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Procedia Engineering 70 (2014) 1304 – 1313

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

Accuracy assessment of leak localisation method depending on available measurements

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Abstract

Model-based leak localization methods are currently developed and applied to real cases. The performance and success of such methods depend highly both on models [Pérez et al. (2011a)] and the measurements available. The optimal distribution of sensors is a good approach [Pérez et al. (2009)]. Nevertheless, in a huge network with hundreds of District Metered Area (DMA) the question of how the methodology can help with the sensors already installed in the network arises. This paper presents a sequence of steps to assess the performance of a given leakage localization methodology [Quevedo et al. (2011)]. Initially, flow sensors at the control points are used, and inner pressure sensors are added sequentially, since flows are often measured in the network control points and pressure sensors are a common choice for new installed sensors. Using the available sensors information, an investment-precision relationship indicator is proposed. The assessment is applied to a real network situated in Barcelona.

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Keywords: Leakage localisation, accuracy assessment, sensor distribution.

1. Introduction

A model-based leak localisation method was successfully applied in a pilot test in a District Metered Area (DMA), called Nova Icaria, of the Barcelona distribution network. This study was the result of two different projects (PROFURED (Pérez et al. (2011a)) and RTNM (Quevedo et al. (2011))) proposed and lead by CETAQUA, the technological Center of Barcelona Water Company managing the DMA (AGBAR), and mainly developed by the Advanced Control Systems (SAC) group of Technical University of Catalunya (UPC). This first approach motivated further steps on this work, related with the accuracy that could be achieved by the initial methodology when applied exhaustively to the whole distribution network if the only available information is coming from the measurements of the sensors already installed in the system.

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Selection and peer-review under responsibility of the CCWI2013 Committee
doi:10.1016/j.proeng.2014.02.144

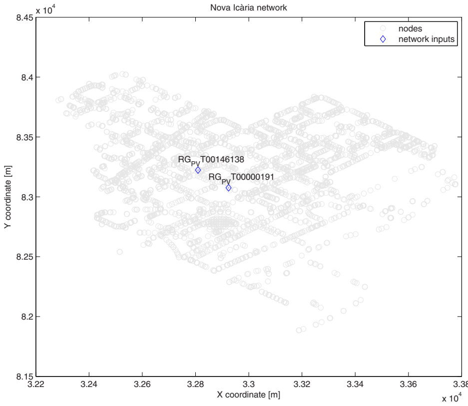

Fig. 1. Nova Icaria DMA with the two inflows Alaba and Llul

1.1. Problem statement

In general a DMA (Walski et al. (2003)) has its inputs monitored, both flows and pressures. This is the actual case in the Barcelona: pressure measurements are used to set boundary conditions to the model together with the demand distribution, based on registered water, and the total demand provided (Pérez et al. (2011a)) by inflow sensors. If no more sensors are present within the network the discrepancies of the distribution of inflow in each input should denote the existence of leakage and the balance between the different inputs could signal the location of the leak. The first contribution of this work is to assess the accuracy provided by the leak localisation method when the only available measurements are provided by the installed network inflow sensors.

However, in the framework of previous works on this DMA (research projects in Section 1) several extra pressure sensors were added to the ones already installed. The sensor distribution methodology considered was based on minimisation of an indicator of leak localisation accuracy. In this work, a new indicator is presented. The results obtained by this indicator suggests the installation of new extra sensors to improve the results obtained by the leak localisation method. Generally, given a certain network, the suggested assessment points are the following:

1. Check the accuracy of the leak localisation method using the existing sensors
2. Consider the use of extra sensors to increase the leak localisation accuracy and assess the potential improvement by the use of these new measurements

The use of this methodology is illustrated on the DMA presented in Section 1 (Nova Icria), which is composed by 3455 pipes and 3377 junctions, 1371 of which are consumers. It has two inflows where pressure and flow are measured (figure 1) and five pressure sensors were installed for leak localisation. The paper is organized as follows: Section 2 describes the leak localisation methodology , providing references of the results achieved with its usage in the DMA under study. Section 3 proposes a methodology for the accuracy assessment. Results obtained by this methodology using a real network model are presented in Section 4.3 . Finally, the conclusions that show up from the results are discussed in Section 5 .

