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Extended-Horizon Analysis of Pressure Sensitivities for Leak Detection in Water Distribution Networks: Application to the Barcelona Network

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Abstract— **In this paper, a model-based leak detection and isolation approach for water distribution networks (WDN), which considers an extended time horizon analysis of pressure sensitivities is proposed. It differs from previous works based on pressure sensitivities analysis since the existing approaches were considering time instant evaluation. This fact makes those approaches very sensitive to demand changes and noise in measurements. A fault isolation approach based on new criterion, known as the angle method, is introduced. This criterion is based on evaluating the angle between the residual vector and the columns of the leak sensitivity matrix. The performance of the proposed approach is compared with two well established methods in the literature (the least square optimization and the correlation methods) when they are applied to the Barcelona WDN.**

I. Introduction

WATER leaks in networks can cause significant economic losses in the fluid transportation and an increase on reparation costs, giving as a consequence an extra cost translated to the final consumer. In many water distribution systems (WDS) losses due to leaks are estimated to account up to 30 % of the total amount of extracted water. Such burden cannot be tolerated in a world struggling with satisfying water demands of a growing population.

Several works have been published on leak detection for WDN. In the paper from Colombo et al. [1], a review of transient-based leak detection methods is offered as a summary of current and past work. A method has been proposed in [2], to identify leaks using blind spots based on previous works that uses the analysis of acoustic and vibrations signals [3] and models of buried pipelines to predict wave velocities [4], among others. In addition, the detection of pipeline leaks can also be possible using the inverse problem [5] which uses pressure and flow measurements.

An LPV model-based leak detection approach that considers uncertainty using zonotopes is introduced and tested in a small water network [6].

In this paper, the leak sensitivity based approach proposed by [7] is improved by making an extended-horizon analysis of pressure sensitivities and residuals, and introducing the angle method [8] as criteria to locate the leaks. In [8], this method was suggested for the first time and tested in simulation using an academic network and assuming that the pressures in all the nodes are measured. In this paper, angle method is tested considering only a few sensors as in practice is the case for a real network, which implies a more difficult isolation of the leakage area. Moreover, the proposed approach method is applied to the Barcelona WDN and compared with two other well established strategies of the literature: the least-square optimization [5] and the correlation methods [7].

This paper is organized as follows: Section II describes the proposed methodology. Section III presents the Barcelona WDN considered in the experiments. In Section IV, we detail the experimental scenarios while in Section V we compare the results obtained with the different methodologies. Finally, Section VI concludes this work.

II. Methodology

A. Introduction

The main objective of the proposed methodology is to detect and isolate leaks in a water distribution network using pressure measurements and their estimation using the hydraulic network model. A leak will be considered as a water flow loss through a defect of a network element that is being monitored. The proposed approach assumes the existence of a single and continuous leak from the appearance time. The leak detection is based on computing the difference (residual) between the pressure measurements $p_i(k)$ against their estimation $\hat{p}_i(k)$ by means of the simulation of the hydraulic model:

$$r_i(k) = p_i(k) - \hat{p}_i(k) \qquad i = 1,\ldots,n \tag{1}$$

where n is the number of pressure sensors available in the network. These residuals are evaluated against a threshold τ_i that is selected to take into account the measurement noise and model uncertainty. If some residual violates its threshold (i.e, $|r_i(k)| > \tau_i$) for a given time window then, the isolation

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process is initiated. The leak isolation is based on comparing the residual vector against the leak sensitivity matrix that contains the effect of each possible leak in each residual. The candidate leaks are those whose effect matches the best in a time window when compared using some metric with the observer residual vector. Once the candidate leak has been isolated, an estimation of the leak could even be provided by means of the residual leak sensitivity. Fig. 1 summarizes graphically the proposed methodology including the leak detection, isolation and estimation processes.

