Experimental Quantification of Contaminant Ingress into a Buried Leaking Pipe during Transient Events

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Abstract: It has been hypothesized that negative pressures caused by transients within water distribution systems may result in ingress of contaminated groundwater through leaks and hence pose a risk to public health. This paper presents results of contaminant ingress experiments from a novel laboratory facility at The University of Sheffield. An engineered leak surrounded by porous media was subjected to pressure transients resulting from the rapid closure of an upstream valve. It has been shown that a pollutant originating externally was drawn in and transported to the end of the pipe loop. This paper thus presents the first fully representative results proving the occurrence and hence, risk to potable water quality of contaminant ingress. **DOI: 10.1061/(ASCE)HY.1943-7900.0001040.**

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Introduction

Water suppliers are responsible for continuously supplying clean and safe drinking water fundamental to society and public health and well being. Potential impacts of failing to adhere to this obligation include economic repercussions, but significantly, the risk posed to public health. Losses from leaks and bursts, are a well-documented issue within water distribution systems (WDS), which impact both customers and suppliers. In England and Wales the average reported levels of leakage for 2009–2010 were estimated at 131 L per property (Ofwat 2010). Phenomena in WDS that are less well understood are pressure transients, which can result in negative pressures (Gullick et al. 2004). The coexistence of negative pressures and leaks in distribution systems means there is a risk of contaminant ingress. Such ingress could result in possible incidents of water quality deterioration and a failure to meet prescribed standards (Lechevallier et al. 2003). A U.K. study (Hunter et al. 2005) into self-reported diarrhea in a control group found a strong association between reported cases of diarrhea and low pressures at consumer taps. The investigation provided a feasible assertion that the presence of low pressures within distribution systems is associated with public health, likely due to contamination events.

While it is generally accepted that negative pressures can result in ingress from surrounding groundwater, there is a perception that, due to the short duration, oscillating nature of pressures transients, only water that has been expelled from the distribution system will reenter the pipe or that if contaminant is intruded it will be expelled on the next positive pressure cycle. In order to ascertain if a contaminant originating externally to a pressurized pipeline can be intruded and remain within the pipeline, thus posing a risk to water quality, an innovative physical investigation was designed and implemented. The work presented here aims to explore via fully representative, but extreme, physical experiments whether a contaminant originating externally to a pressurized pipeline can be intruded and remain within the pipeline.

Contaminant Ingress

Lindley and Buchberger (2002) define the three requirements that must coexist for contaminant ingress to take place within water distribution systems; the existence of a contaminant source external to the distribution pipe, a pathway providing a route into the system, and a driving force.

Contaminant Source

An American Water Works Association Research Foundation sponsored study (Kirmeyer et al. 2001) identified and quantified pathogens occurring in the ground surrounding mains water pipes. Within the investigation, researchers collected soil and water samples external to existing water pipelines from six different U.S. states and tested for a range of microbial indicators and viruses. Results of the study showed that 50% of the soil samples tested contained fecal coliforms in addition to the identification of other bacterium and viruses within the samples. Whereas isolated nonreplenishable contamination events create a potential environment for contaminant ingress to occur, continuously renewed contamination sources such as a leaking sewer above a failed mains distribution pipe, as presented by Karim et al. (2003), increase the likelihood of the occurrence of this phenomenon. The risk posed by contaminants, in both solute and particulate form, is further magnified due to the widespread existence of biofilms within water distribution systems which may provide shelter and a platform for such pathogenic bacteria and viruses to multiply (Eboigbodin et al. 2008). Contaminant ingress may therefore result in direct exposure to customers and/or less direct risks such as seeding of biofilms.

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Pathway

Pathways through which external contaminant may enter the distribution system exist in various forms. Kirmeyer et al. (2001) ranked the potential routes of entry (pathways) into the distribution system based on the associated risk level. Water treatment breakthrough and water main breaks were among the highest risk pathways, with new main installation and purposeful contamination events ranked as low risk. Failures in the integrity of distribution pipes resulting in a system leak are therefore classed as high risk routes of entry. Examples of typical leak types in water distribution system pipes are pin holes, cracks, corrosion clusters, and joint/connection failures (Clayton and van Zyl 2007). Another potential pathway particularly relevant to low pressure and transient events is through air valves when the chamber in which they are located becomes flooded (Ebacher et al. 2012).

Driving Force

Fluids will always flow from high to low pressures, thus when the pressure within a pipe drops below the local groundwater pressure, a potential driving force for contaminant ingress exists. Longer term depressurization due to maintenance/repair work may therefore result in the formation of such conditions leading to steady-state intrusion (Collins et al. 2012b). The differential pressures required for intrusion into WDS can also result from the presence of negative pressure transients within a system.

Water industry data regarding pressures in WDS is typically recorded at 15 min intervals. This is a good measure of daily trends and patterns, but also provides an artificially smooth representation of the system characteristics leading to an assumption that the pressures are approximately steady. Observations from field studies reported on the occurrence of pressure waves, in a series of locations in two separate systems, recorded using high speed pressure data loggers confirming the occurrence of transients within operational systems (Kirmeyer et al. 2001). A qualitative comparison of the influence data sampling rates have on the perceived steadiness of system pressures was presented by Fox et al. (2013) with high frequency data from live distribution systems demonstrating the complex and dynamic nature of the hydraulic conditions within WDS. As part of a larger data logging exercise, Starczewska et al. (2013) presented two case studies highlighting the occurrence of pressure transients within complex distribution networks. The researchers identified the source of the transients as the pump feeding the region, with the transient data aligning with the pump switching (on and off).