2. Leak location methodology

The methodology used in this work for leak location is model-based. Given a set of measurements and models that represent different leakage scenarios, the methodology aims to select the model that is more consistent with these measurements. Each scenario considers only one leak in a different location (node) of the network. Therefore, selecting the most consistent scenario is equivalent to selecting the most consistent location for the leak. Different authors have studied the problem of leak location from different perspectives. In Pudar and Liggett (1992) a complete mathematical view of the consistency problem as an inverse problem is given. In Pérez et al. (2011b), Quevedo et al. (2011) the point of view of model-based fault diagnosis is taken (Blanke (2006)). In all mentioned works, the idea is to solve the consistency problem with algorithms that can use existing efficient network solvers for the forward problem. This work takes the approach described in Quevedo et al. (2011), which is reviewed in the next paragraphs. In this approach, a leak in a node will be considered to be a fault that is to be localized. The algorithm gives the most consistent location for a leak given a set of measurements from the network.

In this work, a static EPANET model (Bryds and Ulanicki (1994)) of a specific DMA in the Barcelona network is used. Given the network boundary conditions in the form of inflows and/or heads in some nodes, as well as the total inflow, the flows in the pipes and the heads in the nodes of the network can be computed. In this work, the total network inflow q_S, and the heads h_A and h_L in two nodes called *Alaba* and *Llull* (Figure 1), respectively, are fixed. Every T minutes, the values of q_S, h_A, h_L and a vector Y of some additional measurements in the network are available. In this work T is 10 minutes. For clarity, the time argument k is made explicit, e. g. $q_S(k)$, when necessary. Vector Y includes the inflows q_A and q_L in nodes *Alaba* and *Llull* respectively, which are not fixed as boundary conditions in the simulation. In the absence of a leak, the total inflow q_S is distributed among the network nodes according to a given demand pattern.

Given boundary conditions, the computation of a prediction for Y for a non-leakage scenario is denoted by

$$\hat{Y}_{nf} = g_{nf}(q_S, h_A, h_L) \tag{1}$$

Subscript nf indicates non-faulty, i.e. non-leakage, scenario. This computation is performed by the EPANET simulator. The difference $R = Y - \hat{Y}_{nf}$ that quantifies the consistency of the measurement with the model prediction is called a *residual*. The effect of a leak over the measurements Y at time k is usually small and has fluctuations due to sensor resolution. Therefore, instead of $R(k)$, its mean $\bar{R}(k')$ over a period of T' is considered. Time index k' is the index associated to samples separated T' minutes. In this work, T' is 1 hour. It is assumed that the working point does not change significatively during T'.

As mentioned, only the possibility of one leak in an unknown node of the network is considered. Therefore, N predictions $\hat{Y}_{f_i}$ for Y have to be computed, each one corresponding to a leak in node i. Subscript f_i indicates a faulty scenario consisting of a leak in node i. Predictions $\hat{Y}_{f_i}$ for leakage scenarios with a nominal leak f in node i are denoted by

$$\hat{Y}_{f_i} = g_{f_i}(q_S, h_A, h_L, f) \qquad i = 1 \dots N \tag{2}$$

The differences $\hat{R}_{f_i} = \hat{Y}_{f_i} - \hat{Y}_{nf}$ are the predicted residuals. They give a quantification of the expected R when a particular leak is present. The value f is considered to be small enough so that the dependency of $\hat{R}_{f_i}(f)$ is approximately linear in f. If $\hat{R}_{f_i}$ is divided by f and arranged in columns the sensitivity matrix mentioned in Pudar and Liggett (1992) is obtained. As done with $R(k)$, and because of the same reason, the mean $\bar{\hat{R}}_{f_i}(k)$ of $\hat{R}_{f_i}(k)$ over one hour is computed.

Because of linearity of $\hat{R}_{f_i}(f)$ in f, if vectors $\bar{\hat{R}}_{f_i}$ are linearly independent, then each $\bar{\hat{R}}_{f_i}$ characterizes a different leak. Therefore a correlation measure to test linear dependency between $\bar{R}(k')$ and $\bar{\hat{R}}_{f_i}(k')$ can be used to select the most consistent leak with $\bar{R}(k')$, thus the selected leak at time k' is the one maximizing the correlation measure

$$\rho(\bar{R}, \bar{\hat{R}}_{f_i}) = \frac{\bar{R}^T \cdot \bar{\hat{R}}_{f_i}}{\| \bar{R} \| \| \bar{\hat{R}}_{f_i} \|} \tag{3}$$

where $\| \, . \, \|$ denotes the norm associated to the vector dot product. In this work the 2 norm is used. In the previous expression, time indexes k' have been dropped for clarity.