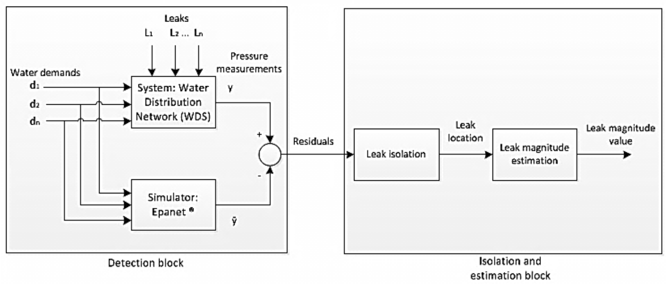

Fig. 1. Diagram of detection, isolation and estimation processes

B. Leak sensitivity matrix

As discussed above, leak isolation is based on the evaluation of the effect of all possible leaks in the available pressure measurement sensors using a sensitivity analysis. As a result of this analysis the *sensitivity matrix* [9] is obtained as follows:

$$\boldsymbol{S} = \begin{bmatrix} \frac{\partial p_1}{\partial f_1} & \cdots & \frac{\partial p_1}{\partial f_m} \\ \vdots & \ddots & \vdots \\ \frac{\partial p_n}{\partial f_1} & \cdots & \frac{\partial p_n}{\partial f_m} \end{bmatrix} \qquad (2)$$

where each element s_{ij} of the sensitivity matrix $\boldsymbol{S}$ measures the effect of leak f_j in the pressure of sensor p_i taking into account that the network has n sensors and m demand nodes, therefore, there are m possible leaks. It is extremely complex to calculate S analytically in a real network because the model is based on a huge set of implicit non-linear equations. This work proposes instead generating the sensitivity matrix by simulation using increments of pressure and maintaining constant the leakage flow. First, the computation of the sensitivity matrix needs the construction of the nominal (non-faulty) operation scenario of the network in a 24-hours horizon, which allows us to obtain the vector $p(k)$ for the nominal pressure of each node of the network

$$\boldsymbol{p}(k) = \begin{bmatrix} p_1(k) \\ \vdots \\ p_n(k) \end{bmatrix} \qquad (3)$$

where $p_i(k)$ represents the pressure of node i at time k without the presence of leak and n is the number of sensors in the network.

Then, leak scenarios are considered in simulation by introducing a leak at a time in each node of the network. The pressures of the sensors in case of each considered leak scenario are stored in the matrix:

$$\boldsymbol{P}_f(k) = \begin{bmatrix} p_1^{f_1}(k) & \cdots & p_1^{f_m}(k) \\ \vdots & \ddots & \vdots \\ p_n^{f_1}(k) & \cdots & p_n^{f_m}(k) \end{bmatrix} \qquad (4)$$

where $p_i^{f_j}(k)$ is the pressure of sensor i at time instant k when a leak is present at node j, m is the number of nodes in the network (possible leaks) and n is the number of sensors in the network.

Finally, using vector (3) and matrix (4), the sensitivity matrix (2) for each time instant of the horizon selected is computed as follows

$$\boldsymbol{S}(k) = \begin{bmatrix} \frac{p_1^{f_1}(k) - p_1(k)}{f_1} & \cdots & \frac{p_1^{f_m}(k) - p_1(k)}{f_m} \\ \vdots & \ddots & \vdots \\ \frac{p_n^{f_1}(k) - p_n(k)}{f_1} & \cdots & \frac{p_n^{f_m}(k) - p_n(k)}{f_m} \end{bmatrix} \qquad (5)$$

C. Leak isolation

Leak isolation is based on analyzing the residuals (1) along the proposed time horizon trying to find some inconsistency between the pressure measurements and their estimated value in order to establish what node is the most affected and has the highest probability of presenting leakage. In this paper, the angle method is proposed. The angle method is based on evaluating the angle between the actual residual vector and each column of the leak sensitivity matrix as follows

$$\alpha_j(k) = \arccos\left(\frac{\boldsymbol{r}^T(k)\,\boldsymbol{s}_{-,j}(k)}{|\boldsymbol{r}(k)|\,|\boldsymbol{s}_{-,j}(k)|} \right) \quad j = 1\ldots,m \qquad (6)$$

Then, according to the selected time horizon L, we compute the angle mean and locate the leak index using:

$$leak_{index} = arg \min_{j \in \{1,\ldots,m\}} \left(\overline{\alpha_j} \right) \text{ with}$$
$$\overline{\alpha_j} = \frac{1}{L} \sum_{k=1}^{L} \alpha_j(k) \qquad (7)$$

The node that presents the smallest leak index is the one that is proposed as the leak location. In a previous work [8], it is shown that this method outperforms the other methods existing in the literature. In this paper, this method will be tested in a real network with a reduced number of sensors (as discussed in the introduction) and compared with two other methods (least square optimization and correlation) that according to [8] perform quite well.

C.1 Least square optimization method

This method works in an opposite way than the angle method, i.e. it computes an inverse optimization problem in order to find an appropriate leak size that explains the pressure measurements present in every node. Then, it performs an analysis of the minimum error finding in this way the node affected by a leak.

