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Improving the efficiency of leak location via optimal pressure sensor placement in water distribution networks

L. Ribeiro[1], J. Sousa[2] and A. Sá Marques[3]
[1] *Institute of Marine Research (IMAR), Department of Civil Engineering (ISEC), Polytechnic Institute of Coimbra & PhD Student of Coimbra University, Portugal, e-mail: luirenco@isec.pt*
[2] *Institute of Marine Research (IMAR),Department of Civil Engineering (ISEC), Polytechnic Institute of Coimbra, Portugal, e-mail: jjoseng@isec.pt*
[3] *Institute of Marine Research (IMAR), Department of Civil Engineering, Coimbra University, Portugal, e-mail: jasm@dec.uc.pt*

Abstract: The location of leaks in water distribution networks with the current techniques (like step testing, ground microphones, listening sticks, or leak noise correlators) requires expensive equipment and well trained staff. The use of water distribution network mathematical models to locate leaks can contribute to reduce the staff effort and the time needed to locate the leaks. The mathematical modelling of leaks location in water distribution networks requires a methodology able to select the optimal pressure sensor placement in order to gather significant data by the sensors installed in the network and to minimize the differences between the measurements and the mathematical model results. The methodology presented in this paper aims to identify the best places to install pressure sensors in order to improve the leak location efficiency. The mathematical model for leak location was applied to a hypothetical water distribution network and the results obtained with the optimal sensor placement are presented and discussed.

Keywords: Water distribution networks, leak location, optimal sensor placement, mathematical models

1. INTRODUCTION

To guarantee our basic lifestyle needs, water must be wisely collected, treated and distributed. The distribution process involves the use of buried networks that hide their potential problems. This paper deals with the hidden problem of leaky pipes and its possible solution.

The leaks in water distribution networks are perceived as non-revenue water for the water company or as a restriction in its use for the customers. The need to identify the location of leaks has promoted the development of several techniques based on expensive equipment (like listening sticks, ground microphones or leak noise correlators) and well trained and motivated staff to handle a long time search.

Several authors have tried to improve the use of the known techniques by establishing an inverse problem and solving it with measurements of pressure and flow. The pioneers of this approach were Pudar and Liggett (1992) and they were followed by several other authors, for example Vítkovsky *et al.* (2003) or Wu and Sage (2006).

This paper presents a methodology to identify the most promising region of a water distribution network where to search for leaks, in order to reduce the resources involved and to increase the success of leaks location.

The methodology uses mathematical modelling of water distribution networks and starts with the optimal pressure sensors placement. A hypothetical water distribution network with leaks is presented and the results obtained seem to be very encouraging.

2. DEVELOPMENT

One of the greatest sources of uncertainty in a water distribution network is the water demand (quantity and geographic distribution). The strategy to overcome this problem is to consider the minimum flow conditions, which usually occur during the night period. For low flows, the piezometric surface is quite flat with small head losses in most pipes, because the network was designed to face the maximum demand expected to occur at the end of the system useful life time.

Besides, the minimum flow analysis also benefits from the pressure-leakage relationship because the leakage flow increases with the pressure. Indeed, theoretically the orifice law should be used to calculate the leakage flow, which states that it is proportional to the square root of the pressure. However, in practice, this relationship tends to be close to linear.

There are many possible locations for the sensors placement in the network. Each location will register different pressure data and the good location of sensors will identify the hydraulic behaviour that explains observations with accuracy.

When dealing with leak location, as Vítkovsky *et al*. (2003) concluded, “more measurement sites lead to a better solution”. However, as the number of measurement sites increases the costs with more sensors and gathering more data also increase but the incremental improvement in the solution rapidly falls. There must be a trade-off between the number of measurement sites and the expected accuracy.

2.1 Methodology description

This paper presents a computational application that incorporates demands and leaks in the mathematical modelling of the water distribution network hydraulic behaviour. The proposed methodology considers knowing the correct location of the demands and its value (one loading condition for the steady-state hydraulic model). The total leaks value is also known but the number of leaks, their locations and flows are unknown. To locate the leaks in the network, the methodology uses an optimization model that seeks to minimize the absolute deviation between the measured pressures and the estimated values obtained with the hydraulic model, equation (1), over the set of pressure measurement sites (nodes with pressure sensors - Figure 2). The configuration of sensors placement used is the one that produced better results with ten sensors. For the water distribution network modelling, leaks are associated with pipes and each leaky pipe has the value of its leak equally transferred to its end nodes.

2.2 Optimization model

The objective function used in the optimization model of this computer application is represented by the equation (1):

$$Min\ F(x) = Min\ \sum_{i=1}^{N} \left| \left(\frac{p}{\gamma}\right)_i^{measured} - \left(\frac{p}{\gamma}\right)_i^{estimated} \right| \tag{1}$$

where: $\left(\frac{p}{\gamma}\right)_i^{measured}$ – pressure measured at node i (m);

$\left(\frac{p}{\gamma}\right)_i^{estimated}$ – pressure estimated at node i (m);

N – number of nodes with pressure sensors.

