Intrusion and leakage in drinking systems induced by pressure variation

Jesús Mora-Rodríguez, P. Amparo López-Jiménez and Helena M. Ramos

ABSTRACT

Pathogen intrusion is a phenomenon that can cause a serious pollution problem in drinking systems. The paper describes the entry of external fluids through pipe defects caused by a pressure drop. This situation is especially important during hydraulic pressure variations. Pressure variations that can cause intrusion are analyzed in this paper. Three cases of pressure transients are modeled with the leak located near the transient origin, thus creating a critical scenario to force the intrusion. A combination of the method of characteristics and computational fluid dynamics is implemented in order to quantify the intrusion and leakage volume during the transient event in a pipe. Laboratory procedures provided data for validation of the results. The objective of this paper is to obtain the volume of intrusion and leakage during the pressure variations through defects in pipes. The flow resulting from the intrusion event will be quantified during the transient pressure, noting the potential implications of this event for public health.

Key words | computational fluid dynamic model, experimental model, intrusion, leakage, transient pressure, water pollution

Jesús Mora-Rodríguez (corresponding author)
Geomatics and Hydraulic Engineering Department,
Universidad de Guanajuato,
Avenue Juarez 77, 36000, Guanajuato,
Mexico
E-mail: *jesusmora@ugto.mx*

P. Amparo López-Jiménez
Hydraulic Engineering and Environmental Department,
Universitat Politècnica de València,
Camino de Vera, s/n, 46022, Valencia,
Spain

Helena M. Ramos
Civil Engineering Department and CEHIDRO,
Instituto Superior Técnico,
Technical University of Lisbon,
Avenue Rovisco Pais,
1049-001, Lisbon,
Portugal

ABBREVIATIONS

c	wave speed
c_f	wave speed value at final calculation time
c_0	wave speed value at initial calculation time
C_d	discharge coefficient
c_F	fluid wave speed
c_t	solid wave speed
CT	time decay coefficient of the wave speed
D	inner diameter
$\vec{F}$	outer forces defined on the control volume
$\vec{g}$	gravitational acceleration
h	head
HIC	vapor pressure
H_{OUT}	outside pressure at the leak
I	unit tensor
k	head correction factor
K	fluid bulk modulus
KH	head decay induced by a discharge variation due to the non-elastic behavior of the fluid
KQ	raised coefficient in the discharge value caused by a head variation, due to a non-elastic response in the recuperation phase of the deformation
p	static pressure
Q_R	discharge at the right of the cavity
Q_L	discharge at the left of the cavity
Q_w	weir discharge
S_m	mass source contained in the control volume
V	cross-sectional averaged fluid velocity
$\forall_{i,j}$	vapor cavity volume
z	pipe elevation at the leak
θ	weir angle
ν	Poisson ratio
t	pipe wall thickness
μ	eddy viscosity
ρ	mass density
σ	normal stress
$\bar{\tau}$	stress tensor
$\dot{u}$	structural velocity

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INTRODUCTION

Mechanism associated with the intrusion event

The pathogen intrusion is a term that refers to the entrance of pollution causing a decrease in the quality of safe water in distribution systems. All networks present the possibility of the entrance of external fluid inside the pipe when certain factors occur. The actual problem with this intrusion phenomenon is the possibility of polluted water generating waterborne disease outbreaks, even when the operators of the distribution systems protect and maintain water sources and networks, as well as disinfecting and monitoring the drinking system. When a contamination event occurs, there are three important actions to prevent more serious outcomes: to detect abnormalities, to report them, and to comply with measures to prevent the propagation of any disease (Wu *et al.* 2009). In 1998 a classification of pathogens' entry routes was made. This classification focused on the level of risk by considering the causes which resulted in intrusion (Kirmeyer *et al.* 2001). The routes identified with higher risk were water treatment breakthrough, transient contamination, cross-connections and water main repair/break. With this background, the work focuses on carrying out mathematical representation of the intrusion phenomenon occurring in networks, considering transient contamination and water main breaks. Before the main breaks, usually the pipes present other kind of failures generating leaks during distribution. Furthermore, the presence of physical failures in the water network gives an idea of the hydraulic performance; if the network is near to optimal performance an intrusion event is less likely, whereas if the performance decreases the possibility of an intrusion occurrence is more likely. Three factors are required to generate pathogen intrusion: *the mechanism* that forces the intrusion event, *the way of entrance* for possible contaminants and *the pollution source*. In Figure 1 a typical scenario of intrusion is depicted.

During a system operation, potential risky weak points and factors can be identified. The occurrence of leaks may be a consequence of failure of operational management, an unknown cause, or an abnormal situation, requiring special expertise and investigation in order to avoid these events. Although the distribution water networks maintain continuous water service, and consequently, the mains are pressurized, during operation pressure transients can occur that are caused by main breaks, sudden changes in demand, pump starting or shutdown maneuvers, opening and closing fire hydrants, power failures, air-valve slam, flushing operations, feed-tank draining, etc. (Karim *et al.* 2003). These conditions can generate negative pressure waves, which can momentarily draw water back into the leaking pipe and, as a result, the volume intrusion can be significant. The appearance of strong transient forces induced by unexpected and uncontrolled surges is a typical consequence of an abnormal situation. Explanation of unexpected behavior requires a detailed analysis of the complex hydraulic and structural interactions. A combined hydraulic and structural model, first described by Wiggert *et al.* (1987), solved by the method of characteristics (MOC) includes a four-equation system as follows:

$$\frac{\partial U}{\partial t}+\frac{\partial F(U)}{\partial x}D(U) \quad (1)$$

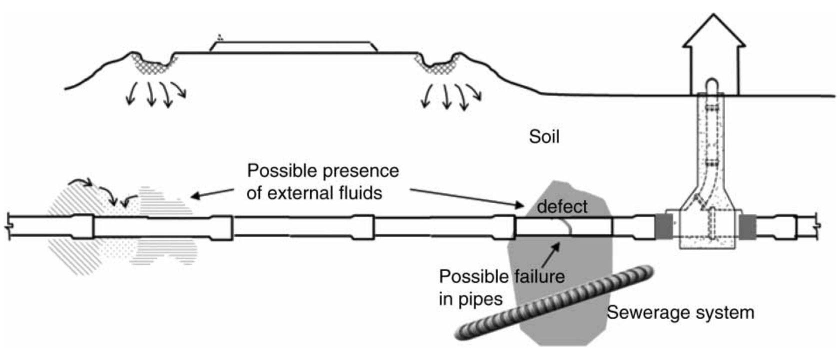

Figure 1 | Pathogen intrusion factors.

being

$$U = \begin{bmatrix} H \\ V \\ \dot{u}_x \\ \sigma_x - \dfrac{H\,g\,\nu\,D\,\rho_F}{2t} \end{bmatrix} \qquad F(U) = \begin{bmatrix} \dfrac{c_F^2}{g}(V - 2\nu\,\dot{u}_x) \\ gH \\ -\dfrac{\sigma_x}{\rho_t} + gZ \\ -\rho_t c_t^2 \dot{u}_x \end{bmatrix}$$

$$D(U) = \begin{bmatrix} 0 \\ -\dfrac{f}{2D}(V - \dot{u}_x)|V - \dot{u}_x| \\ -\dfrac{f}{8\,t}(V - \dot{u}_x)|V - \dot{u}_x| \\ 0 \end{bmatrix} \tag{2}$$

in which

$$c_F^2 = \left(\rho_F\left(\frac{1}{K} + (1 - \nu^2)\frac{D}{E_p t}\right)\right) \tag{3}$$

and

$$c_t^2 = \frac{E_p}{\rho_t} \tag{4}$$

where c_F^2 and ${c_t}^2$ are the squares of the fluid and solid wave speeds, respectively, V is the cross-sectional averaged fluid velocity (m/s), p the pressure (pa), E_p the Young's modulus of the pipe material (pa), c wave speed (with subscripts: F for the fluid, t for the pipe (m/s)), ν Poisson ratio, t pipe wall thickness (m), D inner diameter (m), ρ mass density (kg·m^3), σ normal stress (pa), K the fluid bulk modulus (pa), and $\dot{u}$ is the structural velocity (m/s).