To improve the characterization of a persistent leak, instead of only $\bar{R}(k')$ and $\bar{\hat{R}}_{f_i}(k')$, two vectors

$$\mathbf{R}(k') = (\bar{R}(k'), \dots, \bar{R}(k' - M + 1))^T$$

$$\hat{\mathbf{R}}_{f_i}(k') = (\bar{\hat{R}}_{f_i}(k'), \dots, \bar{\hat{R}}_{f_i}(k' - M + 1))^T$$

that are the concatenation of $\bar{R}(k')$ and $\bar{\hat{R}}_{f_i}(k')$, respectively, over the last $H = MT'$ hours, are considered. In this work, H is 10 hours. Therefore, the correlation to be maximized to select the most consistent leak at time k' is $\rho(\mathbf{R}(k'), \hat{\mathbf{R}}_{f_i}(k'))$.

Algorithm 1 summarizes the leak location procedure in steady state, i.e. after H hours:

Algorithm 1 Leak location in steady state

Every T minutes (time index k):
  Measure $Y(k), q_S(k), h_A(k), h_L(k)$
  Compute $\hat{Y}_{nf}(k)$, $\hat{Y}_{f_i}(k)$, $\quad i = 1 \dots N$
  Compute $R(k) = Y(k) - \hat{Y}_{nf}(k)$
  Compute $\hat{R}_{f_i}(k) = \hat{Y}_{f_i}(k) - \hat{Y}_{nf}(k)$, $\quad i = 1 \dots N$
Every T' hours (time index k'):
  Compute the means $\bar{R}(k')$ and $\bar{\hat{R}}_{f_i}(k')$
  Construct vectors $\mathbf{R}(k')$ and $\hat{\mathbf{R}}_{f_i}(k')$
  Select the leak $f_I(k')$ that maximizes $\rho(\mathbf{R}(k'), \hat{\mathbf{R}}_{f_i}(k'))$, $\quad i = 1 \dots N$
  Output $f_I(k')$ to the user

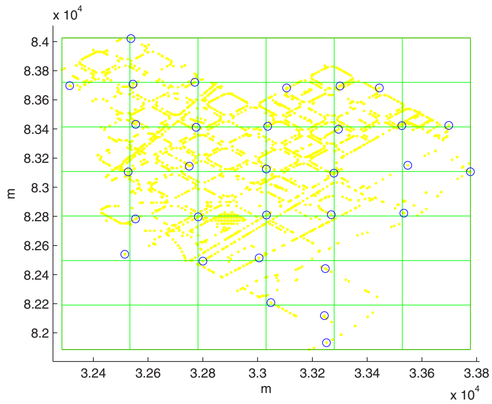

Fig. 2. grid for nodes selection

3. Accurancy assessment methodology

Given a certain network, or a sector if it is a sectored network, an important issue to assess is the accuracy of the leak localisation method. The first question stated by the company managing the network is how can the leak localisation methodology help using the existing measurements. The second question arising is how the leak localisation accuracy is improved as new sensors are introduced. This work proposes an assessment methodology, described by Algorithm 2, carried on by means of simulation results. First, a set of nodes representative of the topology of the network is selected (Figure 2). Scenarios with a leak in each of these nodes are simulated including uncertainty in the model. The leak localisation methodology is applied using the simulation results as measurements and assuming different available sensor sets. In this work, the localisation methodology applied is described in Section 2 and an accuracy indicator is given. This indicator is used during the assessment process to guide the introduction of new sensors, using again the same set of representative nodes. The leak localisation is affected by four main factors:

- Localisation of the leak in the network
- Size and estimation of the leakage
- Calibration of the model
- Number and characteristics of the sensors

In the assessment methodology, the topology of the network is taken into account through the model used in the leak localisation procedure. The location of the simulated leaks to be found in Nova Icària sector is decided geographically with a homogeneous distribution of a limited number of nodes (Figure 2).