The pressures estimated for the monitored nodes are calculated by a hydraulic simulator developed by Sousa (2006). This hydraulic simulator verifies the hydraulic constraints and estimates the hydraulic behaviour of the water distribution network based on the nodes equations and applies the Newton-Raphson method with optimized step control to solve the system of nonlinear equations. The final value of pressure calculated by the hydraulic simulator guarantees a maximum of 1 cm error. The sensors measurements of pressure assume three digits for accuracy.

The head losses in the pipes were obtained using the Hazen-Williams equation (2):

$$\Delta H_{ij} = 10.674 \cdot \frac{L_{ij} \cdot Q_{ij}^{1.852}}{C_{HW_{ij}}^{1.852} \cdot D_{ij}^{4.87}} \tag{2}$$

where: ΔH_{ij} – head loss in the pipe between nodes i and j (m);
L_{ij} – length of the pipe between nodes i and j (m);
Q_{ij} – flow in the pipe between nodes i and j (m^3/s);
D_{ij} – diameter of the pipe between nodes i and j (m);
$C_{HW_{ij}}$ – Hazen-Williams roughness coefficient, depending on the pipe material between nodes i and j.

The optimization model deals with the nonlinear relationship between head loss and flow in a non-convex space and has continuous variables (flows from leaks). The solution of this optimization model is obtained through a simulated annealing algorithm.

2.3 Simulated annealing algorithm

The simulated annealing algorithm was inspired in a thermodynamical process (heat treatment of material with the goal of altering its properties), aiming to obtain low energy states of a solid in a heat bath (heat bath temperature increases to a value at which the solid melts, followed by a slow temperature decrease of the heat bath until the particles arrange themselves in the ground state of the solid) (Kirkpatrick *et al.* 1983).

The optimization model starts the search with an initial solution that corresponds to splitting the total leaks in 15 portions. This initial solution (x_0) is obtained by assigning each isolated portion to one pipe which minimises equation (1). In the neighbourhood of the initial solution, a new candidate solution is selected ($x_{candidate}$). The hydraulic behaviour of the candidate solution is evaluated and the objective function is calculated. If the evaluation of the candidate solution $F(x_{candidate})$ is better than the evaluation of the current solution $F(x_{current})$, the candidate solution becomes the current solution. Else, the candidate solution can be accepted as the next current solution with a probability that depends on the merit of both solutions and the temperature. Systematizing, the execution of a simulated annealing algorithm includes the following steps (see Table 1):

- Step 1: Choose the initial solution (x_0) and the initial temperature (Tqt_initial) and fix the initial number of solutions to be generated;
- Step 2: Generate a candidate solution accessible from the current solution ($x_{candidate}$);
- Step 3: Evaluate the candidate solution: first the hydraulic behaviour is checked and after the solution is evaluated with the objective function (1);
- Step 4: Accept or reject the candidate solution against the currently accepted one at that temperature. If the candidate solution is accepted by the Metropolis criterion (3), it becomes the next current solution of the search, otherwise the current solution is kept and another candidate solution is generated;

$$random \quad number < exp\left(-\frac{F(x_{current}) - F(x_{candidate})}{Tqt_i}\right) \tag{3}$$

- Step 5: Increment counters by one, update memory and variables. If the iteration counter value does not exceed the fixed number of solutions to be generated at each temperature, go to step 2.
- Step 6: The cooling schedule defines how the temperature should decrease (Tqt_{i+1}) and the number of solutions to be generated at the new temperature as a function of the percentage of accepted solutions (Pa) at the previous temperature (Tqt_i);
- Step 7: If stopping criteria is not achieved, return to step 2.

Each candidate solution is generated by making random perturbations in the current solution. Two processes were used to create candidate solutions: 1) transfer the leak from a leaky pipe to one of its adjacent pipes; 2) choose a pipe and concentrate in it the leaks from all its adjacent pipes.

Table 1. Resume for simulated annealing implementation.

Criterion	*Chosen option*		
Initial solution (x_0)	*The total leak is split and each part is assigned to a selected pipe*		
Initial temperature (Tqt_initial)	*Tqt_initial=-0.1*(F(x_0))/(Log(0.5))*		
Cooling schedule	*If Pa>80%*	$Tqt_{i+1}=0.60*Tqt_i$	$IA_{i+1}=40$
	If Pa>50%	$Tqt_{i+1}=0.75*Tqt_i$	$IA_{i+1}=60$
	If Pa>20%	$Tqt_{i+1}=0.90*Tqt_i$	$IA_{i+1}=80$
	If Pa<=20%	$Tqt_{i+1}=0.95*Tqt_i$	$IA_{i+1}=100$
Number of evaluations at each temperature Tqt_i	*IA_i*Number of network pipes*		
Stopping criteria	*Pa<5% and 2 temperatures without solution improvement*		

3. CASE STUDY

The gravity fed water distribution network used in this study has 101 nodes and 111 pipes, organized in 11 loops and has only one reservoir. The network characteristics, its design and demands were created by WaterNetGen (Muranho *et al*. 2012). The network details and description are in Annex (Tables A1 and A2) and the Hazen-Williams coefficient is 140.

The minimum night demand for this network is 2.315 L/s (corresponding to the consumption). To identify the nodes with maximum pressure fluctuation, the daily peak demand with a flow ten times greater than the night flow (23.148 L/s) was also analysed. For each node, the maximum and minimum pressure, the pressure fluctuation (absolute difference) and its relative difference (%) was calculated.