Pipe breakage is likely to occur when environmental and operational stresses act upon pipes, accessories, and supports whose structural integrity has been compromised by stability, resistance, corrosion, degradation, inadequate installation, or manufacturing defects. The pressure transient occurs during distribution network operations. Those events are more common than expected and the system networks usually diminish these kinds of event (Kirmeyer *et al.* 2001; LeChevallier *et al.* 2003; Boyd *et al.* 2004; Friedman *et al.* 2004; López *et al.* 2006) allowing their dissipation. However, there are different events that generate strong pressure transients due to rapid maneuvers induced by valve operation (open and close), pump startup and shut down, opening and closing fire hydrants, and the sudden changes in demand.

As identified by Fleming (2007), there are some characteristics that make the presence of low or negative pressure a major risk on networks: i.e., systems with a groundwater source, small networks (less than 0.45 m^3/s of delivered flow), networks with a sharp topography (more than 45 m difference in level), networks with small storage facilities, or without floating storage.

The physical mechanisms associated with the structural behavior of water mains are very complex, involving several important factors (Rajani & Kleiner 2001): (1) pipe structural properties, the material type behavior, the pipe–soil interaction, and the quality of the pipe fixing; (2) internal loads due to unbalanced pressure actions and external loads due to soil overstrain, traffic loads, temperature variation; and (3) material deterioration due to largely external and internal chemical, biochemical, electrochemical, and environmental reactions. Mostly pipes and accessories, such as valves and joints, are predominantly of metallic material. Damage to cast iron is often represented by a corrosion pit that will grow with time and eventually lead to a water main break. Furthermore, the physical adjacent environment of a pipe can have a significant impact on the deterioration rate.

Type of breaks and pollution sources

Failure in pipes depends on environmental and operation tensions. A first leak can generate other failures in a main pipe, close to and later in time, even if the first leak has already been identified and repaired. The leak could also produce erosion on the bed and associated economic damage (Burn *et al.* 1999), as well, during and after repair of the failure (Hu & Hubble 2007). O'Day *et al.* (1986) presented a classification of the type of failures divided into three categories: circumferential failure caused by longitudinal tension, longitudinal failures caused by cross-sectional tension (radial tension), and failures in union caused by cross-sectional tension in pipe union (Figure 2). This classification can be complemented by failures caused by corrosion. Depending on the severity of the corrosion, the holes could be of a few millimeters, or of a high grade of severity corrosion. In Figure 2 different schemes of kinds

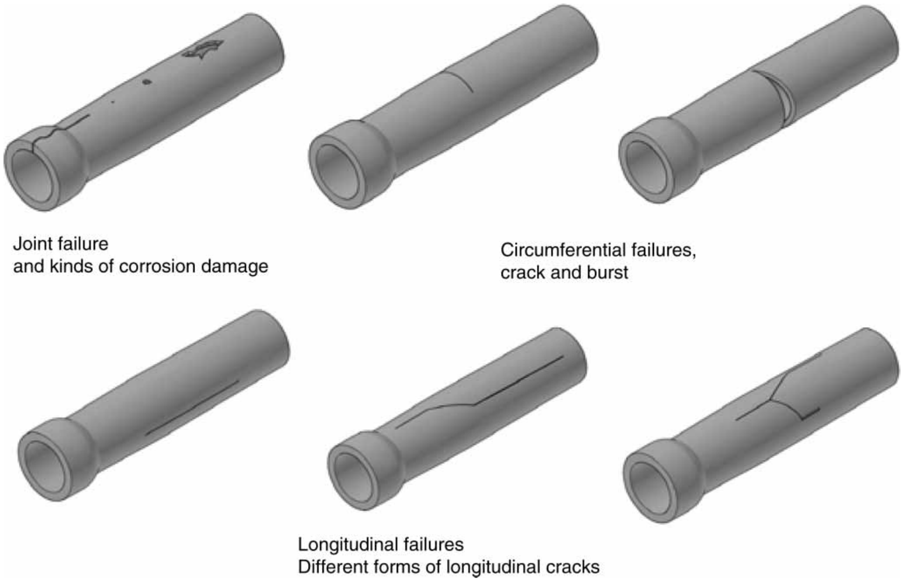

Figure 2 | Failures in pipes.

of failures in pipes are shown. With knowledge of the presence of failures and their possible location, besides the type of failures, operators are able to estimate the physical condition of networks. Consequently, they could implement rehabilitation projects, but the investment in localization and rehabilitation can be very expensive and, frequently, operators consider a percentage of water loss acceptable compared to the costs of rehabilitation. Hence, studying the possible intrusion volume through water main failures when the conditions generate pathogen intrusion, is of the utmost importance.

Corrosion failures are caused by electrochemical interaction resulting from the contact between the metallic pipes with soil and water. This contact produces degradation of the pipe material through the years. Metal pipes are an important element in water distribution networks; most of the half mains installed during the 20th century were metallic (Mora *et al.* 2008). A circular hole has been modeled to simulate a general kind of corrosion failure (Figure 3).

Several factors are considered as pollution sources. In many cases the sources of contaminants are difficult to identify, but their presence is evident. Pollutant can occur from the environs, besides groundwater, runoff, and wastewater (Zloczower & Kibbutz 2009), from some other medium that can transport pathogens, or even from the soil around the mains. Other sources of pollution are related to superficial urban water, i.e., from rainfall to the drainage network system, which normally has a higher level of leaks than drinking distribution water networks.

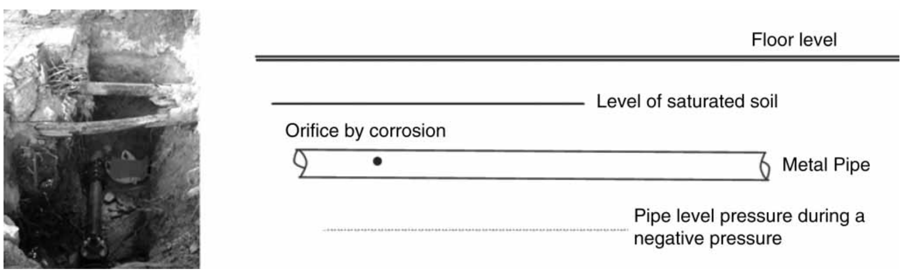

Figure 3 | Prototype of the pathogen intrusion through an orifice.

Public health significance for different levels of intrusion

As intrusion represents the entry of pathogenic agents into clean water, low pressure events may result in adverse health effects. This risk has been considered in the last few years (McInnis 2004; Besner 2007; Teunis *et al.* 2010). In 2005, the US Environmental Protection Agency mandated a committee of the National Academies' Water Science and Technology Board to identify and prioritize the issues affecting water quality in water distribution in terms of risk of pollution and potential health risks (NRC 2006). In this study, the following issues were prioritized. In the highest priority category, cross-connections and backflows were considered, also repairing water mains, finished water storage, premises' plumbing, and distribution system operational training. Biofilm growth, decrease in residual disinfectant by water aging and nitrification, and low pressure transients and intrusions were regarded as medium priority issues. Finally, other aspects, such as the effects on water age and nitrification, permeation, leaching, and control of post-precipitation were considered of lower priority. Among the listed factors, cross-connections, repairing water mains, and low pressure transients are probably the most likely to result in the intrusion of microbial contamination in a distribution system, and are ranked as high or medium priority regarding their potential health risk.

The potential health problem concerned with pathogen intrusion occurs when external surrounding water mains are contaminated. The presence of pathogenic microorganisms (bacteria, protozoa, viruses) in close proximity to drinking water mains has been reported. In Karim *et al.*'s (2003) research, soil and water samples were collected at sites immediately exterior to drinking water pipelines during pipe repairs. An indicator of microorganisms and enteric viruses were detected in more than 50% of the 65 samples examined. Similar results were found by Mora (2011) in water surrounding repairs, with detection of the presence of *Escherichia coli* and *Salmonella* bacteria. Microbial characterization of the water found in 30 flooded air-valve vaults was performed by Besner *et al.* (2010); more than 60% of the collected samples contained *E. coli*, *Clostridium perfringens*, enterococci and Bacteroidales fecal bacteria.