Dynamic pressure conditions occur due to a rapid change in the water velocity, which may be a result of operational changes including valve closures, system depressurization for maintenance work and changes in demand, or due to asset failures such as pump trips and bursts (Collins et al. 2012b). These extreme changes of flow within the system incur the risk of oscillating high and low pressure transients, where the lowest pressures may be negative (Brunone and Ferrante 2004; Gullick et al. 2004). Low and negative pressures are most likely to occur downstream from an imposed obstruction (e.g., valve closure) where the momentum of a flowing column of water may result in the formation of low or negative pressures bounded at water vapor pressure (Ghidaoui et al. 2005). The greater the initial velocity of the body of fluid the more extreme the negative pressure wave formed following a sudden change in flow conditions. Along with the previously discussed risk of contaminant ingress and the subsequent water quality issues, there is also a recognized threat to the structural integrity of the system from extreme transient pressures.

Quantifying the Risk of Ingress

Researchers have adopted different approaches to quantifying the risk of contaminant ingress into water distribution systems. Statistical analysis techniques have been used (Sadiq et al. 2006; Deng et al. 2011) as well as field (Ebacher et al. 2012) and experimental studies aimed at improving the understanding of the mechanism of contaminant ingress in order to better define the associated risk. At its simplest the physical risk of contaminant intrusion, according to reasonable engineering judgment, may be considered greatest when the external contaminant is above or directly in the line of the leak jet (providing the shortest pathway along a flow route into the orifice).

Experimental work to quantify the intrusion magnitude through leak orifices under steady state (López-Jiménez and Mora-Rodríguez 2010; Collins et al. 2012b) and dynamic pressure conditions (Boyd et al. 2004; Collins et al. 2011a; Mora-Rodríguez et al. 2011) provide a greater understanding to this phenomena, in particular the influence of porous media surrounding a failed pipe. Collins and Boxall (2013) derived and fully validated an analytical model, improving on the standard orifice equation, to define the flow into a system through a failure aperture in a pipe buried in porous media subject to steady-state conditions. Furthermore, work to quantify the pressure-dependent behavior of different failure types in pressurized distribution mains (Fox et al. 2012; van Zyl and Cassa 2014) and the continual evolution in the reliability and accuracy of transient modeling techniques provide a platform to better understand and mitigate the risk of ingress of contaminants within WDS.

The experimental research presented here aims to build upon and develop the understanding of the physical process of contaminant intrusion in order to better define the threat posed to water quality in real networks. Ultimately this paper seeks to prove or otherwise if a contaminant originating externally to a pressurized pipe can be intruded into, remain within and be transported.

Experimental Methodology

A large-scale and fully representative laboratory facility has been constructed at the University of Sheffield to investigate pressure transients, leakage and particularly the various factors associated with the potential for contaminant ingress into distribution systems. The general features of this facility are described in the laboratory facility section, with the specific configuration for determining whether external contaminants can be ingressed into the pipe, detailed in the ingress configuration section.

Laboratory Facility

The contaminant ingress in distribution systems laboratory facility is a recirculating pipe system; a schematic of the system is shown in Fig. 1. The 141 m length facility is constructed from 63 mm diameter (nominal internal diameter of 50 mm, SDR 11) medium density polyethylene (MDPE) pipe produced by GPS PE Systems (Huntingdon). The system consists of seven loops that are supported and restrained by 16 stands mounted on footings integral to the concrete slab floor. The system has an oval plan form with the pipe always rising to facilitate air removal. Water is fed into the system from a single upstream reservoir (holding tank) and returns to this same tank, with a maximum capacity of 1,080 L, by a 3.5 kW Wilo MVIE variable speed pump (WILO, Staffordshire, U.K.) (range 1,000–3,380 rpm). Quarter turn butterfly valves, located at items *c*, *f*, and *j* in Fig. 1, allow for the isolation of different sections of the pipe loop including the test box section (*h*). The

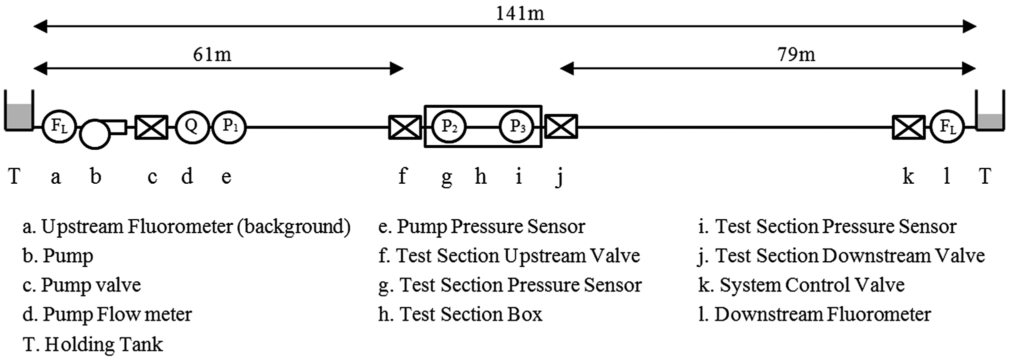


Fig. 1. Schematic of the contaminant ingress into distribution systems facility at the University of Sheffield

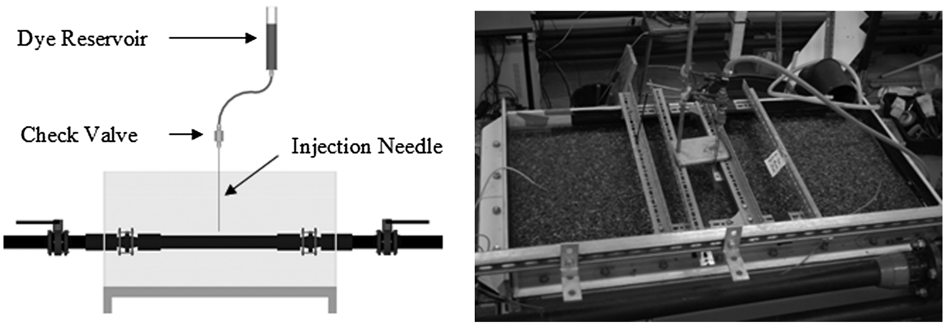
flow conditions (pressure head and system flow rate) are controlled by the pump speed and a single downstream globe control valve (*k*). Gems 2200 series pressure sensors (Gems Sensors, Basingstoke, England) located at *e*, *g*, and *i* were used to record the pressure heads whereas the system flow rate was measured using an Arkon Flow System Mag-900 electromagnetic flow meter (Arkon Flow Systems, Brno, Czech Republic) located immediately downstream from the pump (*d*). Data was logged at 300 Hz using National Instruments' *LabVIEW* software (National Instruments Corporation, Berkshire, U.K.) and a measurement computing PMD1820 data acquisition device (DAQ) (Measurement Computing Corporation, Norton, Massachusetts).