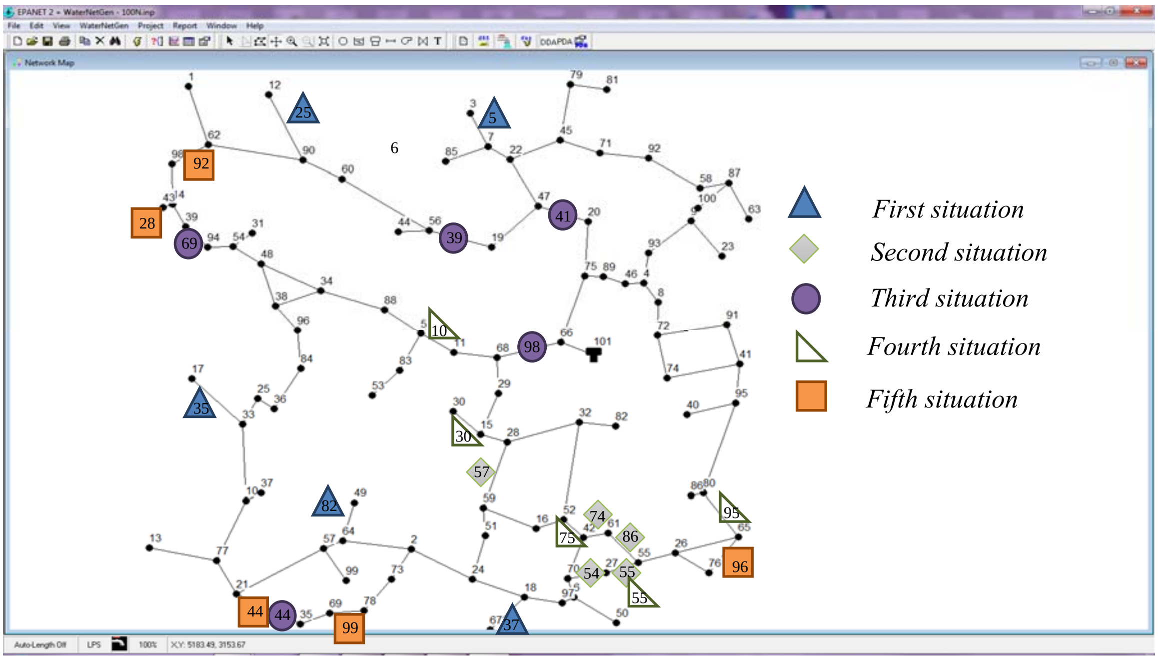

Figure 1. Water distribution network with five different situations.

This case study was submitted to five different situations based on typical leaks location conditions, Figure 1 (the numbers inside the symbols identify the leaky pipes). Each situation was conceived to test the computer application performance in specific situations like leaks in branched pipes (first situation), in adjacent pipes (second situation), in pipes spread through the network in one large loop (third situation) or in different loops (fourth situation) or in peripheral loops pipes (fifth situation). The situations descriptions are presented in Tables 2 to 6. For all situations there are five leaky pipes with a flow in the range of 0.1 L/s to 5.0 L/s.

The low demand condition produces low flow velocity in pipes as well as low head losses caused by pipe roughness. So, for each situation two leakage scenarios were considered: 1.50 L/s (scenario 1) and 15.0 L/s (scenario 2). Scenario 1, with 1.50 L/s leakage flow, was considered to evaluate the model behaviour in a tricky situation when the leakage value is lower than the network demand and both can be confused due to the demand uncertainty.

As this case study is a hypothetical water distribution network without functional or location restrictions for placing sensors, they were placed in the nodes with maximum relative pressure fluctuation along the day (pressure difference between the peak daily demand and the night demand divided by the maximum pressure). All nodes (i.e. candidates for sensor placement) were ranked in descendent order. Once one node is selected to place a sensor, its adjacent nodes (and their adjacent nodes) were excluded from the set of nodes for additional sensor placement. This guarantees a minimum influence area for each sensor placed, looking for a better coverage of the entire network and collecting more independent data. The final locations of sensors are presented in Figure 2.

At first, the methodology identifies the most promising region of the water distribution network considering the minimum night flow in each leakage scenario. To confirm the leaks locations the network hydraulic behaviour was evaluated including a fire flow scenario (simulating the opening of a fire hydrant during the night – delivering a fire flow of 15.0 L/s). As expected, all leakage scenarios and situations considered here profited from the inclusion of the fire flow scenario due to the significant increase of the total demand (and head loss).

An alternative to fire flow tests (which might be impossible to execute in some situations) are flushing tests. These tests involve less flow, have less impact on the distribution network behaviour but can be done in more places along the network (they are not constrained by the existence of hydrants), as for example in end nodes of pipes with the minimum legal diameter.

The computer application was executed in a Workstation Intel® Xeon® CPU E5-2620 0 @ 2.00GHz. For all the case studies 50 different sets of random numbers were used.

Table 2. Leaky pipes list according to the scenario analysed in the first situation.

