of supply. However, research suggests IWS leads to increased water wastage (Klingel 2012), negatively impacts the water infrastructure (Christodoulou and Agathokleous 2012), and deteriorates water quality (Kumpel and Nelson 2016). In IWS systems, the available water volume is rationed through a multitude of different supply protocols that could be scheduled or unscheduled, systematic, or variable (Galaitsi et al. 2016).

During IWS, the distribution system is filled from a source when operational, then drained by consumer demand, leakage, and other forms of water use when supply is stopped. The characteristic cyclical filling and emptying of IWS, concomitant with the spatial complexities of water distribution systems, lead to large inequalities in supply across space and time (Batish 2003; Fontanazza, Freni, and La Loggia 2007; Fontanazza et al. 2008). Depending on the distribution system hydraulic grade line during periods of filling, supply and draining, coupled with ground elevations at different locations, varying degrees of water volume and pressure will be available to consumers. This variation typically leads to supply inequalities, where users within the same distribution system experience different levels of water supply services.

For a given hydraulic grade line, consumers at high elevations in the network (at the 'top of the hill' in Figure 1) will likely receive the shortest duration of supply, as the pressure may not be sufficient during the filling and draining cycles to supply the highest elevations. Conversely, consumers at low elevations in the network (at the 'bottom of the hill' in Figure 1) are more likely to have longer durations of supply as pipes in these locations may not fully drain even when supply is turned off. These relationships are subject to the configuration of the distribution system for any supply zone, including the existence of storage and location of supply connections relative to the elevation differences (De Marchis et al., 2010a). Understanding the short-term filling cycle at different elevations and how related system parameters influence the hydraulic effects induced is critical for characterising the impact of IWS and the supply inequalities induced for consumers.

Background

IWS is characterised by regular supply interruptions that cause pipelines to drain partially or completely. When the next supply period is initiated, water is transmitted through the network, which acts as a pressure-driven open channel until the air in the system has been expelled and the pipelines are repressurised. Few studies have examined this refilling process during intermittent conditions, known as the 'first flush', 'charge-up' or 'restart'. This process has been specifically linked to infrastructure deterioration (Freni, De Marchis, and Napoli 2014; Vairavamoorthy et al. 2001) and degradation of water quality (Bautista-de Los Santos, Chavarría, and Nelson 2019; Erickson, Quintero, and Nelson 2017; Kumpel and Nelson 2014). Tokajian and Hashwa (2003) detected significantly high heterotrophic plate count (HPC) and turbidity values (both indicators of poor water quality) immediately as flow restarted in an IWS network in Lebanon. Similarly, Coelho et al. (2003) measured HPC values

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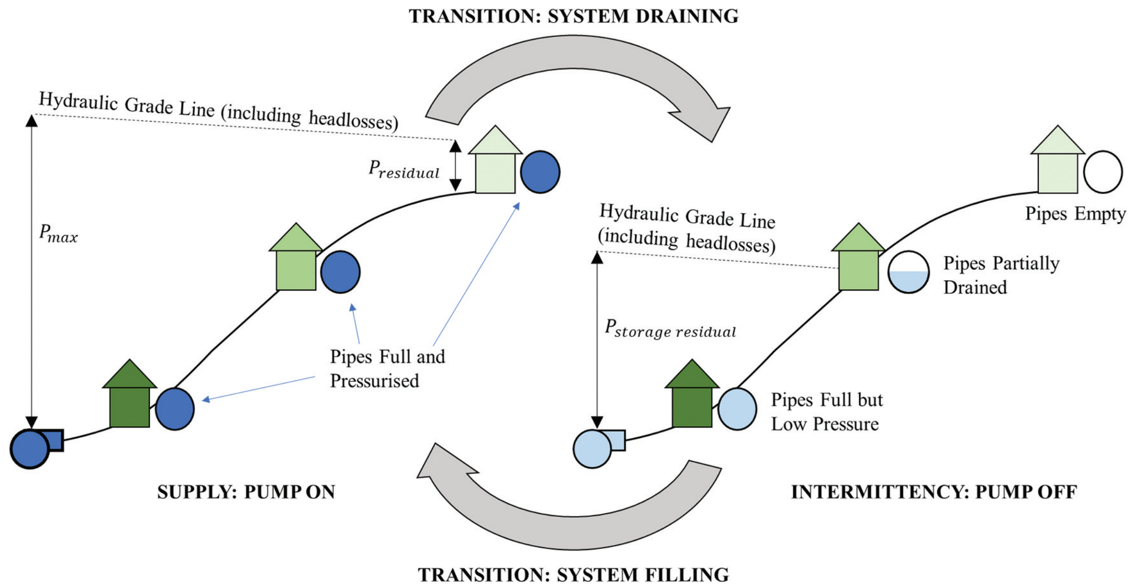

Figure 1. Schematic representation of IWS cycling between supply and non-supply periods. Pipeline cross-sections illustrate water volume and pressure for consumers at different ground elevations.

within an IWS network in Palestine. Within the first few minutes of flow restart they saw a substantial rise in HPC values, approximately six times higher than during the following supply. These studies indicate consistent mechanisms occurring within the first flush, which are vastly different from those taking place in continuous systems (Coelho et al. 2003). Understanding the short-term effects of the filling transition is, therefore, vital to effectively minimise the water quality and infrastructure impacts.

