

# Experimental Evidence of Leaks in Elastic Pipes

Mauro De Marchis<sup>1</sup> · Chiara M. Fontanazza<sup>1</sup> ·  
Gabriele Freni<sup>1</sup> · Vincenza Notaro<sup>2</sup> · Valeria Puleo<sup>2</sup>

Received: 7 September 2015 / Accepted: 4 February 2016 /

Published online: 13 February 2016

© Springer Science+Business Media Dordrecht 2016

**Abstract** Several studies have been carried out in recent decades to establish a relationship between total head and leaks. In literature, the leakage governing equations have been analysed in light of pipe materials, water head, leak dimension or shape. Most of these contributions questioned the classical Torricelli equation, demonstrating through experimental evidence that the classical orifice law can give unsatisfactory results. Nevertheless, starting from the Torricelli equation, other exponential or linear governing equations have been proposed as mathematical models able to reproduce the leakages in water distribution systems (WDSs). To investigate the validity of the proposed governing equations, an experimental campaign was carried out by means of a water distribution network composed of approximately 500 m of polyethylene pipes. The experiments were designed to investigate the effects of leak area and pipe rigidity on discharge. Furthermore, the effect of leak size enlargement with water head was analysed. Finally, the proposed research contributes to the population of a database for estimating the coefficients of head-discharge relationships.

**Keywords** Elastic pipes · Experiment · Laboratory tests · Head-leakage formula · Leaks · Water distribution network

## 1 Introduction

For efficient and sustainable water resources management, the reduction of water losses in water distribution systems (WDSs) represents a focal issue. Leakages reduce the hydraulic performance of WDSs and could cause considerable damage to buildings and infrastructures

---

✉ Vincenza Notaro  
vincenza.notaro@unipa.it

<sup>1</sup> Faculty of Architecture and Engineering, University of Enna “Kore”, Cittadella Universitaria, 94100 Enna, Italy

<sup>2</sup> Department of Civil, Environmental, Aerospace, Materials Engineering, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy

located in the area around the leaking pipe. Moreover, in the presence of low or negative pressure in the distribution network, leaks represent vulnerable points of interaction between the environments inside and outside the pipe, thus allowing contaminant intrusions (Lindley and Buchberger 2002; Collins and Boxall 2013; Mora-Rodriguez et al. 2014; Fontanazza et al. 2015). These operational conditions are accentuated in systems with intermittent supply (De Marchis et al. 2010, 2011; Freni et al. 2014), where water network experienced cyclically emptying and filling process and, as a result, pipes integrity could be further compromised.

The scientific and technical contribution to understand the hydraulics of leakages, their detection and reduction is extensive (see Puust et al. 2010 for a review). The behaviour of pipe material and the type of crack can affect the leak outflow, whereas no evidence of influence of the surrounding soil is shown by several experimental results (Walski et al. 2006; van Zyl and Clayton 2007; van Zyl et al. 2013; Bailey and van Zyl 2015). On the contrary pressure is one of the most significant factors influencing leakages in WDSs (Lambert 2002; Farley and Trow 2003; van Zyl and Clayton 2007), thus active pressure control management is widely considered a cost-effective way to reduce losses in the short term (Walski et al. 2006).

Numerical models are often applied for the leakages assessment and control (Almandoz et al. 2005; Walski et al. 2006; Tabesh et al. 2008; Karadirek et al. 2012; Ferrante et al. 2014). Therefore defining reliable and accurate relationship between leak outflow and network operational conditions is essential. Various studies about head-dependent leakage modelling in a main pipe can be found in the literature as reported in the following section. Namely, the recent research was focused on the analysis of the behavior of different types of leak openings (e.g. round holes, longitudinal and circumferential cracks) in pressurized pipes made of different materials (uPVC, steel, cast iron, polyethylene, etc.). Major findings were in the definition of the governing leak equations for elastic pipes, which differ from those of the rigid pipes due to the leak-area deformation.

Despite the great efforts to develop accurate leakage modelling formulas, the search for a unifying theory is still open and further research is needed. In particular, the governing equation and related parameters of a leakage formula have to be better analysed in elastic pipes with small diameter (such as the secondary pipes in a WDSs) in order to estimate the actual leak discharge.

The present study aims at contributing to current research by showing the results of an experimental analysis reproducing longitudinal leaks, with variable sizes, in a secondary pipe of a WDS. Small pipes were in fact neglected in previous research that was focused on main pipes even if secondary pipes largely represent the most part (in length) of WDSs and those more frequently affected by background undiscovered leakages. The experimental setup is a looped distribution network made up of high-density polyethylene pipes with diameter equal to 63 mm, which can simulate an actual secondary looped network of an urban supply system. Several tests were carried out to simulate different operational conditions in terms of head boundary values and pipe material rigidity.

## 2 State-of-the-Art of the Head-Leakage Relationship

Frequently, a leak is modelled by means of the well-known Torricelli equation:

$$Q_L = C_L A_L \sqrt{2gH} \quad (1)$$

where  $Q_L$  [ $\text{m}^3/\text{s}$ ] is the leak outflow;  $C_L$  is the non dimensional discharge coefficient;  $A_L$  [ $\text{m}^2$ ] is the orifice (leak) area;  $C_L A_L$  represents the leak effective area;  $g$  [ $\text{m}/\text{s}^2$ ] is the gravity acceleration;  $H$  [ $\text{m}$ ] is the water head.

More recently, the International Water Association (IWA) water loss task force (e.g., Thornton 2003), proposed a power equation given by:

$$Q_L = a_I H^{b_I} \quad (2)$$

The parameter  $a_I = C_L A_L \sqrt{2g}$  can be related to the effective leak area at zero pressure  $A_{E0} = C_L A_L$  [ $\text{m}^2$ ].

Field studies have shown that the sensitivity of the leakage rate  $Q_L$  [ $\text{m}^3/\text{s}$ ] to total head  $H$  [ $\text{m}$ ] (expressed by  $b_I$ ) can be significantly larger than 0.5 and typically varies between 0.5 and 2.79, with a mean value of 1.15 (Farley and Trow 2003). The value of the exponent  $b_I$  depends on leak type and pipe material behaviour (Greyvenstein and van Zyl 2007; Collins and Boxall 2013). The orifice equation can lead to misleading results when the pipe is not made of a rigid material and pressure-induced deformation of the leak area is not considered (Greyvenstein and van Zyl 2007; Cassa et al. 2010; Ferrante et al. 2011, 2013).