In the case of pathogen intrusion in a distribution system, ingestion of drinking water is generally assumed to be the main contributor to health risk. Some authors have evaluated the risk of transient pathogen intrusion into distribution systems. McInnis (2004) compared the relative risk-reduction achieved by alternative transient-intrusion mitigation strategies; as a consequence, a quantitative reduction in the risk of receptor infection is achieved by using alternative mitigation strategies. Teunis *et al.* (2010) concluded that the probability of a consumer drinking water contaminated with virus is small, but when this does happens the virus concentration tends to be high and the risk of infection may be considerable.

In this sense, reference to epidemiologic studies analyzing the possible relationship between low pressure events and public health have been reported. As shown in Besner *et al.* (2011), some examples consider this significant. For instance, Blackburn *et al.* (2004) reported cases of an outbreak of *Giardia intestinalis* in a trailer park, related to a power outage which created a negative pressure condition in New York's distribution system.

In Europe, studies have found the following. A case–control study performed in England about sporadic cryptosporidiosis concluded a strong association between self-reported diarrhea and reported low water pressure at the tap (Hunter *et al.* 2005). In this case, association of up to 15% of gastrointestinal illnesses could be related to burst water mains and pressure loss events. An epidemiological study conducted in Norway related low pressure episodes (situations in which part of the water distribution network was closed off due to main breaks or maintenance work) with presumed loss of water pressure in the distribution system, which caused an increased risk of gastrointestinal illness in water consumers (Nygard *et al.* 2007). In this case, comparison between households exposed to 88 low pressure episodes taking place in seven different distribution systems were compared to unexposed ones. One week after the episode, 12.7% of the exposed households reported gastrointestinal illness compared with 8% in the unexposed consumers.

As many of the consulted references state, the authors conclude that the assessment of potential risk associated with pathogen intrusion events is a complex process. The risk of population exposure to this problem depends on several factors, among them the quantity of pathogens entering the system, duration of the negative pressure event, or presence of high concentration of disinfectants in the network. In any case, estimation of the potential volume of polluted flow is one of the first steps to predict the final degree of potential possible health problems for consumers.

Experimental and numerical investigation

In this research the influence of pressure fluctuations induced by transient events associated with a pump shutdown or a valve closure is analyzed. Transient pressure can attain sub-atmospheric values, which will affect the system performance in terms of possible contamination of a drinking water pipe system.

In pressure flow, cavitation is an effect that occurs when the pressure decreases until vaporization pressure occurs, causing the formation of vapor bubbles. The occurrence of cavitation in unsteady conditions is called macro-cavitation.

The water contains a small quantity of air, which flows with the liquid either as free air (bubbly flow) and/or dissolved air. In numeric modeling, the fluid is considered as a pseudo (homogeneous) liquid. Special attention must be given to pressure-dependent wave celerity. The free gas is considered as isothermal and ideal to induce a variation in the wave speed of about 40–70% (Ramos *et al.* 2005) of the initial value of the wave speed. The conventional vapor–liquid model assumes that discrete vapor cavities are formed at fixed pipe sections and considers a constant wave speed in pipe reaches between the cavities. Numerical results presented in this paper are obtained based on the traditional vapor–liquid model, with a second order approximation for the calculation of quasi-steady friction losses, introducing adequate changes in different characteristic parameters (e.g., wave celerity, head losses) in order to better simulate observed dissipation and dispersion effects due to mechanical, frictional, and inertial effects.

For modeling purposes, the effect of air release is neglected and discrete vapor cavities can open at all pipe sections. Hence macro-cavitation (large cavities) can be characterized by the existence of a vapor cavity volume $\forall_{i,j}$ at the pipe section i and for the time j as

$$\forall_{i,j} = \forall_{i,j-1} + \left(Q_{\mathrm{R}i,j} + Q_{\mathrm{R}i,j-1} - Q_{\mathrm{L}i,j} - Q_{\mathrm{L}i,j-1}\right)\Delta t/2 \tag{5}$$

where Q_R and Q_L = discharge at the right and the left of the cavity, respectively.

This condition is imposed when the absolute pressure drops to the liquid vapor pressure (vaporous cavitation inception) HIC (about 98.06 kPa at room temperature) and maintains this value as long as the cavity volume is positive. The piezometric head within the cavity is given by Equation (6).

$$H_\forall = H_\mathrm{IC} + \frac{P_\mathrm{atm}}{\gamma} \tag{6}$$

The application of the MOC to the typical 'reservoir-pipe-valve' gives the following equations (Ramos *et al.* 2004):

$$\begin{aligned} C^+ &: H_\mathrm{P} - H_\mathrm{L} + (Q_\mathrm{P} - Q_\mathrm{L})B + R|Q_\mathrm{L}|Q_\mathrm{L} = 0 \\ C^- &: H_\mathrm{P} - H_\mathrm{R} - (Q_\mathrm{P} - Q_\mathrm{R})B - R|Q_\mathrm{R}|Q_\mathrm{R} = 0 \end{aligned} \tag{7}$$

with

$$B = \frac{c}{gS}$$

The modification of the headloss coefficient is obtained by a multiple constant factor. In the simulation of the variable celerity (Ramos *et al.* 2005) due to air releasing during the cavitation period, an exponential variation along time is considered, uniform along the entire pipe, according to the following equation:

$$c = c_\mathrm{f} + (c_0 - c_\mathrm{f})e^{-t/\mathrm{CT}} \tag{8}$$

where c_0, c_f, and c are the wave speed values at initial, final, and calculation time, respectively; CT is the time decay coefficient of the wave speed.

For the description of non-elastic behavior due to fluid (water and mixed vapor–water) and pipe material (plastic pipe), two additional parameters (KH and KQ) were included in the MOC equations (Ramos *et al.* 2005). Parameter KH stands for the head decay induced by a discharge variation due to the non-elastic behavior of the fluid (i.e., with the presence of free gas) and the pipe viscoelasticity. KQ is a raised coefficient in the discharge value caused by a head variation, due to a non-elastic response in the recuperation phase of the deformation.

Hence, the paper focuses on a numerical representation and experimental analyses of the intrusion during a hydraulic transient event, considering the variation of incoming and outgoing flow volumes according to the range of pressures. The volumes of intrusion and leakage are obtained based on extreme conditions of the pressure variation induced by a typical transient event in any water supply system. First, a reproduction is made experimentally. Then, a computational fluid dynamic (CFD) transient model is used to analyze some scenarios that the experimental model could not represent and to measure the intrusion and the leak flows during the event.

The modeling of the leakage, from the hydraulic point of view, can be done as analyses of flow through an orifice (Covas *et al.* 2005; López *et al.* 2005), remaining valid in cases of upper and low pressure, which can favor the entry of pollutants. In the CFD model, the leak is simulated through the following formulation:

$$Q_0 = C_d A_0 \sqrt{2\,g\Delta H_0} \tag{9}$$

Leaks are treated as an off-line orifice as specified in Bergant *et al.* (2003). The two relationships that relate the upstream head and flow to the downstream head and flow are

$$Q_P^+ - Q_P^- - C_d A_0 \sqrt{2\,g(H_P - H_{OUT} - z)} = 0 \quad \text{where} \quad H_P = H_P^+ = H_P^- \tag{10}$$

where z = pipe elevation at the leak and H_{OUT} = outside pressure at the leak. In most cases the outside pressure is the atmospheric pressure and assumed zero. The leakage flow depends on different factors, such as the differential pressure, the resistant characteristic of the structural imperfection, the pipe material, and the type of orifice (May 1994).

MODEL OF THE INTRUSION

Physical modeling: experimental facility

As explained earlier, the numerical representation is calibrated and validated by an application of experimental intrusion simulation adequately measured and monitored. Based on experiments, numerical simulations by means of the MOC and adequate boundaries are then implemented.

The system is composed mainly of a long pipe of 200 m length, connected upstream to an air vessel, which can fix a pressure charge up to 1.6×10^5 pa. In order to generate a pressure transient, a valve closure maneuver is used upstream of the pipe system. At the downstream end, the flow discharges into an open tank, the water being pumped again to the upstream air vessel. Figure 4 shows part of the representation of the physical model, in the intrusion pipe section, where the diameter of the pipeline is 0.05 m and the leak is simulated with an orifice of 0.002 m.