Highly variable demands can be placed on IWS systems as consumers rush to collect water (Andey and Kelkar 2007). These demands add dynamic complexity to the system, including inducing hydraulic transients – a rapid change in pressure produced when water is forced to change velocity abruptly. Transients are assumed to be generated during IWS filling transitions due to: 1) valve operations distributing supply through the network and filling private storage; 2) rapid fluctuation of Pressure Reduction Valves (PRVs) that are often used in pressure management areas; and 3) collision of water fronts at junctions (De Marchis et al., 2010b; Freni, De Marchis, and Napoli 2014). The frequency of transients has been established in continuous systems (Creasey and Garrow 2011; Starczewska, Collins, and Boxall 2015; Xing and Sela 2019) but documentation is lacking in their intermittent counterparts. Quantifying transients and other hydraulic effects generated by IWS requires high-speed temporal measurements taken during the filling transition.

Intermittency also results in the presence of air within the network as the pipelines drain during non-supply phases. In some instances, the air is gradually expelled through available outlets during the filling cycle; however, the low water pressures typical of many IWS areas (Strijdom, Speight, and Jacobs 2017) may be unable to push out the air, creating long-lasting air pockets. This effect could be compounded by local high points in the network configuration and flooded, non-operational, or poorly designed air relief valves. Many studies have analysed filling a pipeline containing air, from theoretical and experimental perspectives (Apollonio et al. 2016; Li, Zhu, and Huang 2018; Malekpour and Karney 2019; Zhou et al. 2011). In these studies, the pipeline is typically horizontal, fully drained, and leakage is limited or excluded, meaning there is reduced transferability of the results to the complexity of operational IWS systems.

The presence of trapped air in IWS can be harmful by reducing pipe capacity for flow and increasing scour at pipe walls, exacerbating supply inequalities and water quality deterioration (Kumpel and Nelson 2016), and increasing the risk of catastrophic bursts (Barr et al. 2020). Moreover, as the system refills, air pockets could be compressed then rapidly expelled, producing an 'air slam'. The resulting hydraulic transient is likely to be significant and contribute to damage to the network infrastructure (Batish 2003; Lieb, Rycroft, and Wilkening 2016). Christodoulou and Agathokleous (2012) showed that the implementation of IWS in a previously continuously operated network increased the number of observed breaks progressively by 30% to 70% per year.

Study aim

This study aims to investigate the hydraulic phenomena induced during the short-term filling period when water supply is initiated in intermittent distribution systems, to better understand which factors contribute to the severity of the phenomena. Three objectives are proposed: 1) to determine how the time taken to repressurise the distribution pipeline relates to different system elevations, 2) to measure the impact of various hydraulic characteristics on the filling process (system velocity, pressure, leakage, and valve operation time), and 3) to measure hydraulic behaviour exhibited in operational IWS networks. Controlled laboratory experiments conducted in the UK and field studies performed in operational networks across two provinces in South Africa are compared to systematically address the study objectives.

Methods

Experimental approach

The complex hydraulic behaviour induced during the filling process of intermittent systems was investigated in a systematic manner by measuring the flow and pressure responses at high frequencies. Laboratory experiments were designed that could reproduce hydraulic conditions without the spatial and temporal variability and uncertainty of an operational network. These experiments were performed in a representative full-scale pipeline facility at the University of Sheffield, UK, which provided reliability and repeatability over a range of conditions. Strict control and high-resolution flow and pressure monitoring equipment enabled laboratory simulation of pipe filling transitions from depressurised (but full) pipes simulating low elevation zones and partially full pipes with air, representing mid-elevation zones, to be studied in detail.

Experimental facility

The pipe test facility is 141.4 m in length consisting of 50 mm internal diameter medium-density polyethylene (MDPE) pipe. It is fed by a reservoir and configured as a positive-gradient recirculating system, approximate average slope 9 mm/m, see Figure 2. The downstream end of the pipeline was not submerged in the reservoir tank to enable an air release point. Artificial leakage was created by a pipeline bypass connected to the main pipeline via a T-junction 84.8 m from the reservoir, highlighted in blue in Figure 2. To control and measure leakage, a globe valve and volumetric flow meter were installed on this bypass.

System flow rate and pressure were fully controlled by a variable speed pump and downstream globe valve; measured with a Flow Systems Model 910E Electronic Flow Meter, accuracy ± 0.01 l/s, and four GEMS 2000 series pressure sensors, accuracy ± 0.16 m pressure head, recording at 2000 Hz. The pressure sensors were placed 2.4 m, 81.9 m, 83.0 m and 101.1 m from the reservoir, respectively, and are denoted PA-PD in the schematic in Figure 2. During the experiments, pressure data were collected and examined at all four locations; however, for clarity, only results from PA and PD are presented here. As these sensors give the furthest upstream and downstream measurements, results from PB and PC fall between PA and PD. System flow rate data was post-processed to produce a bulk system velocity by dividing by the internal pipe area and, to reduce noise from electrical interference, a Butterworth filter was applied. In line with the expected average field conditions in South Africa, air temperature in the laboratory ranged between 23.5°C and 25.5°C.

System characteristics

Intermittent systems transition from a stationary to a flowing pressurised state. In these experiments, four supply parameters (post-filling) were varied individually to isolate and study their relative impact on the filling process – system velocity, leakage ratio of leakage flow rate to system flow rate, system pressure head (measured at approximate mid-pipe location PC), and valve operation time. These parameters are known to impact the dynamic responses of continuous water supply systems; for example, rapid valve operation times may induce transients, where leakage may act as an in-built air relief network. Points of leakage and other sources of non-revenue water loss in operational networks will never be fully known yet are often assumed as ubiquitous. In these experiments, those losses were mimicked as a single point-source so that a leakage ratio could be determined accurately.