Greyvenstein and van Zyl (2007) presented a basic model for the flow rate,  $Q_L$  [ $\text{m}^3/\text{s}$ ] through a round hole in an elastic pipe after carrying out extensive laboratory tests on different pipe materials (uPVC, asbestos cement and steel). The authors proposed a relationship (not shown here), more complex than Torricelli Formula (Eq. 1), given by the sum of three terms where total head  $H$  exponents are 0.5, 1.5 and 2.5, respectively, which better fitted field and experimental observations.

Cassa et al. (2010) investigated the behaviour of different types of leak openings (round holes, longitudinal and circumferential cracks) in pressurised pipes for different pipe materials (uPVC, steel, cast iron and asbestos cement) using finite element analysis, and the following relationship was proposed:

$$Q_L = a_c H^{0.5} + b_c H^{1.5} \quad (3)$$

where  $a_c = A_{E0} \sqrt{2g}$  and  $b_c = m \sqrt{2g}$ , with  $m$  [ $\text{m}$ ] being the head-area slope.

Although May (1994) stated that some leaks have a fixed area (exponent equal to 0.5) and others a variable area (exponent equal to 1.5), the relationship proposed by Cassa et al. (2010) assumes that all of the leaks have an area that varies linearly with pressure.

Recently, Ferrante (2012) analysed some experimental results related to leaks in steel and polyethylene pipes. The experimental data were analysed by means of different leak head-discharge relationships according to pipe material and thickness. The results revealed a strong correlation between leak area deformation and water head in the pipe as well as a correlation between the stresses and strains of the pipe wall. Correlation is also evident when plastic deformations occur in the pipe or when viscoelastic effects take place. Because plastic deformation depends on the time history of the stresses in the pipe, this dependence should be taken into account in the leak head-discharge relationship as well.

Cassa and van Zyl (2013) investigated the head-leakage outflow relationship in pipes with linear elastic behaviour by considering longitudinal, spiral and circumferential cracks. The authors analysed the effects of the orientation, length and width of cracks; pipe material properties; pipe internal diameter; and wall thickness on the behaviour of each crack. The authors formulated an equation to predict the responses of different cracks to variations in

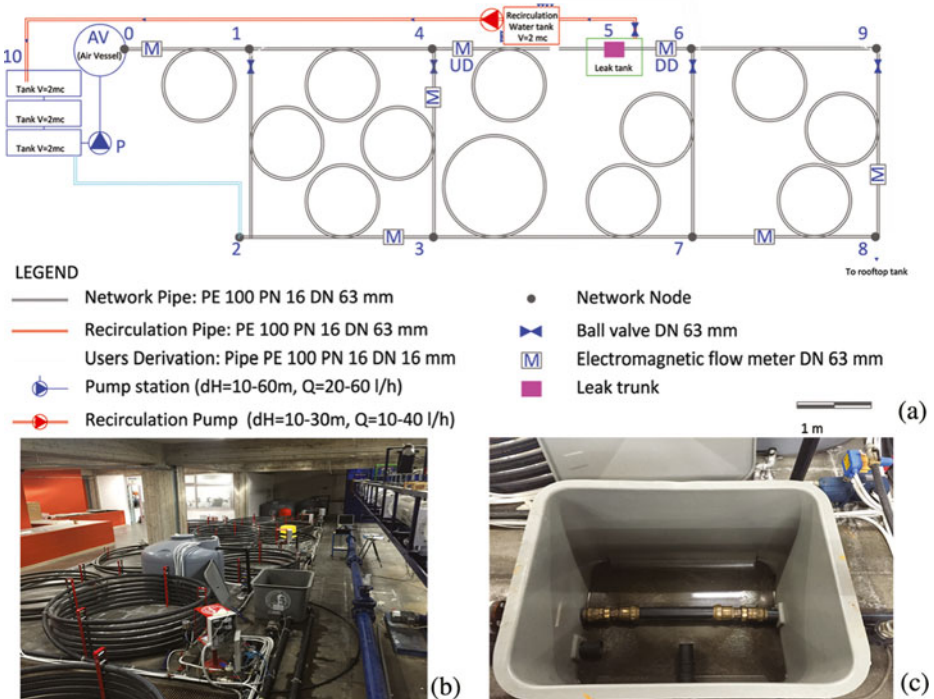
pressure. Afterward, van Zyl and Cassa (2014) proposed a dimensionless Leakage Number, defined as the ratio between the variable and fixed area of a leak, and found a single function to describe the relationship between the Leakage Number and the leakage exponent of the power relationship (Eq. 2).

The previously discussed formulations show the great effort of researchers on the definition of accurate formulations of leak outflow in order to obtain reliable leakage modelling. However, nowadays a unifying theory aiming at leakages modelling was not still defined and further experimental tests are needed in order to better investigate the interactions between leak, water head and pipe material behaviour.

### 3 Experimental Setup

The tests were carried out at the Environmental Hydraulic Laboratory of the University of Enna (Italy), using a high-density polyethylene (HDPE 100) looped distribution network with Pressure Nominal equal to 16 bar (PN16). It has three loops, nine nodes and eleven pipes (DN 63 mm, thickness 5.8 mm and approximately 45 m long) arranged in almost horizontal concentric circles with bends having a radius of 2.0 m, thus ensuring that form-resistance losses due to pipe bend can be neglected (see Fig. 1a, b).

Four pumps (P) supply the needed discharge from the water tanks to the upstream air vessel (AV), which behaves as a constant head tank, keeping the pressure at the inlet node of the



**Fig. 1** a Layout of the experimental water distribution network; b Overview of the water distribution network; c Leak trunk

network constant and equal to a prescribed value by varying the speed of the pumps (total water head ranging from 10 to 60 m). The experimental setup aims at simulating the operational condition of an actual secondary pipe network.

The system is monitored by electromagnetic flow metres and pressure cells and multi-jet water metres installed at each node position. Four hand-operated ball valves are installed in pipes 1–2, 4–3, 6–7, 10–9, to control the flow in each loop.

In order to simulate the presence of a leak in pressurised pipe systems a small portion of pipe 4–6 can be replaced with a leak trunk, approximately 70 cm long (see node 5 in Fig. 1a and c). The leak discharges into a free surface tank. Thus, the experimental facility permits to easily simulate leaks with different shapes and sizes as well as the behaviour of different pipe materials by simply substituting the leak trunk. Thanks to a recirculation system, the leak discharges are pumped to supply water tanks.

To evaluate the water volume lost, two electromagnetic flow metres, with measurement accuracy of 0.4 %, were placed 1 m upstream (UD) and downstream (DD) of the leak trunk. The pressure was measured by means of a piezoresistive pressure transducer ( $p_1$ ), with a 6-bar full scale (f.s.) and an accuracy of 0.1 % f.s. located approximately 1 m upstream of the leak. Data from  $p_1$  were used to evaluate the time history of water head values. At the same position as the  $p_1$ , another pressure cell ( $p_2$ ) was installed to exclude measurement errors. Correct calibration of the instruments was checked before each tests.