This method also uses the leak sensitivity matrix, and solves the following optimization problem for each leak candidate

$$J_{f_j} = \min_{f_j} \sum_{k=1}^{L} \left| \boldsymbol{r}(k) - \boldsymbol{s}_{-,j}(k) f_j \right|^2 \quad j = 1, \ldots, m \quad (8)$$

where f_j is the variable that is optimized in order to minimize the error and corresponds to the magnitude of the present leak. Then, the leaky node is found as the one that produces the smallest index (8), i.e.,

$$leak_{index} = arg \min_{j=1,\ldots,m} \left(J_{f_j} \right) \quad (9)$$

As one can see, this method allows obtaining more information about the leak since it provides the leak size that best fit the observed pressure data.

C.2 Correlation method

The correlation method is based on correlating the current residual vector with each column of the leak sensitivity matrix

$$c_{jk} = \frac{\sum_{i=1}^{n} \left(r_i(k) - \overline{r_i(k)} \right) \left(s_{ij}(k) - \overline{s_{ij}(k)} \right)}{\sqrt{\sum_{i=1}^{n} \left(r_i(k) - \overline{r_i(k)} \right)^2} \sqrt{\sum_{i=1}^{n} \left(s_{ij}(k) - \overline{s_{ij}(k)} \right)^2}} \quad j = 1 \ldots m \quad (10)$$

Then, looking at the maximum correlation along the time horizon, we can find the leaky node. We include the correlation method in this work because it was already applied to the Barcelona DWN in [9]. This will allow a comparison against the method proposed in this paper.

III. Case Study

The case study considered in this paper is based on a District Metering Area (DMA) of the Barcelona WDN. This network is located in Nova Icaria area in Barcelona, Spain. It is composed of 3320 nodes, where 1900 are demand nodes and the rest is used to simulate street or junction nodes. In our case, leaks for the total of 3320 nodes are considered. Using the method presented in [11] an optimal sensor placement of 6 sensors, taking budget restrictions of the Barcelona water company, were installed (see Fig. 2).

Matlab® and Epanet were combined to simulate the leaks and to obtain and analyze the network data using the algorithms proposed in the paper. All the leaks are assumed to be located in the nodes of the network. This is a standard assumption in model based leak detection and isolation literature (see for example, [5]). In simulation with Epanet, leaks are introduced by finding the corresponding emitter coefficient that provides the desired leak magnitude in the network, according to the equation:

$$EC = Q / F_p^{\ P_{exp}}$$

where EC is the emitter coefficient, Q is the flow rate, F_p is the fluid pressure and P_{exp} is the pressure exponent. Data of node pressures are obtained from extensive simulations of normal and leak scenarios. The leak sensitivity matrix (2) is computed for a leak magnitude of 1.67 lps, that corresponds with the middle of the range of leak sizes (between 0.7 and 3 liters per second) that are wanted to be located according to the company. In all the experiments performed, the proposed angle method is compared first with the least square optimization method and then with the correlation method. In all the cases, the efficiency achieved by each method is evaluated and compared with the one achieved when all the network pressures are fully accessible.

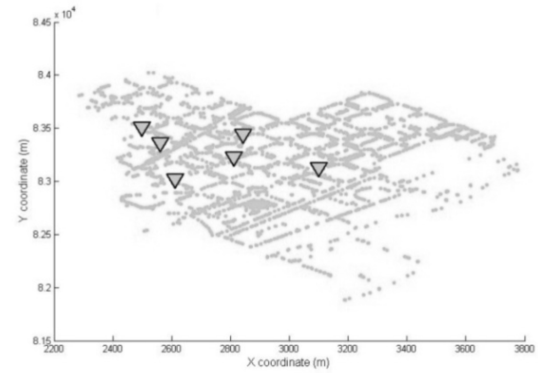

Fig. 2 Optimal sensor placement of 6 sensors as validated by the water company for the Nova Icaria network.

IV. Results

In order to test the performance of the considered methods, several scenarios have been proposed in this paper. Due to space limitations, this section shows the results obtained when considering only one of the leaky nodes, subject to different conditions corresponding to the scenarios described below and for the methods considered in this paper. In the figures showing leak isolation results, the nomenclature presented in Fig. 3 will be used.

