Unreported leaks location using pressure and flow sensitivity in water distribution networks

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ABSTRACT

Water distribution systems are made up of many interdependent elements that enable water supply to meet a demand that is variable in time and space. One of the main concerns for utility managers is quickly locating and repairing a leak after detection, during regular network water balance. This paper presents a two-stage methodology for locating a leak that is based on the hydraulic model of the network, and, particularly, on the conservation equations that govern network behaviour. In the first stage, the sensitivity of each element (nodes and pipes) is obtained for a given demand increase in any node. In the second stage, that sensitivity is combined with additional real data provided by the (possibly) existing pressure sensors and flowmeters installed throughout the network. As a final result, the system of equations thus obtained produces the theoretical leak flow at each network node that matches the network conditions. A subsequent analysis of the leak flows obtained highlights the node or nodes in which the leak is occurring. The presented methodology is applied and assessed in a case study.

Key words | hydraulic modelling, sensitivity analysis, sensors, water leak detection

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INTRODUCTION

Drinking water distribution systems in cities are large and complex infrastructures. Their operating points vary according to the demands at each moment and their management is complex – and even more so, if the appropriate renewal investments are not made. This complexity and gradual aging of the infrastructure does not help managers address one of the main problems in pressurised water distribution systems: the struggle against unreported leaks (IWA 2000).

The traditional approach in the management of such leaks is essentially passive: the leaks are repaired when the water becomes visible, so allowing leaks to run for weeks, months, or even years.

One of the most common policies to avoid wasting water is active leakage control (Armon *et al.* 2011; Charalambous *et al.* 2014; Berardi *et al.* 2016). This approach aims at early detection, location (Mounce *et al.* 2002), and repair of broken pipes – thereby reducing possible damage to third parties, minimising unplanned work, and reducing the volume of water lost.

Methods for the detection and monitoring of leaks are generally efficient, such as night minimum flows (Boulos & Aboujaoude 2011; Alkasseh *et al.* 2013), and sectorisation of networks (Gomes *et al.* 2012; Guistolisi & Ridolfi 2014; Tzatchkov *et al.* 2014). Once the existence of a leak is detected, it is located using acoustic techniques (Li *et al.* 2015). For large networks, this approach may require many resources and considerable time.

New methodologies based on the sensorisation of distribution networks are gaining momentum for the rapid localisation of uncontrolled leaks. These methods are based on pressure measurement and sensitivity analysis of the distribution networks, taking advantage of the interdependence of all the operating parameters. These fundamentals were proposed by Pudar & Liggett (1992),

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who studied the relationship between leaked volume, network pressure, and the leaking section. Most recent studies have focused on the location of sensors to facilitate fault detection and maximise leak location performance (Sarrate *et al.* 2014; Casillas *et al.* 2015; Blesa *et al.* 2016; Gamboa-Medina & Reis 2017). The result depends on the number of sensors installed (Xie *et al.* 2017) and will be limited by the budget and strategy followed (Fuchs-Hanusch & Steffelbauer 2017). Based on the measurements of the pressure sensors, Pérez *et al.* (2011) propose analysing the difference between said data and the equivalents provided by a simulation model, and in the event of a discrepancy, using the leak sensitivity matrix to determine the location. Under ideal conditions, these methodologies offer excellent results – but these results are less good if errors exist in the demands and measurements. To minimise this effect, subsequent studies (Casillas *et al.* 2014) introduce in their calculations an extended-period analysis of the measurements. Other authors propose similar approaches based on sensitivity analysis for locating leaks (Möderl *et al.* 2011; Steffelbauer *et al.* 2014; Gamboa-medina & Reis 2017); but all these approaches demand the posing of multiple scenarios and their corresponding simulations in a hydraulic model to explore the changes obtained. Considering the dynamic operation of distribution networks and the always unpredictable appearance of leaks, the time required for such analyses may limit their practical use.

The present work proposes a new methodology for locating leaks that is based on a simplified calculation of the sensitivity of the elements of the network. This methodology combines knowledge of the specific average behaviour of each element following an increase in demand at any point of the network, and the information provided by the pressure sensors. The aim is to produce a matrix formulation of the equations for the network behaviour in which the leak flows in each node are the unknowns, but which can continue to be resolved using the classical gradient procedure (Todini & Pilati 1987). Finally, the methodology is applied to a study network and the results are discussed.

