Multi-Leak Detection with Wavelet Analysis in Water Distribution Networks

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Abstract— **In this work detection of single and multiple leaks using an extended horizon analysis of pressure sensitivities is proposed. The method also includes other techniques, such as wavelet analysis, phase-quadrant demodulation code, and a weighting and voting system. This approach is tested in simulations for two different water distribution networks: Hanoi a network with high consumption, and Quebra, a larger network. Detection performance was measured by indicating the leaking node or one of the neighbors, and simulation results showed that in presence of two leaks, the efficiency is around 80%, detecting the leaking nodes or one of the neighbors around the leak, and 95% of efficiency to detect the leaking nodes, a neighbor node or the second order neighbors nodes, being these the neighbors of the neighbors; in presence of three leaks, the detection success is around 97% detecting the leaking nodes, the neighbor nodes or the second order neighbors nodes. Other simulations were also realized for single leak scenarios, showing our method better performance than a recently proposed algorithm.**

Index Terms—**Multiple Leak Detection, Phase-quadrant demodulation code, Water Distribution Systems, WDS, Wavelet Analysis.**

I. INTRODUCTION

WATER demand exceeds the water supplied in many parts of the world. With the increase of the population at an unprecedented rate, the increase of the supply needs from the industry, the agriculture and the farming, many more areas are expected to experience this imbalance in the near future.

In most water distribution networks, a large percentage of the water is lost in transit from treatment units to consumers. Typically around 25% of production is lost or unaccounted due to several causes, mainly leakages, false measurement errors, public usage such as fire-fighting, earthquakes and sometime severely cold weather [1].

A typical distribution system (in urban areas or strategically important trunk mains) is subdivided into discrete zones or district meter areas (DMA), by the permanent closure of valves. A DMA is generally constituted by 500–3000 properties. Flow (and sometimes pressure) sensors are placed on the DMA boundaries and the collected data is subsequently analyzed for leakage trends. The most popular operational use of flow data is the analysis of measured minimum night flows. If leakage has increased sufficiently then further investigation is needed to find the location of leaks [2]. In this research a new methodology is proposed to deal with the problem of leaks detection in a Water Distribution Network. Our work addresses the detection of multiple leaks, and will prove its effectiveness in multiple leaks scenarios, by identifying the node containing the leak or some nearby node on the Network. The proposed method is a combination of different methods, such as pressure sensitivities matrix, wavelet analysis, phase-quadrant demodulation code, and a weighting and voting system. This approach is tested in simulations for two different water distribution networks: a network with high consumption, Hanoi network, and a larger network, Quebra. Simulation results showed that in presence of two leaks, the detection efficiency is around 80%, detecting the leaking node or one of the neighbors nodes around the leak, and 95% of efficiency detecting the leaking node or one of the neighbor nodes or the second order neighbors nodes, being these the neighbors of the neighbors; in presence of three leaks, the detection success is around 97% detecting the leak node, a neighbor node or the second order neighbors nodes. Other simulations were also realized for single leak scenarios, showing that our method has better performance than the Angle between Vectors Method.

II. RELATED WORK

Several works have been published on leak detection for Water Distribution Systems (WDS). In [2] a method to locate leaks is presented using Support Vector Machines (SVM). In [3] a method to detect and locate leaks based on the transitory inverse analysis is proposed. In [1] a technique to isolate leaks using fuzzy analysis of the residuals is demonstrated. In [4] a method that uses pressure measurements and the sensitivity residuals is presented. In this methodology, first a model free of leaks is obtained offline and then the residuals are analyzed on-line against a proposed threshold. If any inconsistency is found, an analysis to detect and isolate the leaks begins using an established mapping. In [5] an extended-horizon analysis of pressure sensitivities and residuals is performed introducing adequate isolation algorithms to locate the leaks; also a comparison between different leak detection methods is done, presenting the Angle between Vectors method as the best one. But, even when good results were obtained here; it was only for single leaks and moderate noise scenarios. The investigation developed until today is mainly focused in the detection of

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one leak in WDS, and in the detection of multiple leaks in small systems with just a few nodes. The research proposed in this investigation develops a new methodology to address the problem of multiple leaks detection in a Water Distribution Network. We will prove the effectiveness of detecting multiple leaks, by identifying the node containing the leak or some nearby node on the Network.