Pipe	***Scenario 1 Total Leaks =1.5 L/s***	***Scenario 2 Total Leaks =15.0 L/s***
5	*0.5 L/s*	*5.0 L/s*
25	*0.3 L/s*	*3.0 L/s*
35	*0.4 L/s*	*4.0 L/s*
37	*0.2 L/s*	*2.0 L/s*
82	*0.1 L/s*	*1.0 L/s*

Table 3. Leaky pipes list according to the scenario analysed in the second situation.

Pipe	***Scenario 1 Total leaks =1.5 L/s***	***Scenario 2 Total leaks =15.0 L/s***
54	*0.1 L/s*	*1.0 L/s*
55	*0.2 L/s*	*2.0 L/s*
57	*0.5 L/s*	*5.0 L/s*
74	*0.3 L/s*	*3.0 L/s*
86	*0.4 L/s*	*4.0 L/s*

Table 4. Leaky pipes list according to the scenario analysed in the third situation.

Pipe	***Scenario 1 Total Leaks =1.5 L/s***	***Scenario 2 Total Leaks =15.0 L/s***
39	*0.1 L/s*	*1.0 L/s*
41	*0.2 L/s*	*2.0 L/s*
44	*0.4 L/s*	*4.0 L/s*
69	*0.5 L/s*	*5.0 L/s*
98	*0.3 L/s*	*3.0 L/s*

Table 5. Leaky pipes list according to the scenario analysed in the fourth situation.

Pipe	***Scenario 1 Total leaks =1.5 L/s***	***Scenario 2 Total leaks =15.0 L/s***
10	*0.1 L/s*	*1.0 L/s*
30	*0.2 L/s*	*2.0 L/s*
55	*0.3 L/s*	*3.0 L/s*
75	*0.4 L/s*	*4.0 L/s*
95	*0.5 L/s*	*5.0 L/s*

Table 6. Leaky pipes list according to the scenario analysed in the fifth situation.

Pipe	*Scenario 1 Total leaks =1.5 L/s*	*Scenario 2 Total leaks =15.0 L/s*
28	*0.1 L/s*	*1.0 L/s*
44	*0.2 L/s*	*2.0 L/s*
92	*0.4 L/s*	*4.0 L/s*
96	*0.5 L/s*	*5.0 L/s*
99	*0.3 L/s*	*3.0 L/s*

As all peripheral pipes have the minimum inner diameter (81 mm), it was not possible to execute fire flow tests with 15.0 L/s at the end nodes of branched pipes.

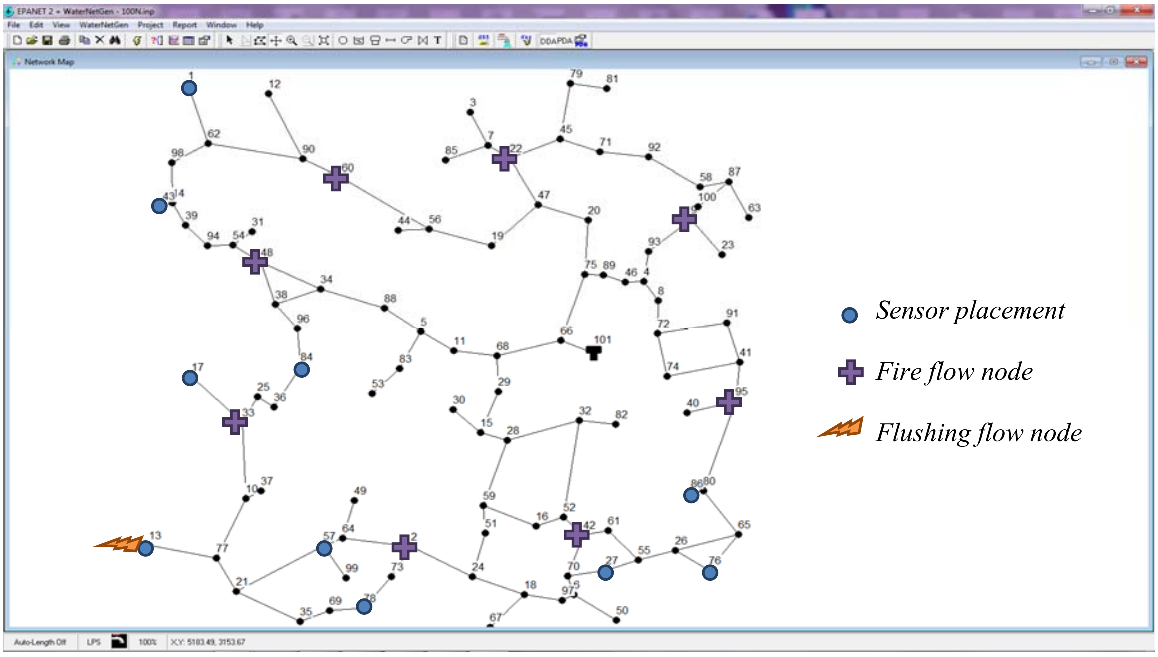

Figure 2. Water distribution network with sensors placement, fire flow nodes and flushing flow node.