Only two additional points need to be highlighted. The first is the versatility of the method: although the work is focused from the perspective of the location of the leak (real losses), the concepts used in the mathematical formulation mean it is equally applicable to the location of clandestine or unauthorised consumption. The second point is that this methodology is notable for its rapid calculation in the resolution of each scenario, which is one of its main advantages over similar studies, due to the vast number of combinations possible when locating leaks.

METHODOLOGY

The methodology is presented in three sections. The first section (basic equations) is a reminder of the conservation equations that govern network behaviour. The contributions of the paper are developed in the second (sensitivity) and the third (location) sections.

Basic equations

Given a water network with p pipes, n nodes, and m supply points, the method for modelling its hydraulic behaviour through conservation equations has already been soundly set (Todini & Pilati 1987; Todini & Rossman 2013). The first equation is the *mass conservation* equation applied to each network node:

$$\sum_{k=1}^{n_i} Q_{ik_0} + q_i = 0 \tag{1}$$

where n_i is the total number of nodes connected to node i, Q_{ik_0} is the circulating flowrate through the pipe that connects node i to node k, and q_i is demand flowrate at node i.

The second equation is the *energy conservation* equation applied to each network pipe:

$$H_{i_0} - H_{j_0} = h_{f_{ij_0}} = r_{ij}\, Q_{ij_0} \left| Q_{ij_0} \right| \tag{2}$$

where H_{i_0} and H_{j_0} are the head values at nodes i and j, respectively; $h_{f_{ij_0}}$ are the friction losses in the pipe that connects nodes i and j; and r_{ij} and Q_{ij_0} are, respectively, hydraulic resistance and flowrate through the pipe between nodes i and j.

Both sets of conservation equations, *mass* and *energy*, can be structured by means of matricial notation (Todini

& Pilati 1987):

$$\begin{bmatrix} A_{11} & \vdots & A_{12} \\ \cdots & \cdots & \cdots \\ A_{21} & \vdots & 0 \end{bmatrix} \begin{bmatrix} Q \\ \cdots \\ H \end{bmatrix} = -\begin{bmatrix} A_{10}\cdot H_0 \\ q \end{bmatrix} \tag{3}$$

where A_{11} is a $(p \times p)$ diagonal matrix that represents the friction losses in each pipe*;* A_{12} is a $(p \times n)$ connectivity matrix that relates nodes and pipes; A_{21} is the transposed matrix of A_{12}; Q is the vector of the (unknown) circulating flows in pipes; H is the vector of the (unknown) piezometric heads in the nodes; A_{10} is the fixed head node incidence $(p \times m)$ matrix; H_0 is the vector with the values of (known) fixed piezometric heads; and q is the vector of (known) nodal demands.

Network sensitivity (full equations development in Appendix A)

To establish the effect of a demand increase throughout the network, this study tackles the sensitivity of the network and analyses the flow and pressure variation caused by small variations in water demand that are significant enough to affect the rest of the elements. This study is structured in three steps.

Step 1: Current situation: The first step is to solve the hydraulic performance of the network, obtaining the piezometric head in the nodes (vector H), and the flowrate circulating through the lines (vector Q). This is the base scenario for which the sensitivity is to be calculated.

Step 2: Definition of a consumption increase and consequences: if in node i, the current demand (q_i) is increased (φ_{q_i}), it will affect the new demand $(q_i + \varphi_{q_i})$ and head $(H_{i_0} + \varphi_{H_{i_i}})$ in node i, and the head $(H_{j_0} + \varphi_{H_{j_i}})$ in any other node j, as well as the circulating flow in any pipe $(Q_{ik_0} + \varphi_{Q_{ik_i}})$.

Therefore, the new formulation of the *mass conservation* equation in any node i will be:

$$\sum_{k=1}^{n_i} \left(Q_{ik_0} + \varphi_{Q_{ik_i}}\right) + q_i + \varphi_{q_i} = 0 \tag{4}$$

where $\varphi_{Q_{ik_i}}$ is the flow variation of the pipe connecting nodes i and k, produced by the demand variation in node i.

