LEAK LOCALISATION METHODOLOGY AND REAL APPLICATIONS

Ramon Perez [1*], **Vicenç** Puig [1], **Joseba** Quevedo [1]

[1] CS2AC-UPC, Rambla Sant Nebridi 10, Terrassa 08222, Catalunya
[*] Rambla Sant Nebridi 10 Terrassa 08222, ramon.perez@upc.edu, +34937398594

Abstract:

The leak localization community is very active and the Research Centre for Supervision, Safety and Automatic Control (CS2AC) is specially implicated in such an important issue. We have developed a methodology for leak localization using pressure measurements and hydraulic models. It is based on the fault detection and isolation theory and it evolved from a first version where binary residuals were generated to a correlation based method. This methodology was successfully applied in real networks. The improved leak localization approach includes contributions from other disciplines such as sensor placement, demand calibration and the accuracy assessment. This paper shows the evolution of a methodology due to the continuous work of a research team. First the algorithm is described. Results obtained in real networks are compared with those obtained in simulation. Finally, the new improvements of the methodology and the current challenges are presented and discussed.

Keywords (leak, water, network, pressure sensors, fault diagnosis).

1. Introduction:

The stress in water resources is becoming dramatic due to the climate change. Water demand increases continuously. Furthermore, allocation of the demand and resources differ in time and geography. One of the basic approaches of a sustainable management is the reduction of the demand. Efficiency in the use of water is important especially in agricultural uses. Nevertheless, in drinking water the main efficiency issue is in the transport and distribution where leakages represent about the 30% of the water use (waste). The benefits of demand reduction include energy demand reduction in production and distribution. Thus, the leakage management is a topic of continuous improvement.

Before addressing the leakage management in a network the analysis of how much water is produced and delivered and under which conditions is carried out. An annual water balance is normally used to assess Non-Revenue Water (NRW) and its components. There is a wide diversity of formats and definitions used for such calculation. Thus, the International Water Association (IWA) produced a standard procedure. The classification of water components in a supply system are presented in Figure 1 following the IWA 'best practices' guidelines (Hirner & Lambert, 2000). It includes the definitions of all terms involved, as the essential first step in practical management of water losses.

For more than a decade the Research Centre for Supervision, Safety and Automatic Control (CS2AC) has focused its attention in the real losses. Its background in fault detection and diagnosis lead its researchers to apply this approach on a model based leak detection and localisation methodology that has evolved during the years being applied to simulation for the development, analysis and validation on real case studies with successful results.

System Input Volume	Authorised Consumption	Billed Authorised Consumption	Billed Metered Consumption	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorised Consumption	Unbilled Metred Consumption	Non-Revenue Water (NRW)
			Unbilled Unmetered Consumption	
	Water losses	Apparent Losses	Unauthorised Consumption	
			Customer Metering Inaccuracies	
		Real Losses	Leakage on Transmission and/or Distribution Mains	
			Leakage and overflows at Utility's Storage Tanks	
			Leakage on Service Connections up to point of Customer metering	

Figure 1. The IWA standard for water balance analysis

Usually a leakage detection method in a DMA (District Metered Areas) starts analysing its characteristics (topology, materials, users, antiquity of the infrastructure, and historical data of burst), input flow data, such as minimum night flows and consumer metering data (Pérez et al., 2009a). Once the water distribution district is identified to have a leakage, techniques are used to locate the leakage for pipe replacement or repairing; the whole process could take weeks or months with an important volume of water wasted. Leakage detection and localisation on field is carried out using different techniques (Farley & Trow, 2003). Acoustic methods are most widely used but new approaches like radar are being studied.

