# Prelocalization and Leak detection in ~~water~~ drinking water distribution network using modeling-based algorithms: Case study: The city of Casablanca (Morocco)

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**Abstract.** The role of a ~~water~~ drinking water distribution network (~~WDDN~~ DWDN) is to supply high-quality water at the necessary pressure at various times of the day for several consumption scenarios. Locating and identifying water leakage areas has become a major concern for managers~~Locating and identifying priorities of water leakage areas becomes major preoccupation for manager~~ of the water supply, to optimize and improve constancy of supply. In this paper, we present the results ~~obtained on the field~~ in the field ~~from a~~ research conducted ~~in order~~ to ~~identify~~ detect and ~~to~~ locate leaks in the (~~WDDN~~ DWDN) ~~focused~~ focusing on the resolution of the Fixed And Variable Area Discharge (FAVAD) equation by use of the prediction algorithms in conjunction with hydraulic modeling and the Geographical Information System (GIS).The leak localization method is applied in the oldest part of Casablanca. We have used, in this research, two methodologies in different leak episodes: (i)The first episode is based on a simulation of artificial leaks on the MATLAB platform using the EPANET code to establish a database of pressures that describes the network's behaviour in the presence of leaks. The data thus established has fed into a machine learning algorithm called Random Forest, which will forecast the leakage rate and its location in the network; (ii)The second was field-testing a real simulation of artificial leaks by opening and closing of hydrants, on different locations with a leak size of 6l/s and 17 l/s. The two methods converged to comparable results, the leaks position is spotted within a 100 m radius of the actual ~~ones~~leaks.

Keywords: FAVAD; WDN; Leak localization; prediction; Epanet.

## 1 Introduction

Climate Change ~~(CC)~~ is a major global issue, more and more important on the international scene. It affects all components of the hydrological cycle. The situation of water resources in Morocco is already critical with a state of water scarcity forecasted for 2020. This problem is accentuated by the effects of ~~CC~~ Climate Change and may hinder any further sustainable development. The expected Climate Change~~CC~~ for Morocco would have direct and indirect harmful consequences on the water resources potential, in terms of both quantity and quality, on the water demand and on the efficiency of use of this resource by the different users. An anticipation of the adaptation to the effects of this Climate Change~~CC~~ must pass by the valorization of the use of the resources and especially the minimization of the water losses. In this regard, in Moroccan urban areas, drinking water distribution networks have particularly low yields. The location and prioritization of leaking areas is a major concern for the public authorities to optimize the use of water resources, reduce losses and improve continuity of service. To guarantee the high-level service of pressure, the detection and repair time of leaks is certainly the most common factor used in the analysis of decreases in contract pressures.

For most of the time, before starting a leak detection campaign in a Discrete Hydraulic Sector (DHS) we start with the analysis of the flows into and out of the sector, in particular the minimum night flow (MNF) between 2:00 AM and 4:00 AM, as well as the volumes of major consumers (Alkasseh et al., 2013).

In the literature it is possible to detect leaks in the DHS, ~~U~~usually the leakage rate is permanent over time, if the DHS records an increase in night flow, this increase should also appear during normal consumption time (Oasen, 2015a). According to research by Farley et al., (2008) An increase in minimum night flow can be used for targeting all "DHS~~-~~"where leakage is more likely.  It is therefore possible to detect leaks in a DHS by making a hydraulic balance between the volume of billed consumption and the volume distributed, by comparing the expected demand and the actual water consumption (Bakker, 2014). Once new leaks by DHS are identified, various techniques are used to locate the leaks. Acoustic leak-detection is a technique which has evolved a lot in recent years and is developing rapidly (Farley, 2003). Some of these techniques require partitioning a DWDN~~WDDN~~ into smaller DHS, by closing certain valves on the network, which can sometimes shutdown the system (Colombo, 2009).