In parallel, the new *energy conservation* equation for any pipe (connecting nodes i and j) will be:

$$\left(H_{i_0} + \varphi_{H_{i_i}}\right) - \left(H_{j_0} + \varphi_{H_{j_i}}\right) - \vartheta_{ij}\, r_{ij} \cdot \left(Q_{ij_0}\left|Q_{ij_0}\right| + \frac{Q_{ij_0}^2 \cdot \varphi_{Q_{ij_i}}}{\left|Q_{ij_0}\right|} + \frac{Q_{ij_0} \cdot \varphi_{Q_{ij_i}}^2}{\left|Q_{ij_0}\right|} + \varphi_{Q_{ij_i}}\left|Q_{ij_0}\right|\right) = 0 \tag{5}$$

where ϑ is a term that adopts the value $\dfrac{Q_{ij_0}\cdot\varphi_{Q_{ij_i}}}{\left|Q_{ij_0}\right|\cdot\left|\varphi_{Q_{ij_i}}\right|}$ if $\left|\varphi_{Q_{ij_i}}\right| > \left|Q_{ij_0}\right|$, and the unit value otherwise.

Step 3: Calculation of network sensitivity: from the equations presented in the previous step, calculating the sensitivity of all the elements of the network is straightforward following a demand increase, in particular, in node i. Therefore, it is sufficient to solve the p Equation (5) and the n Equation (4), for the total of p unknowns that correspond to the variation of the flow of each pipe $\varphi_{Q_{ij_i}}$ and the n unknowns corresponding to the variation of the head of each node $\varphi_{H_{j_i}}$.

Since the network consists of n nodes, the repetition n times of this complete resolution of the network (one for each node) will give a complete view of the sensitivity of the network. Using this approach, a complete and quantified range of variation of the properties of each element is obtained. Although this is perfectly feasible from the equations presented here, it may not be very operative in practice, since the calculation time for as many network resolutions as there are nodes may be excessive. For this reason, the proposed method includes a simplification that means the system of network equations needs to be solved just once.

Instead of working separately with the specific variation in each element caused by the increase of flow in each node, the single average of all these variations is considered. That is, the general sensitivity of the head in each node i is shown by:

$$\varphi_{H_i} = \frac{\sum_{m=1}^{n} \varphi_{H_{i_m}}}{n} \tag{6}$$

and the general sensitivity of the flowrate in each pipe ik, is shown by:

$$\varphi_{Q_{ik}} = \frac{\sum_{m=1}^{n} \varphi_{Q_{ik_m}}}{n} \tag{7}$$

By introducing these averages in the calculation of the sensitivity of the network elements, and also averaging all the n equations for each node, then the total of $n \cdot (n+p)$ equations (n Equation (4) plus p Equation (5), and multiplied by the n nodes of the network) is reduced to n node equations such as:

$$\sum_{k=1}^{n_i} \left(Q_{ik_0} + \varphi_{Q_{ik}}\right) + q_i + \frac{\varphi_{q_i}}{n} = 0 \tag{8}$$

and p pipe equations such as:

$$\left(H_{i_0} + \varphi_{H_i}\right) - \left(H_{j_0} + \varphi_{H_j}\right) - \vartheta_{\mathrm{ij}} \cdot \mathrm{r}_{\mathrm{ij}} \cdot \left(\mathrm{Q}_{ij_0} \cdot \left|\mathrm{Q}_{ij_0}\right| + \frac{\mathrm{Q}_{ij_0}^2 \cdot \varphi_{\mathrm{Q}_{ij}}}{\left|\mathrm{Q}_{ij_0}\right|} + \frac{\mathrm{Q}_{ij_0} \cdot \varphi_{\mathrm{Q}_{ij}}^2}{\left|\mathrm{Q}_{ij_0}\right|} + \varphi_{\mathrm{Q}_{ij}} \cdot \left|\mathrm{Q}_{ij_0}\right|\right) = 0 \tag{9}$$

where $\varphi_{Q_{ij}}$ y φ_{H_i} are, respectively, the average variation of the flow in pipe i, and the piezometric head in node i produced by the consumption variation in any node. The new set of $n+p$ equations, with $n+p$ unknown factors can be expressed in a matrix format as follows:

$$\begin{bmatrix} A_{11\varphi} & \vdots & A_{12} \\ \cdots & \cdots & \cdots \\ A_{21} & \vdots & 0 \end{bmatrix} \begin{bmatrix} \varphi_Q \\ \cdots \\ \varphi_H \end{bmatrix} = - \begin{bmatrix} A_{11\vartheta} & \vdots & A_{12} \\ \cdots & \cdots & \cdots \\ A_{21} & \vdots & 0 \end{bmatrix} \begin{bmatrix} Q \\ \cdots \\ H \end{bmatrix} - \begin{bmatrix} A_{10}\, H_0 \\ \cdots \\ q + \dfrac{\varphi_q}{n} \end{bmatrix} \tag{10}$$