Ingress Configuration

A test section box (total volume of 458 L), item *h* in Fig. 1, housed a 0.8 m length test section pipe containing a single engineered 5 mm diameter circular orifice facing horizontally. An overflow weir at the top of the box (0.45 m above the pipe center line) provided a means to maintain a constant water level during testing. The mean flow rate through the leak was obtained by collecting the water from the weir in an isolated collection tank and measuring the volume increase over time. The test section was manufactured from the same specification pipe as the main loop, with flanges to secure the section 61 m downstream from the holding tank. The test section was buried under 0.45 m depth of mixed-grade pea gravel (approximately 5–12 mm diameter) consistent with the British Standard for backfill material for plastic pipework [British Standards Institution (BSI) 1973], with the leak orientated horizontally to minimize the movement of the gravel surrounding the pipe. Nonpreferential boundary conditions were ensured through the addition of a green roof drainage lining for the box. A fine metallic mesh (wire diameter 0.5 mm, square grid at 2 mm centers) was affixed over the leak to ensure that no gravel entered the system during testing.

Rhodamine WT fluorescent dye, at a concentration of 1×10^{-3} L/L, was used as a pseudo pollutant. An injection system was used to create a discrete cloud of pollutant at selected locations around the leak. Fig. 2 shows the setup of the injection system which consisted of a dye reservoir, connected via a 6 mm internal diameter flexible tube to a check valve, to prevent backflow, and finally to a 1 mm hollow steel needle affixed to a structural support frame. The open end of the needle was positioned in the gravel at different locations relative to the leak, the location of the needle tip is defined using a Cartesian coordinate system. The x, y, and z axes refer to the horizontal distance parallel to the pipe, the horizontal distance perpendicular to the pipe and the vertical distance perpendicular to the pipe, respectively, with (0,0,0) representing the center of the leak. The structural support frame provided an accurate method for positioning the injection needle in preparation of each test and also ensured the needle was secured in place during the repacking of the gravel. A quarter-turn valve below the reservoir enabled a controllable and repeatable volume of dye to be injected for each test.

In order to quantify the volume of any pollutant ingressed into and net transported to the end of the system (rather than being extruded on the next positive cycle of the transient), a Turner Designs' Cyclops 7 fluorometer (Turner Designs, Sunnyvale, California) was located 71 m downstream of the test section (item *l* in Fig. 1) and the output recorded using the PM1820 DAQ device also at 300 Hz. The fluorometer was located at the outlet, downstream of the control valve at a sufficient distance from the leak to ensure



(a) (b)

Fig. 2. (a) Cross section diagram of injection system and test section box; (b) experimental setup in the contaminant ingress in distribution system facility

that any rhodamine WT was cross-sectionally well mixed. A second fluorometer (item *a* in Fig. 1) was located upstream of the test section to record any variations in background concentration of rhodamine WT due to the recirculatory nature of the system. The chemical stability of the dye used ensured there was negligible concentration decay during the course of testing. The volume of ingressed pollutant was quantified by taking the integral of the measured dye concentration from the downstream fluorometer. Both fluorometers were installed at the edge of the pipe (essentially flush with the fluorometer head slightly convex whereas the inside of the pipe is concave) to minimize distortion of the flow.

Experimental Procedure

The accuracy and repeatability of the proposed experimental work was evaluated during a phase of preliminary testing, the results of which are discussed but not presented herein. Details of the developed experimental parameters are listed in Table 1. The maximum feasible range of injection locations, the significance of the degree of gravel packing on the leakage flow rate, and the influence of the fine mesh placed across the leak were assessed. It was shown that the packing of the gravel had no measurable effect on the leakage flow rate and that there was a negligible head loss through the mesh. Following the preliminary work, a procedure was finalized to ensure repeatable results were obtainable. A total of 61 injection locations (coordinates) were explored within the investigation, providing a wide range of distances from the leak orifice in three-dimensional space to assess the zone of influence of the intrusion phenomena.

The tests were all conducted under fully turbulent flow conditions using the same initial pipe flow rate of 3.0 L/s, equating to a velocity of 1.53 m/s, and test section pressure head of 20.0 m. The pipe flow velocity is relatively high and the pressure head low but fully realistic when compared with the typical flows and pressures expected within WDS in the U.K. These extreme but realistic conditions (high flow velocity and low pressure) result in negative pressure transients following rapid valve closure. The pressure transients for the tests were generated by closing the quarter turn butterfly valve immediately upstream of the test section box (item *f* in Fig. 1). The repeatability of transient pressure generation in this manner was demonstrated in Collins et al. (2012a) and can also be seen in Fig. 3. The valve closure time was less than the characteristic time of the system and was therefore assumed to be an instantaneous valve closure.