Here, attention was first focused on leakages having the same geometrical shape but different width and length, then on polyethylene with different rigidity (i.e., different nominal pressure, PN). To this aim 12 different leak trunks with cracks rectangular in shape and oriented in the longitudinal direction were tested.

To evaluate the relationship between the leak outflow and the water head, several experiments were carried out. Namely, the effect of the crack width on the water head-leakage discharge relationship (especially on the leakage exponent above all) was analysed and the plastic deformation in the pipe due to variations in water head was examined. To this aim, three sets of experiments were carried out. In each set, four leaks, with different lengths, were considered.

The first set (1st set) of tests was carried out using pipes with PN 16 bar and simulating four longitudinal cracks having width equal to 1.5 mm and lengths equal to 20, 50, 80 and 110 mm, respectively. The same tests were also carried out with a different material rigidity (2nd set) and crack width (3rd set). The second set of tests used a PN 6 bar; the third set of tests differed from the first in the crack width, which was equal to 5 instead of 1.5 mm. For the sake of clarity, in Table 1, the pipe and crack properties adopted for the experiments are summarised.

To analyse the variation of the leak discharging with respect to the water head upstream of the leak, for each tested leaking pipe, the network boundary conditions were changed. In particular, the head at the inlet node of the network was modified by means of the pump station from 1.0–5.5 bar, with a step of 0.5 bar.

For all the experiments the leak discharge ( $Q_L$ ) and the water head upstream of the simulated leak ( $H$ ) were acquired simultaneously with a sampling frequency of 0.2 Hz. Measurements were collected starting 5 minutes after the beginning of the experiment, thus ensuring steady-state conditions for water head and leak discharge. In the following, the experimental results are reported and discussed.

**Table 1** Details of the pipe and leak characteristics for the three sets of experiments

	No.	Test case	Pipe			Crack		
			Nominal Pressure (bar)	Internal diameter (mm)	Wall thickness (mm)	Length (mm)	Width (mm)	$A_L/A_P$
1st set	1	TC1-1	16	51.4	5.8	20	1.5	0.014
	2	TC1-2	16	51.4	5.8	50	1.5	0.036
	3	TC1-3	16	51.4	5.8	80	1.5	0.057
	4	TC1-4	16	51.4	5.8	110	1.5	0.079
2nd set	1	TC2-1	6	55.8	3.6	20	1.5	0.012
	2	TC2-2	6	55.8	3.6	50	1.5	0.031
	3	TC2-3	6	55.8	3.6	80	1.5	0.049
	4	TC2-4	6	55.8	3.6	110	1.5	0.067
3rd set	1	TC3-1	16	51.4	5.8	20	5.0	0.047
	2	TC3-2	16	51.4	5.8	50	5.0	0.119
	3	TC3-3	16	51.4	5.8	80	5.0	0.190
	4	TC3-4	16	51.4	5.8	110	5.0	0.261

$A_L$  leak area,  $A_P$  pipe cross-sectional area

## 4 Experimental Results

In Fig. 2, the leak discharge  $Q_L$  [ $\text{m}^3/\text{s}$ ] is plotted versus the water head  $H$  [m] for each of the three tests performed to investigate the leak-head discharge relationship (each experiment was repeated twice). As stated before, the plotted data represent the mean values measured in each experiment.

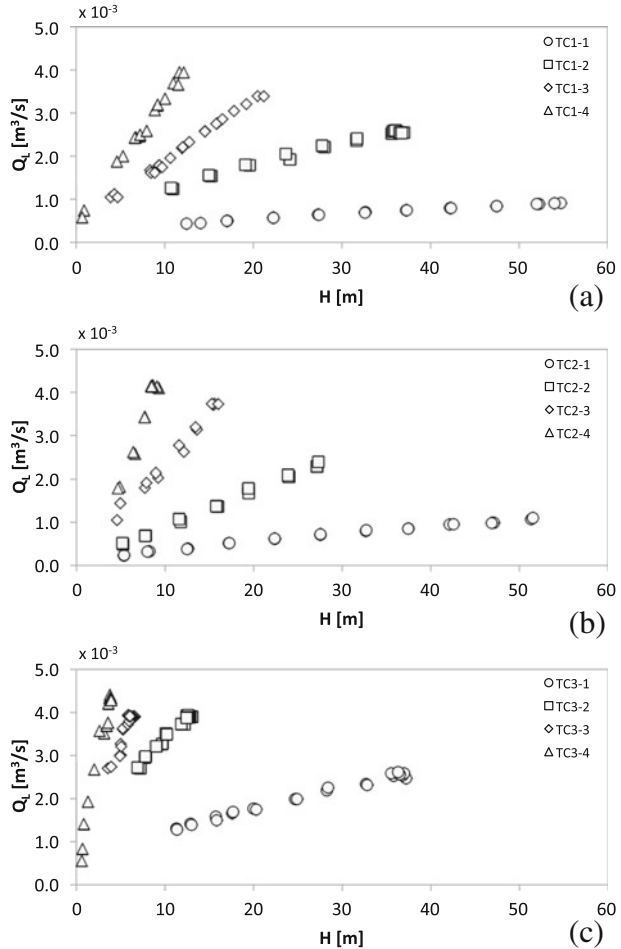
For the smallest leaks tested (TC1-1 and TC2-1, with length equal to 20 mm and width equal to 1.5 mm), the results show low leak discharge,  $Q_L$ , with small increases with the water head  $H$ , due to head losses at the leak caused by the small leak area. Conversely, for larger cracks (longer or wider),  $Q_L$  significantly increases with  $H$  until it reaches a maximum value beyond which  $Q_L$  does not vary even if the head at the network inlet node increases. This is an effect of the high head losses occurring in the network pipes due to the high flow rates caused by the leak.

All of the experiments show that the head-discharge relationship follows a curvilinear trend typical of leakage exponential equations. To better address this issue, the results of each experiment were analysed in light of the leak head-discharge relationships found in the literature and applicable to the specific experiments carried out in the study. To the above mentioned aim, experimental results were analysed in light of the power governing equation (Eq. 2) (hereafter referred to IWA) and the relationship proposed by Cassa et al. (2010) (Eq. 3) (hereafter referred to CAS).