4. RESULTS

In a previous paper (Ribeiro *et al.* 2012), the methodology presented here was able to correctly identify leaky pipes using twenty sensors placed at the end of each branched pipe and assuming more accuracy in sensors measurements and hydraulic simulator results.

Now the goal is to demonstrate the possibility of identifying the same leaks but using only ten sensors placed in specific locations (Figure 2) and using fire flow tests (15.0 L/s flows at the end nodes of pipes with internal diameter greater than 81 mm when all adjacent pipes had this diameter) or a unique flushing test (5.0 or 7.5 L/s flows at the end node of one smaller branched pipe).

It was assumed that the nodes pressure drop does not affect the leakage flow.

Table 7 presents the results obtained in five different situations with two possible scenarios for each of them. For each analysis, the methodology aims to identify the leaky pipes. For each leaky pipe in each situation (first number) the numbers inside the round brackets indicates the number of correct identifications in the set of 50 runs.

The first row was obtained considering only the night flow demand. The identification of leaky pipes in scenario 2 is better than in scenario 1, which is an expected conclusion because the leak flow is bigger. Three situations were then solved (situations 1, 3 and 5 for scenario 2): leaks in branched pipes, leaks spread through one large loop and leaks spread in peripheral loops pipes of the water distribution network. The other two situations are more difficult to analyse: situation 2 describes a set of leaky adjacent pipes in a loop and situation 4 describes leaks spread through different loops.

Based on the last evidence, the impact of an incremental demand caused by the fire flow was analysed. To assess the benefit from sudden flow increase, some independent hydrant openings were considered (15.0 L/s) and the correspondent flow and pressure data were introduced in the model. In Figure 2 the eight hydrants used to execute the eight fire flow tests are represented with a cross. After adding the fire flows to the network demand in the most remote nodes which may have a hydrant with capacity to deliver 15.0 L/s, the results obtained improved and the final solutions become more accurate in terms of leaks location. The majority of situations within scenario 2 had better results than in scenario 1 based on the night demand and also with the addition of fire flow tests, giving more confidence to the leaks location process.

Table 7. Pipes with leaks and number of forecasts of leaky pipes in the final solution.