Table 1. Experimental Parameters As Defined within Test Planning and Procedure

Parameter	Value
Initial flow rate (L/s)	3.0
Pressure head (m)	20.0
Leak orifice diameter (m)	0.005
Reservoir initial positive pressure head (m)	0.4
Dye injection time (s)	10
Number of injection locations	61
Minimum/maximum Euclidian distance from leak (mm)	10 and 103
X plane locations range (mm)	−50 to 50
Y plane locations range (mm)	−60 to 55
Z plane locations range (mm)	−90 to 100
Mean steady-state leak flow rate (L/s)	0.269
Upstream (of leak) flow Reynolds number	76,210

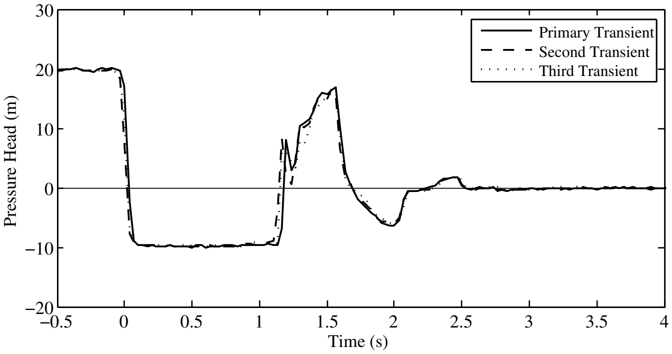


Fig. 3. Overlaid pressure head traces from primary and subsequent generated transients during single test for point source pollutant injection location (0,0,10)

The primary and subsequent pressure transients generated from a single test, where the injection location coordinates were (0,0,10), have been overlaid in Fig. 3. This figure with a short time period view of the test section pressure trace shows the formation of the transient pressure waves following the instantaneous closure of the upstream butterfly valve. The traces show the approximate 1 s duration of the negative pressure head during the three oscillations. The minimum recorded pressure head was −10.04 m (cavitation pressure, with corresponding *flat* component of trace) with a maximum second peak of 16.8 m. The transient pressure waves dissipated within approximately 3.0 s. Statistical analysis of the comparison between the individual generated transients and the mean values, produced an average coefficient of determination (R^2) of 0.997 and an average root-mean-square error (RMSE) of 0.472 m over a 13 s time period showing that highly repeatable transients were generated.

Following accurately locating of the needle tip in the designated test location (±1 mm), the gravel was repacked around the needle and fully submerged under a constant depth of water. Initial steady-state hydraulic conditions were then set in the pipe loop and leak flow, and allowed to stabilize. Dye was then injected into the box for a period of 10 s, controlled by the manual operation of a single valve beneath the dye reservoir. A negative transient (primary transient) was generated 5 s after the start of the dye injection by closing the valve immediately upstream of the test box. Once the transient pressure wave within the system had dissipated the valve was opened and then closed twice more to generate a total of three negative pressure transients during the test (these repeated transients were generated to check for any secondary effects such as re-extrusion of contaminant). The two subsequent transients were generated without any additional injection to check for remaining dye solution in the porous media. The approximate 25 s time interval between each transient initiation allowed for the dissipation of the pressure wave and allowed approximate steady-state conditions to be reached before subsequent valve closures. The total volume of dye injected into the test section tank was recorded by measuring the change in dye solution level within the reservoir (measurement error ±0.015 mL). For each of the point source pollutant locations, a minimum of three repeat tests were conducted. The background concentration of dye within the system was recorded using the fluorometer immediately upstream from the pump (item *a* in Fig. 1). During the analysis of the recorded data, this background concentration was removed to allow for the accurate calculation of the recovered volume of simulated pollutant ingress.