For each parameter, a range of values were then individually tested, keeping all other parameters constant at their baseline values, with five experimental repeats taken for each condition. These values are presented in Table 1 and are similar to the operational parameters of the IWS systems in South Africa and field observations where variation of flow over time was recorded. The same post-filling conditions were tested for both low and mid-elevations.

Filling the system

To simulate filling the system, a drained condition was first established. To create low elevation conditions, without air in the pipeline, the system was filled with water but depressurised with zero flow. To create mid-elevation conditions with air in the pipes, the system was partially emptied by draining through the leakage bypass to waste. After achieving the required drained condition, the upstream butterfly valve (Figure 2b) was manually opened to transition the system into pressurised flow at the designated conditions.

A bespoke timing device was constructed that enabled the valve operation time between closed and open positions to be controlled and measured reliably. This device consisted of

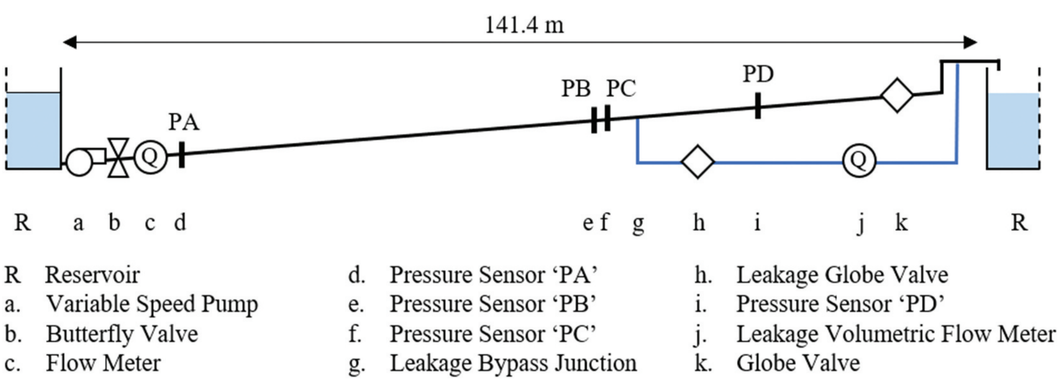

Figure 2. Laboratory schematic with key features, including the leakage bypass highlighted in blue. Not drawn to scale.

Table 1. Testing conditions for low and mid-elevation experiments performed. The average and standard deviation of results across repeats is given, with the baseline values highlighted.

	Velocity (m/s)	Leakage Ratio	Pressure Head (m)	Valve Operation Time (s)
Condition 1	0.25 ± 0.00	0.10 ± 0.00	5.21 ± 0.09	1.00 ± 0.21
Condition 2	0.50 ± 0.00	0.20 ± 0.00	10.28 ± 0.32	2.98 ± 0.23
Condition 3	1.00 ± 0.01	0.30 ± 0.00	15.17 ± 0.01	5.01 ± 0.20
Condition 4	1.51 ± 0.01	0.40 ± 0.00	20.02 ± 0.08	10.03 ± 0.19
Condition 5	1.99 ± 0.01	0.50 ± 0.00	25.25 ± 0.08	15.15 ± 0.21

a small button magnet attached to the valve lever and Hall sensors closely positioned above the valve, calibrated to indicate the position of the lever and consequently the valve. Valve operation times were accepted as valid within 0.5 s of the desired time. In this work, the time taken to transition from intermittent (depressurised) to the supply conditions (pressurised) was calculated from the start of the butterfly valve operation to the time when the pressure head stabilised within three standard deviations of its supply value, referred to as the 'transition time'.

Field data

To observe the short-term hydraulic behaviour exhibited during the filling cycle in operational IWS systems, representative sites in South Africa were selected where drinking water has been supplied intermittently for a number of years (Loubser, Chimbanga, and Jacobs 2021). A total of 11 monitoring sites were chosen to record flow measurements: three sites across the towns of Matsulu and Kanyamazane in Mpumalanga Province (north-eastern South Africa) and eight sites in the town of Makhanda in Eastern Cape Province (southern South Africa).

Matsulu and Kanyamazane sites

The residential towns of Matsulu and Kanyamazane comprise formal and informal areas where the levels of water and sanitation infrastructure vary (Bender and Gibson 2010). The populations of Matsulu and Kanyamazane are approximately 66,000 and 274,000, respectively, and the towns experience a subtropical climate with very warm humid summers and cool dry winters. Water is supplied intermittently twice a day between 05:30–09:00 and 16:00–17:00 in some supply zones in Matsulu (6.5 hours total), and between 04:00–10:00 and 16:30–21:30 in some supply zones in Kanyamazane (11 hours total).

Point Orange 3 G pulse-volume loggers were installed on water meters at three different sites, and flow data was recorded between 19 July and 11 October 2019. Each logger recorded the volumetric flow rate measured at a temporal frequency of 5 min, i.e. the number of flow pulses per five-minute period. Pulse volumes were 1 m^3 for Sites 1 and 3 and 0.1 m^3 for Site 2. The data was uploaded via the cellular network to an online remote monitoring platform in almost real time. Pipe diameters for each site were known, enabling conversion of the measured flow rate into calculated velocity. Site 1 was a reservoir site supplying a large District Metering Area (DMA) in Matsulu. Site 2 supplies a small isolated DMA in Kanyamazane. Site 3 supplies a larger DMA in Kanyamazane, which includes the Site 2 DMA.