III. WAVELETS

A wave is usually defined as an oscillating function of time or space, such as a sinusoid. A wavelet is a brief oscillation, which has its energy concentrated in time to give a tool for the analysis of transient, non-stationary, or time-varying phenomena. The main idea is to take the wavelets and use them in a series expansion of signals or functions much the same way Fourier series uses the wave or sinusoid to represent a signal or function. The signals are functions of a continuous variable, which often represents a signal or function [1].

The wavelets are near optimal for a wide class of signals for compression, denoising, and detection.

The wavelet expansion allows more accurate local description and separation of signal characteristics. A wavelet expansion coefficient represents a component that is itself local and is easier to interpret. The wavelet expansion may allow a separation of signal components that overlap in both, time and frequency. In the other side, wavelets are adjustable and adaptable. Because there is not just one wavelet, they can be designed to fit specific applications.

The continuous wavelet transform (CWT) is defined as the sum over all time of the signal multiplied by a scaled and shifted version of the wavelet function Ψ:

$$\mathrm{C(scale, position)} = \int_{-\infty}^{\infty} \mathrm{f(t)\Psi(scale, position, t)dt} \quad (1)$$

The results of the CWT are many wavelet coefficients C, which are a function of scale and position. Multiplying each coefficient by the appropriately scaled and shifted wavelet yields the constituent wavelets of the original signal [6].

Complex Shannon Wavelets

The expansion used in this paper is the Complex Shannon Wavelets which is obtained from the frequency B-spline wavelets. A complex Shannon wavelet is defined by

$$\Psi(R) = \sqrt{f_b} sinc(f_b R) e^{2i\pi f_e R} \quad (2)$$

Depending on two parameters:

- f_b is the bandwidth parameter.
- f_c is the wavelet center frequency.

The condition $fc > \frac{fb}{2}$ is sufficient to ensure that zero is not in the frequency support interval [7].

IV. PHASE-QUADRANT DEMODULATION CODE

Based on the demodulation process phase used to encode iris patterns [9], each pressure residue is transformed into a complex matrix using wavelets, and then is demodulated to extract its information phase. Residues are projected into complex Shannon wavelet (2), generating complex-value coefficients whose real and imaginary parts specify the coordinates of a phasor in the complex plane. The angle of each phasor is quantized to one of the four quadrants, setting two bits of information phase. This process is repeated for each residue generated by each leak and for each residue of the time horizon being analyzed, generating as many matrices as residues exists. This means $n \times m$ matrices, being n residues for each Sensitivity Matrix and m the number of samples in the time horizon.

Then, Ψ(R) can be regarded as a complex-valued bit whose real and imaginary parts are either 1 or 0.

The main objective of the proposed scheme is to detect, isolate and identify leaks in a hydraulic network, using pressure measurements in the nodes of the hydraulic network. A leak will be considered as a water flow loss through a defect of an element of the network that is being measured. Fig. 2 shows the leak detection, isolation and identification process. We consider the existence of two and three leaks of different size at a given time. Data of node pressures are obtained from extensive simulations of normal and leak scenarios. From these data, pressure sensitivities and residuals are obtained for a time window and then analyzed by the leak detector algorithm.

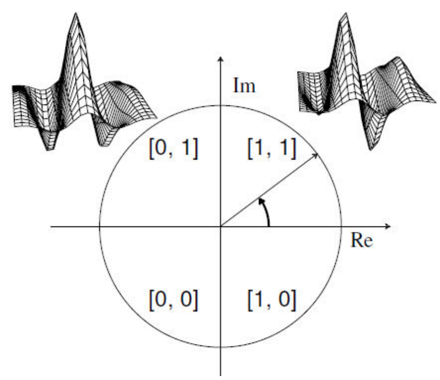

Fig. 1. Demodulation Process Phase, [9].

V. METHODOLOGY

All the leaks are simulated in the nodes of the network. This is performed by adding an extra demand of water at a specific node and by using two patterns of water demands: one to simulate the nominal water demand and the other one to simulate the leak.