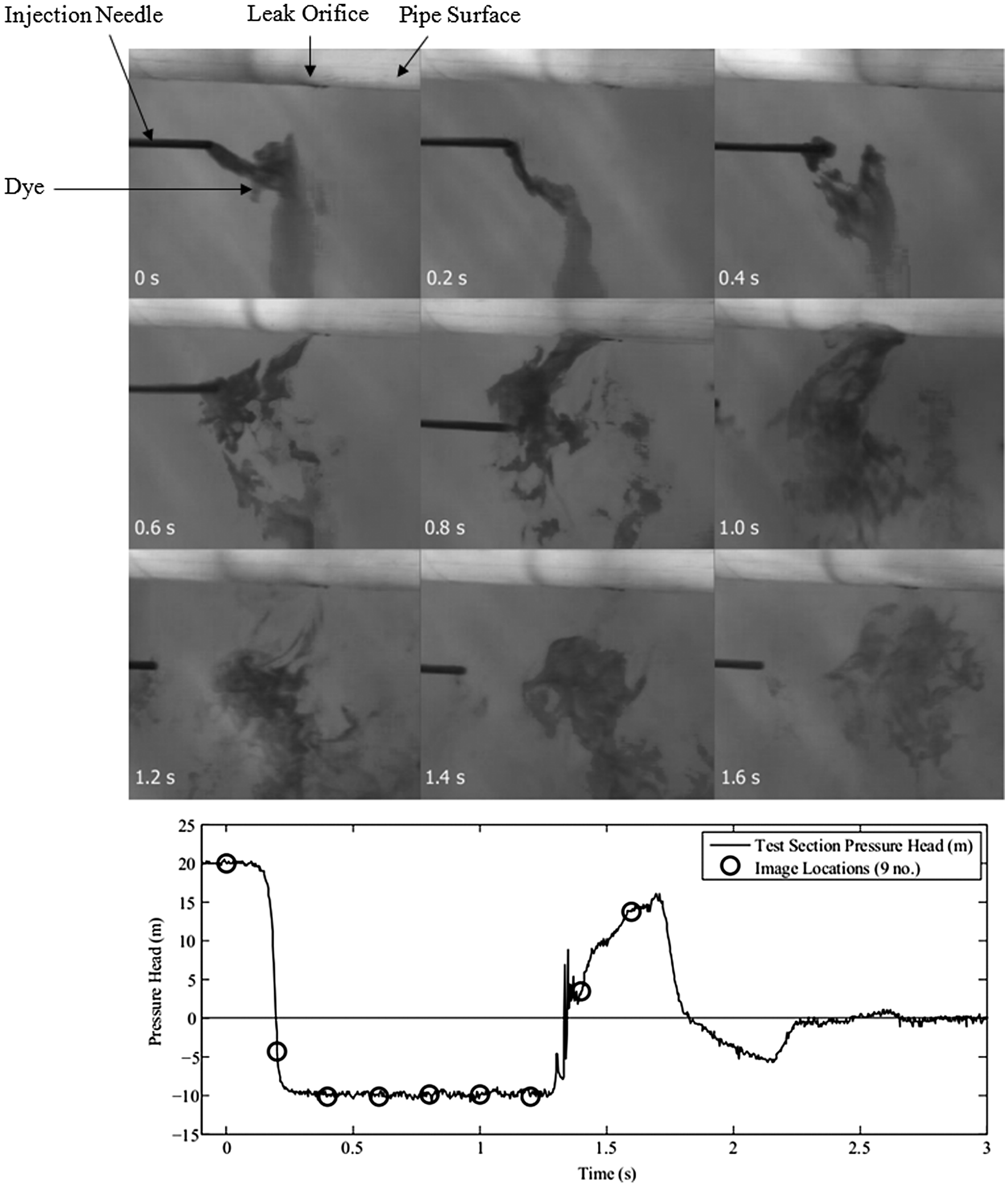


Fig. 4. Sequence of images (0.2 s intervals) and recorded pressure head trace showing the contaminant ingress phenomena during a single transient event; images are for a horizontal leak, taken from vertically above

Results

Qualitative Results

A qualitative demonstration of the phenomenon of contaminant ingress is depicted in the sequence of images shown in Fig. 4. An experimental setup equivalent to the aforementioned configuration, but without the inclusion of gravel in the test section box, was used to show the ingress of a representative point source pollutant during a single transient event. Rhodamine dye was injected external to the pipe leak contained in the water filled test section box. Dye injection was stopped after 1 s to facilitate observation of possible re-extrusion of contaminant. A clear correlation between the recorded pressure heads and the direction of the representative pollutant flow, away from or towards (and into) the leak orifice, may be observed. In addition, no re-extrusion of contaminant was noted within the recorded images.

Quantitative Results

Three examples of the results recorded from different point source locations are presented in detail herein. Fig. 5 is taken from a test where the representative point source of pollutant was injected at (0,0,10), i.e., 10 mm directly above the center of the leak orifice. Fig. 5 shows the recorded data from the test section pressure transducer (solid line) approximately 1 m downstream of the leak (item *i* in Fig. 1), the injection start and stop time (dash-dot line), as well as the two fluorometer traces located upstream (dashed line) and downstream (solid line) of the leak. The start of the primary transient has been assigned $t = 0$ s (assumed instantaneous closure of the upstream valve).

The total injection volume over the 10 s injection period was measured at 7.4 mL and, as can be seen from the fluorometer trace, a peak concentration of 1.35×10^{-7} L/L was recorded following the generated pressure transients. The recorded pulse equates to a

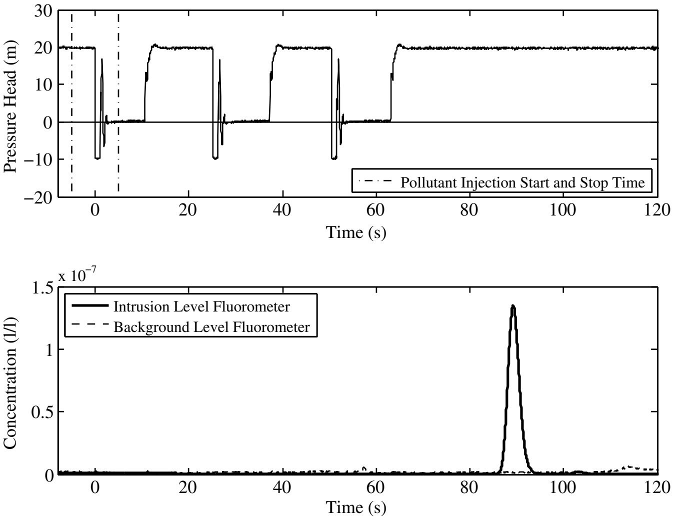


Fig. 5. Representative point source pollutant injection location at (0,0,10); background and intrusion fluorometer traces and synchronous pressure head at test section

recovered volume of 1.1 mL or 14.9% of the initial injection volume. Four additional repeat tests were conducted with total injection volumes of 7.9, 7.3, 8.2, and 7.8 mL, and recorded pollutant ingress volumes of 1.2, 0.92, 1.2, and 1.0 mL (approximately 15.2, 12.6, 14.6, and 12.8% recovery respectively). The peak value of the pulse of dye recorded at the downstream fluorometer was at 89.2 s after the primary transient valve closure. No secondary ingress of dye was registered following the subsequent transients and no significant recirculation was recorded by the upstream fluorometer. Assuming zero net flow during the valve closure time period, and an average velocity in the pipe of 1.39 m/s downstream of the leak when the valve is open, the expected peak arrival time is approximately 92 s, giving a 2.9% difference in expected and actual time of arrival for the pulse of dye. There is a small difference in the peak arrival time due to the difference in time of the valve closure.

Figs. 6 and 7 show the results from tests where the representative point source of pollutant was injected at (0,25,30) and (25, 5, −50) respectively. Table 2 summarizes the results from the three detailed example tests presented, showing the mean values from the five repeat tests for each discrete injection location.