Makhanda sites

Makhanda is a residential town comprising formal and informal areas, with a total population of 70,000 and a continental climate with warm dry summers and cold wet winters. Bulk flow rate was recorded on Sensus Meistream water meters at eight different sites (Sites 4–11) between 9 November 2019 and 31 March 2020. The times of water supply varied greatly across the eight sites, which included an army base, a hospital, and residential communities. Each water meter was recorded at a temporal frequency of 15 minutes, except for Site 5 which recorded at 30-min intervals. Similar to previous sites, the data was uploaded via the cellular network to an online remote monitoring platform in almost real time, and pipe diameters were known to enable velocity conversions.

Experimental results

Transition time

In the low elevation experiments where the pipes remained full of water before filling, transition times ranged from 1.8 s to 15.4 s (average 6.3 s, n = 100) across all pressure transducers. In the mid-elevation experiments, where the pipes were partially drained and air entered the system prior to filling, transition times ranged from 27.6 s to 51.6 s (average 36.8 s, n = 95). These values demonstrate that partially drained pipes with air in the system (mid-elevation) take considerably longer to repressurise, as much as 18.8 times longer than the low elevation cases. This contrast is demonstrated in Figure 3, which presents pressure data during a 1 s valve operation time experiment.

Figure 4 shows that in low elevation experiments, valve operation time had the greatest influence on transition time, while the other factors had little influence. Although velocity and pressure appear to be lacking a strong relationship to transition time, the Pearson coefficients indicate a potential relationship (Pearson coefficient 0.77 and −0.79, respectively). However, these relationships are not as prominent as valve operation time.

Figure 4 also demonstrates that for mid-elevation experiments, velocity and pressure influenced the transition times observed to a greater extent than for low elevation experiments. Strong inverse relationships can be seen at all pressure transducers (Pearson coefficients −0.97 to −1.00); the higher the system velocities and pressures, the shorter the transition time. Valve operation time correlates positively with transition time at all pressure sensors (Pearson coefficients 0.91 to 0.94). However, in contrast to the low elevation experiments, valve operation time had less of an impact than velocity and pressure. Leakage exhibits a weakly positive relationship with transition time at both elevations.

High velocities and pressures

In the majority of low elevation experiments, drained conditions transitioned smoothly to pressurised flow conditions without generating significant short-term spikes in velocity or pressure. Velocity and pressure surpassed the supply value by less than 5% on average (n = 95). The only exceptions were transitions to the lowest velocity investigated of 0.25 m/s

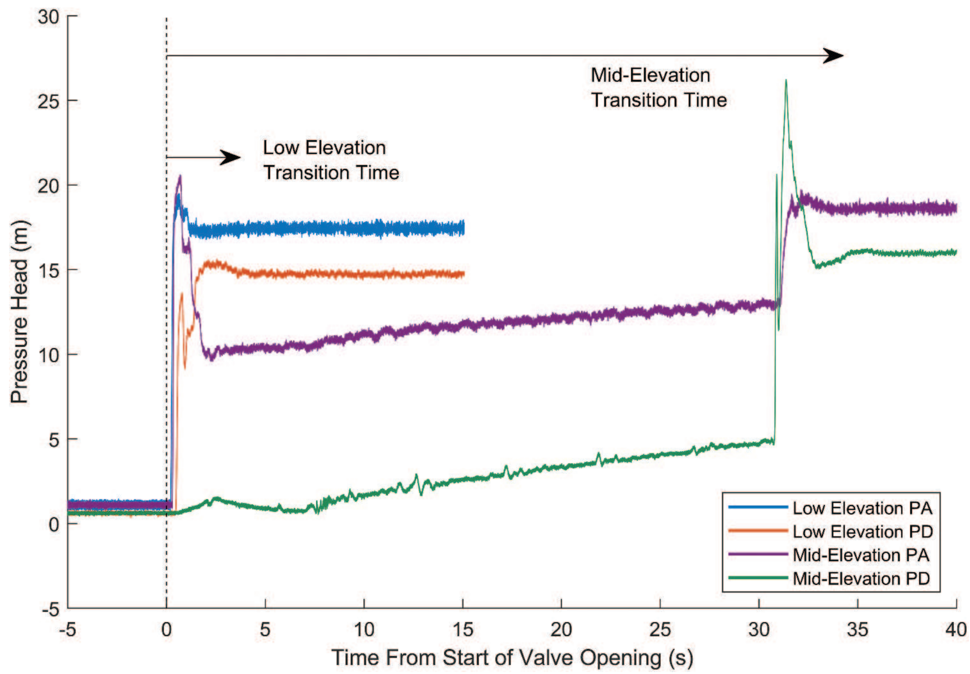

Figure 3. Comparison of low elevation and mid-elevation transitions from intermittent conditions with 1 s valve operation time. The transition times range from 2.4 s (PA) to 5.0 s (PD) for the low elevation transition and 34.1 s (PA) to 35.6 s (PD) for the mid-elevation transition.