Leakage size is a relevant factor when the investment payback is assessed. Flows below 10 l/s are the leakages that can remain long time hidden and thus the leak localisation methodology implies a reduction of the fixing time, which also implies a saving of water-loss volume. The estimation of the leakage size influence the accuracy of the localisation but it has been already studied that it is not a main factor in this methodology (Quevedo et al. (2011)). In this work the simulated leakage has a loss of 6 l/s.

In order to simulate the misfit of the model and the real network, a uniform noise of 10 % of the current demand value is introduced. Demands are the less reliable parameters in the network and represent the main uncertainty (Pérez et al. (2011b)). This noise should be estimated from the misfit between the measurements and the simulation using the existing sensors for each particular case. Resolution of the measurements is taken into account on basis of the manufacturer information.

The set of selected nodes where the leaks are simulated is given by $\eta_{1\times L}$ (Figure 2) which is also considered for the potential nodes to have extra pressure sensors. L is the number of representatives nodes selected. The set of best sensors selected by the assessment method in Algorithm 2 is given by $\psi_{1\times J}$. The assessment is done for each sensor distribution and each leakage scenario. In each iteration, an extra sensor is considered in node $\eta(s)$ for $s = 1 \ldots S$, where S is the number of sensors available from the sensor subset η_j at sensor localisation iteration j ($S = L - j + 1$). Each leakage scenario considers a leak in node $\eta(l)$ for $l = 1 \ldots L$. The results of the leak localisation are given by two figures of merit: the mean distance (over the localisation horizon W) from the real leakage to the node with maximum correlation d_{pl_t} (Equation 4) and the mean distance to the gravity centre of those nodes with correlation over 99 % of the maximum correlation d_{gc_t} (Equation 5).

$$\bar{d}_{pl} = \frac{1}{W}\sum_{t=1}^{W} d_{pl_t} \tag{4}$$

$$\bar{d}_{gc} = \frac{1}{W}\sum_{t=1}^{W} d_{gc_t} \tag{5}$$

The mean distance for all the possible leakage scenarios L for a given sensor distribution may be then obtained ($\bar{\mathbf{d}}_{\mathbf{gc}}$). From the latter, the maximum (worst) distance over all the leaks is obtained

$$d_{max} = \max_{L}\left(\bar{\mathbf{d}}_{\mathbf{gc}}(l)\right), \qquad l = 1 \ldots L \tag{6}$$

The maximum distance in (6) may be obtained for every sensor distribution considered, taking into account all the possible S extra sensors ($\mathbf{d_{max}}$). Hence, the best extra sensor $\psi(j)$ is selected using a min-max criteria in (7)

$$\phi(j) = \min_{S}\left(\mathbf{d_{max}}(s)\right), \qquad s = 1 \ldots S \tag{7}$$

The use of the gravity centre instead of the potential fault introduces stability to the indicator. This process is performed iteratively on j while the worst localisation distance d obtained over all the leaks considered is not below a certain threshold distance d_t. The latter is a parameter given by the company managing the network and is about 200 m for this particular problem (i.e. below d_t, there exist alternative more precise methods to isolate the leak e.g. ground penetrating radar (Farley and Trow (2003))). The sensor addition is performed incrementally, adding one sensor per j iteration (the one with best $\phi(j)$ index). This procedure is summarized in Algorithm 2.

The results of the leak localisation method are presented graphically in Figure 3. These two indicators in (4) and (5) will be used to assess the leak location accuracy. The evolution of the indicator as the sensors are added will give the assessment of accuracy depending on the investment. It can be done in different conditions of leakage size and model calibration.

4. Results

The assessment methodology presented in this work has been applied to the Nova Icria DMA in the Barcelona Water Network, presented in Section 1.1. The assessment has been carried on following the algorithm 2 presented in