### 4.1 Discussion on the Effect of Pipe Material Rigidity

To investigate the effect of pipe material rigidity on the leak head-discharge relationship the results of the 1st set of tests (PN16, leak width equal to 1.5 mm) and 2nd ones (PN6, leak

**Fig. 2** Data from tests in head-discharge domain: (a) 1st set; (b) 2nd set; (c) 3rd set



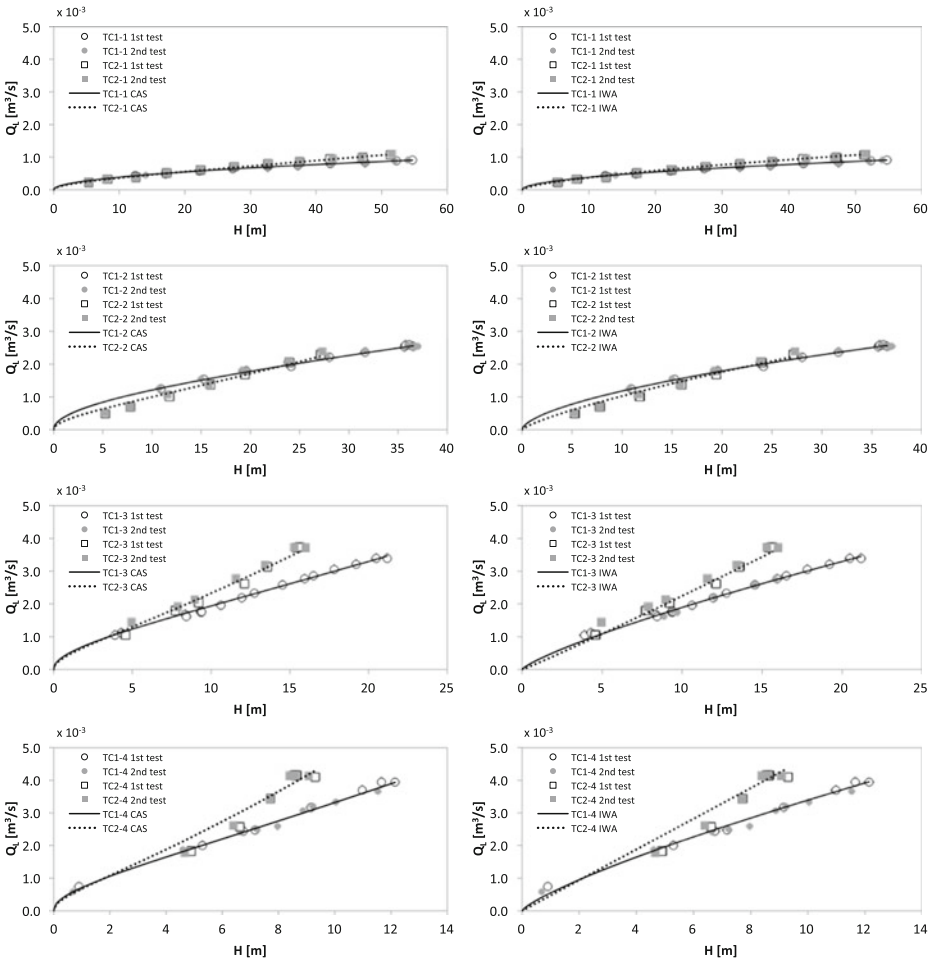
width equal to 1.5 mm) were compared. Figure 3 shows the variation in head-leak discharge for pipe trunks in the 1st and 2nd sets of tests. The experiment was repeated twice; therefore, two points (1st and 2nd test) are plotted.

The figures clearly show a perfect overlap of the experimental data with both the CAS and IWA head-discharge formulas. The leak head-discharge relationships from TC1-1, TC1-2, TC2-1, and TC2-2 are about the same (Fig. 3); whereas the effect of material rigidity becomes evident for bigger cracks: the head-discharge relationship for the 2nd set of tests is still linear but steeper.  $Q_L$  is greater for a given  $H$  because of leak area deformation due to a more elastic pipe material.

These results are coherent with recent literature findings (see Cassa and van Zyl 2013) and suggest that the leak area is a function of water head  $H$ . Specifically, when  $H$  and leak area are greater than a specific value,  $Q_L$  increases with  $H$ . This effect is much more evident for the 2nd set of tests, in which a more elastic material was adopted.

To better address this issue, leak area variation was plotted against  $H$ . Following the research of Ferrante (2012), the effective area  $A_E = C_L A_L$  was considered. It is not trivial to





**Fig. 3** Head-leak discharge variation for pipe trunks belonging to the 1st and 2nd sets

separate the relative contributions of  $C_L$  and  $A_L$  with varying leak dimension and  $H$ .  $A_E$  was calculated according to the relationship  $A_E = Q_L / \sqrt{2gH}$ , as a function of the experimentally measured values  $Q_L$  and  $H$ .

To understand the variation of  $A_E$  with water head  $H$ , two effective area equations were derived by IWA (Eq. 2) and CAS (Eq. 3) relationships. According to Ferrante et al. (2013), the effective area follows a power law like the IWA equation, as follows:

$$A_E = a_{II} H^{b_{II}} \tag{4}$$

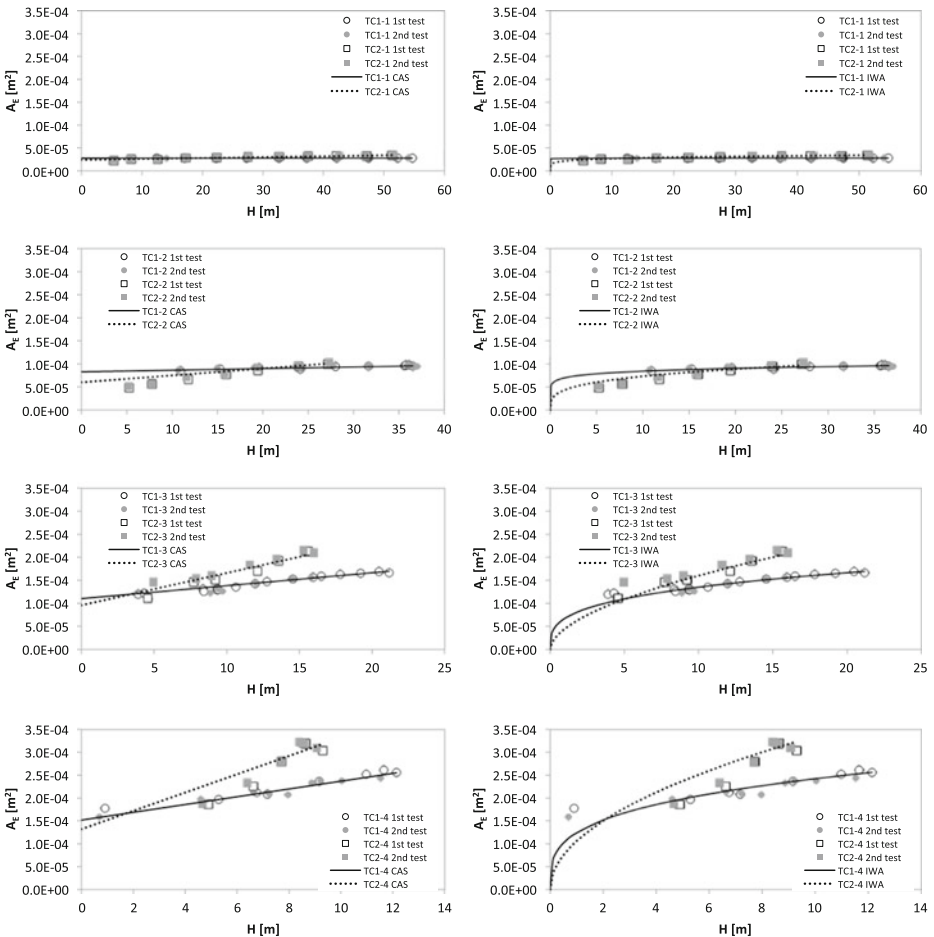
where the coefficients  $a_{II} = \frac{a_I}{\sqrt{2g}}$  and  $b_{II} = (b_I - 0.5)$  are calculated using Eq. (2).