In addition, various research projects noted that it is difficult to apply the leak-detection to certain areas due to the complexity of isolating and partitioning (Andrea et al., 2011). Through the applied works in modeling leakage, in particular, those of Babel et al., (2009) and Sebbagh et al., (~~2018~~2017), a reduction in pressure at the inlet of DHS, induces a reduction in leakage rate. For Al-Ghamdi et al (2011), a 25% reduction in pressure contributes to a leakage flow reduction of about 25% for a 50% rigid 50% plastic network.

Our approach, as we will see through the following paragraphs, is to do a virtual leak search without partitioning a DWDN~~WDDN~~ into smaller DHS.

The deficiency of leak management is one of the key problems, given its impacts on production cost and resource exhaustion. The scope of this paper will be mainly focused on the application of the two approaches in two different leak events. The case study is a pilot sector in the city of Casablanca (Morocco), which covers around 24 000 inhabitants as displayed in Fig. 1

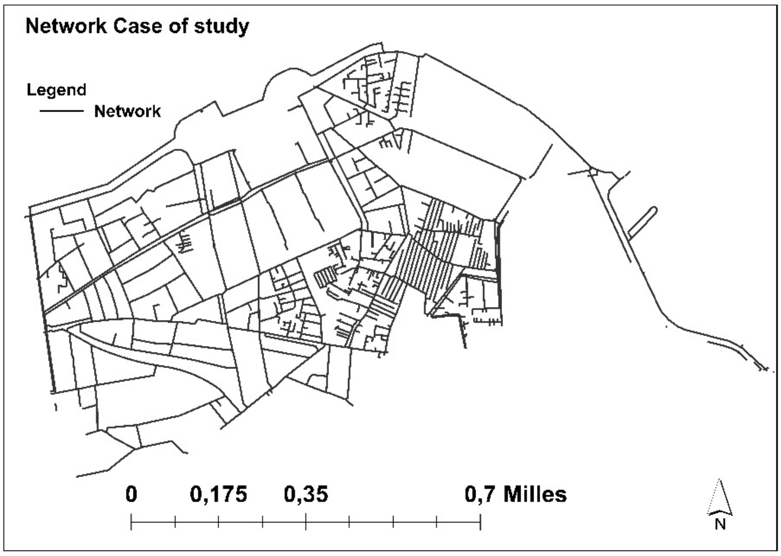



**Figure 1 Delimitation of the study area.**

The study area is a micro modulated sector with a single critical pressure point that is continuously monitored. It area has three inlets, 493 nodes and 42 km of pipes. Each of the three inlet of the zone has its own flow meter in diameter 300, and the hydraulic model was calibrated at each inlet.

Concerning the instrumentation, tThe network flow and pressure are monitored through flowmeter in diameter 300 mm and pressure sensors at each inlet.

The following figure 2 shows the daily average of measured water demand

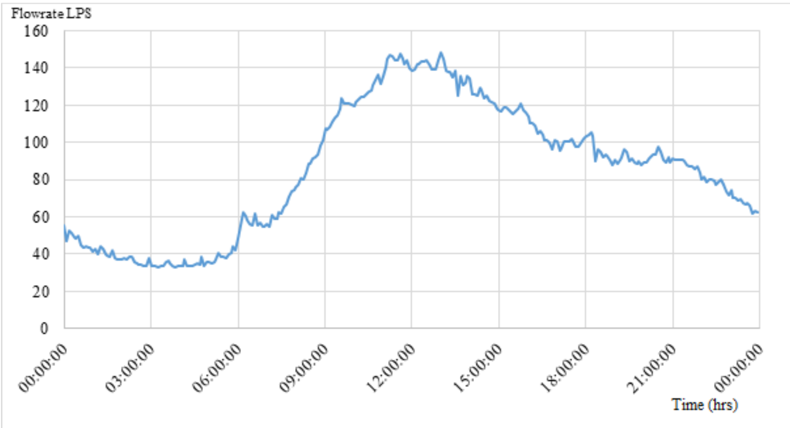



**Figure 2 Daily average water demand of the study area.**

The figure above shows a significant minimum night flow around 40 LPS between 2:00 and 4:00 AM, with a linear loss index (LLI) of 54 m3/day/km which implies a high probability of the presence of physical losses.