The intensive use of models and data coming from the network to the control centre improve the efficiency of the direct search of leaks on the field. The transient models have been studied as they can point the location of a leak in a main with high accuracy (Colombo, Lee & Karney, 2009). Results of these transient models are much poorer when applied to a highly meshed distribution system. Furthermore, the models present in any water company are extended to a static period (Brdys & Ulanicki, 1994). The use of flow measurements would simplify the problem as the relation between flows, demands and leaks remain linear. However, it is not the case in water distribution networks where there is a dense mesh of pipes with only flow measurements at the entrance of each DMA. In this situation, water companies suggest as a feasible solution to install some pressure sensors inside the DMA. Pressure sensors in this situation are preferred because they are cheaper and easy to install and maintain. Therefore, the detection and location of leakages based on differences in predicted and measured pressures is being explored (Pudar & Liggett 1992). The sensitivity of pressures to the leakages is evaluated in the Sensitivity Matrix:

$$S = \begin{pmatrix} \frac{\partial p_1}{\partial f_1} & \cdots & \frac{\partial p_1}{\partial f_m} \\ \vdots & \cdots & \vdots \\ \frac{\partial p_m}{\partial f_1} & \cdots & \frac{\partial p_m}{\partial f_m} \end{pmatrix}$$

where p_i is the pressure in node i, f_j is the leak at node j and m is the number of nodes in the network. Figure 2 shows the sensitivity matrix of a DMA. This matrix is the basis for leakage detection using pressure measurements and hydraulic models.

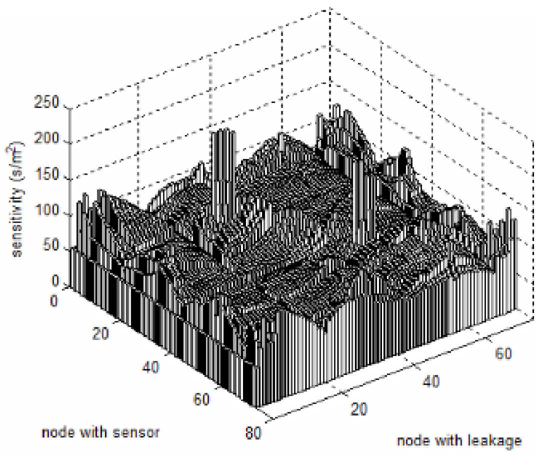

Figure 2. Sensitivity matrix corresponding a DMA.

It allows the generation of the signatures of each leak in the network using the model. These signatures are compared with the residuals obtained combining the measurements and the model following the fault detection and isolation theory (Gertler1998). In Section 2, the methodology is presented both in its original binary approach and then the evolution that made it more robust to the uncertainties. Finally, the technological issues related with this methodology that are being addressed so that it can be applied to any water company. In Section 3, the results obtained on real case studies validate the methodology and assess its performance. Finally in section 4 the conclusion, current and future work are discussed.