In the CAS equation the effective area varies linearly with the head, as follows:

$$A_E = A_{E0} + mH \tag{5}$$

Figure 4 shows the experimentally determined  $A_E$  values as well as values calculated using IWA and CAS equations.





**Fig. 4** Variation of the effective area with the total head for pipe trunks belonging to the 1st and 2nd sets

Considering leak trunks TC1-1 and TC1-2, the effective area remains constant with respect to water head  $H$ . All data points are horizontally aligned, indicating that upon increasing  $H$ , the leak’s effective area is not affected by deformation. In contrast, increasing the longitudinal dimension of the crack causes very different behaviour, and  $A_E$  is affected by  $H$ .

In the 2nd set of tests, the  $A_E$  remains constant with respect to  $H$  for only the smallest longitudinal leak length simulated, TC2-1. Due to the lower PN or rigidity of the pipe material, the effect of water head on effective area deformation is more evident: increasing the crack dimension increases leak deformation and the slope of the area-head line. Moreover, the CAS equation (Eq. 5) seems to provide an adequate fit to the experimental data from both sets of tests. Only the head-area relationship in TC2-4 shows a linear trend that is not well described by Eq. (5). In Table 2 the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE) and the Mean Bias Error (MBE) are reported for both the discharges ( $Q_L$ ) and the leak area ( $A_E$ ), thus to assess the differences between measured and predicted values.

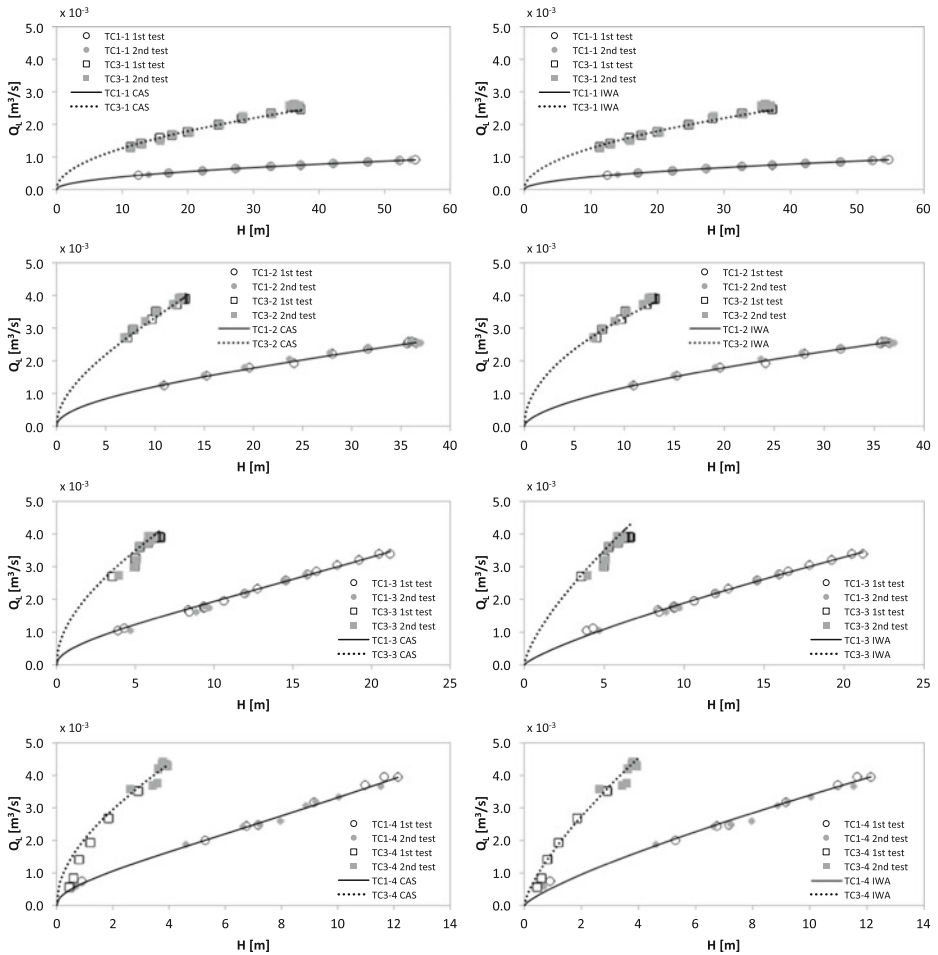
**Table 2** RMSE, MAE and MBE of  $Q_L$  and  $A_E$  calculated by means of CAS and IWA formulations