Figure ~~2~~3 reveals that the network consists mainly of greycast iron (40%). The average age is 40 years, increasing vulnerability and promoting leaks.

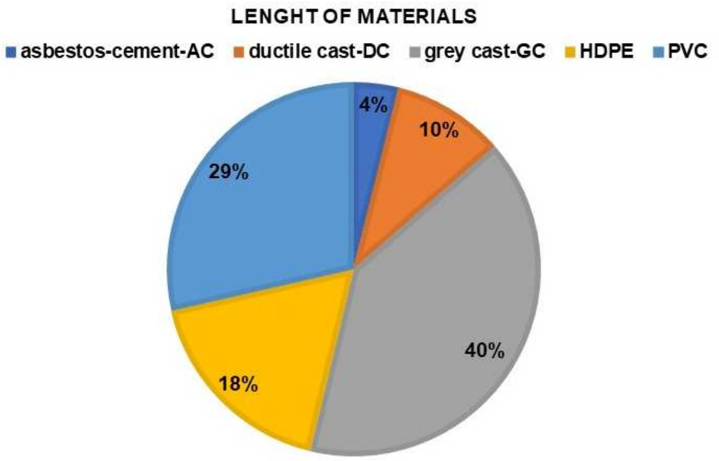



**Figure ~~2~~ 3 Types of materials constituting the network**

## 2 Materials and methods

### 2.1 Software

EPANET is a free software developed by the US Environmental Protection Agency (U.S. EPA). From the representation of the distribution network (nodes, pipes, tank, valves, pump, etc.), it allows the hydraulic balancing of the network by the calculations of pressure losses, flow velocity, flow in the pipes and pressure at the nods. (Rossman, 2000).

In practice EPANET is used by water utilities (EPA 2005) and in literature (Farina et al., 2014).

The basic demand for the hydraulic modeling software EPANET 2.0 is defined as a water output at each node, We consider that there are two main methods to simulate a water leak in EPANET, as an additional demand; or even water flow rate through a Valve, the formula to calculate the head loss (Darcy-Weisbach) was used with the default values for the roughness (Brown, 2002).

### 2.2 Method

(i) Relationships between pressure and leakage rates in distribution networks.

Pressure management not only involves reducing pressure, but also other pressure control and optimization methods without compromising customer service. A definition of pressure management in its broadest sense is given by Thornton et al., (2005), "pressure management is about controlling the pressure of the system to achieve a level of optimal service, to ensure an efficient supply to consumers while avoiding the unnecessary excesses of this pressure which would unduly increase leaks".

Water utilities often take to design their distribution networks the minimum pressure that occurs at the critical point at maximum demand. Understanding this concept is of great importance as pressure regulation can significantly reduce leakage without compromising the level of customer service.

Empirical research has repeatedly shown that the Fixed and Variable Area Discharges (FAVAD) principle, which demonstrates the fact that most discharges from pressurized pipelines vary with pressure to a greater or lesser extent. This concept, via the definition of an exponent N1, defines the relationship between the leakage rate and the pressure in case of pressure modulation According to (Lambert, 2000) and (Rozental, 2010) the ~~The term "FAVAD" comes from the English "Fixed and Variable Area Discharge Paths". This concept, through the definition of an exponent N1, defines the relationship between the leak rate and the pressure (Rozental, 2010):~~

~~The~~ relationship between pressure and flow leaks is given by Eq. (1):

$$L1 = L0 \times (P1/P0)^{N1} \tag{1}$$

~~With L0 and L1: the leakage flow before and after pressure reduction.~~

~~P0 and P1: the pressure before and after reduction.~~ where L1 and P1 are respectively the leakage rate and the average pressure in the DHS during the day, L0 and P0 are respectively the leakage rate and average pressure at the minimum night flow (MNF) time, between 2:00 AM and 4:00 AM.