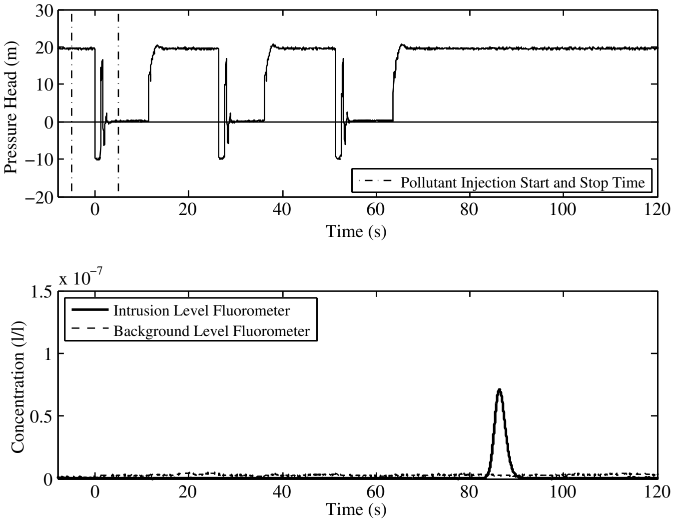


Fig. 6. Representative point source pollutant injection location at (0,25,30); background and intrusion fluorometer traces and synchronous pressure head at test section

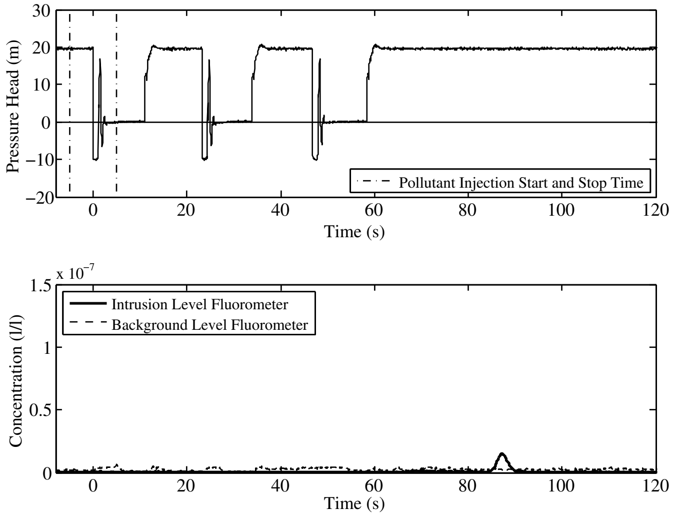


Fig. 7. Representative point source pollutant injection location at (25, 5, −50); background and intrusion fluorometer traces and synchronous pressure head at test section

A total of 61 different point source locations distributed around the leak were studied. The mean recovery volumes for each discrete location were calculated and plotted against the Euclidean distance as shown in Fig. 8. A linear trend line (dashed line) was fitted to the data, defined by the equation $V(\%) = 15.03 - 0.20(D)$ producing an R^2 of 0.774, where V is the percentage volume of dye recovered and D is the Euclidean distance from the leak (mm). All data points with zero recovered volume were removed during the regression analysis in order to determine a threshold value for zero ingress, using the developed trend line. The compiled results shown in Fig. 8 illustrate that the magnitude of contaminant ingress decreases with increasing distance from the leak orifice. Fig. 9 shows the standard deviation associated with the recorded data for the repeat tests in three main reference planes, where $x = 0$, $y = 0$, and $z = 0$, and a single line above the leak orifice, where $x = y = 0$, alongside the linear trend line defined in Fig. 8.

Discussion

The qualitative experimental results provide good proof of the net intrusion of external contaminant into a pressurized pipe due to

Table 2. Experimental Results for Three Discrete Injection Locations: Mean Values from the Five Repeat Tests for Each Location Are Summarized

Parameter	Test 1	Test 2	Test 3
Injection coordinates	(0,0,10)	(0,25,30)	(25, 5, −50)
Euclidean distance from leak (mm)	10.0	39.1	56.1
Mean peak concentration (L/L)	1.28×10^{-7}	7.98×10^{-8}	1.36×10^{-8}
Standard deviation (L/L)	1.30×10^{-8}	5.54×10^{-9}	1.52×10^{-9}
Mean injection volume (mL)	7.72	8.08	9.81
Standard deviation (mL)	0.37	0.41	0.30
Mean ingress volume (mL)	1.08	0.75	0.10
Standard deviation (mL)	0.124	0.087	0.013
Mean percentage recovery volume (%)	14.02	8.54	1.03

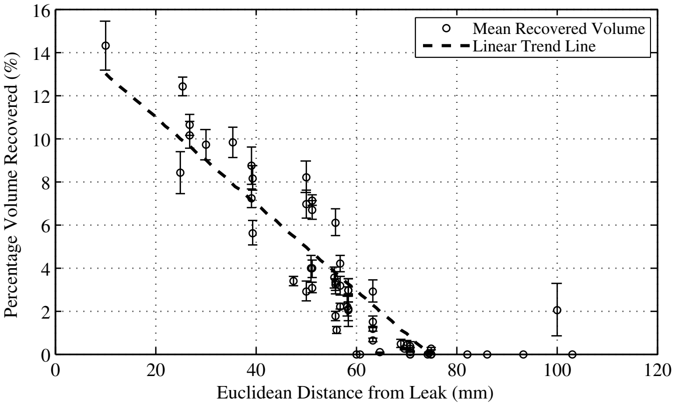


Fig. 8. Relationship between the discrete point source pollutant Euclidean distance from the leak, and the percentage volume of injected dye recovered, including associated ±1 standard deviation error bars

negative transient pressures. The work showed that no re-extrusion of the contaminant occurred and even for a leak into water only, not all the contaminant was washed away or diluted by the leak flow during the initial steady-state conditions prior to the initiation of the transient. Such visual evidence is useful for informing operational staff of the risk of contaminant ingress into water distribution systems.

The quantitative experimental methodology and test procedure developed to explore the phenomena of contaminant ingress during a transient event was shown to be very repeatable and produced consistent data. This is highlighted by the repeatability of the generated transients shown in Fig. 3 and the relatively low variability between repeat tests displayed by the error bars shown in Fig. 9. Data presented in Fig. 8 shows a negative linear association between the Euclidean distance of the pollutant injection from the leak and the volume of pollutant measured downstream of the leak point. This inverse relationship between the distance of a point source pollutant to a leak and the volume of ingress determined under physically representative conditions corresponds with the concept of a zone of influence surrounding a leak as presented by Collins et al. (2011b). This zone of influence indicates the flow path lines into the leak from different regions, and therefore distances, in an external porous media, providing a means to conceptualize the risk of contaminant ingress considering the location of the pollutant external to a leak. It is significant that volume is primarily a function of distance and not location relative to the pipe, as this counters the practitioner argument that the risk is primarily from sources above the pipe; i.e., not leaking sewers which are usually below distribution pipes. The results presented here confirm that there is a real risk of contaminant ingress from all pollutant sources located within the three-dimensional zone of influence, where a bigger negative transient will result in a larger zone of influence. The quantifiable risk of contaminant ingress is therefore a function of scale of the zone of influence and the distance of the point source pollutant from the leak.