The model simulation begins with the initial flow and pressure coming from the air vessel tank. When the steady-state conditions are attained, the transient is then induced. Table 1 depicts the initial data for the three CFD

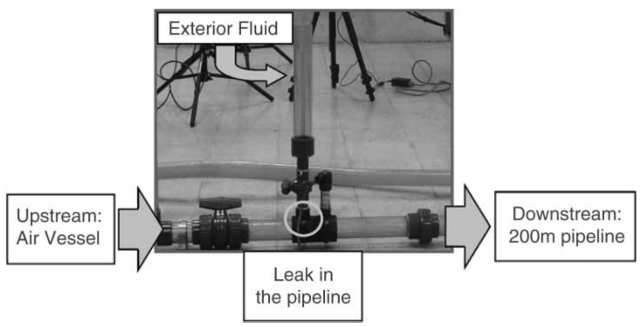

Figure 4 | Scheme of the physical model.

Table 1 | Initial pressure and flow for three experimental tests

Test	H_0^a (pa)	h weir (m)	Q^b (m³/s)
E2-1	1.5×10^5	0.081	0.0025
E2-2	1.3×10^5	0.078	0.0023
E2-3	9.3×10^4	0.072	0.0019

[a]Transducer is used to measure the pressure on the air-vessel and on the intrusion pipe section, being the range of both transducers from -1.0×10^5 to 2.4×10^6 pa. The frequency of acquisition is 500 Hz.
[b]The flow in the pipe is measured by a weir. At downstream of the 200-m length of pipeline there is a V-notch (triangular) weir. Using the weir discharge formulation by the Kindsvater-Shen equation suggested by USBR-1997 and supported by ISO-1980 and ASTM-1993 (LMNO 2007) the flows were obtained with the adjustment of the LMNO engineering software.

simulated scenarios.

$$Q_w = 4.28 C_d \tan\left(\frac{\theta}{2}\right)(h+k)^{5/2} \quad (11)$$

where Q_w is the weir discharge (m^3/s), C_d is the discharge coefficient, θ is the weir angle; h is the head (m); k is the head correction factor (8.85×10^{-4} m; this value depends on the weir angle, in this case 90°).

After the initial conditions, the transient is induced by an effective closure maneuver of the globe valve located upstream. The pressure data were collected by a *picoscope*™ data acquisition system. The transient's duration was between 20 and 30 s. Figure 5 shows the pressure variation measured at upstream along the first 20 s, for a fast flow closure maneuver, generating the intrusion of contaminants into the pipe system due to initial sudden pressure decreasing. The intrusion that results in the leak is also recorded to validate the numerical CFD results.

Numerical CFD-3D analysis

A CFD model has been developed to obtain the volume of intrusion and the leakage in a drinking system induced by pressure variation associated with a shutdown of the pumping station or an upstream valve closure. Finally, the potential intrusion volume during a transient event is then quantified. CFD modeling is used for solving numerically the governing laws of fluid dynamics. Equations based on conservation fluid mechanics, considering dissipative and turbulent effects, are solved in a mesh domain, given suitable initial and boundary conditions.

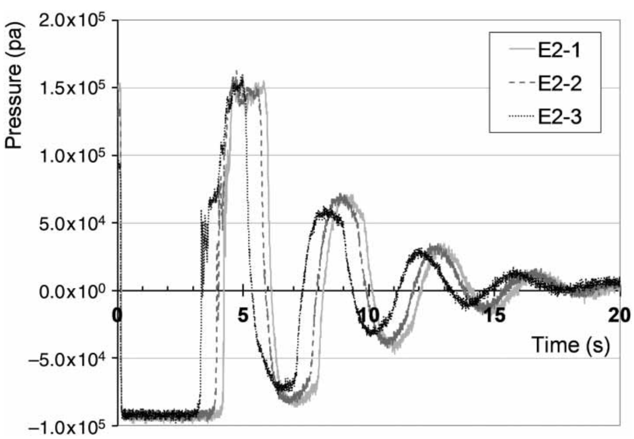

Figure 5 | Transient pressure variation: results from experiments.

The conservation laws are expressed by Reynolds transport equation of mass and momentum. The continuity or mass conservation equation used in this hydrodynamic study is given by:

$$\frac{\partial \rho}{\partial t} + \nabla \rho \vec{v} = S_m \quad (12)$$

where ρ is the fluid density, v is the flow velocity, and S_m the mass source contained in the control volume. For other geometries, suitable coordinates, namely spherical or cylindrical, should be used. Also, the momentum equation is considered through the following equation:

$$\frac{\partial(\rho \vec{v})}{\partial t} + \nabla \rho(\vec{v}\,\vec{v}) = -\nabla p + \nabla \bar{\tau} + \rho \bar{g} + \vec{F} \quad (13)$$

in which p is the static pressure, $\vec{g}$ and $\vec{F}$ are the gravitational and outer forces defined on the control volume, respectively, and $\vec{\tau}$ the stress tensor defined by:

$$\bar{\tau} = \mu\left[\left(\nabla \vec{v} + \nabla \vec{v}^{T}\right) - \frac{2}{3}\nabla \vec{v} I\right] \quad (14)$$

where μ is the eddy viscosity, I is the unit tensor, and the third term accounts for the effect of the expansion of volume.

The geometry of the intrusion pipe section is represented in AutoCAD™ including the orifice and the exterior zone. The mesh is designed considering polyhedral elements. In this CFD model, the control volume is established in three dimensions, defining the computational dominium and for the mesh constructed (Figure 6). Different meshes were analyzed to evaluate the best hydrodynamic results depending on the mesh characterization.

The geometry is constructed considering a symmetry plane on the middle section of the pipe. The orifice, representing a leak of 0.002-m diameter, is also mesh refined. The length of the pipe is established considering two pipe diameters (0.09 m) upstream from the orifice and four pipe diameters (0.18 m) downstream from the orifice. This analysis was done using various combinations of pipe length; this one represents in an adequate way the transient and intrusion event. Originally, the intrusion source was represented by cylinder geometry. This geometry produces high turbulences in this model. To diminish the high values of turbulence coefficient, the conical geometry shown in Figure 6 was considered, improving the behavior of the model and getting good calibration in the intrusion area.

Turbulence effects are simulated with one of the variations of the $\kappa-\omega$ model. This model is termed shear stress transport (SST) and takes the properties of the standard models, $\kappa-\varepsilon$ and $\kappa-\omega$. The SST $\kappa-\omega$ model is adequate with low Reynolds due to equations representing the inner and the wall through the viscous sub-layer. The SST model improves the behavior on the free surface by the $\kappa-\varepsilon$ technique, being less sensitive to the turbulence properties in this zone. The SST model is recommended on the separate flow and on adverse pressure gradients because it presents a good response in most of these cases. The model produces slightly higher turbulence than the standard $\kappa-\varepsilon$, in a case like stagnation zones and with high acceleration, but it is an adequate model for this type of analysis.

The first step of the procedure is to define how the three scenarios for the initial conditions presented in Table 1 are to be considered. Using the constant pressure on the outlet boundary and the velocity on the inlet obtained from the flow data the stationary-time event is modeled. Results of the CFD model show the pressure and velocity in each time instant inside the pipe. Figure 7 represents the maximum and minimum pressure graphical representations for scenario 1.