According to Al Ghamdi, (2011) et Cobacho et al., (2014), the main method for representing leaks in a hydraulic network model is through adding a leakage valve for each node, the emitter parameter is used to model flow rate through a valve. These emitters devices permit the modelling of flow evacuated to the atmosphere through a nozzle.

the equation below represents the concept of FAVAD, through a flow rate, pressure and emitter coefficient Eq. (2):

$$\text{Qleak j} = \text{C x Pj}^{N} \tag{2}$$

where Qleak is the flow rate at node j, C is the emitter coefficient, P pressure at node j and N is the pressure exponent.

The exponent N~~1~~ of the above equation varies according to the material of the pipeline (mainly its elasticity), for a circular opening on a rigid pipe (cast iron, steel), N1 is of the order of 0,5 whereas it reaches 1,5 or more for longitudinal slots on plastic materials (PVC, PEHD). However, international feedback shows a variation of N1 between 0.36 and 2.95 depending on the networks experienced, as shown in Fig. ~~4~~ 4(Rozental, 2010). Figure ~~3~~4 illustrates the influence of N1 the exponent emitter on the impact of pressure reduction on leakage rate.

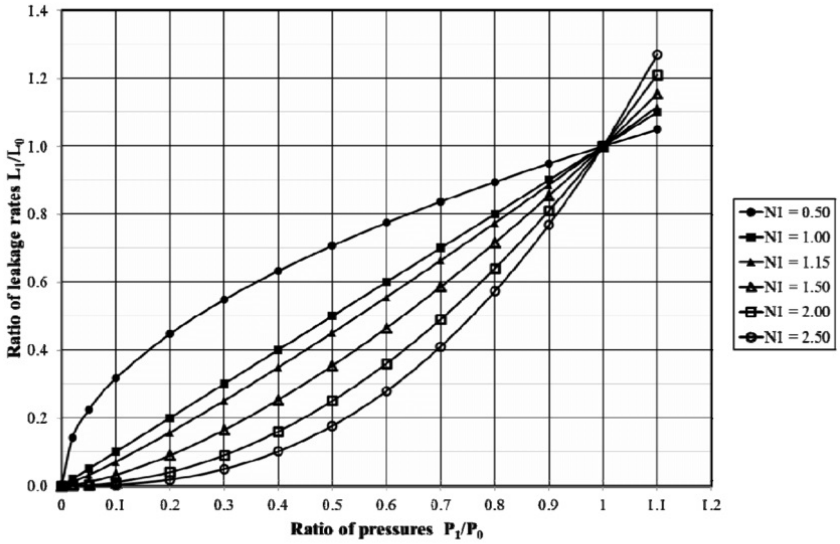



**Figure 43 Relationships between pressure and leakage rate using the N1 Approach (Rozental, 2010)**

The data collection relative to the various components of the drinking water networks (pipes, reservoirs, well, drilling, pumps, valves) is made by means of shapefile exported from the database cart@jour. It's an interface GIS (Geographical Information System) available for consultation in intranet which includes three networks managed by the drinking water operators as well as all of the hydraulic structure which constitutes them. The interface allows extracting all the desired layers while geometrically targeting the study area (zone of study). tThe following Table illustrates the roughness values used during modeling (Chadwick et al., 2013).

**Table 1 Roughness coefficient of materials (values from Chadwick et al., 2013)**

| Material | Age [year] | Darcy-Weisbach roughness coefficient [mm] |
|---|---|---|
| AC | 0-10 | 0.10 |
| | 10-40 | 0.15 |
| | >40 | 1.2 |
| All plastics: HPE, PVC, ZPE | 0-10 | 0.05 |
| | 10-40 | 0.10 |
| | >40 | 0.15 |
| ST | 0-10 | 0.3 |
| | 10-40 | 1.0 |
| | >40 | 2.0 |

The elevations are extracted from the Digital Elevation Model (DEM) layer and automatically assigned to network nodes. The annual average consumption for 2017 in addition, are distributed into each node in the model according to the geographical distribution of subscribers within the tour. Once the network template is prepared using ArcGIS, it is transferred to the EPANET software in .inp file.