To compare the efficiency of the method under more realistic scenarios, changes in the leak magnitude and noise in the demands were simulated. Also a time horizon window of 24 hours was selected for the simulations. Matlab® and Epanet® are used altogether to simulate the leaks and to obtain and analyze the network data using the algorithms proposed in the paper.

In the proposed method a sensitivity matrix that quantifies the effect of leaks in all nodes and pressure sensors in the network is needed, to initiate the detection of the leak.

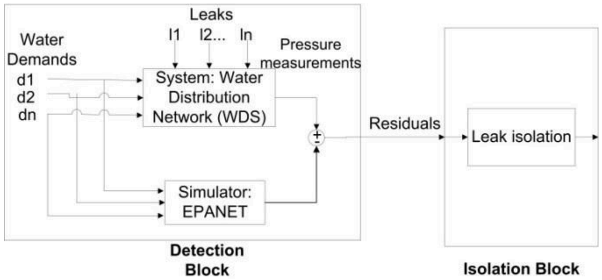

Fig. 2. Detection and isolation diagram.

Sensitivity matrix algorithm

This algorithm is divided into three main stages. The first stage is the construction of the nominal operation scenario of the network. At this stage, two matrixes are obtained, one for the pressure on each node of the network, another one for the water demand of each node. For the above we define:

$$\boldsymbol{P} = \begin{bmatrix} p_{1,1} & \cdots & p_{1,m} \\ \vdots & \ddots & \vdots \\ p_{n,1} & \cdots & p_{n,m} \end{bmatrix}, \boldsymbol{P}_a = \begin{bmatrix} p_{a_{1,1}} & \cdots & p_{a_{1,m}} \\ \vdots & \ddots & \vdots \\ p_{a_{n,1}} & \cdots & p_{a_{n,m}} \end{bmatrix} \quad (3)$$

Where:

$\boldsymbol{P}$ is the matrix of pressures in no leak situation

$p_{i,j}$ represent the pressure of node $\boldsymbol{i}$ at time $\boldsymbol{j}$ in no leak situation

$\boldsymbol{P_a}$ is the matrix of current pressures

$p_{a_{i,j}}$ is the current pressure of node $\boldsymbol{i}$ at time instant $\boldsymbol{j}$

n is the number of nodes in the network

m is the number of samples through the simulation time

The second part is the construction of scenarios with the presence of a leak. The pressures in nodes when a leak in the network is present are stored in the following matrix:

$$\boldsymbol{P}_f^k = \begin{bmatrix} p_{f_{1,1}}^k & \cdots & p_{f_{1,m}}^k \\ \vdots & \ddots & \vdots \\ p_{f_{n,1}}^k & \cdots & p_{f_{n,m}}^k \end{bmatrix} \quad (4)$$

Where:

$\boldsymbol{P_f^k}$ is the matrix of pressures when a leak is present at node $\boldsymbol{k}$

$p_{f_{i,j}}^{k}$ is the pressure of node $\boldsymbol{i}$ at time instant $\boldsymbol{j}$ when a leak is present at node $\boldsymbol{k}$

In the third part of the algorithm, the residual matrices are obtained as follows:

$$\boldsymbol{\mathcal{R}}_k = \boldsymbol{P} - \boldsymbol{P}_f^k = \begin{bmatrix} r_{1,1}^k & \cdots & r_{1,m}^k \\ \vdots & \ddots & \vdots \\ r_{n,1}^k & \cdots & r_{n,m}^k \end{bmatrix} \quad (5)$$

$$\boldsymbol{\mathcal{R}}_a = \boldsymbol{P} - \boldsymbol{P}_a = \begin{bmatrix} r_{a_{1,1}} & \cdots & r_{a_{1,m}} \\ \vdots & \ddots & \vdots \\ r_{a_{n,1}} & \cdots & r_{a_{n,m}} \end{bmatrix} \quad (6)$$

Where:

$\boldsymbol{\mathcal{R}_k}$ is the matrix of residuals when a leak is present at node $\boldsymbol{k}$

$r_{i,j}^k = \boldsymbol{p_{i,j}} - \boldsymbol{p_{f_{i,j}}^k}$ is the residual of node $\boldsymbol{i}$ at time $\boldsymbol{j}$ when a leak is present at node $\boldsymbol{k}$