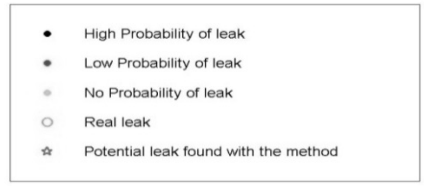

Fig. 3 Nomenclature For The Leak Isolation Results

A. Scenarios

The first scenario involves the presence of a leak of 1.67 lps that corresponds to the size used for computing the leak sensitivity matrix (2). In that case, the three methods find exactly the node in which the leak is present. Fig. 4 presents the location of this leak without noise applying the angle method. It can be noticed that the exact location of the leaky node is obtained. The second scenario involves the presence of a leak of the same size by taking also into account noise in the measurements and in the demands with a magnitude between 1 and 5%. In this case, the method efficiency is reduced as it can be seen in Fig. 5 and Fig. 6. The third scenario corresponds to the case the leak size is different from the one (i.e. 1.67 lps) used to compute the leak sensitivity matrix and noise is added. Fig. 7, Fig. 8 and Fig. 9. show the behavior of each method in the case of a 6.3 lps leak and when random noise is added.

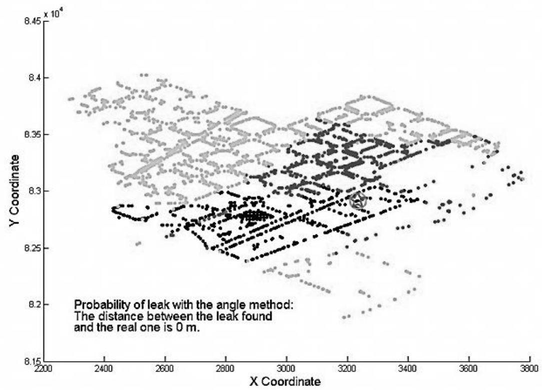

Fig. 4. Location of a nominal leak of 1.67 lps without noise applying the angle method. In that case the exact correct location of the leak node is guaranteed.

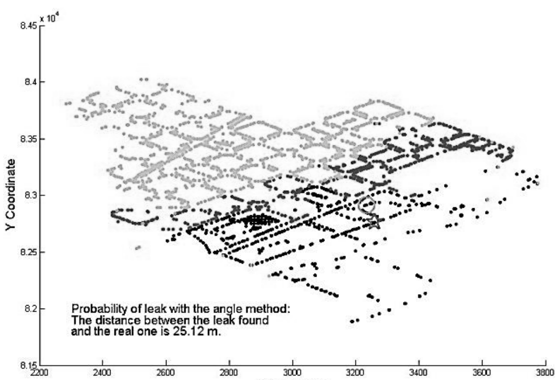

Fig. 5. Location of a nominal leak of 1.67 lps in presence of noise and when applying the angle method. The leak node is found 25.12 meters farther than the real leakage node.

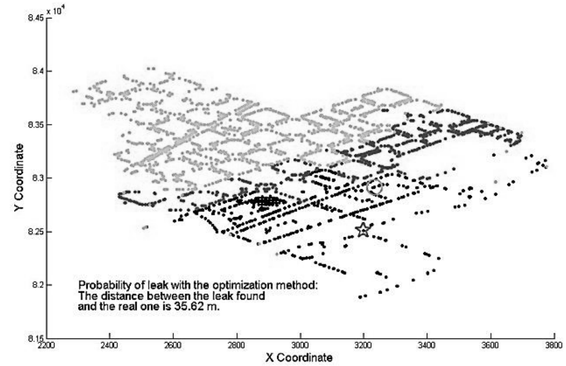

Fig. 6. Isolation of a nominal leak of 1.67 lps in presence of random noise, when applying optimization method. The leakage node was located 36.62 meters farther than the real leak.

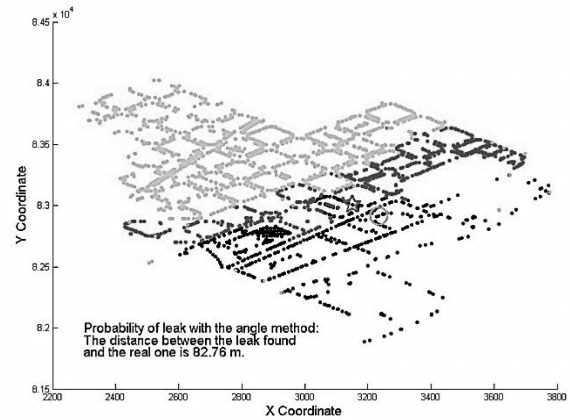

Fig. 7. Leak isolation of a no nominal leak of 6.3 lps magnitude in case of random noise using the angle method, the leakage node was located 82.76 meters from the real leak.