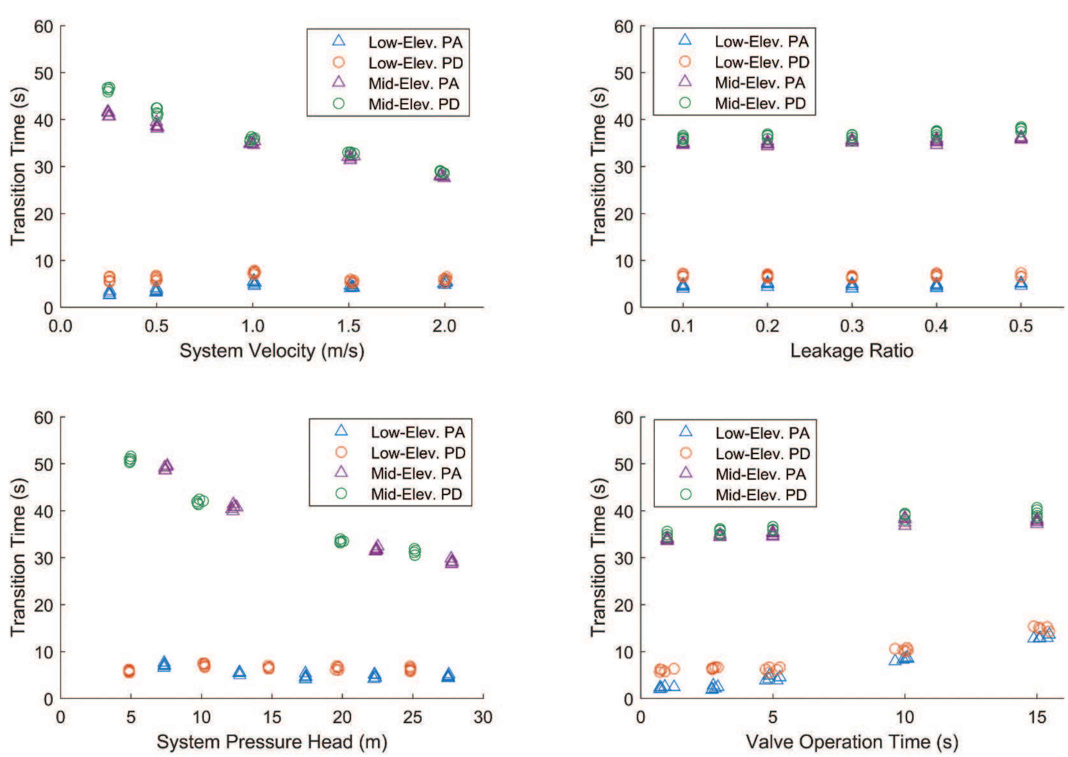

Figure 4. Transition times for low elevation experiments, where pipes are depressurised without air in the system, and mid-elevation experiments where pipes are partially drained, introducing air into the system during intermittency.

(n = 5). In these cases, the system experienced maximum velocities and pressure heads of 0.03 m/s (11.5%) and 2.12 m (14.2%) above the supply conditions, respectively.

In mid-elevation experiments, the transition time was observed to split into two temporal phases, as indicated in Figure 6. During the first phase, the air was being pushed through the system by the water front whilst the pipeline was being refilled, causing higher flow velocities. When any entrapped air was compressed at the downstream globe valve in the second phase, higher pressures were observed as dynamic pressure spiked. Figure 6 presents the mid-elevation equivalent transition to 0.25 m/s. In this transition, the partially drained pipes and air in the system caused maximum velocity and pressure heads of 1.85 m/s (844.7%) and 28.86 m (270.9%) above the supply conditions, respectively. These spikes represent dynamic hydraulic behaviour of approximately eight and three times the supply conditions, respectively.

The example transition presented in Figure 5 was considered the most severe, yet this behaviour was induced during all mid-elevation experiments. Figure 6 shows how different system parameters impact the high velocities and pressures induced, expressed as the maximum velocity or pressure value induced during transition relative to the supply conditions, i.e. how many times greater the hydraulic behaviour became during the transition. This figure shows that the velocity is comparatively more impacted than the pressure by the presence of air during transition. Figure 6 also demonstrates strong relationships between system velocities and pressures; low system velocities and high system pressures induce the greatest dynamic conditions relative to supply conditions. Similar to transition time, leakage produces weak positive relationships with maximum velocity and pressure ratios, but these relationships are not as strong as for system velocity and pressure. Valve operation time does not appear to have an impact above experimental scatter.

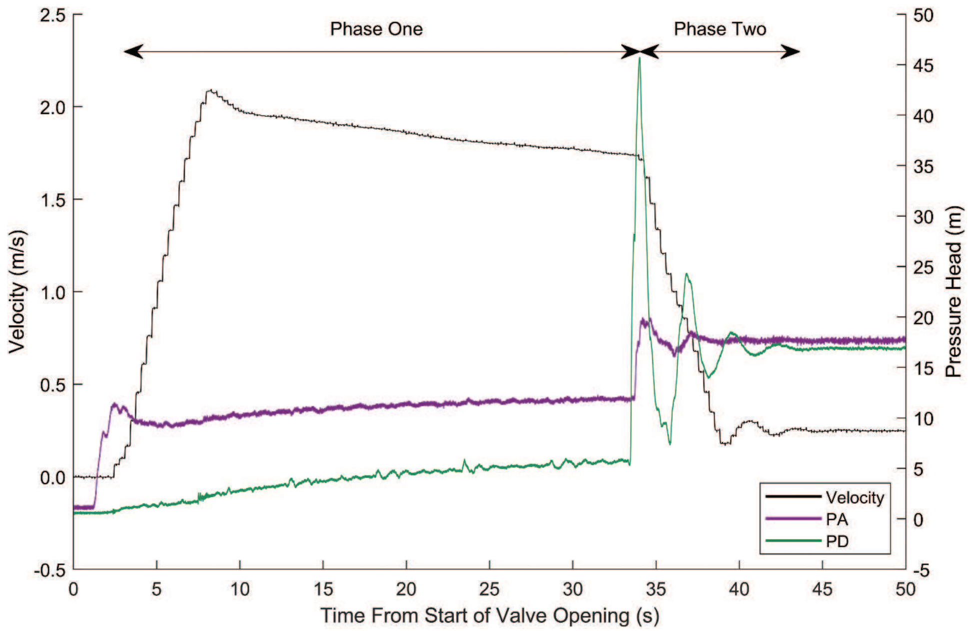

Figure 5. Example mid-elevation transition from non-supply conditions to 0.25 m/s.