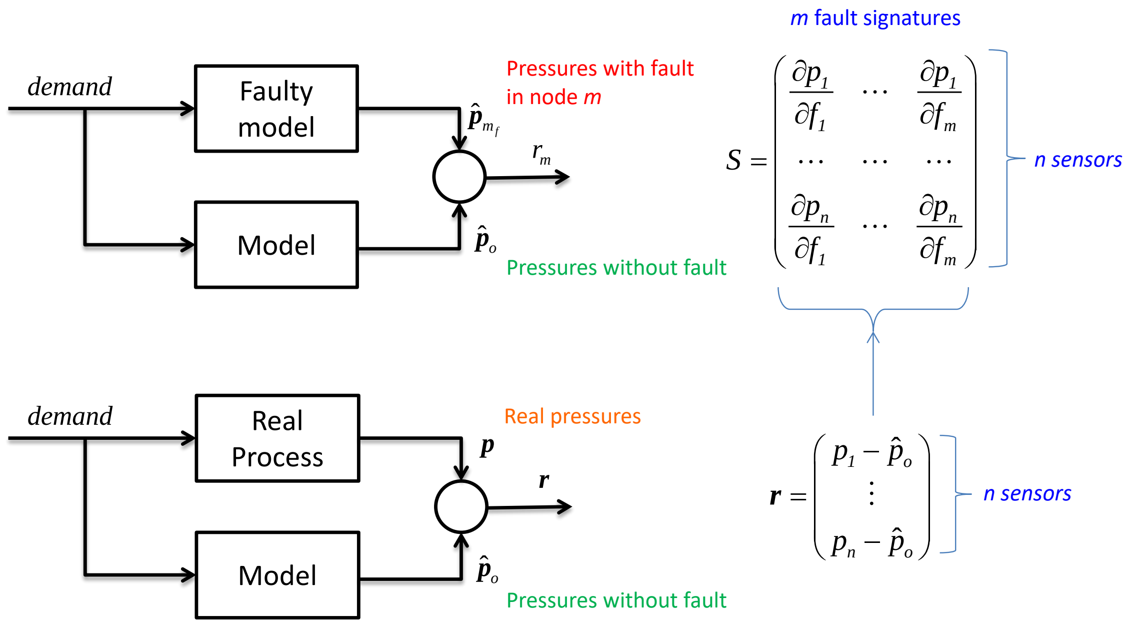

Figure 3. General methodology of leak localization based on Sensitivity Matrix and pressure measurement.

2. Proposed Approach

The pressure sensors installed within the DMA should detect a change when a leak appears. This change in the pressure is calculated comparing to the expected pressure value assuming that there is no leak in the network. The vector obtained with the variations on the *n* sensors available is the residual vector (**r**). This vector is compared with the Residual Matrix (generated in simulation using the DMA model) that have *n* rows and as many columns as possible leak locations and is a reduced Sensitivity Matrix (**S**). We assume that the leak can be in any of the *m* nodes of the network. Figure 3 describes the model and residual generation.

The inaccuracies in the model, noise and precision in measurements and uncertainty in the size of the leak produce discrepancies between the model signatures and the residuals. The approach to overcome the discrepancies has evolved. Here, we present the original methodology and the improvement introduced through the experience in different networks and projects.

2.1. Leak localization with binary Signature Matrix

The comparison is traditionally done by means of binary signatures and residuals while the results of the simulation and measurements are discrete values depending on the precision of the sensors (Pérez et al., 2011). A threshold has to be defined in order to decide when a sensor should (signature) and actually does (residual) detect a leak. The value of the threshold is obviously crucial in the interpretation of the data. Figure 4 shows how this value changes the information contained in the Signature Matrix.

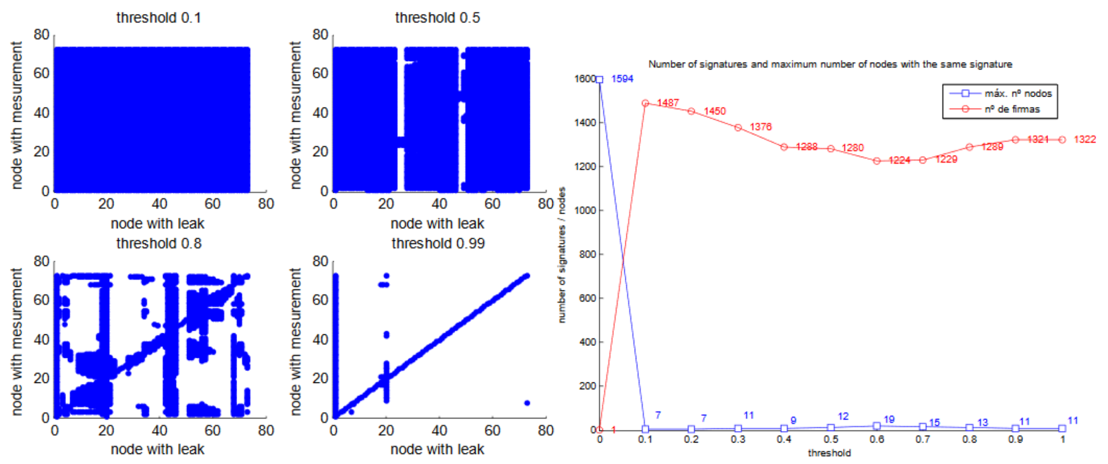

Figure 4. Number of 1's and 0's in the Binary Sensitivity Matrix depending on the threshold (a) Evolution of the Signature Matrix depending on the threshold.

The threshold election is carried out during a task previous to the leak localization. The distribution of the sensors (Pérez et al., 2009a) in the network is another important factor as the sensitivity to any leak is different depending on this distribution. Once the binarisation is assumed the aim of the methodology is to signal a group of nodes where the leak could be. The sensor placement methodology minimizes the size of the greatest group of nodes that present the same behaviour in a leak case guaranteeing that all the leaks are detected. This minimization is done by means of genetic algorithms (GA) that fit perfectly in a binary formulation of the problem and is done for different thresholds. Figure 5 presents the results in terms of the maximum size of a group of nodes depending on the threshold.