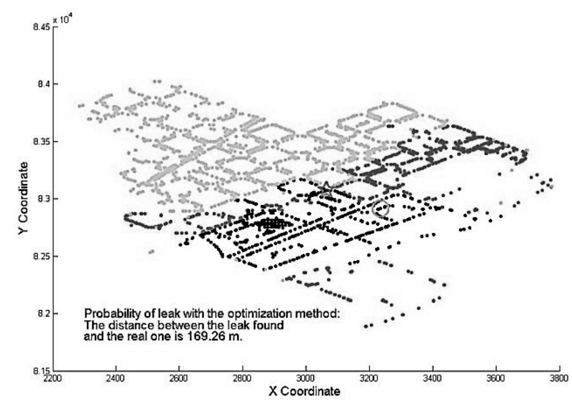

Fig. 8. Leak isolation of a no nominal leak of 6.3 lps magnitude using the optimization method. The presence of noise causes that the leakage node is found at a distance of 169.26 meters from the real leak node.

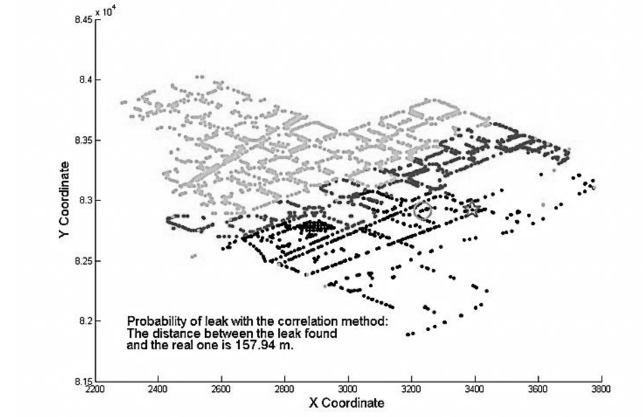

Fig. 9. Leak isolation of a no nominal leak of a 6.3 lps magnitude in case of random noise using the correlation method, the leakage node was located 157.94 meters from the real leak.

Another important case is when a leak begins during the process of simulation in a given point of the time horizon. Such a situation is shown in Fig. 10 where the pressure and the demand change when a leak appears at the hour 8.

As one can see, the difficulty is that when the leak appears at a given instant of the time horizon, it may be difficult to discriminate between measurement noise and a significant variation, i.e. the very small pressure change can lead to some confusion in the detection process.

We have noticed that in all the cases the angle method is more precise performing the leak detection.

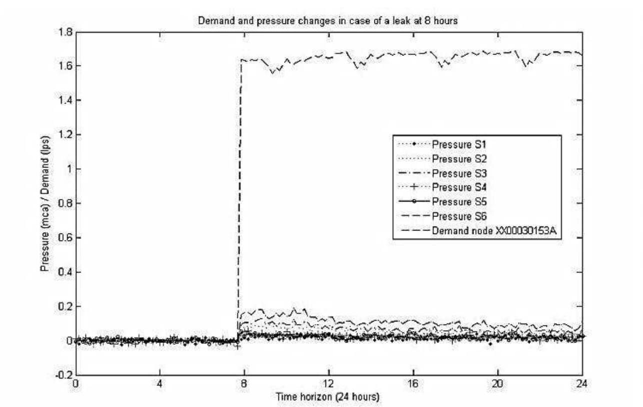

Fig. 10. Behavior of the demand and the pressure in case of a single leak appearing at the 8th hour in the time horizon. It shows that the pressure varies only slightly and that the noise may affects the detection.

V. Comparative Results

In the previous section, we have seen examples of results for different types of scenarios. Here, we show a brief summary of the results obtained in each experiment performed and a result discussion is provided.

In the following, we find the tables that sum up the efficiency for each method in the considered experiments.

A. *Angle method*

By computing an isolability test in which every possible leak was tested, we found that the angle method is able to find the exact leakage node with an efficiency of 80.06% of the cases, while almost 88% of possible leaks are located within a distance lower than to 2 meters from the real leak. According to the results of this test, we can say that 266 of the 3220 nodes are non-isolable in the network.