The steady-state regime is achieved and then the initial conditions to simulate the transient mode. In this case, a developed transient model is used to obtain the adequate boundary conditions in the vicinity of the intrusion pipe section as detailed by CFD analysis. Therefore, pressure and velocity variation are obtained based on the MOC modeling with the incorporation of localized vapor cavity modeling (Borga et al. 2004; Ramos et al. 2005). The model also includes the variable of the wave speed to describe the presence of vapor in the flow, that is a possible representation required to obtain the physical behavior of the macro-cavitation occurrence induced by sudden transient events generated upstream of the main pipe on the experimental transient simulation. Special dynamic effects decoded by dissipative coefficients applied to the characteristic equations of the MOC will correct the real transformation of the kinetic energy into an elastic one and vice versa (Ramos et al. 2004) during each transient event. Table 2 shows the time

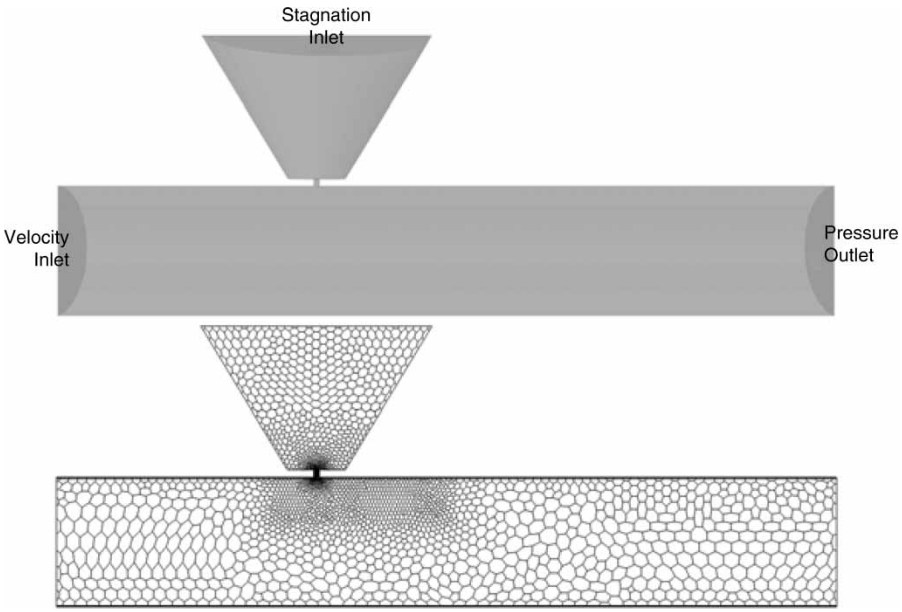

Figure 6 | Volume control, mesh on the symmetry plane, and boundary conditions.

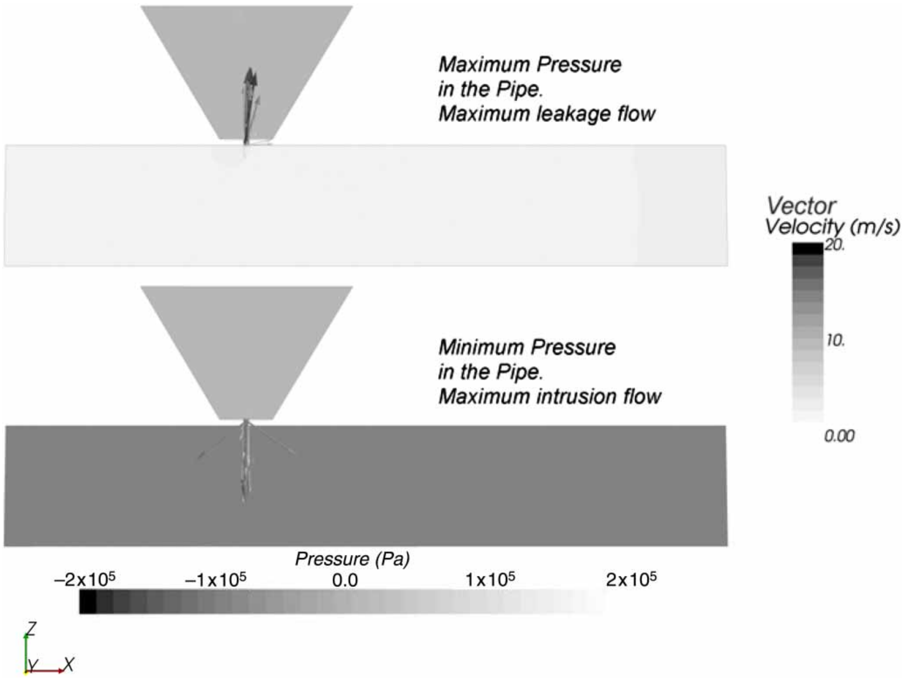

Figure 7 | Pressure and velocities for leak and intrusion into main pipe.

characteristics resulting from the experimental simulations; they are the primary data for the MOC model. The head and the flow were measured from the experiments. The wave speed is obtained from the field pressure variation and is 240 m/s. The time of the valve closure was obtained from the real movement seen during the film of the experimental simulations (Mora *et al.* 2011) which also defined the total simulation time for the comparison procedure.

A fixed grid is used for the transient vapor-cavity model based on the MOC, and the pipe sections where the vapor cavity occurs are analyzed as internal boundaries. The numerical solution for the vapor–liquid model is then obtained, in which a second order approximation to characterize the quasi-steady friction losses is implemented.

The vapor–cavity model reproduces adequately the transient events for the three different scenarios analyzed experimentally (Figure 8), giving the information about the flow and time characteristics parameters, which will define the boundary conditions for the CFD model simulations.

Table 2 | Time characteristics from the simulated scenarios

Parameter	Data E2–1	Data E2–2	Data E2–3
Time closure of the valve (s)	0.12	0.11	0.12
Total simulation time (s)	27	28	23

The CFD model is then adapted to simulate the transient regimes for these three scenarios, where the solution on the time scale is unsteady implicitly and the numerical results for the velocity and the pressure at the inlet and outlet pipe section, respectively, are obtained by the developed MOC vapor–cavity model as the boundary conditions (Figure 8) of the pipe element to be analyzed. The time step is 0.2778 s, running 100 steps, and the solution to each step is until 800 iterations. After numerical simulations of the CFD model, the volumes of intrusion and leakage during each transient event can be estimated in order to quantify the potentiality of the pathogen contamination that can occur in drinking water pipe systems.

ANALYSIS OF RESULTS

Intrusion and leakage

Velocities and flows through the leak in the pipe are the results of the previously described CFD analysis, allowing

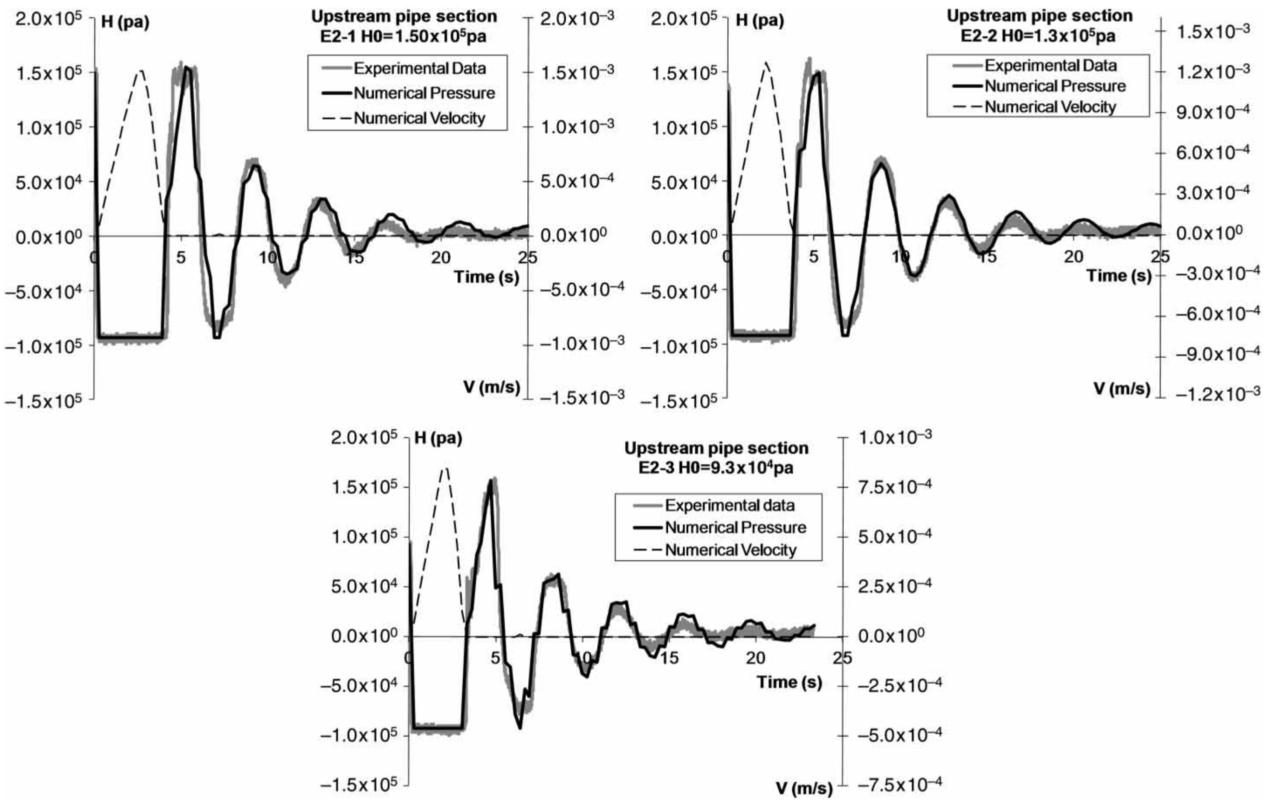

Figure 8 | Adjustment of vapor–cavity MOC model to the experiments in the three scenarios.

the quantification of the volume of intrusion and leakage. Those values are compared with the experimental data obtained in the laboratory tests during the transient occurrence in the three stated scenarios as presented in Table 2.