	RMSE [m <sup>3</sup> /s]		MAE [m <sup>3</sup> /s]		MBE [m <sup>3</sup> /s]	
	$b_c$		$b_c$		$b_c$	
	$b_c$	$b_c$	$b_c$	$b_c$	$b_c$	$b_c$
	$b_c$	$b_c$	$b_c$	$b_c$	$b_c$	$b_c$
TC1-1	4.28E-06	4.11E-06	3.72E-06	3.14E-06	-2.14E-06	-8.92E-07
TC1-2	3.84E-05	3.53E-05	3.41E-05	2.75E-05	-1.28E-05	-4.19E-06
TC1-3	5.68E-05	6.31E-05	4.60E-05	2.75E-05	1.99E-05	-1.26E-06
TC1-4	8.18E-05	1.09E-04	6.59E-05	7.64E-05	2.01E+00	-2.77E-05
TC2-1	2.02E-05	2.40E-05	1.81E-05	2.08E-05	3.02E-07	2.08E-05
TC2-2	1.01E-04	1.10E-04	8.44E-05	9.72E-05	5.45E-05	7.50E-05
TC2-3	1.29E-04	1.07E-04	1.17E-04	9.43E-05	2.81E-05	-4.98E-05
TC2-4	2.79E-04	3.08E-04	2.50E-04	2.56E-04	7.93E-05	1.66E-04
TC3-1	4.39E-05	8.50E-05	9.04E-06	1.60E-05	4.97E-06	3.14E-06
TC3-2	6.69E-05	1.25E-04	3.86E-05	4.87E-05	-1.25E-05	-2.98E-05
TC3-3	1.95E-04	2.76E-04	1.16E-04	1.45E-04	1.16E-04	1.45E-04
TC3-4	4.95E-04	2.00E-04	4.18E-04	1.47E-04	4.18E-04	9.95E-05
	RMSE [m <sup>2</sup> ]		MAE [m <sup>2</sup> ]		MBE [m <sup>2</sup> ]	
	$A_E$		$A_E$		$A_E$	
	CAS	IWA	CAS	IWA	CAS	IWA
TC1-1	1.98E-07	2.19E-07	1.64E-07	1.49E-07	-8.41E-08	-5.72E-08
TC1-2	1.70E-06	1.55E-06	1.52E-06	1.20E-06	-4.59E-07	-1.75E-07
TC1-3	4.00E-06	6.37E-06	3.06E-06	1.73E-06	1.62E-06	3.49E-08
TC1-4	2.69E-03	2.70E-03	6.66E-06	1.11E-05	2.20E+00	-6.07E-06
TC2-1	1.20E-06	1.31E-06	9.32E-07	1.06E-06	1.73E-07	1.06E-06
TC2-2	1.10E-05	8.33E-06	8.66E-06	6.87E-06	8.66E-06	5.88E-06
TC2-3	9.73E-06	6.91E-06	8.52E-06	6.37E-06	3.39E-06	-3.40E-06
TC2-4	2.50E-05	2.79E-05	2.14E-05	2.23E-05	8.30E-06	1.53E-05
TC3-1	3.12E-06	3.31E-06	1.87E-06	8.46E-07	-1.87E-06	3.02E-07
TC3-2	3.36E-03	3.40E-03	2.75E-06	3.43E-06	-1.08E-06	-1.84E-06
TC3-3	3.23E-03	3.30E-03	1.15E-05	1.38E-05	1.15E-05	1.38E-05
TC3-4	1.74E-03	1.80E-03	9.08E-05	5.04E-05	-2.16E-06	4.78E-05

### 4.2 Discussion on the Effect of Leak Size

In the following paragraph, the results from the 1st and 3rd sets of tests are compared to assess the effect of leak size on the head-leak discharge variation relationship. The leaks simulated during the 1st and 3rd sets of tests differ only in leak width, with values equal to 1.5 and 5.0 mm, respectively. For each leak trunk and boundary condition tested, the experiment was repeated twice; therefore, two points (1st and 2nd test) are plotted in Fig. 5, showing the head-leak discharge variation for pipe trunks belonging to the 1st and 3rd sets of tests (TC1 and TC3, respectively in Table 1).

The head-discharge relationship for the 3rd set (Fig. 5) attests to the set's larger leak area (5 mm) than in the 1st set (1.5 mm). The head-discharge relationship for the 3rd set of tests is still linear but is steeper than the trend line fitting the results of the 1st set of tests. The gap

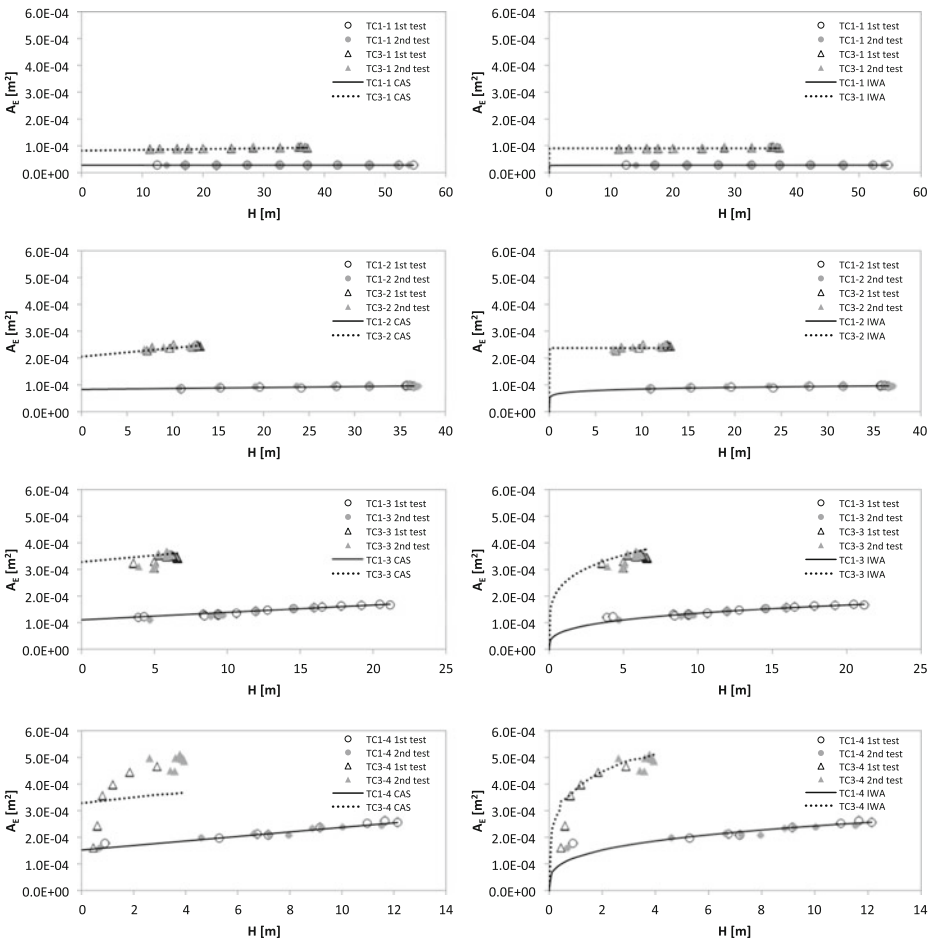


**Fig. 5** Head-leak discharge variation for pipe trunks belonging to the 1st and 3rd sets

between the two curves increases with leak area, most likely because of the deformation of the 5-mm cracks. To investigate this issue, in Fig. 6 the experimental  $A_E$  values are plotted with  $H$  to better understand the effect of leak size on the head-area relationship.