Algorithm 2 Leak location accuracy assessment

Require: η
  $j := 1$
  $\psi := []$
  while $d > d_t$ **do**
    for $s = 1 \ldots S$ **do**
      for $l = 1 \ldots L$ **do**
        set leak in node $\eta(l)$
        Generate by simulation with boundary conditions $q_S(k), h_A(k), h_L(k)$ the measures $Y(k)$ every T for W hours
        for $k' = 1 \ldots W$ **do**
          obtain $f_{i_{sl}}(k')$ (Algorithm 1)
        end for
        compute $\bar{d}_{gc_{sl}}(k')$ and $\bar{d}_{pl_{sl}}(k')$ over W
      end for
      obtain $\mathbf{d_{max}}(s)$
    end for
    compute $\phi(j)$
    choose the best sensor $\psi(j) := f(\eta_j, \phi(j))$
    $j := j + 1$
  end while
  return $[\psi, \phi]$

Section 3. In this particular case, the size of the leakage for the simulated scenarios is 6 l/s. A noise in the demands of 10% of the nominal demand is introduced in the model for the scenario generation. The simulations period W is of 72 hours. Figures of merit in (1) and (2), based on mean localisation distances over T, are used to assess the leak localisation method. Leak localisation is done by means of algorith 1 assuming a nominal leakage of 6 l/s. The concatenation of residuals is performed for a window of $H = 10$ hours product of filtering 10 minutes data each hour truncated in the first decimal due to the sensors resolution. Leaks and sensors are located during the process in any of the 31 nodes shown in figure 2 while the leak localisation methodology looks for the leaks in any of the 3377 real nodes. Three groups of results are presented in following subsections:

- Actual installed flow sensors
- New pressure sensors resulting of the assessment method
- Actual installed pressure sensors, provided by an alterntaive method (Pérez et al. (2009))

4.1. Flow sensors

The distribution of flows in the two inputs of the network may change depending on where the leak is. The two complementary flows give one independent measurement each time-step. These two inputs are very close each other thus very poor results are obtained. Figure 3 shows both the mean distances of each leak to the potential fault signalled with maximum correlation (o) and the gravity centre of all nodes with a correlation over 99% (*).

In Figure 4 the results presentation of the leak localisation methodology are shown for the worst and the best localisation achieved with this sensor configuration.

4.2. Pressure sensors introduction

Results obtained using the two already installed flow sensors (Figure 3 and 4) confirm that extra pressure sensors should be added in the network in order to improve the leak localisation. The flow sensors information is kept in further approaches with extra pressure sensors, because they provide information and improve the leak localisation when only pressure sensors are considered. Previous studies were carried out using the optimal distribution of sensors proposed