Experimental and numerical simulations allow the quantification of the flow through the orifice that exists in the main pipe, associated with the mixture between external incoming flow and the circulating one. Flows and the velocities through the orifice are shown in Figure 9. The values of the intrusion and the leakage flow, both numerical simulations, and experimental tests are depicted. The velocity and the flow are positive when the pipe is leaking, while these values are negative when the intrusion occurs.

The velocities in the three scenarios present similar maximum values, even for different initial pressure. A joint evaluation of the velocity at the leak orifice for the three scenarios (Figure 10) was performed. Regarding the velocity behavior it can be seen that the lower the initial pressure, the shorter the period of velocity oscillations.

Determination of intrusion and leakage volumes

The intrusion and leakage volumes can be calculated based on the velocity and pressure fields through the orifice (López *et al.* 2010). In the laboratory case, the intrusion and leakage volumes have been obtained from images captured from a film (slow motion) performed during the experimental tests. Figure 11 shows the difference level generated in the intrusion tank simulating the external fluid of a possible contamination. The intrusion can be estimated based on the difference between the extreme water levels, i.e., the maximum and minimum values induced by the pressure variation occurred during the transient event. Knowing the geometric characteristics of the intrusion tank, the maximum volume is then quantified.

In Figure 12, the flow volumes for both intrusion and leakage associated with the three transient events analyzed are then observed. The intrusion volumes are 1.6×10^{-3}, 1.4×10^{-3}, and 1.1×10^{-3} m^3 for the scenarios $H_0 = 1.5 \times 10^5$, 1.3×10^5, and 9.3×10^4 pa, respectively. The maximum leak volume is around 7.0×10^{-4} m^3, a quite similar value

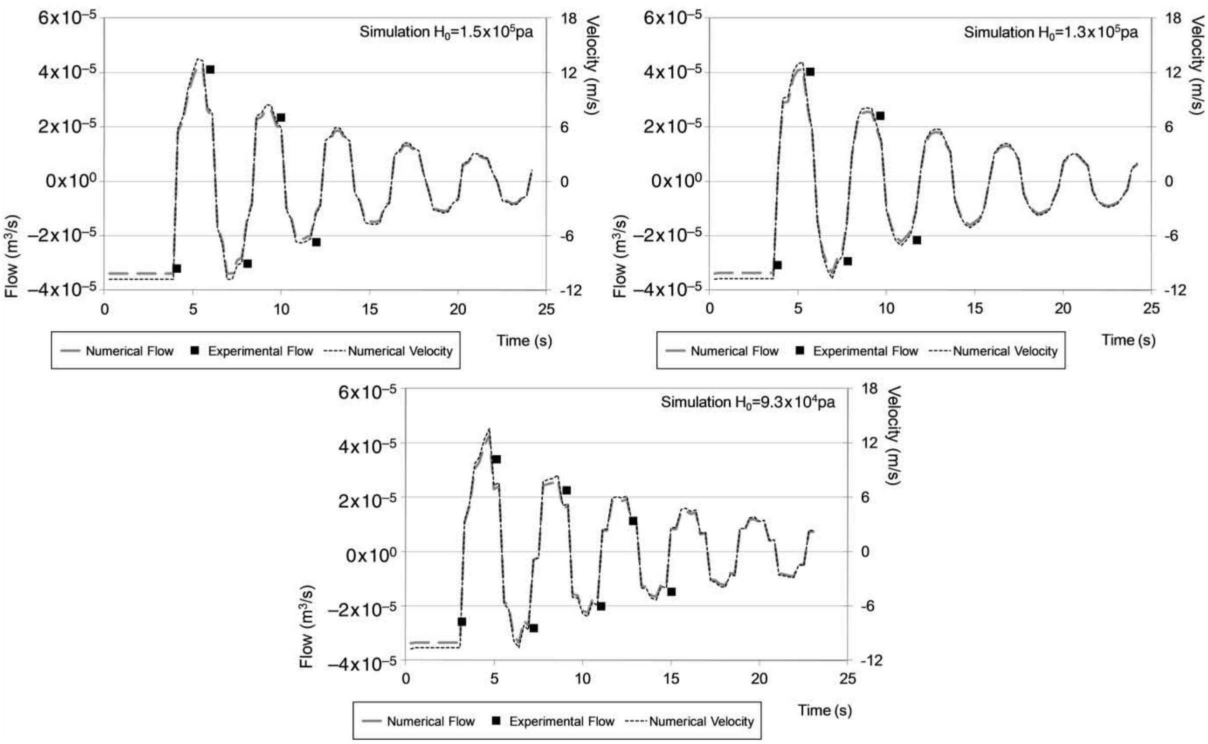

Figure 9 | Velocity and flows through the orifice in the three scenarios.

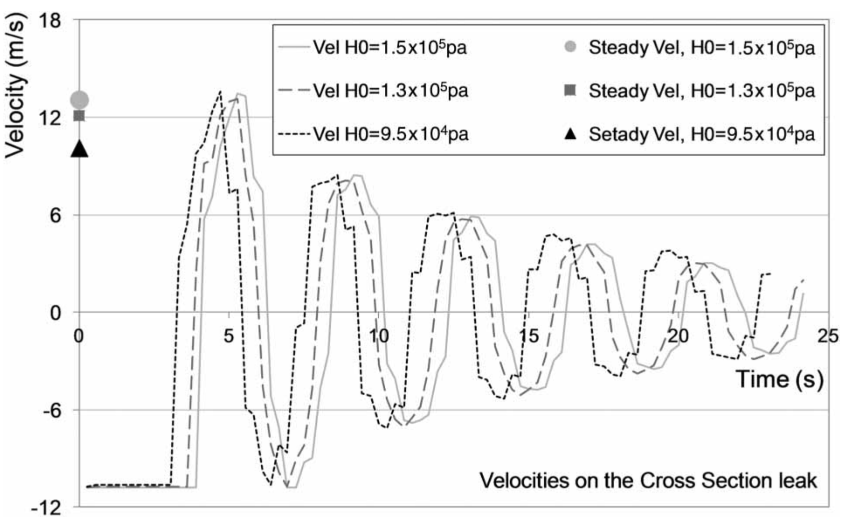

Figure 10 | Velocities of the flow through the leak orifice in the three scenarios.

for all analyzed scenarios. In the same figure, the accumulated volumes during the time are also shown. Simulated values by the CFD model are compared with experiments allowing the validation of the magnitude in the flow variation. Scenarios $H_0 = 1.5 \times 10^5$, 1.3×10^5 pa are more accurate than the 9.3×10^4 pa scenario.