$\boldsymbol{\mathcal{R}_a}$ is the matrix of current residuals

$r_{a_{i,j}} = \boldsymbol{p_{i,j}} - \boldsymbol{p_{a_{i,j}}}$ is the current residual of node $\boldsymbol{i}$ at time $\boldsymbol{j}$

If is necessary to isolate the leak magnitude, the residuals are converted into sensitivities for each node, as in (7).

$$\boldsymbol{S}_k = \frac{(\boldsymbol{P}-\boldsymbol{P}_f^k)}{l} = \begin{bmatrix} s_{1,1}^k & \cdots & s_{1,m}^k \\ \vdots & \ddots & \vdots \\ s_{n,1}^k & \cdots & s_{n,m}^k \end{bmatrix} \quad (7)$$

$$\boldsymbol{S}_a = \boldsymbol{P} - \boldsymbol{P}_f^a = \begin{bmatrix} s_{1,1}^a & \cdots & s_{1,m}^a \\ \vdots & \ddots & \vdots \\ s_{n,1}^a & \cdots & s_{n,m}^a \end{bmatrix} \quad (8)$$

Where:

$\boldsymbol{S_k}$ is the matrix of sensitivities when a leak is present at node $\boldsymbol{k}$

$s_{i,j}^k = \frac{r_{i,j}^k}{l}$ is the sensitivity of node $\boldsymbol{i}$ at time $\boldsymbol{j}$ when a leak is present at node $\boldsymbol{k}$

$\boldsymbol{l}$ is the assumed leak magnitude (liters/second)

$\boldsymbol{S_a}$ is the matrix of sensitivities when a leak is present on a specific and unknown node.

Reordering the matrices of sensitivities in a way that each matrix contains the sensitivities from all nodes, give us equation (9):

$$\boldsymbol{S}_m = \frac{\boldsymbol{P}-\boldsymbol{P}_f^k}{l} = \begin{bmatrix} s_{1,1}^k & \cdots & s_{1,n}^k \\ \vdots & \ddots & \vdots \\ s_{n,1}^k & \cdots & s_{n,n}^k \end{bmatrix} \quad (9)$$

Where:

$\boldsymbol{S}_m$ is the matrix of sensitivities when a leak is present in node $\boldsymbol{k}$ at instant m.

$s_{i,j}$ measures the effect of a leak in node $\boldsymbol{j}$ over the pressure of node $\boldsymbol{i}$.

Wavelet analysis method

After obtaining the sensitivities matrices for each leak, the binarization process using wavelet analysis is performed, using the following parameters and based on equation (1) and (2) which were defined previously:

Where:

$f_b = 1$; Bandwidth parameter

$f_c = 1.5$; Wavelet center frequency

$a = 1{:}1{:}16$ Scale

$$\mathbf{C_s} = \mathrm{cwt}(\boldsymbol{S}\mathrm{m}_{1:n,n}) = \begin{bmatrix} C_{1,1} & \cdots & C_{1,n} \\ \vdots & \ddots & \vdots \\ C_{a,1} & \cdots & C_{a,n} \end{bmatrix} \quad (10)$$

$$\mathbf{C_{sa}} = \mathrm{cwt}(\boldsymbol{S}\mathrm{a}_{1:n,m}) = \begin{bmatrix} C_{1,1} & \cdots & C_{1,n} \\ \vdots & \ddots & \vdots \\ C_{a,1} & \cdots & C_{a,n} \end{bmatrix} \quad (11)$$

Where:

$\mathbf{C}$ is a complex wavelet coefficient obtained from (1) depending of the scale and position

$\mathbf{C_s}$ is the complex matrix of each column from $\boldsymbol{S}_m$, therefore obtaining n matrices for each time sample.

$\mathbf{C_{sa}}$ is the complex matrix for each column of $\boldsymbol{S}$a, obtaining m matrices for each sample of the current leak.