The results show that the angle method is able to detect and isolate single leaks in a real network even in the worst case with a maximum distance of approximately 700 meters from the exact leak location (see Table I). However, it is remarkable to note that the mean distance for each experiment is close to 100 meters in presence of random noise. This is an important result since it means that there is an improvement in the leak location precision with respect to the previous results [9]. Another important result is that even when the number of sensors affects the behavior of the method, the efficiency when the network has only 6 sensors was not too much affected. This means that we may reduce significantly the instrumentation of the network without affecting severally the efficiency of the leak location.

Table I
Efficiency in the Random Leak Location With the Angle Method

Leak size (lps)	Maximum distance	Mean distance	Distance between ranges* (%)	Random Noise
1.67 (Nominal)	383.37	17.50	82	No
0.7	471.19	74.44	58	No
3	284.22	53.03	64	No
6.3	444.71	129.11	34	No
1.67 (Nominal)	479.41	101.95	66	Yes
0.7	449.15	119.88	58	Yes
3	525.97	103.88	68	Yes
6.3	554.85	112.27	58	Yes

*Ranges are: 3m for nominal leak without noise, 50m for non-nominal leak without noise, 100m for leak with noise.

B. *Optimization method*

Similarly to the angle method, an isolability test was performed for the optimization method. From this analysis, the efficiency of finding the exact node with optimization method is 74.25%, while the efficiency of finding a node within a distance lower than 2 meters is 84.78%. In Table II, we can see the efficiency of the optimization method for different leak sizes and with or without noise. We have to highlight that even when the optimization method behavior is not as good as the angle method, it has the advantage that it provides an approximate leak magnitude and a degree fitting of the candidate leak with measured data that can be exploited as an extra information in order to improve the leak detection and isolation process.

and leak isolation approaches.

Table II
EFFICIENCY IN THE RANDOM LEAK LOCATION WITH THE OPTIMIZATION METHOD

Leak size (lps)	Maximum distance	Mean distance	Distance between ranges* (%)	Random Noise
1.67 (Nominal)	15.04	1.34	88	No
0.7	754.06	89.48	56	No
3	1251.8	123.85	40	No
6.3	768.85	181.1	26	No
1.67 (Nominal)	794.52	143.95	56	Yes
0.7	595.56	150.27	48	Yes
3	684.16	155.86	56	Yes
6.3	769.16	209.92	44	Yes

*Ranges are: 3m for nominal leak without noise, 50m for non-nominal leak without noise, 100m for leak with noise.

C. *Correlation method*

Finally, the results obtained with the angle and least square optimization methods are compared against the behavior with the correlation method already applied to this network in [9]. We performed the same experiments with and without noise using the correlation method. Using the isolability test, we found that the correlation method locates with an efficiency of almost 80% in finding the exact leak and an efficiency of 87% within a distance lower than 2 meters from the real leak, although with this approach there are 408 non-isolable leaks. Results obtained with the exhaustive tests are shown in Table III. As it can be seen, both the mean distance and the distance between expected ranges reach higher values when using the correlation method than with the two other leakage isolation strategies.

Table III
EFFICIENCY IN THE RANDOM LEAK LOCATION WITH THE CORRELATION METHOD

Leak size (lps)	Maximum distance	Mean distance	Distance between ranges* (%)	Random noise
1.67 (Nominal)	757.28	26.64	76	No
0.7	453.46	86.88	52	No
3	757.28	107.6	56	No
6.3	614.24	136.15	40	No
1.67 (Nominal)	920.42	240.39	30	Yes
0.7	982.43	293.97	30	Yes
3	893.7	193.47	36	Yes
6.3	842.73	144.61	58	Yes

*Ranges are: 3m for nominal leak without noise, 50m for non-nominal leak without noise, 100m for leak with noise.

VI. CONCLUSION

This paper presents the application of angle method for leak isolation and the comparison with two other well established methodologies to the case of a real water network where the number of pressure measurements is very small in comparison with the number of nodes in the network. The results obtained demonstrate that it is possible to improve the leak detection and isolation in the Nova Icaria network by applying the angle method that we proposed instead of the correlation method already applied in [11]. Results show that the angle method increases the capability of detecting leaks in a great number of cases. Moreover achieved distances between the estimation of the leak position and its real location are reduced by 200 meters in the presence of noise. As future work, we would like to perform an improved demand calibration and a better sensor placement based on the same principle as our leak isolation method in order to investigate if there exist a relation between sensor location

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