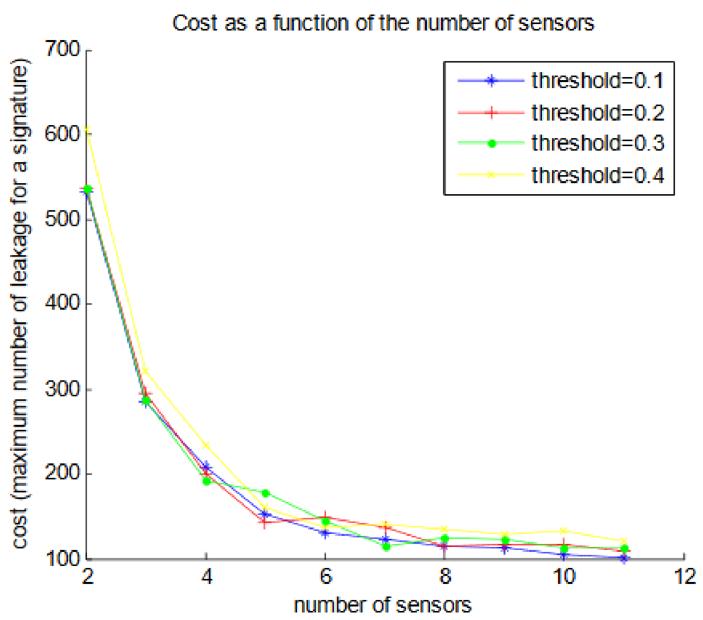

Figure 5. Evolution of the cost function (maximum size of group of possible leaky nodes) depending on the number of sensors and threshold**.**

The introduction of a huge number of sensors does not improve the result as there is a limitation due to the precision of the sensors. This problem is mitigated repeating the procedure for each sample time and aggregating the results so that the area signalled was reduced. This aggregation could be done following three different approaches:

- Mean the sensitivities
- Mean the binarised sensitivities
- Voting

Finally the voting process was found to be the best choice. The nodes with maximal number of times that have been included in the leaky group in a horizon of samples are those that are suspicious of being leaky. In Section 3.1, the results both for the sensor placement and the leak localization are presented.

2.2. Leak localization using correlation of residuals

The methodology, as was first developed, was highly dependent on the estimation of the leak size. In order to improve its robustness and avoid the threshold dependence in the binarisation process an alternative comparison between the model (signatures) and the measurements (residuals) was proposed (Quevedo et al., 2011). It is based on the fact that the leak signatures of nodes close to the leaky node should be more correlated (equation 1) with the residual.

$$\rho_{s_i r} = {cov(s_i, r)} \Big/ {\sqrt{cov(s_i, s_i) cov(r, r)}} \qquad \text{eq. 1}$$

The precision of the sensors is improved by means of an oversampling. Each 10 minutes the signatures and residuals are calculated with the current boundary conditions and using the hydraulic model (Figure 3). These results are averaged in an hour sample time. The results of a sliding horizon of 10 hours are aggregated before the correlation is performed in order to filter the noise and the uncertainty in the model. The maximum correlated zone is produced as a result. It should be low correlated and randomly distributed in the network in absence of leak and persistent in an area with higher correlation when a leak appears. The results obtained are presented in Section 3.2.

3. Results: Real Application

Most of the projects related with the leak detection and localization have been collaborations with CETAQUA (Centro Tecnológico del Agua). This collaboration provided real case studies in terms of DMA models and real data. DMAs have one or more water inputs where pressure and flow are monitored. These data are used for a previous calibration of the models. The simulation using EPANET connected with Matlab through the EPANET toolkit was used both for the sensor distribution and the leak localization procedures.

3.1. Leak localization with binary Signature Matrix

The case study used to illustrate the binary leak localisation methodology presented in this paper is based on a DMA that contains 1600 nodes and 41.153m of pipes. Simulated leaks introduced in the network are of 1 l/s, more or less 3% of the total demand of the sector (in the night time). Figure 6 presents the theoretical groups obtained by the 8 sensor distributed.