Once the n matrices for every time sample are obtained, binarization is the next step, for which is used the phase demodulation process, shown previously in Fig. 1:

$$\mathbf{C_{sb}} = \begin{bmatrix} \mathrm{Cb}_{1,1} & \cdots & \mathrm{Cb}_{1,2*n} \\ \vdots & \ddots & \vdots \\ \mathrm{Cb}_{a,1} & \cdots & \mathrm{Cb}_{a,2*n} \end{bmatrix} \tag{12}$$

Where:

$$\mathbf{C}\mathrm{b}_{a,1} = \begin{cases} \text{if real}(\mathrm{C}_{a,1}) \geq 0 & \mathrm{Cb}_{a,1} = 1 \\ \text{if real}(\mathrm{C}_{a,1}) < 0 & C\mathrm{b}_{a,1} = 0 \end{cases}$$

$$\mathbf{C}\mathrm{b}_{a,2} = \begin{cases} \text{if imag}(\mathrm{C}_{a,1}) \geq 0 & \mathrm{Cb}_{a,2} = 1 \\ \text{if imag}(\mathrm{C}_{a,1}) < 0 & C\mathrm{b}_{a,2} = 0 \end{cases}$$

$\mathbf{C_{sb}}$ is the binarized matrix of $\mathbf{C_s}$. The same process is repeated for the matrix $\mathbf{C_{sa}}$. Now the representation for each leak is one matrix $\mathbf{C_{sb}}$, for one sample. The same procedure is performed for current residues matrix $\boldsymbol{R_a}$, obtaining m number of matrices, one for each sample.

Leak isolation method

The test for leak isolation is implemented by the Boolean Exclusive-OR operator (XOR) applied to the binarized residues (Fig. 1), comparing each matrix $\mathbf{C_{sb}}$ against the binary matrix obtained from $\boldsymbol{R_a}$. The result from this operation is a binary matrix with the differences between two pressure residues. Then, all the differences in each matrix generated from the XOR operation are summed up and a new vector is generated containing these differences, repeating this process for all the leaks analyzed for the time horizon m, and generating the following matrix:

$$\text{Comparison Matrix(n,m)=}$$
$$\mathbf{CM}(\mathrm{n,m}) = \sum(\mathbf{Csb}^{\mathcal{R}_k}_{(n,m)} \otimes \mathbf{Cbs}^{\mathcal{R}_a}_{(1,m)}) \tag{13}$$

From the above matrix, a voting system is now applied where the node with fewer votes is selected as the most likely place of a leak. The votes are obtained summing all columns, where every row represents each node in the network.

Multiple leaks isolation method

In the case of multiple leaks the same methodology is performed, adding some steps, as enlisted below:

-1-. Obtain sensitivity matrices;
-2-. Perform the Wavelet Analysis;
-3-. Obtain binary matrices for the current leak (unknown location) and for the simulated leaks at each node;
-4-. Perform XOR operation between the binary matrices;
-5-. Sum up the matrices result from the XOR operation;
-6-. Select the three indexes with the smaller values as the most possible leaks in the network;
-7-. Define a rank of possible leak magnitudes, and a number of iterations $\boldsymbol{h}$ to perform simulations;
-8-. Simulate the index with the smaller value as the node with leak with the magnitude defined (from the smallest to the largest), and perform the Wavelet Analysis for each simulation;
-9-. For each simulation performed at step -8-, subtract the real part of the complex matrix obtained to the complex matrix from the current leak, (this is done with the intention to remove the effect of the most possible leak in order to be able to observe other possible leak present in the network at the same time).
-10-. The complex matrix obtained at -9- then is transformed into a binary matrix, then steps -4- to -6- are repeated obtaining three possible leaks for each iteration $\boldsymbol{h}$.
-11-. Once all the simulations are performed, a matrix with all the possible leaks is completed, with 3 rows and $\boldsymbol{h+1}$columns.
-12-. Each column from this matrix is then analyzed, where each time a node is present or one if its neighbors it gets a vote.
-13-. From -12- a matrix with $\boldsymbol{h+1}$ rows and $\boldsymbol{n}$ (number of nodes in the network) columns is formed, and a weighing system is applied, where the node with more votes gets 5 points, the second place 2 points and the third place 1 point. This applies for all the rows except the first row because this represents the first leak detected, which is the most possible, this is why this index gets a 25 instead of a 5.
-14-. A new matrix is obtained from -13- with $\boldsymbol{h+1}$ rows and $\boldsymbol{n}$ columns. All the columns from this matrix are summed up and the five indexes with the highest values are considered as possible leaks in the network.