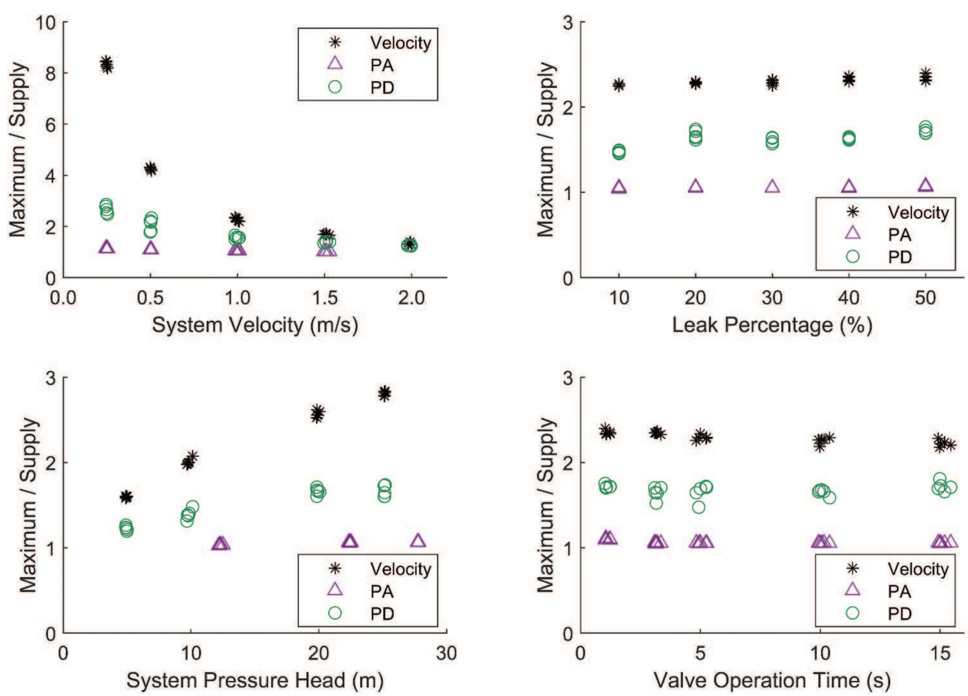

Figure 6. Induced maximum velocity and pressure relative to the supply conditions for mid-elevation experiments.

Field results

Bulk flow rates were recorded over the testing periods described at all 11 sites. Each site received unique flow rates and durations of water supply, thus experienced intermittency in different ways. For example, Site 3 in Kanyamazane regularly received water twice a day, peaking at 70.0 l/s (3.96 m/s), where Site 10 in Makhanda experienced several shut off periods including 20 days without water, and flow rate peaked at 160.4 l/s (5.11 m/s).

Figure 7 presents the flow rate data recorded at the 11 sites, converted into bulk velocity, from a two-week period: in Matsulu and Kanyamazane (Sites 1–3) between the 15th and 29th of September 2019 and in Makhanda (Sites 4–11) between 23 February and 8 March 2020. These two-week periods were selected as hydraulically representative of the data collection periods and demonstrate changing hydraulic patterns across hours and days.

Figure 7 shows that at several of the sites (Sites 2, 4 and 7 through 11), when supply is instigated, the velocity rapidly increased to a value much higher than the following supply (circled in red). These dynamic spikes in velocity were observed to either regularly occur, such as at Sites 2 and 11, or occur at certain times but not others, such as Sites 4 and 9. The phenomenon does not correlate with the type of flow meter deployed. To better understand the impact elevation has on these flow spikes, the locations of the flow meters within the same Makhanda supply zone (Sites 4–11) were plotted on a topographic map, see Figure 8. Dynamic spikes in velocity were recorded at sites with higher elevations (>600 m) but were not recorded at sites with lower elevations (<600 m).

Discussion

This study investigated the short-term filling period when water supply is initiated in intermittent distribution systems. This transition to supply creates instabilities and potentially influences supply equality within a distribution system.; therefore, it would be helpful to better understand which factors contribute to this phenomenon. Similar behaviour was observed in the laboratory experiments, and field studies performed will be discussed across three key behaviours – transition time, dynamic velocities and transients induced.

Transition time

Transition time in this study was taken as the time from the start of filling process to when the system was in its stabilised supply state. This is conceptually meaningful for intermittency as the time taken for consumers to receive supply can indicate potential inequalities and consumer dissatisfaction. Transition time was robustly quantified in the laboratory to enable repeatable and reliable measurements, facilitated by high-speed instrumentation. Whilst the absolute experimental values measured were relatively short due to the small scale of the pipeline facility, key insights were gained from the comparison between the simulated elevations. Without monitoring at the source and