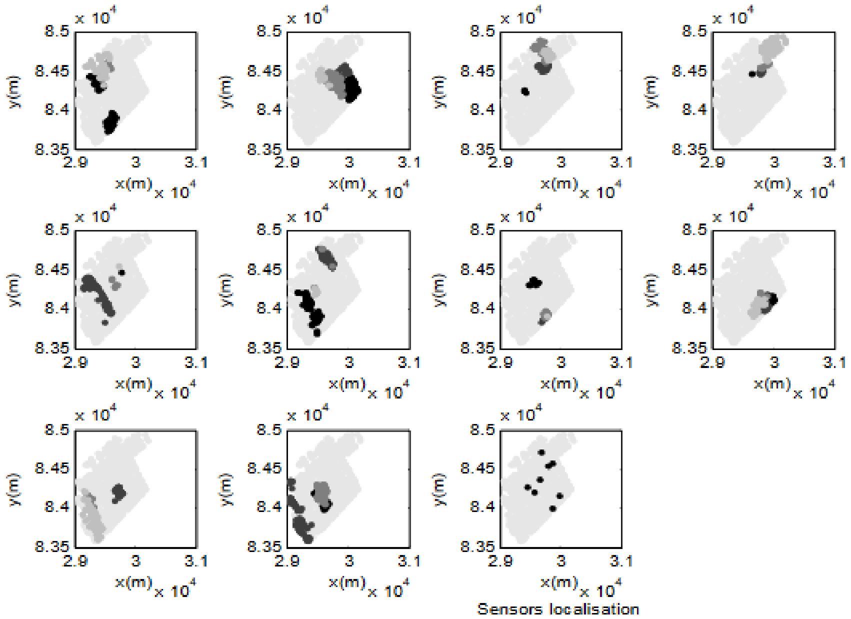

Figure 6. Groups of nodes with the same leakage signature with 8 sensors and placement of sensors

The localization results in simulation were pretty good as can be seen in figure 7. Here the voting result for 15 samples horizon is presented. Both for an exact model and a model with 18% of uncertainty in the demand distribution were considered. The result is presented in grey scale. With the uncertainty in demand some leaks are not in the most voted group but even so the most voted group is in the neighbourhood of the real leak.

The methodology was applied to a real leak introduced by the company for testing purposes. The DMA contains 260 nodes and two water input points, where a flow meter and a pressure meter are installed. Input flows in the network and pressures at these points are fixed in the simulation model, boundary conditions. In addition to this information, this DMA have 3 installed pressure sensors, which have been used to apply leakage localization methodology. The water company provided boundary conditions (pressure and flow) and pressure inside the DMA (three sensors) data with 10 minute time-step. This information was for 5 days in the last day a leakage was forced. With a leak of 5 l/s results were promising as the leak was in the most voted group (31 votes out of 64) together with 88 nodes. Figure 8 presents the results on a grey scale both for leaky and non-leaky scenario. It is important to highlight the low level of false alarms, one of the main issues in fault detection theory. In this case, only 4 and 5 (two groups) false alarms appeared out of 42 votes.

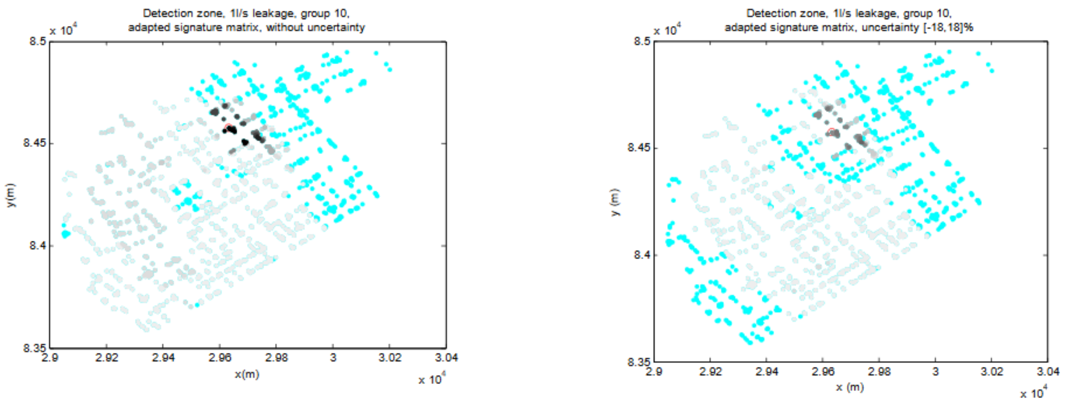

Figure 7. Localization of a leak with the nominal model (a) and 18% of uncertainty in the demand (b)