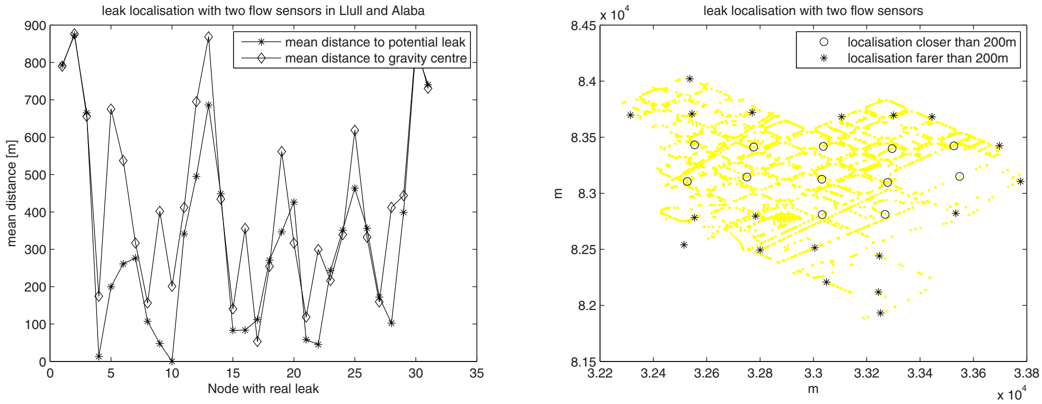

Fig. 3. (a) Localisation mean distance ; (b) Map of localisation of leaks

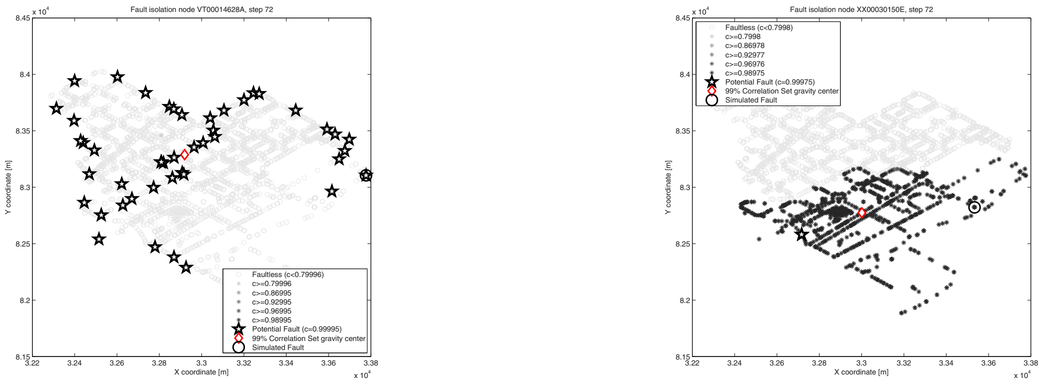

Fig. 4. (a) Localisation result presentation for the worst case (dgc=877m); (b) Localisation result presentation for the best case (dgc=53m)

in Pérez et al. (2009), based on binarisation of the sensitivity matrix for the leak localisation. In this assessment a new sensor distribution is proposed and results are compared with the previous one for the scenarios with 5 pressure sensors.

The new approach is based on the leak localisation methodology described in Section 2, where no binarisation process is performed, hence no information is lost (Quevedo et al. (2011)). In this case, the objective function minimised in the iterative process of introducing new pressure sensors is the indicator proposed for the assessment (the maximum distance of a leak to the gravity centre of the 99% of correlation nodes (Equation 7)). Figure 5a shows the evolution of the maximum mean distance to the gravity centre, its mean for the thirty-one possible leaks and its standard deviation. Figure 5b shows the evolution of the mean distance to potential leak for all the possible leaks. From Figure 5 it may be observed how the distance indicators evolution get smoother when considering more than five pressure sensors. In figure 6 it can be seen that including two new pressure sensors represents little improvement in the number of leaks detected with a mean distance under 200 m.

4.3. Results with 5 sensors

Finally, the comparison of the two sensor distribution approaches is done by means of comparing the worst and the best leak localisation for each configuration. The results presented graphically are those that an end user of the leak localisation method would get each time it is applied on-line. In particular results for the 72nd time step are presented. These results accumulate information of the last 10 hours as explained in section 2. The first results (figure 7) were generated using five pressure sensors that were introduced on basis of an optimal incremental methodology

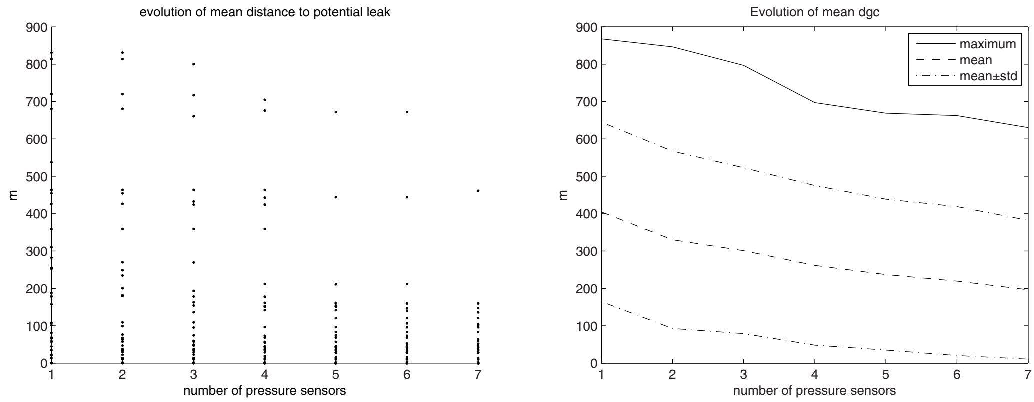

Fig. 5. (a) Evolution of the mean distance to centre of gravity; (b) Evolution of potential leak distance