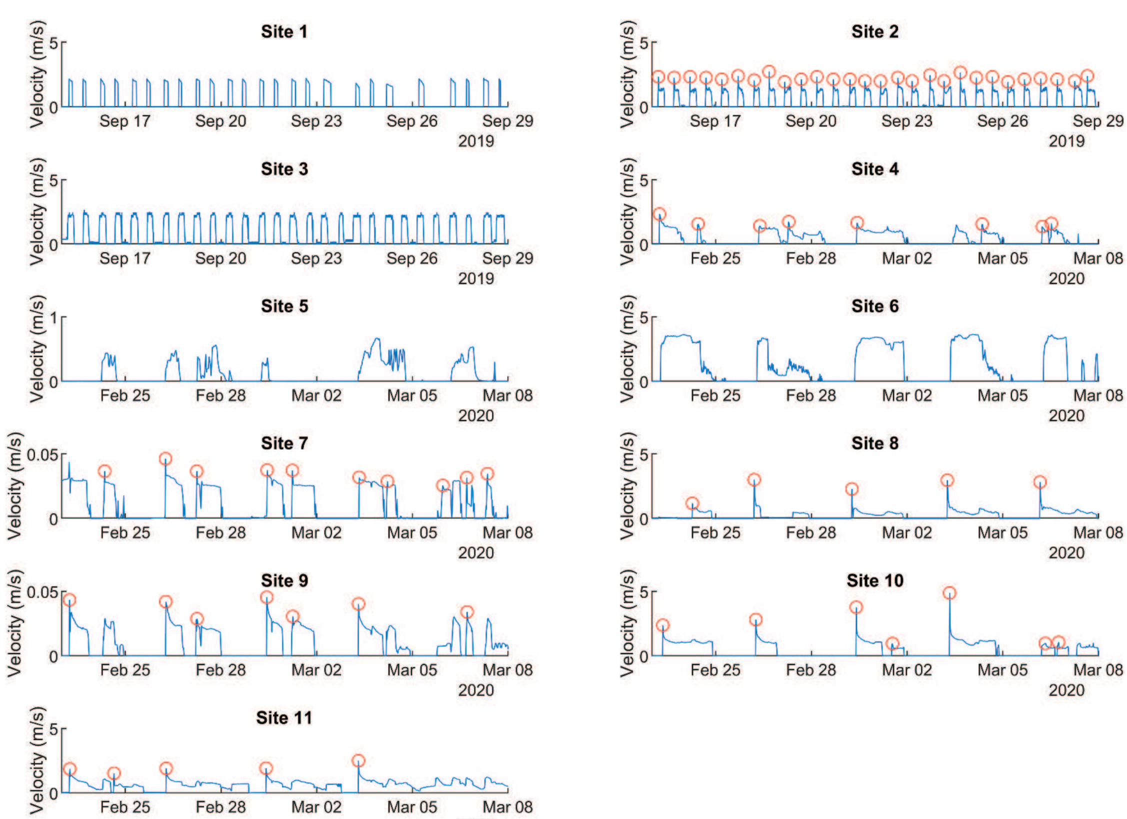

Figure 7. Bulk velocity data collected from Sites 1–3 (Matsulu and Kanyamazane) between the 15th and 29th of September 2019, and from Sites 4–11 (Makhanda) between 23 February and 8 March 2020. Dynamic spikes in velocity at the beginning of the filling transition are circled in red.

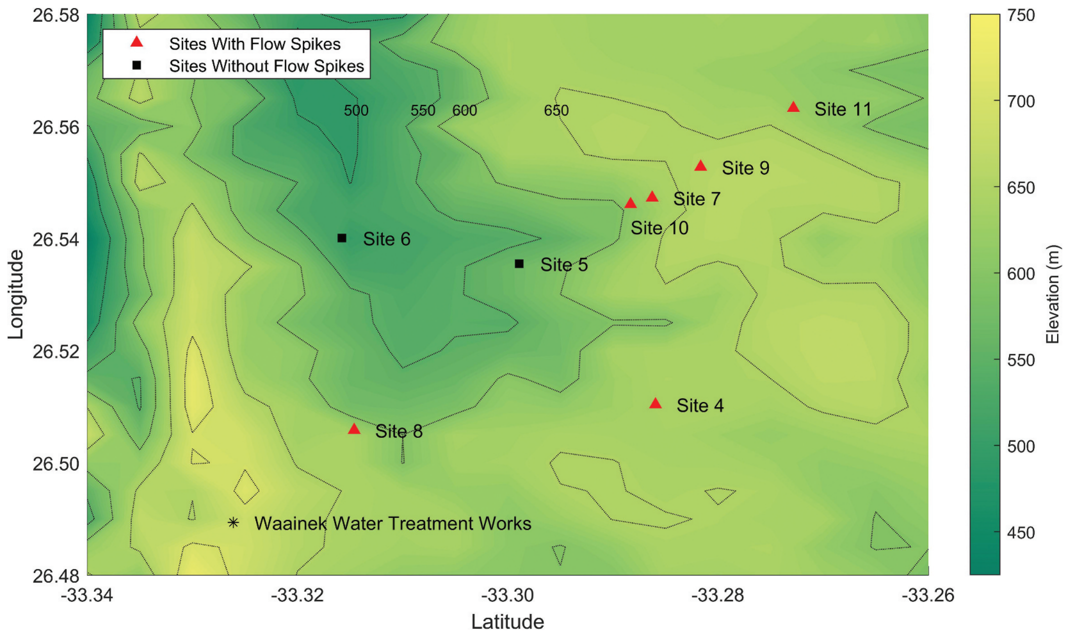

Figure 8. Topographic map of the Makhanda network indicating locations where flow meters did (Sites 4, 7 through 11) and did not (Sites 5–6) experience spikes in velocity during the filling transition.

key locations around the distribution system, transition time can be difficult to predict in IWS operational systems due to a lack of spatio-temporal data, variable demand, and complex network configurations including loops, multiple supply sources and lack of secure boundary valves.