Signature				
Sensor 1	***Sensor 2***	***Sensor 3***	***Nº of nodes***	***Nº of detections***
0	0	0	55	0
1	0	0	23	17
1	1	0	88	31
1	1	1	94	4
		Total (max = 64)		52

Table 1. Signatures and voting results for a real leak

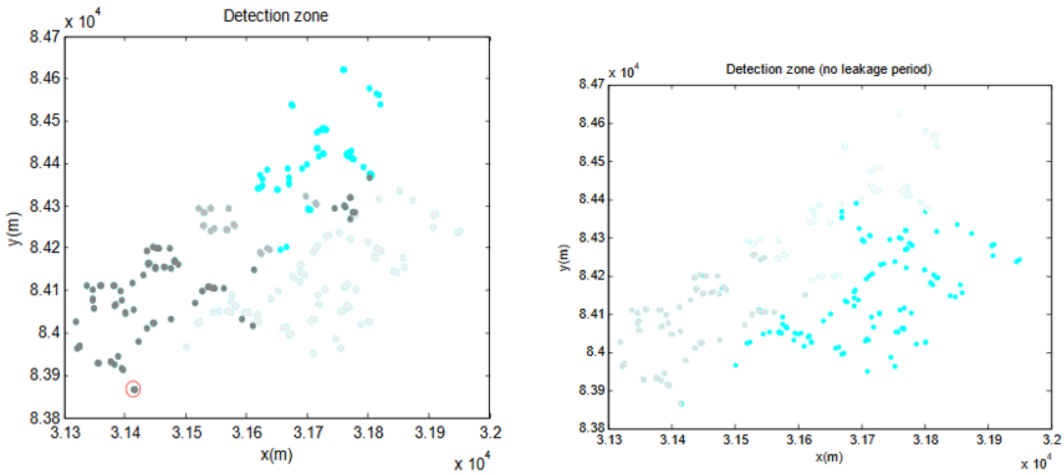

Figure 8. Localization results in leaky (round circle) and non-leaky scenario. The votes are represented in grey scale.

3.2. Leak localization using correlation of residuals

This pilot implementation used a DMA with two inlets, 3377 nodes, and 3442 pipes. The real leak was of 5.6l/s while the mean night consumption of the DMA is around 30l/s. Five pressure sensors with a 0.1 m of precision where installed. The results are presented in figure 9. The red star represents the actual leak while the size of the black stars represents the highest correlated nodes. The geographic distance of the search area produced is satisfactory for the company (below 200m). This is very helpful for the in-situ leak localisation because the search effort is highly reduced (Pérez et al. 2014).