Although not investigated in detail here, the magnitude of contaminant ingress may also be influenced by several additional factors. These include the size and duration of the pressure transient, dependent on the initial flow and pressure conditions and the characteristics of the system, as well as the size of the leak which has complicated energy dissipation effects impacting the dissipation of the generated pressure waves. Further, the nature of the media external to the pipe will influence the energy dissipation, flow rates, and zone of influence. First approximations of these

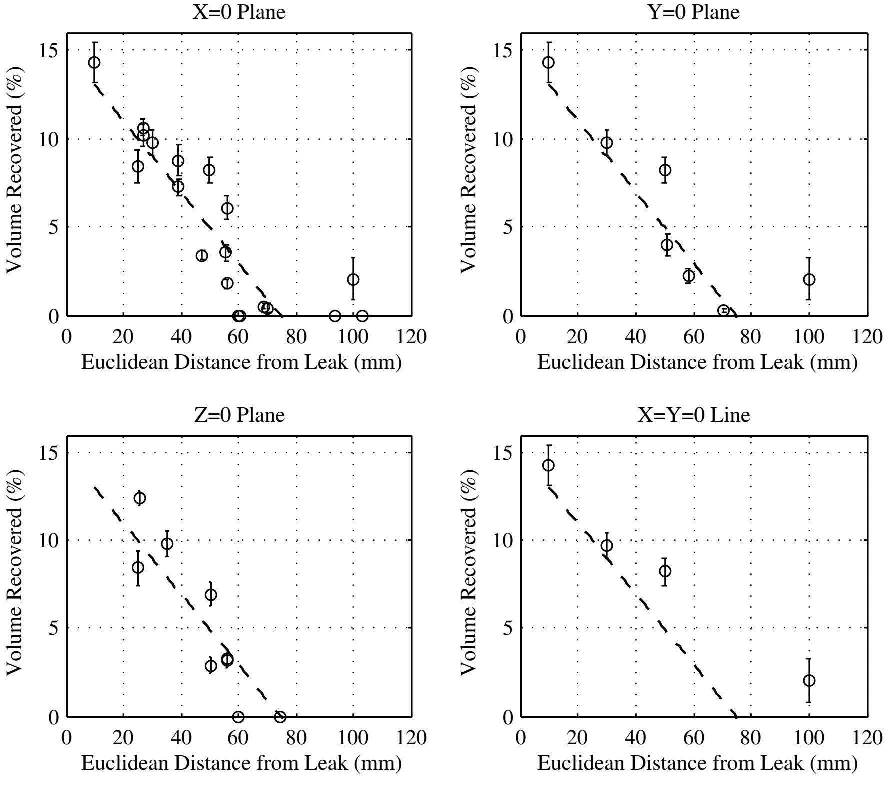


Fig. 9. Data from the three main reference planes (where $x = 0$, $y = 0$, and $z = 0$) and single line above the leak (where $x = y = 0$) including associated standard deviation error bars, plotted against linear trend line for the whole data set (dashed line) evaluated in Fig. 8

may be gained from the steady-state work presented in Collins and Boxall (2013).

For each repeat, three pressure transients were generated, the first during the injection of the pollutant. The downstream fluorometer only recorded one pulse of pollutant at a time consistent with the travel time in the pipe. The results indicate that, in the test cases, flows from the leak were able to dilute and flush the pollutant away from the ingress area before the second and third transients were generated. This effect was also evident within the qualitative test conducted, Fig. 4. However, this does not necessarily mean that all pollutants would be automatically flushed away in a real system. The effect of groundwater flows may serve to renew pollutant in to the zone of ingress, or small particulate contaminate may be trapped within the zone. Additionally, the dynamics of a leak jet into water or fluidized soil potentially creates recirculating vortices surrounding the leak orifice (van Zyl et al. 2013). Such recirculation due to a leak jet could therefore also draw contaminant in to the zone of ingress. Further work is required to fully understand the zone of influence for ingress, the effects of groundwater flows and soil mechanics in presenting contaminants into the ingress zone. The presented work consists of a single finite magnitude point source pollutant; although in reality we may also expect the existence of an unlimited pollutant source around the leak, nonuniformly distributed within the surrounding media such as due to net ground water flow bringing a contaminant plume from a leaking sewer.

In order to understand the zone of influence from which pollutants may be drawn through a leak into a WDS pipe, a wide range of discrete point source locations within a three-dimensional space surrounding the pipe were investigated within the experimental work. Fig. 10 highlights the importance of considering the zone of influence, where contaminants located in all directions from a single leak may be susceptible to the effects of negative pressure transients within the pipe, resulting in contaminant ingress. An anecdotal impression that only those contaminants located above the leak or along the line of the *jet* from the leak are susceptible to the phenomena of ingress as introduced by the authors is negated by the recorded data which showed significant ingress of the representative point source pollutant from below the axis of the leak. This was also shown for locations adjacent to the leak, above and below the origin. This phenomenon is due to dissipation effects of the surrounding media as highlighted in Collins et al. (2011b). The ovality of the contaminant ingress contours depicted in Fig. 10, biased above the horizontally orientated leak orifice, reflect the composition of the zone of influence developed by Collins et al. (2011b) using a steady-state computational fluid dynamic (CFD) model. These models defined the flow path lines surrounding an orifice during a steady-state intrusion event. By referencing these models it can be reasoned that the Euclidean distance used within the aforementioned experimental work is not directly equivalent to the flow path line distance that the point source pollutant travels along when drawn into the pipe. It may be inferred that the shorter the flow path line distance to the leak from the point source pollutant, the greater the resulting volume of contaminant ingress. In the CFD simulations the flow path line length for discrete locations with equal Euclidean distance was shorter for those flow path lines directly above the vertically orientated leak compared with those in other directions. Similarly, these physical experimental results, shown in Fig. 9 for the injection locations $x = y = 0$, i.e., directly above the leak, display the highest volumes of pseudo pollutant ingress, a phenomenon that may be interpreted as a direct result of the formation of preferential flow lines for the leakage flow to the gravel surface. However, this interpretation is potentially limited due to the steady-state conditions used within the CFD model as opposed to the transient conditions used within the experimental investigation, the difference between the orientation of the leak orifices in the two situations and also potential uncertainty in absolute intrusion volumes based on the linear interpolation conducted between the discrete injection locations in Fig. 10.