Directly comparing equivalent transitions between simulated elevations in the laboratory showed that transition time was significantly impacted when air was in the system. Depending on whether the pipe is initially drained (mid-elevation zone) or undrained (low elevation zone), the system took between 3 and 19 times longer to fill and repressurise. It follows that consumers in high elevation zones, where the pipelines drain completely, would experience even further delay in their supply. The findings presented in this paper agree with previous examination of the Palermo network in southern Italy (Sicily) by De Marchis et al. (2010b) and Freni, De Marchis, and Napoli (2014). The authors observed that the time taken for the filling process differed between the points monitored; some pipes near the inlet were filled within 15 minutes, yet others at the end of the network required over an hour to fill and longer to repressurise. Campisano, Gullotta, and Modica (2018) modelled transition time (denoted in their paper by tp_{min}) across the Ragalna network (also in Sicily). They remarked that the values calculated, range 5 to 105 minutes, were significantly affected by node elevation as well as the distance from the reservoir. Using the data provided in their paper, a positive relationship can be seen between elevation and transition time (Pearson coefficient 0.64).

Velocity behaviour during filling

Transitions measured at high resolution in the laboratory demonstrated periods of accelerated flow during filling in mid-elevation zones. Velocity quickly increased as water pushed the air through the pipeline, causing the velocity to temporarily spike up to eight times beyond the stabilised supply conditions, see Figure 5. This has implications for water quality, as particles and biofilms accumulating during the non-supply phase are likely to be mobilised by the unstable and substantial shear of the velocity spikes, resulting in the quality degradation which has been observed elsewhere (Coelho et al. 2003; Tokajian and Hashwa 2003).

The dynamic velocity behaviour quantified at mid-elevation zones was expected based on existing literature (Freni, De Marchis, and Napoli 2014; Li, Zhu, and Huang 2018; Malekpour and Karney 2019); however, this work enabled comparison between different system conditions that might affect the observed behaviour. The peak velocity induced was more significantly impacted by slow system velocities than any other system parameter. An increase in low system velocitiesfor example, by increasing pumping rate during the filling time, could drastically reduce the significant maximum velocity generated.

Data from field measurements also exhibited dynamic spikes in velocity, validating the laboratory experiments. The field work has clearly demonstrated that this velocity behaviour occurs across multiple sites in complex operational IWS networks. The peak velocity in some locations differed temporally between supply periods, either changing in magnitude or occurring irregularly, and does not appear to correlate with system velocity in these cases given that these spikes occur across a range of velocities. This result reflects the high variability of IWS in complex operational networks compared to laboratory conditions. The Makhanda sites do, however, support the findings of a correlation between dynamic velocity spikes and elevation; spikes were recorded at sites with higher elevations but were not recorded at sites with lower elevations. Further research is needed to determine if this correlation is valid in other systems and to demonstrate that this is a causal relationship as suggested by the laboratory experiments.

Transients in IWS filling

Pressure measured at high-temporal resolution in the laboratory clearly evidenced transients caused by air in the system during the filling of mid-elevation zones. The pressure rapidly peaked at values greater than the supply conditions and oscillated before stabilising. This finding aligns with previous modelling and experimental studies (Apollonio et al. 2016; De Marchis et al., 2010b; Li, Zhu, and Huang 2018; Malekpour and Karney 2019). The transients induced in this study were particularly substantial when the system was transitioning to low supply velocity (such as in Figure 5), high pressure and high leakage. It was thought that leakage may act as an air release mechanism, i.e. higher leakage ratios would reduce the maximum pressure induced. However, this did not occur, most likely due to the single mid-way point means of creating leakage utilised in the laboratory. Future research should aim to further understand the role of leakage in operational networks. It is important to note that low pressures were induced as well as significantly high pressures. Under certain supply conditions, such as low velocity and low pressure, it may be possible for filling transients to drop to negative pressures. This could establish a means for contaminants to intrude into the network, posing a water quality risk to consumers (Besner et al. 2010, 2007). Transients induced during filling have been linked to damaging network infrastructure (Batish 2003; Lieb, Rycroft, and Wilkening 2016). Therefore, capturing transients at high spatial and temporal resolution in operational networks should explore these behaviours in greater detail.

Practical implications

The findings presented here emphasise the importance of understanding that the filling transition varies in IWS across elevations. Only when this transition process is completed will the network function effectively and in line with its intended service. Mid- and high-elevation zones are particularly susceptible to exacerbating the negative consequences of IWS due to the presence of air in the pipeline. The elevation across a network cannot be readily altered; however, the findings from this study emphasise the need for well-maintained air relief valves in strategic locations. Utilities should balance their operations by considering that as pressures and velocities increase, particularly at mid-elevations in the network, transition time will decrease but the risk of generating harmful transients, which could lead to pipe bursts, is increased. Recognising and quantifying the filling phenomenon as a function of the spatial changes across the network is vital to effectively minimise potential negative impacts for consumers.

Conclusions

The experimental and field work presented in this paper provide rigorous evidence of the hydraulic phenomena induced during IWS filling transitions. The results demonstrate that elevation plays a crucial role in how the network responds. In mid- and high-elevation zones where the system can partially or fully drain, the presence of air can cause longer transition times and undesirable dynamic hydraulic behaviour. The velocities and transients induced may be substantial under certain system conditions, and consequently contribute to the degradation of water quality and accelerated infrastructure deterioration commonly found in IWS. Importantly, this response is not exhibited in low elevation zones where the system remains full but depressurised during the non-supply period, indicating that locations with different elevations require different handling of the filling process. Elevation is therefore a critical parameter, leading to unequitable and unreliable distribution of supply as consumers in low elevation locations within a zone may be able to access the supply prior to those in higher elevations, and should be considered more prominently in studies of IWS in the future.

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