The EPANET hydraulic simulation model calculates node pressure and pipe flow for a fixed reservoir level and variable water demands over time and space. It predicts the dynamic hydraulic behavior within a drinking water distribution system operating over an extended period of ~~The~~time. The pressure changes due to discharge, pressure calculating and changes according to base demand and daily consumption patterns at each ~~-~~node. The pressure drop during a peak period of consumption is due to higher consumption patterns in the DHS (The pattern provides multipliers that are applied to the Base Demand to determine actual demand in a given time period).

The Figure 5 bellow shows an example of daily consumption patterns in the study area.

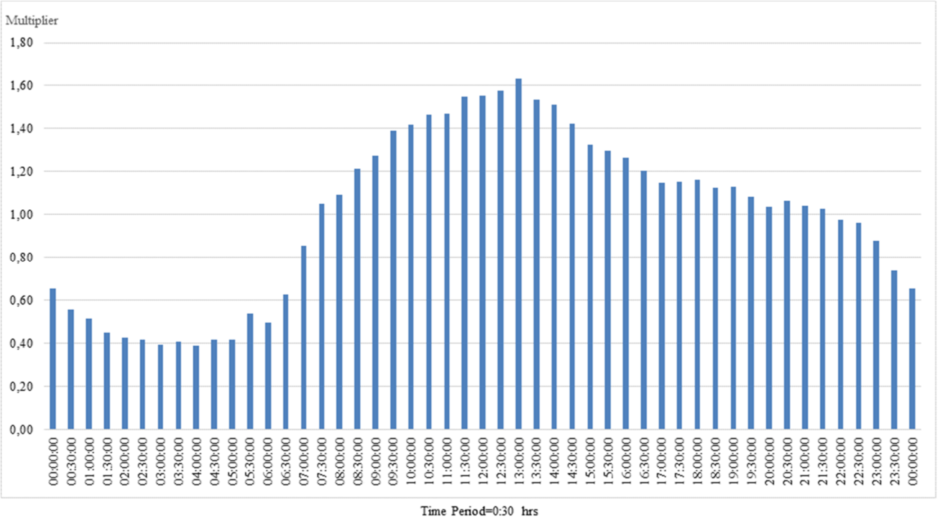



**Figure 5 daily consumption patterns in the study area**

~~calculation of the head and the flow at a particular point in time involves the simultaneous resolution of the flow conservation equation for each of the nodes and the equation of the pressure drop in each pipe of the network. Dynamic simulation is used to describe the operation of the network during a given period, while taking into account the variation in customers' consumption over time.~~

Several simulations using the Epanet software were used to determine the roughness coefficients of the pipes to obtain calculated pressures which indicate the actual pressures in different nodes of the hydraulic system.

Different factors are attributable to the uncertainty of the pressure measured on the network, the most important of which is the fluctuation of the pressure in the network. According to the pressure differences observed on the ground when determining roughness, according to the work of Paquin et al., (2000) this error is estimated at 0.3 mCE. Regarding the error in modeling the reference pressures, a value of 0.2 mCE is considered realistic. The total uncertainty related to the pressure difference between the measured pressure and the reference pressure is therefore 0.5 mCE.

Various factors including the measuring devices and the state of equilibrium of the network can influence the accuracy of the value of the roughnesses measured in the field, as well as for the estimation of roughness for the other conduits of the network. The following figure 6 presents 3 curves which correspond to the pressure drop caused by a leak in the middle of a pipe without a junction, one with roughness as measured in the field, and two others with limit values taking into account a +/- 10% error related to this parameter (Ɛ + 10%, Ɛ –10%).