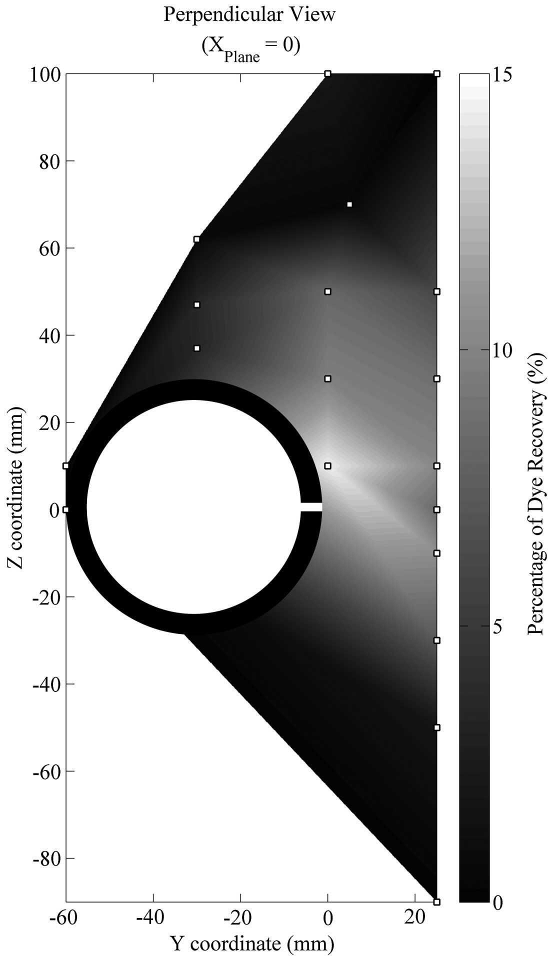


Fig. 10. Contour plot, using linear interpolation, showing experimental results of the dye recovery percentage in single plane ($x = 0$) external to 5 mm engineered leak orifice; discrete injection locations indicated by small squares

Modeling-based research has attempted to identify and quantify the risks of contaminant ingress across different networks (Sadiq et al. 2006; Deng et al. 2011; Ebacher et al. 2012). These typically include estimation of intrusion volume using the orifice equation. However the work presented here suggests that this is likely to overestimate the volume of pollutant ingress. The orifice equation will provide a worst case, upper bound, estimate of the maximum volume of fluid intruded, not the pollutant volume specifically. The equation misses the resistance effects of ground conditions, reducing the volume, as highlighted for steady-state conditions by Collins and Boxall (2013). It also does not represent the zone of influence effects reported here and the low recovery percentages observed here. Thus, the work presented suggests that the risk of direct exposure (the threat to human health due to consumption of water directly contaminated by intrusion) is significantly less than estimated by previous modeling studies. Further the risk due to the overestimated volumes reported by these modeling studies may be further reduced by consideration of reaction with disinfection residuals. However, this does not consider the risk of indirect exposure, such as the seeding of pathogenic organisms into biofilms. In this scenario even very small volumes of contaminant can seed a biofilm local to the site of ingress with pathogenic organisms, that can then be protected from the disinfection residual within the bulk water and potentially survive and proliferate within the biofilm and further seed the downstream system. At some point in the future the biofilm may lose strength or be disturbed, such as due to hydraulic changes in the system, and biofilm containing pathogens originating from the intrusion event may be mobilized with a variety of other material that rapidly depletes the disinfection residual and hence does pose a risk to human health. Discoloration research has confirmed the association between biofilm hydraulic mobilization and organic and inorganic material in water quality samples (Douterelo et al. 2014). Disinfection depletion has also been observed in these samples. Further research is required to better understand the behavior of pathogenic organisms within biofilms, in particular the impact of different bulk water characteristics such as organic carbon and disinfection strategy on biofilm communities and matrix, and the ability for pathogens to shelter and proliferate within them.

Conclusions

The results of the novel experimental work reported here showed that under extreme, but realistic, conditions the ingress of contaminants originating externally to a leak orifice in a pressurized pipe can occur due to the occurrence of pressure transients within the system. The perception that only water expelled from the pipe, under positive steady-state or dynamic pressures, will reenter through the leak has been shown to be unfounded as has the reextrusion of contaminant on the next positive cycle of the transient. Contaminants have been shown to be ingressed from a significant area outside the leak, with the ingress volume having an inverse relationship with the distance of the contaminant from the leak. Three detailed example results for different representative point sources of pollutant are presented, with increasing Euclidean distance from the leak, demonstrating that contaminants can be drawn into the pipe from a significant area outside the orifice. Results of 61 different injection locations are also summarized showing the ingress volume having an inverse relationship with the distance of the contaminant from the leak, but largely independent of location (e.g., above, below).

This paper conclusively shows, for the first time, that for fully representative physical conditions, there is a threat to potable water quality due to net contaminant ingress and transport during extreme short duration oscillating pressure transient events within water distribution networks.

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