where A_{12}, A_{21}, A_{10}, H_0 and q are the same terms as in Equation (3); H and Q are the vectors obtained in Step 1; φ_Q is the vector of the (unknown) sensitivities (average variations) of flow in network pipes; φ_H is the vector of the (unknown) sensitivities (average variations) of head in network nodes; $A_{11\varphi}$ is a $(p \times p)$ diagonal matrix with components $A_{11\varphi}(r, r) = \vartheta_{\mathrm{ij}}\, \mathrm{r}_{\mathrm{ij}} \left(2 \left|\mathrm{Q}_{ij_0}\right| + \frac{\mathrm{Q}_{ij_0}}{\left|\mathrm{Q}_{ij_0}\right|}\, \varphi_{\mathrm{Q}_{ij}}\right)$, and $A_{11\vartheta}$ is a $(p \times p)$ diagonal matrix with components $A_{11\vartheta}(r, r) = \vartheta_{\mathrm{ij}}\, \mathrm{r}_{\mathrm{ij}}\, |\mathrm{Q}_{ij_0}|$.

The process for solving Equation (10) is the same for Equation (3) and, hence, the network sensitivity of an uncontrolled consumption of a given value at any node can be calculated.

Leak location (full equations development in Appendix B)

In the case of a leak occurrence, whose magnitude and location (node) were known, the resulting pipe flows and node heads could be easily calculated by solving Equation (3). However, in water distribution networks, while estimating the magnitude of a newly detected leak though a quick water balance is not difficult, it is not so easy to determine its spatial location. In this leak scenario, new unknown factors must be introduced (Figure 1): circulating flows in pipes change (Q_{ij_L}), node heads change (H_{i_L}), and in addition to normal demand, a leak flow (q_{i_L}) should be considered in each node. It is clear, that most of these added leak flows will be zero, and only those ones (ideally, just one) in the area close to the leak location will differ from zero, but there is usually no further information to clarify this question. Therefore, the new system would present $2n+p$ unknown factors (which are the pressures and leak flowrates in the n nodes and the flows through the p pipes) and only $n+p$ equations.

To limit the scope of the problem and find a finite and real solution, two sources of additional information can be introduced. The first takes advantage of the calculation of node sensitivity explained above. Since the real magnitude of a leak can be estimated through a quick water balance, the average head variation for each network node that corresponds to that magnitude of increase in demand, can also be calculated by Equation (10). Now the following hypothesis is proposed: in a leak situation, the unknown piezometric head of any node can be approximated to the head under that node's normal working conditions plus its average calculated variation, ($H_{i_L} = H_{i_0} + \varphi_{H_i}$). Therefore,

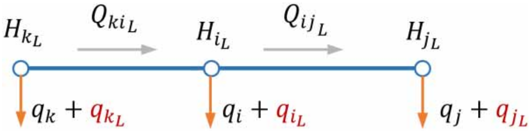

Figure 1 | Hypothetical leaks in a distribution network.

n terms corresponding to the node heads are now considered as known, and the new scenario can be solved.

The second source of additional information is the real measurements of the (likely) existing flowmeters and pressure sensors installed in specific network pipes and nodes. Whatever the number of devices of each kind, the measurements they provide can be organised in a vector H_D for the known node heads, and a vector Q_D for the known flowrate pipes.

If these two new data sources are introduced into the equations that solve the hydraulic behaviour of the network, and the resulting set is simplified and adequately reordered, the following matrix formulation is produced:

$$\begin{bmatrix} A_{11} & \vdots & 0 \\ \cdots & \cdots & \cdots \\ A_{21} & \vdots & 1 \end{bmatrix} \begin{bmatrix} Q_L \\ \cdots \\ q_L \end{bmatrix} = -\begin{bmatrix} A_{11} & \vdots & A_{12} \\ \cdots & \cdots & \cdots \\ A_{21} & \vdots & 0 \end{bmatrix} \begin{bmatrix} Q_D \\ \cdots \\ H_D \end{bmatrix} - \begin{bmatrix} A_{10}\, H_0 \\ \cdots \\ q \end{bmatrix} \tag{11}$$

where A_{11}, A_{12}, A_{21}, A_{10}, H_0 and q are the same terms as in Equation (3), Q_L is the vector of the (unknown) pipe flows (in which values corresponding to flowmetered pipes are set to zero); q_L is the vector of the (unknown) nodal leak flows; Q_D is the vector of the (known) flowrates as measured by the meters in the pipes (and zero being the value for the rest of the pipes); H_D is the vector of the (known) node heads (these values being directly measured by the pressure sensors installed in some nodes, or the approximation $H_{i_0} + \varphi_{H_i}$ for the rest of the nodes).