Figure 13 illustrates the good validation between experimental and computational results. The flow, both

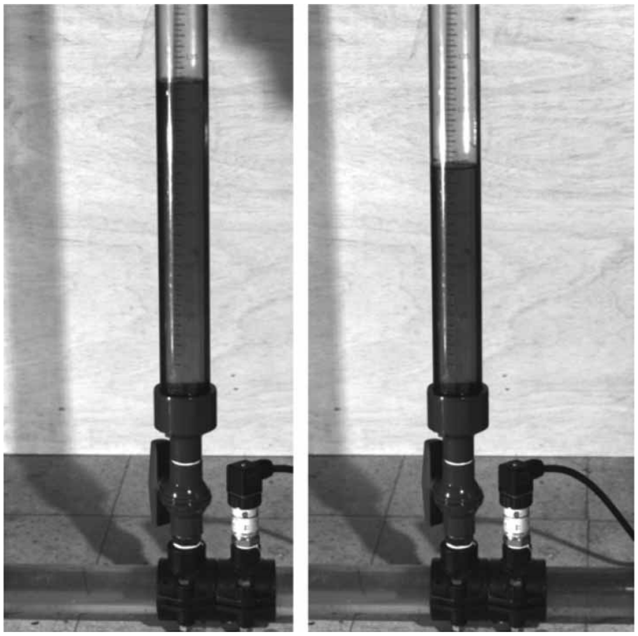

Figure 11 | Experimental water level variation in the intrusion tank.

positive and negative, through the leak can therefore be quantified. In these experiments, the quantification of the total intrusion volume during the transient resulted in an intrusion of 2.6% of the steady-state flow in the main pipe. This value seems small compared to the experimental scale used in the laboratory set-up, but can represent a crucial possible pollution source in real drinking water systems.

CONCLUSIONS

This study presents the problem of the intrusion and leakage volumes in a trunk main pipe of drinking pipe systems associated with pressure variations. Three scenarios are tested for different initial pressure heads at upstream imposed by a tank (air-vessel) under laboratory conditions. These conditions, matching the circumstances of a pressure drop in the tested pipe system, along with the presence of a small leak, are analyzed. A fluid pollutant around failures can induce pathogen intrusion and, consequently, drinking water contamination. Regarding the potential contamination of surrounding water mains, the introduction of an external volume containing only a small amount of bacteria,

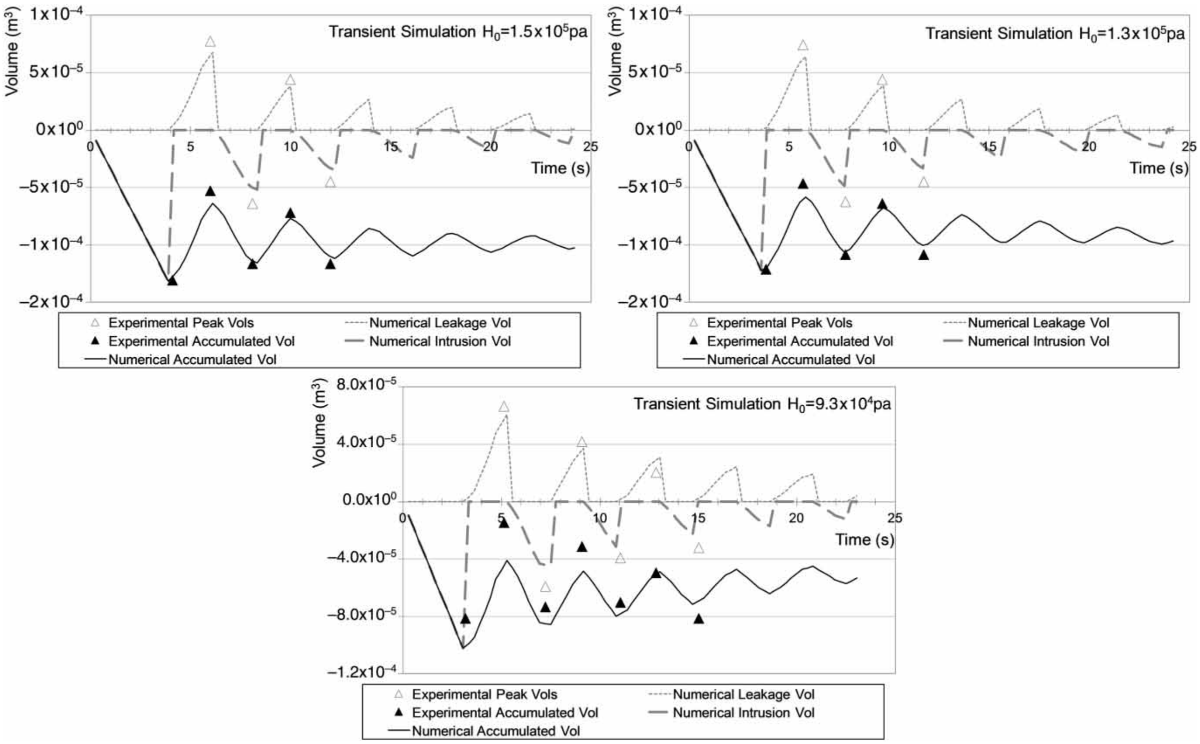

Figure 12 | Numerical and experimental volume variation through the leak orifice.

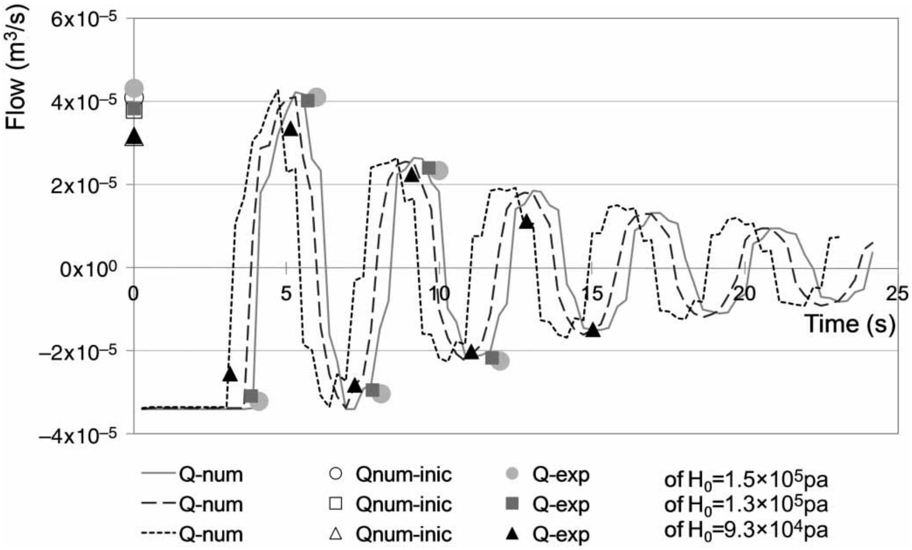

Figure 13 | Comparisons of the numerical and experimental orifice (pipe failure) flow.

protozoa, or viruses could lead to a significant level of risk for public health, as documented in the consulted studies.

The described analysis includes numerical and experimental modeling through a small orifice in a trunk main pipe. Two computational techniques are combined and applied to the phenomenon of pathogen intrusion: on one hand, the relationship between the flow on the pipe considering a leak orifice with the pressure variation (generated by the MOC), and on the other hand, CFD-3D is used to model the intrusion volume through the leak orifice, under transient conditions for the pressure and velocity obtained previously by the MOC model.

The estimation of the discharge flow, such as intrusion and leakage volumes, is analyzed in an innovative way. This analysis is useful for assessing the total volume of a possible contamination from the external soil envelope of a drinking water system even under normal operating conditions. The volume of contamination can be small, especially in small orifices with a short-term pressure variation, or quite significant, in abrupt pressure changes occurring frequently in a pumping system.

An important contribution of this work is also the way used to quantify the volume of intrusion and the leakage occurrence during a pressure variation event. A laboratory campaign developed, allowed authors to validate the results generated by the mathematical modeling, accounting for, at least, 60% of the external volume of pollutants during the transient of 9.3×10^4 N/m^2 and 70% for the transient 1.5×10^5 N/m^2. These results can be considered as a basis for establishing to what degree an intrusion can contaminate a pipe system network. For the developed analysis, the volume of intrusion represented 2.6% of the flow in the rated pressure conditions, a significant potential source of external pollution in potable water pipe systems.

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REFERENCES

Bergant, A., Tijsseling, A., Vítkovský, J., Covas, D., Simpson, A. & Lambert, M. 2003 Further investigation of paramenters affecting water hammer wave attenuation, shape and timing part 1: Mathematical tools. Proceedings of the 11th *International Meeting of the IAHR Work Group on the*

Behaviour of Hydraulic Machinery under Steady Oscillatory Conditions, Stuttgart, Germany, p. 12.