The effective area can be considered constant for the 1st and 3rd sets, considering only the leak trunks TC1-1, TC1-2, TC3-1, and TC3-2 (Fig. 6). All data points are horizontally aligned, indicating that upon increasing the head, leaks are not affected by deformation. The experimental results confirm the validity of the CAS relationship for almost all pipe trunks belonging to the 1st and 3rd sets, in which the head-area relationship seems to be linear for all  $H$  values; only the largest leakage in the 3rd set shows some differences.

TC3-3 and TC3-4 behave in a different way: the trend suggests that a power equation (Eq. 4) would be more appropriate to reproduce the dependence of the leak effective area on water head, according to the recent findings of Ferrante et al. (2013). The head-area relationship for these cracks may be due to the greater deformation effect derived from the larger area (5 mm) as well as modifications to fluid flow caused by the crack side effect.



**Fig. 6** Variation of the effective area with the total head for pipe trunks belonging to the 1st and 3rd sets

### 4.3 Variation of the Parameters of the CAS and IWA Equations with Leak Length

Crack length influences leak deformation due to the internal pressure and consequently the contribution of the fixed area and the deformation term to the leakage discharge. Parameters  $a_c$ ,  $b_c$ ,  $a_I$  and  $b_I$  can be used to examine this contribution. Their values were obtained by fitting, respectively, the IWA (Eq. 4) and CAS (Eq. 5) relationships to the experimental data.

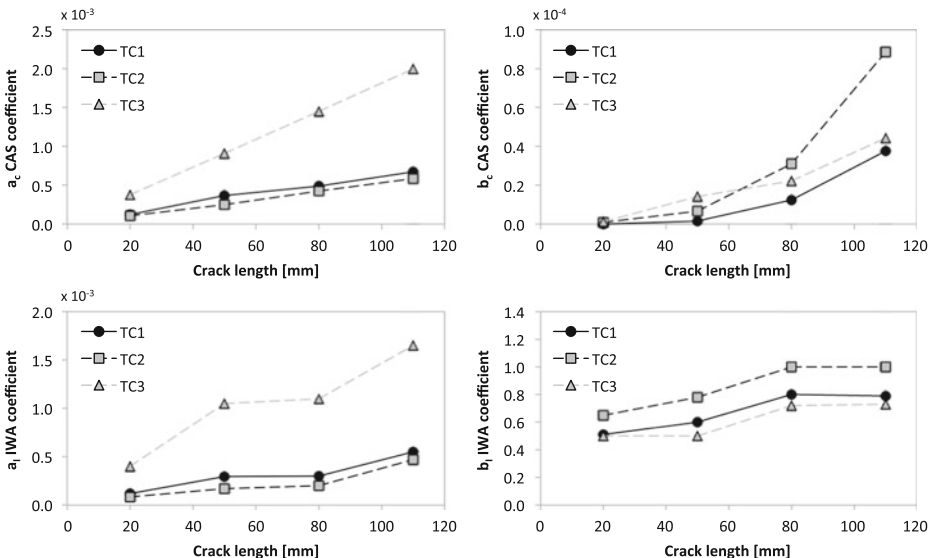
As shown in Table 3 and Fig. 7, the parameter  $a_c$  increases almost linearly with crack length. The slope of the line is approximately the same for the 1st and 2nd sets of tests but is steeper for 3rd set. This result confirms that  $a_c$  represents well the contribution of the fixed leak area to the discharge. Regarding to the share of the leak discharge caused by deformation of the crack area, the coefficient  $b_c$  increases with crack length; its trend is nearly linear, and the trends for longer cracks in the 1st and 3rd sets of tests appear to be parallel. Considering the same leak length,  $b_c$  is higher for the 3rd set than the 1st set, confirming that wider cracks are more deformable; for the 2nd set of tests (adopting the most elastic pipe material),  $b_c$  increases at a greater than linear rate with length and tends to higher values for longer cracks.

**Table 3** Parameters of the CAS and IWA head-discharge relationships

			CAS		IWA	
			$a_c$	$b_c$	$a_I$	$b_I$
1st set	1	TC1-1	0.000122	8.857E-09	0.000119	0.51
	2	TC1-2	0.000367	1.550E-06	0.000296	0.60
	3	TC1-3	0.000489	1.240E-05	0.000300	0.80
	4	TC1-4	0.000672	3.764E-05	0.000550	0.79
2nd set	1	TC2-1	0.000106	8.857E-07	0.000084	0.65
	2	TC2-2	0.000249	6.643E-06	0.000170	0.78
	3	TC2-3	0.000425	3.100E-05	0.000200	1.00
	4	TC2-4	0.000585	8.857E-05	0.000470	1.00
3rd set	1	TC3-1	0.000376	1.240E-06	0.000400	0.50
	2	TC3-2	0.000908	1.417E-05	0.001050	0.50
	3	TC3-3	0.001453	2.214E-05	0.001100	0.72
	4	TC3-4	0.001997	4.429E-05	0.001650	0.73

The coefficient  $a_I$  in the IWA relationship (Eq. 2) behaves like  $a_c$  and shows higher values for the 3rd set of experiments, but the trend of increases with crack length is not linear for all sets. The parameter is constant for 50- and 80-mm cracks and increases in the ranges 20–50 and 80–110 mm. The parameter  $b_I$  deviates from the initial value of 0.5 and increases with crack length, achieving a maximum value of 1.0 for TC2-3 and TC2-4.

Particularly looking at the 3rd set, Fig. 7 shows a strong link between the parameters of the IWA equation:  $a_I$  increases and  $b_I$  remains constant in the range 20–50 and 80–110 mm.  $a_I$ , accounting for the share of the discharge due to the leak area, shows constant values that are higher than in the 1st and 2nd sets. The parameter  $b_I$ , responsible for the impact of the water



**Fig. 7** Variation of the CAS and IWA parameters with crack length

head on the leak discharge, is higher for the 2nd set (in which the pipe trunk material is the most elastic). The 3rd set, which used pipe trunks with a larger area, is less influenced by the water head effect. This effect becomes negligible for cracks longer than 110 mm and achieves its maximum value (equal to 1.0) for the 2nd set.

Finally, the results obtained for experiments carried out with the shortest crack length (20 mm), TC1-1, TC2-1, and TC3-1, suggest that at least for the first experiments, the leak area does not change with water head, thus confirming the validity of the Torricelli equation (Eq. 1). Analysing the values of parameters  $b_c$  and  $b_l$ ,  $b_c$  is almost zero and  $b_l$  is approximately 0.5 for TC1-1 and TC3-1, and a bit higher (0.65) for TC2-1, showing elastic behaviour.