VI. Description of Water Networks for Experiments

To test the above methodology, two networks were used: Hanoi from [10], and Quebra (provided by EPANET).

Hanoi network

This network is presented in

Fig. 3 and is used to test the method efficiency on a network with big flows.

According to [10], we design the demand pattern and carried out a simulation of 24 hours with a sampling time of 15 minutes. This gives a total of 97 samples.

This network has 31 demand nodes with indexes from 2 to 32; an arbitrary leak size of 50 liters per second magnitude was applied to design the sensitivity matrices.

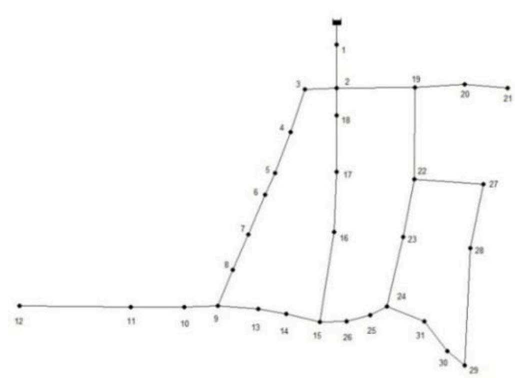

Fig. 3 Hanoi network

Quebra Network

This network is presented in [10] and it pretends to analyze the performance of the proposed method using a network of bigger size than the Hanoi network. Quebra is a network designed according to the method shown in the EPANET webpage.

In this network, the demand pattern was designed using samples every hour; the simulation is carried out for 24 hours, giving a total of 25 samples. The following parameters used in the network simulation are established: The network is composed of 55 nodes, the samples are taken every hour and the leak is placed in the node 34 which corresponds to the 32 index. The sensitivity matrices were calculated with a leak magnitude of 0.01 liters per second and were calculated using each leak.

VII. Experiments and Results

To test the proposed methodology, the following experiments were developed. In addition, the experiments were compared to the Angle between Vectors method developed in [5]. For every network it was performed each of the following experiments:

- Analysis of the impact of a change in the leak magnitude for 1, 2 and 3 leaks (having calculated sensitivity matrices with nominal leak magnitude of 50 l/s for Hanoi, and 0.01 l/s for Quebra).
- Application of random demand noise between ±1% and ±4% of the medium demand along the time horizon.
- Application of random demand noise between ±1% and ±10% of the medium demand along the time horizon.
- Application of random measurement noise between ±1% and ±4% of the medium demand along the time horizon.
- Application of random measurement noise between ±1% and ±10% of the medium demand along the time horizon.
- Finally, the effects of both demand noise and measurement noise with random leaks (1, 2 and 3 leaks) location were tested. The leak magnitude depends of the network with sizes between 30 and 80 liters per second for the Hanoi Network, and from 0.01 to 0.1 liters per second for Quebra network.

Defining used terms:

- *First order Neighbors*: represents the index of the node (or nodes) to evaluate and the indexes of the node's neighbors (closest nodes).
- *Second order Neighbors*: represents the indexes of the first order neighbors, and the indexes of the neighbors of the neighbors.
- *Efficiency percentage for one leak*: represents the percentage corresponding to the number of times that the simulated leak was identified on the correct node.
- *Efficiency percentage for first order neighbors*: represents the percentage corresponding to the number of times that the exact node or a first order neighbor of the leaking node was identified.
- *Efficiency percentage for second order neighbors*: represents the percentage corresponding to the number of times that the exact node, a first order neighbor, or a second order neighbor of the leaking node was identified.

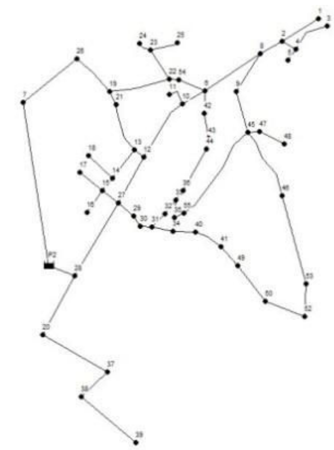

Fig. 4 Quebra network

The results of experiments are shown in Tables 1-6, demonstrating the capabilities of the Wavelets Analysis Method in different scenarios.