	Situation 1		**Situation 2**		**Situation 3**		**Situation 4**		**Situation 5**	
	Scen. 1	**Scen. 2**	**Scen. 1**	**Scen. 2**	**Scen. 1**	**Scen. 2**	**Scen. 1**	**Scen. 2**	**Scen. 1**	**Scen. 2**
Analysis based on pressure	5 (6/50) 25 (29/50) 35 (50/50) 37 (0/50) 82 (50/50)	5 (32/50) 25 (39/50) 35 (50/50) 37 (50/50) 82 (50/50)	54 (15/50) 55 (19/50) 57 (6/50) 74 (19/50) 86 (33/50)	54 (17/50) 55 (17/50) 57 (14/50) 74 (13/50) 86 (26/50)	39 (0/50) 41 (42/50) 44 (50/50) 69 (43/50) 98 (46/50)	39 (45/50) 41 (45/50) 44 (50/50) 69 (45/50) 98 (50/50)	10 (13/50) 30 (8/50) 55 (21/50) 75 (18/50) 95 (45/50)	10 (18/50) 30 (5/50) 55 (24/50) 75 (18/50) 95 (39/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 2 with 15.0 L/s Fire flow	5 (50/50) 25 (50/50) 35 (50/50) 37 (50/50) 82 (50/50)	5 (47/50) 25 (47/50) 35 (50/50) 37 (49/50) 82 (50/50)	54 (20/50) 55 (32/50) 57 (18/50) 74 (36/50) 86 (28/50)	54 (12/50) 55 (26/50) 57 (8/50) 74 (32/50) 86 (48/50)	39 (3/50) 41 (0/50) 44 (50/50) 69 (44/50) 98 (3/50)	39 (50/50) 41 (50/50) 44 (50/50) 69 (50/50) 98 (50/50)	10 (15/50) 30 (1/50) 55 (28/50) 75 (30/50) 95 (50/50)	10 (39/50) 30 (23/50) 55 (43/50) 75 (30/50) 95 (46/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 9 with 15.0 L/s Fire flow	5 (2/50) 25 (17/50) 35 (50/50) 37 (46/50) 82 (50/50)	5 (35/50) 25 (41/50) 35 (50/50) 37 (50/50) 82 (50/50)	54 (18/50) 55 (15/50) 57 (19/50) 74 (21/50) 86 (33/50)	54 (17/50) 55 (22/50) 57 (2/50) 74 (17/50) 86 (15/50)	39 (0/50) 41 (1/50) 44 (50/50) 69 (41/50) 98 (10/50)	39 (50/50) 41 (50/50) 44 (50/50) 69 (46/50) 98 (50/50)	10 (12/50) 30 (10/50) 55 (50/50) 75 (12/50) 95 (50/50)	10 (35/50) 30 (18/50) 55 (35/50) 75 (20/50) 95 (46/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 22 with 15.0 L/s Fire flow	5 (3/50) 25 (10/50) 35 (50/50) 37 (10/50) 82 (50/50)	5 (28/50) 25 (27/50) 35 (50/50) 37 (50/50) 82 (50/50)	54 (14/50) 55 (8/50) 57 (12/50) 74 (28/50) 86 (31/50)	54 (9/50) 55 (24/50) 57 (5/50) 74 (5/50) 86 (27/50)	39 (28/50) 41 (28/50) 44 (50/50) 69 (29/50) 98 (15/50)	39 (37/50) 41 (36/50) 44 (50/50) 69 (39/50) 98 (48/50)	10 (13/50) 30 (7/50) 55 (49/50) 75 (0/50) 95 (50/50)	10 (39/50) 30 (16/50) 55 (27/50) 75 (21/50) 95 (47/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 33 with 15.0 L/s Fire flow	5 (34/50) 25 (34/50) 35 (50/50) 37 (50/50) 82 (50/50)	5 (40/50) 25 (38/50) 35 (50/50) 37 (50/50) 82 (50/50)	54 (24/50) 55 (32/50) 57 (19/50) 74 (31/50) 86 (46/50)	54 (10/50) 55 (11/50) 57 (13/50) 74 (21/50) 86 (37/50)	39 (50/50) 41 (50/50) 44 (50/50) 69 (50/50) 98 (50/50)	39 (50/50) 41 (50/50) 44 (50/50) 69 (50/50) 98 (50/50)	10 (36/50) 30 (32/50) 55 (36/50) 75 (34/50) 95 (47/50)	10 (27/50) 30 (11/50) 55 (31/50) 75 (15/50) 95 (42/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 42 with 15.0 L/s Fire flow	5 (0/50) 25 (22/50) 35 (50/50) 37 (13/50) 82 (47/50)	5 (28/50) 25 (35/50) 35 (50/50) 37 (37/50) 82 (50/50)	54 (2/50) 55 (10/50) 57 (25/50) 74 (26/50) 86 (47/50)	54 (19/50) 55 (18/50) 57 (25/50) 74 (17/50) 86 (29/50)	39 (0/50) 41 (28/50) 44 (50/50) 69 (45/50) 98 (50/50)	39 (50/50) 41 (50/50) 44 (50/50) 69 (47/50) 98 (50/50)	10 (34/50) 30 (12/50) 55 (21/50) 75 (11/50) 95 (50/50)	10 (45/50) 30 (9/50) 55 (16/50) 75 (10/50) 95 (48/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 48 with 15.0 L/s Fire flow	5 (22/50) 25 (24/50) 35 (50/50) 37 (50/50) 82 (50/50)	5 (44/50) 25 (45/50) 35 (50/50) 37 (50/50) 82 (50/50)	54 (13/50) 55 (13/50) 57 (17/50) 74 (27/50) 86 (33/50)	54 (23/50) 55 (17/50) 57 (9/50) 74 (21/50) 86 (25/50)	39 (49/50) 41 (49/50) 44 (50/50) 69 (49/50) 98 (49/50)	39 (46/50) 41 (46/50) 44 (50/50) 69 (45/50) 98 (50/50)	10 (49/50) 30 (0/50) 55 (49/50) 75 (0/50) 95 (49/50)	10 (26/50) 30 (14/50) 55 (31/50) 75 (19/50) 95 (44/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 60 with 15.0 L/s Fire flow	5 (19/50) 25 (29/50) 35 (50/50) 37 (44/50) 82 (50/50)	5 (19/50) 25 (24/50) 35 (50/50) 37 (48/50) 82 (50/50)	54 (20/50) 55 (12/50) 57 (7/50) 74 (30/50) 86 (25/50)	54 (12/50) 55 (23/50) 57 (12/50) 74 (16/50) 86 (27/50)	39 (25/50) 41 (22/50) 44 (50/50) 69 (34/50) 98 (45/50)	39 (15/50) 41 (43/50) 44 (50/50) 69 (19/50) 98 (50/50)	10 (40/50) 30 (33/50) 55 (38/50) 75 (32/50) 95 (41/50)	10 (30/50) 30 (13/50) 55 (33/50) 75 (18/50) 95 (45/50)	28 (49/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 95 with 15.0 L/s Fire flow	5 (11/50) 25 (30/50) 35 (50/50) 37 (32/50) 82 (35/50)	5 (39/50) 25 (34/50) 35 (50/50) 37 (47/50) 82 (50/50)	54 (6/50) 55 (23/50) 57 (37/50) 74 (11/50) 86 (47/50)	54 (13/50) 55 (15/50) 57 (5/50) 74 (25/50) 86 (13/50)	39 (16/50) 41 (16/50) 44 (49/50) 69 (18/50) 98 (49/50)	39 (50/50) 41 (50/50) 44 (50/50) 69 (48/50) 98 (50/50)	10 (39/50) 30 (0/50) 55 (48/50) 75 (40/50) 95 (50/50)	10 (38/50) 30 (25/50) 55 (43/50) 75 (29/50) 95 (49/50)	28 (49/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 13 with 5.0 L/s Flushing flow	5 (46/50) 25 (47/50) 35 (50/50) 37 (50/50) 82 (50/50)	5 (42/50) 25 (48/50) 35 (50/50) 37 (50/50) 82 (50/50)	54 (17/50) 55 (29/50) 57 (9/50) 74 (30/50) 86 (33/50)	54 (24/50) 55 (11/50) 57 (5/50) 74 (23/50) 86 (28/50)	39 (49/50) 41 (47/50) 44 (50/50) 69 (47/50) 98 (49/50)	39 (50/50) 41 (49/50) 44 (50/50) 69 (49/50) 98 (50/50)	10 (19/50) 30 (20/50) 55 (30/50) 75 (27/50) 95 (46/50)	10 (14/50) 30 (9/50) 55 (17/50) 75 (11/50) 95 (40/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)
Node 13 with 7.5 L/s Flushing flow	5 (44/50) 25 (46/50) 35 (50/50) 37 (45/50) 82 (50/50)	5 (41/50) 25 (40/50) 35 (50/50) 37 (50/50) 82 (50/50)	54 (10/50) 55 (25/50) 57 (9/50) 74 (39/50) 86 (29/50)	54 (8/50) 55 (27/50) 57 (8/50) 74 (10/50) 86 (38/50)	39 (17/50) 41 (23/50) 44 (50/50) 69 (6/50) 98 (45/50)	39 (50/50) 41 (50/50) 44 (50/50) 69 (50/50) 98 (50/50)	10 (28/50) 30 (15/50) 55 (29/50) 75 (20/50) 95 (49/50)	10 (32/50) 30 (14/50) 55 (29/50) 75 (16/50) 95 (44/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)	28 (50/50) 44 (50/50) 92 (50/50) 96 (50/50) 99 (50/50)