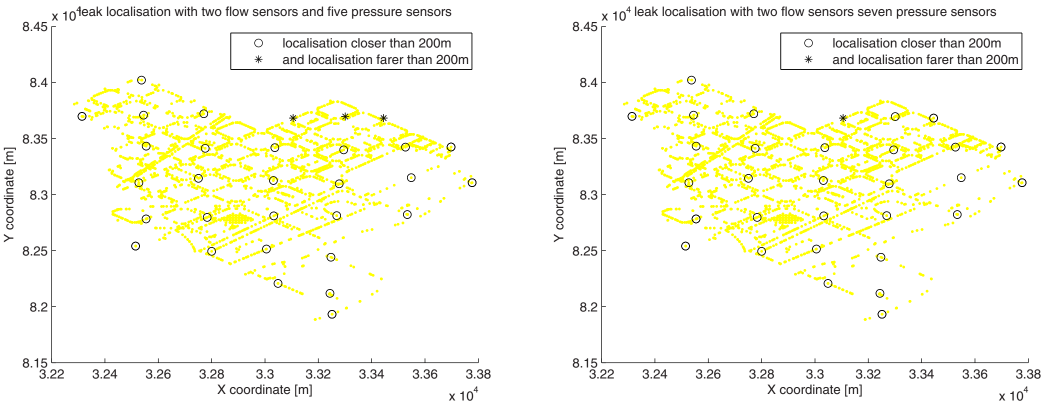

Fig. 6. Map of localisation of leaks, (a) 5 pressure sensors (b) 7 pressure sensors

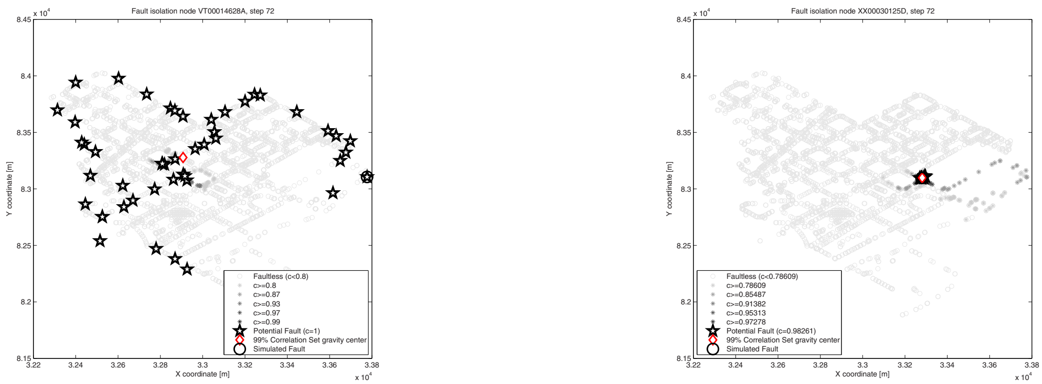

Fig. 7. Leak localisation with present sensors(a)worst case; (b) best case)

that minimised an indicator based on the first approach of leak detection. The approach binarised the sensitivity matrix by means of a threshold, with a voting strategy provided a set of nodes where the leak could potentially be located. The indicator was the cardinal of the biggest set for any leak, the meaning of this cardinal was the discriminality of the method. Figure 8 shows the results obtained by the five pressure sensors distributed using the mean distance to the

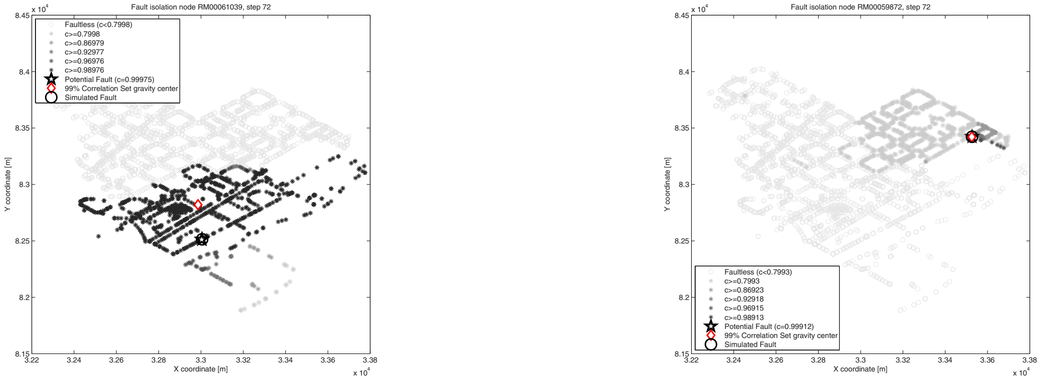

Fig. 8. Leak localisation with proposed 5 sensors and 2 flow sensors(a)worst case; (b) best case)

gravity centre, as explained in Section 3. Comparing resultsin Figures 7 and 8, it seems that that sensor distribution promotes a reduction of the search area for the best case. The area with high correlation is bigger, but the distance to the gravity centre improves thanks to the new purposed criteria of sensor selection.