The evaluation of our work was performed for one leak, comparing the Wavelet Analysis Method against the Angle between Vectors Method (this method was selected based on the experiments shown in [5], which present this method as the one with better performance between several others methods based on pressure analysis). The results showed better performance for almost all the cases for the Wavelet Analysis Method.

For experiments with two and three leaks detection the results are very good in noise-free scenarios, and encouraging when noise in demand and measurements are introduced, detecting the zone (neighborhood) where the leak takes place.

VIII. Conclusion

A methodology for the detection of multiple leaks based on the Wavelet Analysis of the pressure residues in a Water Distribution System was developed and implemented successfully for two Networks scenarios (Quebra and Hanoi). To show the performance of the approach, single and multiple leak scenarios were simulated with different leak sizes, and noise in measurements and demands. For single leak scenarios, a comparison was made against the Angle between Vectors Method, showing better results in 9 out of 16 experiments.

For multiple leak scenarios, encouraging results are shown to detect the zone (neighborhood) were leaks are located.

TABLE 1. COMPARISON OF METHODS: VARIATION IN MEASUREMENT NOISE, IN THE DEMAND NOISE, AND LEAK SIZE FROM 30 TO 80 L/S, HANOI NETWORK

Leak magnitude	50 l/s		30-80 l/s						
Measure-ment noise	0%					1-4%	1-10%	1-4%	1-6%
Demand noise	1-4%	1-10%	1-4%	1-10%	0%				
Angle Between Vectors	**65%**	**47%**	**65%**	**48%**	**100%**	**32%**	**20%**	**31%**	**24%**
Wavelet Analysis	**73%**	**55%**	**74%**	**57%**	**100%**	**21%**	**13%**	**21%**	**16%**

TABLE 2. COMPARISON OF METHODS: VARIATION IN MEASUREMENT NOISE, IN THE DEMAND NOISE, AND LEAK SIZE FROM 0.01 TO 0.1 L/S, QUEBRA NETWORK

Leak magnitude	0.01 l/s		0.01-0.1 l/s					
Measure-ment noise	0-2%	0-4%	0-10%	0%			0-4%	0-10%
Demand noise	0%				1-3%	1-4%		
Angle Between Vectors	**45%**	**36%**	**28%**	**98%**	**80%**	**77%**	**56%**	**50%**
Wavelet Analysis	**50%**	**42%**	**34%**	**98%**	**80%**	**77%**	**62%**	**51%**

TABLE 3. HANOI NETWORK 2 LEAKS

	No Noise	Demand noise 4%	Measurement noise 4%	Demand and measurement noise 4%
First order neighbors	82.25%	75.66%	53.53%	54.66%
Second order neighbors	96.32%	90.56%	67.58%	69.01%

TABLE 4. QUEBRA NETWORK 2 LEAKS

	No Noise	Demand noise 4%	Measurement noise 4%	Demand and measurement noise 4%
First order neighbors	81.48%	52.28%	42.16%	41.46%
Second order neighbors	93.95%	64.08%	55.71%	55.00%

TABLE 5. HANOI NETWORK 3 LEAKS

	No Noise	Demand noise 4%	Measurement noise 4%	Demand and measurement noise 4%
First order neighbors	58.70%	56.30%	48.13%	47.98%
Second order neighbors	95.92%	93.93%	78.96%	74.28%

TABLE 6. Quebra Network 3 leaks

	No Noise	Demand noise 4%	Measurement noise 4%	Demand and measurement noise 4%
First order neighbors	67.26%	60.81%	48.45%	47.31%
Second order neighbors	98.60%	87.93%	73.38%	72.86%

IX. FUTURE WORK

There are several improvements that could be done to this work: for instance, enhance the performance of the method for the case with measurement noise; also our method could be used for optimal sensor placement and for a network with less pressure sensors than nodes. It is a challenge to apply the method in a larger network, with more than 3 simultaneous leaks, and try to determine the magnitude of every leak.

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