Besner, M. C. 2007 Risk Evaluation of Drinking Water Distribution System Contamination due to Operation and Maintenance Activities. PhD Dissertation, Université de Montreal, Quebec, Canada, 272pp.

Besner, M. C., Broseus, R., Lavoie, J., Di Giovanni, G., Payment, P. & Prévost, M. 2010 Pressure monitoring and characterization of external sources of contamination at the site of the Payment drinking water epidemiological studies. *Environ. Sci. Technol.* **44** (1), 269–277.

Besner, M. C., Prévost, M. & Regli, S. 2011 Assessing the public health risk of microbial intrusion events in distribution systems: conceptual model, available data, and challenges. *Water Res.* **45** (3), 961–979.

Blackburn, B. G., Craun, G. F., Yoder, J. S., Hill, V., Calderon, R. L., Chen, N., Lee, S. H., Levy, D. A. & Beach, M. J. 2004 Surveillance for waterborne-disease outbreaks associated with drinking water-United States, 2001–2002. *MMWR Surveill. Summ.* **53** (SS08), 23–45.

Borga, A., Ramos, H., Covas, D., Dudlick, A. & Neuhaus, T. 2004 Dynamic effects of transient flows with cavitation in pipe systems. *Proceedings of the 9th International Conference on Pressure Surges – The Practical Application of Surge Analysis for Design and Operation*, bHrGroup – The Fluid Engineering Centre, Chester, UK, pp. 24–26.

Boyd, G., Wang, H., Britton, M., Howie, D., Wood, D., Funk, J. & Friedman, M. 2004 Intrusion within a simulated water distribution system due to hydraulic transients I: Description of test rig and chemical tracer method. *J. Environ. Eng. ASCE* **130** (7), 774–777.

Burn, S., DeSilva, D., Eiswirth, M., Hunaidi, O., Speers, A. & Thornton, J. 1999 Pipe leakage – future challenges and solutions. *Proceedings of the Conference 'Pipes Wagga Wagga'*, Wagga Wagga, Australia.

Covas, D., Ramos, H., Young, A. & Jon, D. 2005 Transient pressure in water pipe systems. Edicao especial (special issue in pressure transients) da revista Recursos Hidricos. *APRH* **26** (2), 69–79.

Fleming, K. 2007 Susceptibility of PWS to negative pressure transients. *Conference, VA AWWA Research Committee Seminar*. Available from: http://www.vaawwa.org/files_PDFs/2007resrch_fleming.pdf (last accessed January 2012).

Friedman, M., Radder, L., Harrison, S., Howie, D., Britton, M., Boyd, G., Wang, H., Gullick, R., LeChevallier, M., Wood, D. & And Funk, J. 2004 *Verification and Control of Low Pressure Transients in Distribution Systems*. American Water Works Association Research Foundation, Denver, CO.

Hu, Y. & Hubble, D. 2007 Factors contributing to the failure of asbestos cement water mains. *Can. J. Civil Eng.* **34**, 608–621.

Hunter, R. M., Chalmers, P. R., Hughes, S. & Syed, Q. 2005 Self-reported diarrhea in a control group: a strong association with reporting of low-pressure events in tap water. *Clin. Infect. Dis.* **40** (4), e32–e34.

Karim, M., Abbaszadegan, M. & LeChevallier, M. 2003 Potential for pathogen intrusion during pressure transients. *J. Am. Water Works Assoc.* **95** (5), 134–146.

Kirmeyer, G. J., Friedman, M., Martel, K., Howie, D., LeChevallier, M., Abbaszadegan, M., Karim, M., Funk, J. & Harbour, J. 2001 *Pathogen Intrusion into the Distribution System*. AWWA Research Foundation and the American Water Works Association, Denver, CO.

LeChevallier, M., Gullick, R., Karim, M., Friedman, M. & Funk, J. 2003 The potential for health risks from intrusion of contaminants into the distribution systems from pressure transients. *J. Water Health* **1**, 3–14.

LMNO Engineering, Research, and Software, Ltd © LMNO Engineering, Research, and Software, Ltd. Ohio USA, 1999–2007 Available from: http://www.lmnoeng.com/Weirs/vweir.htm.

López, A., Fuertes, V., Iglesias, P. & Martínez, J. 2005 Modelación mediante cfd de fugas en tuberías de redes de abastecimiento. *Proceedings of the V Seminario Iberoamericano de planificación, proyecto y operación de sistemas de abastecimiento de agua*. Valence, Spain.

López, A., Martínez, J., López, G. & Fuertes, V. 2006 Análisis de la problemática de calidad de los abastecimientos: desde la planta de tratamiento hasta el grifo. V Congreso Ibérico sobre Gestión y Planificación del Agua, Portugal.

López-Jiménez, A., Mora-Rodriguez, J., Fuertes-Miquel, V. & Platero-Gaona, C. 2010 Modeling external pathogen intrusion in pipes during pressure transients. First European IAHR Congress, Edinburgh, UK.

May, J. 1994 Pressure-dependent leakage. *World Water Environ. Eng.* October, 10.

McInnis, C. 2004 A relative-risk framework for evaluating transient pathogen intrusion in distribution systems. *Urban Water J.* **1** (2), 113–127.

Mora, J. 2011 Modeling Pathogen Intrusion Across Failures and Implications in Water Distribution System Networks. PhD Dissertation, Universitat Politècnica de Valencia, Spain, 337p.

Mora, J., López, A., Delgado, X. & Alonso, C. 2008 Estudio sobre la modelación de defectos en tuberías. *Proceedings of the VIII Seminario Iberoamericano, Alterações climáticas e gestão da Água e Energia em Sistemas de Abastecimento e drenagem*, SEREA, Lisboa, Portugal.

Mora-Rodriguez, J., Lopez-Jimenez, A. & Ramos, H. 2011 Intrusion problematic during water supply systems' operation. *Int. J. Energy Environ.* **2**, 391–400.

NRC (National Research Council – Committee on Public Water Supply Distribution Systems: Assessing and reducing risks) 2006 *Public Water Supply Distribution Systems: Assessing and Reducing risks*. National Accademy of Sciences, Washington DC, USA.

Nygard, K., Wahl, E., Krogh, T., Tveit, O. A., Bohleng, E., Tverdal, A. & Aavitsland, P. 2007 Breaks and maintenance work in the water distribution systems and gastrointestinal illness: a cohort study. *Int. J. Epidemiol.* **36** (4), 873–880.

O'Day, K., Weiss, R., Chiavari, S. & Blair, D. 1986 *Water Main Evaluation for Rehabilitation/Replacement*. AwwaRF & US-EPA, Denver, CO.

Rajani, B. & Kleiner, Y. 2001 Comprehensive review of structural deterioration of water mains: physical based models. *Urban Water* **3** (3), 151–164.

Ramos, H., Borga, A., Bergant, A., Covas, D. & Almeida, A. 2005 Analysis of surge effects in pipe systems by air release/venting. Edicao especial (special issue in pressure transients) da revista Recursos Hidricos. *APRH* **26** (2), 45–55.

Ramos, H., Borga, A., Covas, D. & Loureiro, D. 2004 Surge damping analysis in pipe systems: modelling and experiments. (Effet d'atténuation du coup de bélier dans les systèmes de conduits: modelation mathematique et experiences). *J. Hydraul. Res.* **42** (4), 413–425.

Teunis, P. F. M., Xu, M., Fleming, K., Yang, J., Moe, C. L. & LeChevallier, M. 2010 Enteric virus infection risk from intrusion of sewage into a drinking water distribution network. *Environ. Sci. Technol.* **44** (22), 8561–8566.

Wiggert, D., Hatfield, F. & Stuckenbruck, S. 1987 Analysis of liquid and structural transients by the method of characteristics. *J. Fluid. Eng.-T ASME* **109** (2), 161–165.

Wu, S., Hrudey, S., French, S., Bedford, T., Soane, E. & Pollard, S. 2009 A role for human reliability analysis (HRA) in preventing drinking water incidents and securing safe drinking water. *Water Res.* **43**, 3227–3238.

Zloczower, N. & Kibbutz, C. 2009 Control of transient induced contaminant leakage and infiltration by implementation of air valves. *Proceedings of the Water Environment Federation*. Collection Systems. 29, 164–192. Available from: http://dx.doi.org/10.2175/193864709793847140.

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