5. Conclusions

This paper describes briefly a leak localisation method successfully applied to a real DMA in Barcelona water network. This includes a description of the leak localisation procedure and further references of the results achieved by this method in a real water network system. This methodology is analysed using simulation models in order to assess its benefits depending on the budget available for sensors investment. The model used as example is a real DMA which includes uncertainty in the demands. The methodology proposed for the assessment includes a sensor placement procedure that can be easily applied to any real water network.

The indicator used for the accuracy assessment of the leak localisation method is based on the leak localisation distance, which is a widely accepted measure for methods assessment by the company experts. Both distances of the real leak to the potential one (d_{pl}), or to the gravity centre of all the high correlated potential leaks d_{pl} are used. However, using a gravity centre of a higher set of nodes, the results achieved by the localisation method are more robust against leak localisation inaccuracies. Nevertheless using d_{gc} for sensor placement the results with d_{pl} are better. The stability introduced by d_{gc} guarantees that no spurious results appear when using the d_{pl}.

The evolution of the accuracy is smooth and the change of tendency that appears around five sensors in this case-study though not very sharp it coincides with a diminution of the number of leaks that improve their localisation introducing new measures, so a reliable decision on the number of sensors to be introduced can be gathered by the method application.

The effect of the distribution of the sensors on the accuracy shows, in section, 4 that a combination of the distance and the area optimisation could be tested (Section 4.3). The assessment can be done using any paradigm of sensor distribution depending on the company interests. Even though, non-incremental distribution could be proposed if the investment is decided before hand. Further real parameters such conditions of the network, noise and resolution of the sensors and uncertainty in other parameters of the system can be modified for the test.

Acknowledgements

This works was partially grant-funded by CICYT SHERECS DPI-2011-26243, CICYT WATMAN DPI- 2009-13744 of the Spanish Ministry of Education and by EFFINET grant FP7-ICT-2012-318556 of the European Commission and the Polytechnic University of Catalunya (UPC).

References

Blanke, M. Kinnaert, J.L.M.S., 2006. Diagnosis and Fault-tolerant Control. 2 edition ed., Springer, Berlin.

Bryds, M.A., Ulanicki, B., 1994. Operational Control of Water Systems: Structures, Algorithms and Applications. Prentice Hall International.

Farley, M., Trow, S., 2003. Losses in Water Distribution Networks. IWA publishing, London.

Pérez, R., Nejjari, F., Puig, V., Quevedo, J., Sanz, G., Cugueró, M., Peralta, A., 2011a. Study of the isolability of leaks in a network depending on calibration of demands, in: 11th International Conference on Computing and Control for the Water Industry, Exeter. pp. 455–460.

Pérez, R., Puig, V., Pascual, J., Peralta, A., Landeros, E., Jordanas, L., 2009. Pressure sensor distribution for leak detection in Barcelona water distribution network. Water Science & Technology: Water Supply 9, 715.

Pérez, R., Puig, V., Pascual, J., Quevedo, J., Landeros, E., Peralta, A., 2011b. Methodology for leakage isolation using pressure sensitivity analysis in water distribution networks. Control Engineering Practice 19, 1157–1167.

Pudar, R., Liggett, J., 1992. Leaks in Pipe Networks. Journal of Hydraulic Engineering 118, 1031–1046.

Quevedo, J., Cugueró, M., Pérez, R., Nejjari, F., Puig, V., Mirats, J., 2011. Leakage Location in Water Distribution Networks based on Correlation Measurement of Pressure Sensors, in: 8th IWA Symposium on Systems Analysis and Integrated Assessment, IWA, San Sebastián. pp. 290–297.

Walski, T., Chase, D., Savic, D., Grayman, W., Beckwith, S., Koelle, E., 2003. Advanced Water Distribution Modeling and Management. Haestad Press.