Fire flow tests executed nearby a leaky pipe helped to identify it. The fire flows in nodes 2, 33 and 48 helped in identifying the leaky pipes in situation 1 and the same occurred with fire flows in nodes 33 and 48 for situation 3. The fire flow in node 42, which is an end node of pipe 74, identified the scenario 2 for situation 3. Sometimes, a fire flow test executed in a node distant from leaky areas can help the identification of a leaky pipe, as for example the identification of scenario 2 with the fire flow in node 9 in situation 3.

Another attempt to increase the leak effect in node pressure was achieved with flushing tests at the end node of a remote branched 81 mm pipe. With this diameter the flushing test flow needed to be less than 7.5 L/s to guarantee no negative pressures in the water distribution network. The results are presented in the last two rows in Table 7. In general, the leaks effects increased but not as much as they were amplified with the fire flows and, in some situations, the number of correct identifications did not guaranteed statistic relevance in the 50 runs.

5. CONCLUSIONS

This paper demonstrates the potential of leaks location with water distribution network models. The methodology presented here is based on a simulated annealing algorithm and hydraulic modelling, with the correct data gathering, and it can help in the identification of leaky pipes and estimation of the respective leakage flows.

Despite the stochastic nature of the simulated annealing method and the sensors and the hydraulic simulation inaccuracies, the results were very consistent. Often the leaky pipes were correctly identified.

The selection of the sensors placement has proved to be crucial. The correct knowledge of demand is very relevant and gives confidence to the results obtained with the hydraulic simulation model. To achieve this goal it is wise to evaluate the network behaviour during the lower night demand. Moreover, during this period, it is guaranteed a near maximum pressure over the entire water distribution network.

The methodology was improved by introducing an additional (but controlled – fire flow and flushing tests) relevant demand which amplifies the head losses along the network, changing the nodes pressure and the flow distribution. Each of the fire flows introduced in a node showed, at least, the presence of the leaky pipes in one scenario of one specific situation. The fire flows (in nodes 2, 33 or 48) were able to help in the identification of leaky pipes in more scenarios than the fire flows in nodes 22 or 42.

It was demonstrated that the flushing flows can also be helpful in identifying the leaks locations. The flushing flows of 5.0 L/s and 7.5 L/s were able to identify more leaky pipes than the ones obtained with the night demand flow but, even though, in some situations (2 and 4) the number of good solutions obtained in the 50 evaluations was not so encouraging. If more flushing tests were executed probably the number of good solutions obtained would increase.

The results obtained highlight that the search for leaks in a water distribution network can be focused in a reduced number of pipes with a good level of confidence, instead of searching along the entire network.

The use of the methodology presented here can contribute to reduce substantially the staff effort and the time needed to locate leaks.

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ANNEX

Table A1. Node list with elevations (Z) and demands (Qc).