## 5 Conclusions

In this study, the results of an experimental analysis aimed at investigating the head- discharge and head-effective area relationships related to a leakage in a secondary pipe of a WDS were shown. Namely, the effects of differently sized longitudinal cracks were analysed in a small diameter pipe (DN 63 mm) with different Pressure Nominal (PN). The analysis was carried out by means of laboratory experiments on a high-density polyethylene looped distribution network simulating an actual secondary pipe network of an urban WDS. The experiments were repeated at least twice consecutively, achieving the same results. Specifically, the experimental data were fitted by means of two relationships widely applied in literature to analyse leaks in main pipes: the IWA equation and the formulation proposed by Cassa et al. (2010). The results showed that also for small diameter pipes when the crack effective area can be considered constant and does not vary with the water head Torricelli's formula can be used. Conversely, when the leak effective area increases with the head, Torricelli's formula fails but the IWA and CAS equations seem to well reproduce the flow discharging through a leak. The best fitting to the experimental data was observed when the IWA relationship was used. The results also confirmed the elastic behaviour of polyethylene pipes. The hysteretic behaviour observed by Ferrante et al. (2011) was not verified in the performed experiments, most likely because tests were carried out far below the nominal pressure of the pipe, thus not reaching inelastic deformation. The experimental setup in fact aims at simulating the operational condition of a secondary pipe network where total water head usually can range from 10 to 60 m in order to effectively supply water to costumers. The results confirmed that the effect of pipe material rigidity depends on the leak dimension and on the water head upstream of the leak. For high values of total head the leakage effective area varies linearly with head, at least for the tests here presented. Namely, a power equation seems the best choice to reproduce the head-effective area relationship. The present study contributes to the practical optimization of the coefficients in the IWA and CAS relationships with regard to small diameter pipes. To confirm this result, further studies are needed to extend the range of experimental pressures and diameters tested.

## References

- Almandoz J, Cabrera E, Arregui F, Cabrera E Jr, Cobacho R (2005) Leakage assessment through water distribution network simulation. *J Water Res Pl-ASCE* 131:458–466
- Bailey ND, Van Zyl JE (2015) Experimental investigation of internal fluidisation due to a vertical water leak Jet in a uniform medium. *Procedia Eng* 119:111–119

- Cassa AM, van Zyl JE (2013) Predicting the head-leakage slope of cracks in pipes subject to elastic deformations. *J Water Supply Res T* 62:214–223
- Cassa AM, van Zyl JE, Laubscher RF (2010) A numerical investigation into the effect of pressure on holes and cracks in water supply pipes. *Urban Water J* 7:109–120
- Collins R, Boxall J (2013) Influence of ground conditions on intrusion flows through apertures in distribution pipes. *J Hydraul Eng-ASCE* 139:1052–1061
- De Marchis M, Fontanazza CM, Freni G, La Loggia G, Napoli E, Notaro V (2010) A model of the filling process of an intermittent distribution network. *Urban Water J* 7:321–333
- De Marchis M, Fontanazza CM, Freni G, La Loggia G, Napoli E, Notaro V (2011) Analysis of the impact of intermittent distribution by modelling the network-filling process. *J Hydroinformatic* 13:358–373
- Farley M, Trow S (2003) *Losses in water distribution networks: a practitioner's guide to assessment, monitoring and control*. IWA Publishing, London
- Ferrante M (2012) Experimental investigation of the effects of pipe material on the leak head-discharge relationship. *J Hydraul Eng-ASCE* 138:736–743
- Ferrante M, Massari C, Brunone B, Meniconi S (2011) Experimental evidence of hysteresis in the head-discharge relationship for a leak in a polyethylene pipe. *J Hydraul Eng-ASCE* 137:775–780
- Ferrante M, Massari C, Brunone B, Meniconi S (2013) Leak behaviour in pressurized PVC pipes. *Water Sci Technol* 13:987–992
- Ferrante M, Meniconi S, Brunone B (2014) Local and global leak laws. The relationship between pressure and leakage for a single leak and for a district with leaks. *Water Resour Manag* 28:3761–3782
- Fontanazza CM, Notaro V, Puleo V, Nicolosi P, Freni G (2015) Contaminant intrusion through leaks in water distribution system: experimental analysis. *Procedia Eng* 119:426–433
- Freni G, De Marchis M, Napoli E (2014) Implementation of pressure reduction valves in a dynamic water distribution numerical model to control the inequality in water supply. *J Hydroinformatic* 16:207–217
- Greyvenstein B, van Zyl JE (2007) An experimental investigation into the pressure-leakage relationship of some failed water pipes. *J Water Supply Res T* 56:117–124
- Karadirek IE, Kara S, Yilmaz G, Muhammetoglu A, Muhammetoglu H (2012) Implementation of hydraulic modelling for water-loss reduction through pressure management. *Water Resour Manag* 26(9):2555–2568
- Lambert AO (2002) International report: water losses management and techniques. *Water Sci Technol* 2:1–20
- Lindley TR, Buchberger SG (2002) Assessing intrusion susceptibility in distribution systems. *J Am Water Works Assoc* 94:66–79
- May J (1994) Pressure dependent leakage. *World Water Environ Eng* 10
- Mora-Rodriguez J, Delgado-Galvan X, Ramos HM, Lopez-Jimenez PA (2014) An overview of leaks and intrusion for different pipe materials and failures. *Urban Water J* 11:1–10
- Puust R, Kapelan Z, Savic DA, Koppell T (2010) A review of methods for leakage management in pipe networks. *Urban Water J* 7:25–45
- Tabesh M, Yekta AHA, Burrows R (2008) An integrated model to evaluate losses in water distribution systems. *Water Resour Manag* 23(3):477–492
- Thornton J (2003) Managing leakage by managing pressure: a practical approach. *Water* 21(10):43–44
- van Zyl JE, Cassa AM (2014) Modeling elastically deforming leaks in water distribution pipes. *J Hydraul Eng-ASCE* 140:182–189
- van Zyl JE, Clayton CRI (2007) The effect of pressure on leakage in water distribution systems. *Proc Inst Civil Eng-Water Manag* 160:109–114
- van Zyl JE, Alsaydalani MOA, Clayton CRI, Bird T, Dennis A (2013) Soil fluidisation outside leaks in water distribution pipes - preliminary observations. *Proc Inst Civil Eng: Water Manag* 166(10):546–555
- Walski T, Bezts W, Posluszny ET, Weir M, Whitman BE (2006) Modeling leakage reduction through pressure control. *J Am Water Works Assoc* 98:147–155