The two results obtained after solving Equation (11) are the circulating pipe flowrates and, most importantly, the leak flow in every node. A quick later analysis of the leak flow results will pinpoint the node (in the best case), or the area (at least) in which the leak is taking place.

CASE STUDY

Network description (full data in Appendix C)

What follows is a case study of a synthetic network as shown in Figure 2. The network has a total length of 50 km with 58 pipelines that supply 38 consumption nodes whose elevation is zero. Some 6,500 m^3 of water is delivered daily (40,000 inhabitants). Both reservoirs are elevated 50 m. The pipe roughness is 0.1 mm, and pipes' lengths and diameters are shown in Table C1 (Appendix C).

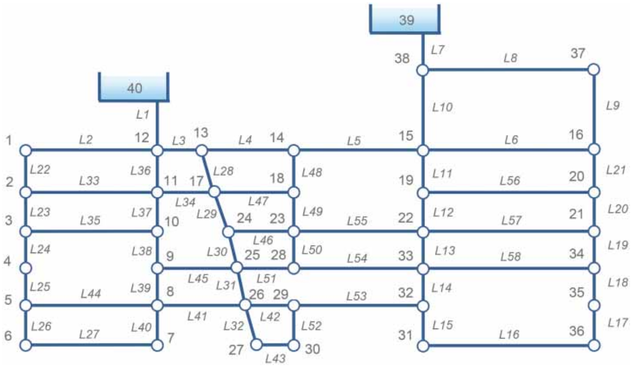

Figure 2 | Layout of the distribution network.

The base demand is 60 L/minute (0.001 m^3/s) for every node between 1 and 16, and nodes 21, 27, and 30; while for the 19 remaining nodes, the base demand is 180 L/minute (0.003 m^3/s).

In its normal operating state, the average pressure is 37.7 mwc, with extreme values of 31.7 and 47.0 mwc (Table C2). Average water velocity and unitary headloss in pipes are 0.41 m/s and 2.50 mwc/km, respectively (Table C1). The contribution of flow for each reservoir is approximately 50%.

Sensitivity analysis (full results in Appendix C)

For an analysis of the sensitivity of the elements of the network, increments of 15, 30 and 60 L/minute have been defined in each node. The reason is that the appearance of leaks from 15 or 30 L/minute on, in monitored sectors of a network, may be detected using night flow analysis or automatic water balances. In addition, these figures are of the same order of magnitude as those considered by Fuchs-Hanusch & Steffelbauer (2017).

After solving Equation (10) for all three scenarios, the detailed node results are shown in Table C2. As expected, the greater the increase in demand, the greater the decrease in pressure at the nodes (those that are furthest away from the inlet points being more affected). Thus, the average pressure decrease for network nodes in general is −0.2% for 15 L/minute, and −0.4% and −0.9% for 30 and 60 L/minute, respectively.

Sensitivity pipe results are shown in Table C3. Magnitudes of average flow changes for each demand increase (15, 30 and 60 L/minute) are 0.52%, 1.05%, and 2.13% (respectively). This gives a better idea of the real sensitivity and explains why the two pipes (27 and 44) with variations of more than 20% have two of the lowest network flowrates (about one hundred times less than the average flow per pipe).

The sensitivity analysis highlights those nodes with larger pressure variations, either in total or percentage terms – nodes 5, 6 and 25; as well as those whose changes are much less relevant, namely, nodes 12, 15 and 34. In parallel, the most sensitive pipes are 8, 36, and 37 (not taking into account those connecting each reservoir), whereas the least significant are 16, 43 and 46.

Leak location (full results in Appendix D)

Once the sensitivity analysis is completed, the problem of leak allocation is approached. For demonstrative purposes, it is assumed that five pressure sensors and five flowmeters are available for installation in the network. The main criterion for the selection of the elements in which to install the sensors is that of greater sensitivity (as obtained in the previous calculation); while a secondary criterion is that of achieving a reasonable spatial distribution of the sensors. Accordingly, pressure sensors are installed in nodes 5, 18, 27, 30 and 37; and the flowmeters in pipes 1, 9, 20, 36 and 45. That is, 13% of the nodes and 9% of the pipes are monitored.