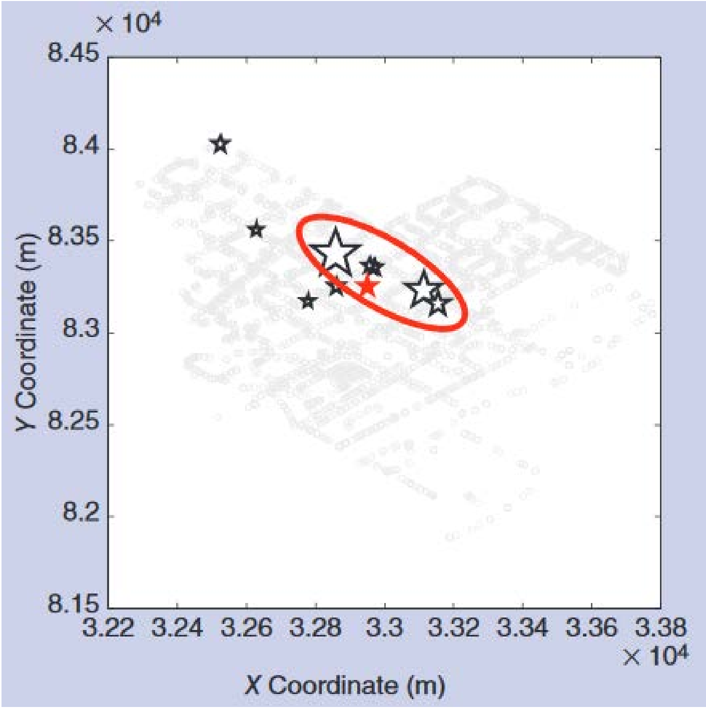

Figure 9. Leak localization results using correlation

4. Conclusions:

This work has presented a model-based methodology for leak localization in DMA using pressure measurements. It is based on the use of residuals obtained from the pressure measurements and their estimates from the network hydraulic model that characterizes the behaviour of the DMA without leakage. The residuals are compared with the leak sensitivity matrix that contains the predicted pressure disturbance caused by each potential leak in all of the monitored network's inner nodes (theoretical fault sensitivity). Leak isolation relies on correlating the observed residuals with the theoretical fault sensitivity contained in the leak sensitivity matrix.

The leak localization methodology has been implemented in a software tool that interfaces with a geographic information system and allows the easy use by water network managers. Finally, a real application of this method on the Nova Icària DMA pilot case study has been presented showing satisfactory results in a real fault scenario.

Regarding the future research related to this subject, several issues remain open. One research issue is to quantify the effect of uncertainty in demands, sensors and leak magnitude estimation on the methodology and accuracy of the leak localization procedure.

5. Acknowledgements:

This work has been funded by the Spanish Ministry of Economy and Competitiveness (MINECO) and FEDER through the projects ECOCIS (ref. DPI2013-48243. C2-1-R) and HARCRICS (ref. DPI2014-58104-R).

References

Brdys M. A., Ulanicki B. (1994) Operational Control of Water Systems: Structures, Algorithms, and Applications. Prentice Hall.

Colombo, A. F., Lee, P., & Karney, B. W. (2009). A selective literature review of transient-based leak detection methods. Journal of Hydro-Environment Research, 2(4), 212–227.

Farley, M., & Trow, S. (2003). Losses in Water Distribution Networks. London: IWA publishing.

Gertler, J. (1998). Fault Detection and Diagnosis in Engineering Systems. CRC Press.

Hirner W and Lambert A.(2000): Losses from Water Supply Systems: Standard Terminology and Recommended Performance Measures. IWA Website, www.iwahq.org.uk/bluepages

Pérez, R., de las Heras, S., Aguilar, J., Pascual, J., Peralta, A., & Landeros, E. (2009a). District management areas characterisation in water network based on clustering. Water Science & Technology: Water Supply, 9(5), 591.

Pérez, R., Puig, V., Pascual, J., Peralta, A., Landeros, E., & Jordanas, L. (2009b). Pressure sensor distribution for leak detection in Barcelona water distribution network. Water Science & Technology: Water Supply, 9(6), 715.

Pérez, R., Puig, V., Pascual, J., Quevedo, J., Landeros, E., & Peralta, A. (2011). Methodology for leakage isolation using pressure sensitivity analysis in water distribution networks. Control Engineering Practice, 19(10), 1157–1167.

Pérez, R., Sanz, G., Quevedo, J., Nejjari, F., Meseguer, J., Cembrano, G., … Sarrate, R. (2014). Leak Localization in Water Networks. IEEE CONTROL SYSTEMS MAGAZINE, (august), 24–36.

Pudar, R. S., & Liggett, J. A. (1992). Leaks in Pipe Networks. Journal of Hydraulic Engineering, 118(7), 1031–1046.

Quevedo, J., Cugueró-Escofet, M. À., Pérez, R., Nejjari, F., Puig, V., & Mirats, J. M. (2011). Leakage Location in Water Distribution Networks Based on Correlation Measurement of Pressure Sensors. In 8th IWA Symposium on System Analysis and Integrated Assessment (Watermatex 2011). San Sebastián.