Node	Z (m)	Qc (L/s)	Node	Z (m)	Qc (L/s)	Node	Z (m)	Qc (L/s)
1	1000	0.014850	35	1001	0.029220	69	999.5	0.013330
2	1000	0.045880	36	996	0.009640	70	1001	0.024090
3	1009	0.008980	37	999	0.003790	71	1003	0.020600
4	1005	0.017060	38	989	0.029160	72	1003	0.030940
5	995	0.028940	39	995	0.013930	73	1000	0.018000
6	1000	0.019070	40	1008.5	0.001780	74	998	0.019670
7	1008	0.025050	41	1004.5	0.033660	75	1010	0.034300
8	1005	0.015330	42	1003	0.022370	76	1013.5	0.020000
9	1008	0.026730	43	997	0.000270	77	1004	0.040570
10	1004	0.038130	44	998	0.006970	78	1001	0.003670
11	992	0.018660	45	1008	0.035400	79	1011	0.022070
12	993	0.017540	46	1006	0.009360	80	1008.5	0.038780
13	1006	0.015490	47	1006	0.039140	81	1007	0.008320
14	996	0.017480	48	991	0.033260	82	1002	0.008320
15	1007	0.02540	49	999	0.009440	83	993	0.018870
16	1007	0.018510	50	997	0.011450	84	999	0.029840
17	1011	0.015820	51	1005	0.017780	85	1009	0.010220
18	999	0.032180	52	1005	0.045650	86	1008.5	0.002840
19	1003	0.029180	53	991	0.008660	87	1004	0.018080
20	1007	0.025010	54	989	0.018760	88	998	0.025110
21	1001	0.047980	55	1002	0.026200	89	1002	0.009340
22	1010	0.030770	56	1002	0.044950	90	996	0.049030
23	1010	0.010940	57	1006	0.036560	91	1003	0.025680
24	1001	0.045160	58	1008	0.033670	92	999	0.038030
25	1003	0.009220	59	1003	0.020150	93	1009	0.019600
26	1011.5	0.032530	60	1000	0.033060	94	992	0.012720
27	1004.5	0.016416	61	1004	0.015560	95	1007.5	0.034140
28	1003	0.039880	62	1000	0.045960	96	987	0.034680
29	1010	0.019450	63	1004	0.002080	97	1001	0.011480
30	1003	0.008420	64	1003	0.029810	98	995	0.019730
31	986	0.005420	65	1012.5	0.038810	99	998	0.009240
32	1007	0.048860	66	1014	0.031840	100	1009	0.012790
33	1007	0.036730	67	997	0.011010	101	1044	0.000000
34	995	0.040940	68	1013	0.033330			

Table A2. Pipe list with end nodes, lengths (L) and diameters (D).

Pipe	End Nodes		L (m)	D (mm)
1	62	1	550.58	81
2	2	73	542.66	81
3	24	2	578.88	113
4	2	64	579.14	81
5	7	3	332.75	81
6	4	93	270.13	99
7	46	4	153.21	145
8	4	8	208.86	113
9	5	83	378.42	81
10	11	5	327.76	163
11	5	88	366.53	145
12	6	50	424.53	81
13	97	6	105.12	81
14	70	6	177.20	81
15	7	85	378.87	81
16	22	7	216.98	81
17	8	72	359.40	113
18	9	23	405.49	81
19	9	100	128.80	81
20	93	9	456.5	99
21	10	37	140.55	81
22	10	77	588.36	81
23	33	10	684.66	81
24	68	11	363.79	163
25	90	12	650.29	81
26	77	13	574.23	81
27	39	14	256.69	81
28	14	43	9.90	81
29	14	98	381.48	81
30	15	30	312.19	81
31	15	28	232.48	181
32	29	15	397.02	181
33	16	52	585.78	81
34	59	16	100.18	81
35	33	17	586.29	81
36	24	18	464.69	81
37	18	67	408.01	81
38	18	97	320.25	81
39	19	56	546.16	99
40	47	19	535.41	113
41	20	47	440.51	145
42	75	20	486.69	145
43	21	77	341.42	81
44	35	21	600.61	81
45	57	21	836.67	81
46	22	45	448.64	81
47	47	22	475.06	99
48	51	24	630.39	127
49	36	25	251.14	99
50	25	33	90.47	99
51	26	76	335.93	81
52	55	26	323.76	81
53	65	26	546.06	81
54	70	27	328.31	81
55	27	55	280.18	81
56	28	32	628.05	113
57	28	59	617.92	145
58	68	29	324.12	181
59	54	31	200.80	81
60	32	82	308.56	81
61	32	52	874.42	99
62	88	34	564.22	145
63	34	38	399.16	113
64	34	48	554.12	99
65	69	35	482.69	81
66	84	36	106.22	99
67	38	96	285.39	113
68	38	48	396.25	81
69	94	39	259.51	81
70	95	40	66.07	81
71	41	95	354.27	99
72	91	41	367.90	81
73	74	41	525.52	99
74	42	61	209.67	81
75	52	42	231.95	99
76	42	70	387.54	81
77	56	44	258.5	81
78	45	79	509.48	81
79	45	71	354.18	81
80	89	46	193.85	145
81	48	54	282.62	81
82	64	49	350.00	81
83	59	51	28.84	127
84	83	53	321.08	81
85	54	94	212.15	81
86	61	55	367.14	81
87	56	60	861.47	99
88	64	57	175.87	81
89	57	99	342.53	81
90	87	58	248.09	81
91	60	90	364.03	81
92	98	62	349.78	81
93	90	62	803.12	81
94	87	63	76.92	81
95	80	65	486.81	81
96	65	76	405.60	81
97	66	75	632.46	203
98	66	68	547.65	226
99	78	69	11.40	81
100	71	92	409.59	81
101	72	74	203.54	99
102	72	91	584.11	81
103	73	78	124.65	81
104	75	89	152.27	145
105	79	81	308.45	81
106	80	86	105.32	81
107	95	80	845.30	81
108	100	87	345.25	81
109	101	66	33.00	285
110	96	84	1000.0	113
111	58	92	1000.0	81