The application and results of the leak location method are demonstrated as follows: it will be assumed, as each case is different, that a leak of 30 L/minute has occurred in each of the nodes of the network. That is, 38 different cases will be resolved. For each, in addition to knowing in which node the leak is located, the five real pressure values and five flowrate values provided, respectively, by the pressure sensors and flowmeters installed in the network, will be known (by direct simulation of the case). These ten items of data will be transferred to the model in which the method is tested, and whose information is completed for the rest of the nodes with the average head affected by the average sensitivity for an increase in demand of 30 L/minute. Finally, and through the resolution of Equation (11) the leak flow for each node is obtained (as well as the circulating pipe flows). The results are considered successful as the leak flow calculated is about 30 L/minute for the leaky node, or for neighbouring nodes, and is negligible for the other network nodes.

Table D2 (Appendix D) shows the obtained leak flow for each node (rows), measured in L/minute, for each of the simulations (columns). The table shows that the methodology has been successful in 63% (24 of the 38 simulations), since in eight cases the leaking node was exactly identified (in green), and in 16 other cases the area was identified (node adjacent to the node with the leak – in yellow). From the data in Table D2, we can observe that the accurate location of the node, or the area where the uncontrolled leak is taking place, depends to some extent on the existence of a nearby flow or pressure sensor. It is also important to highlight the existence of nodes with a negative consumption (as in the case of node 36 for most simulations). It is apparent that some nodes may need a flow input to counterbalance the deviations introduced when estimating the known piezometric heads.

As expected, the leak location is less accurately shown if instead of choosing elements with a large variation in pressure and flow, those with a lower average variation are chosen. Thus, if nodes 1, 12, 15, 16 and 38, and pipes 6, 16, 43, 46 and 56 were selected, then less than 50% of the cases (16 of the 38) would be successful (Table D3). If sensitivity criteria is left aside and only spatial distribution criteria is considered, then the results show a greater variability. For example, if nodes 2, 8, 18, 20 and 32; and pipes 11, 17, 25, 36 and 42 were monitored, the success rate would be exactly 50% (Table D4).

Logically, the more sensors installed in the network, the better the results. Thus, in Appendix D up to seven cases with different configurations of sensors are resolved, and a success rate of 87% is reached with 15 pressure sensors and five flowmeters. Generalised conclusions on the usefulness and versatility of the proposed method follow below.

CONCLUSION

Leakage control is a crucial part of the daily management of water distribution networks, and one of its key pillars is the rapid localisation of leaks. The range of instrumentation currently available for the monitoring of hydraulic variables in the network is very helpful in this task. Thus, pressure sensors and flowmeters whose measurements can be transmitted in real time are frequently used, and this is of great value for the methodology proposed in this article. The number and location of these devices is limited by several factors, but mainly the cost of purchase, installation, and maintenance.

A methodology is proposed in this article that is doubly useful for the control of leaks. Firstly, based on the characteristics of the network and on the direct measurements provided by sensors, it reveals the location of a leak whose magnitude has been previously detected. Secondly, this same methodology can be used to determine the optimal location for the installation of sensors and control flowmeters in a network – given that the effectiveness of any possible configuration can be simulated.

The potential provided by the proposed methodology for both objectives is based on its versatility and speed of calculation. Versatility because only the mathematical model of the network is needed and this is a very common support tool in supply management, and also because model equations are used directly – without need for (nor dependence on) specialised software. Thus, the speed of the resolution of the system of equations proposed here (using any spreadsheet and with a minimum of customised programming ability by the user) is the same, or even faster, than when using hydraulic simulation software.

The methodology itself is structured in two parts. In the first part, the sensitivity analysis focuses on the variations in the circulating flows and the piezometric heads in the nodes when a slight demand increase occurs. As a result, the average variation of these parameters is obtained and this enables a prioritisation of the hydraulic importance of the elements. The second part resolves mass and energy conservation equations – while considering as variables the unknown and uncontrolled water demands in each circulating flow and node, as well as considering an approximation of the piezometric head in the nodes as known variables. The measurements recorded by the pressure and flow sensors are considered as additional information. The final leak location may vary considerably depending on the number and location of the sensors, while the best locations for installing these sensors are on those elements whose variation is greater than average in the sensitivity analysis. This methodology is finally used in a case study network with a limited number of sensors to detect a water leak of 30 L/minute.

APPENDICES

Appendices A–D are available with the online version of this paper.

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