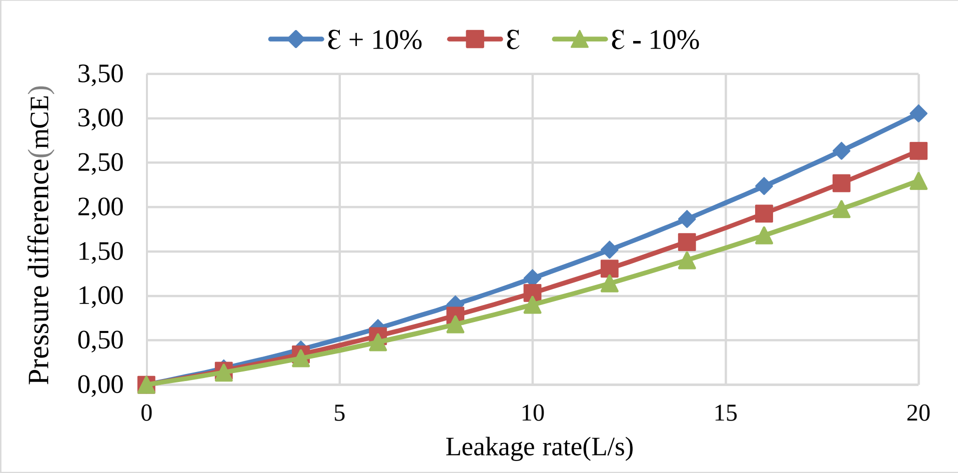



**Figure 6 Influence of the error on the roughness of the pipe**

When the roughness is increased, the pressure difference caused by a leak is greater. Conversely, when the pipes are smoother (plastic), the pressure difference decreases. Leak detection by the method studied therefore seems more promising on networks whose hydraulic capacity is weakened by corrosion rates.

To solve this localization of leakages we will use the random forest algorithm (R Learning and Prediction Algorithm). Algorithm 1 (Section 2,3,2) illustrates briefly the suggested leakage detection procedure.

The leakage localization methodology displayed in Fig. ~~4~~ 8is based on data mining algorithms, the starting point of the algorithm is the learning of the data obtained by simulation using EPANET simulator. Then four training data elements are used to predict the location of the leak:

- The distance between simulation node and the sensor
- The leakage flow
- Emitter Coefficient
- Pressure at the sensors

In order to estimate the network flow, the leakage outflow at each node, and the distance of leak from sensors, a leakage model is implemented within a classical hydraulic simulation model (EPANET).

There are two ways to model a water leak in a hydraulic network model EPANET (i) as an additional nodal demand, and (ii) by adding a leak valve to each as shown in figure 7 below.

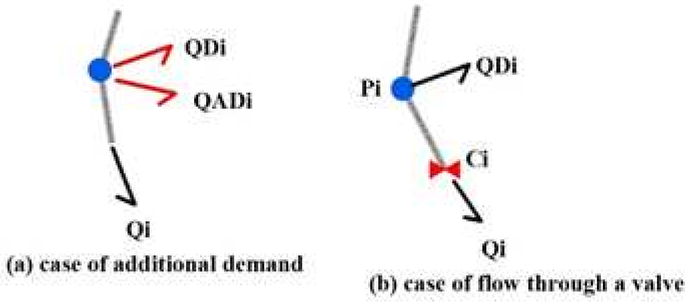



**Figure 7 Ways to model a water leak in a hydraulic network model**

where QDi is the node base demand (consumption), QADi is the node additional demand, Pi is the node pressure, Ci is the leak valve coefficient and Qi is the leakage flow.

According to Cobacho et al., 2014 the best way to represent leakage in a hydraulic network model is not by means of an additional demand, but rather by adding a leak valve to each node, the dynamic behavior of leakage is appreciated in this case rather than the case as an additional demand.

In Epanet, the closest element to a leak valve is the emitter, which presents an open valve to the atmosphere, the emitter behaviour equation is as shown above in Eq 2.

The emitter coefficient is placed at the junctions, 4 emitter coefficients ( 0.8, 1.6, 2.4 and 3.2) were used in this simulation step at each node, which correspond respectively to approximate flow leaks: 5, 10, 15 and 20 l/s, the objective of this simulation step is to vary the leak rate at nodes, to calculate and generate the new profile of pressures at each changes in flow rate.

The simulation results obtained constitute the training data for our machine learning model.

(ii) Leak simulation in Epanet:

This training data is obtained by using EPANET toolkit available in [https://github.com/OpenWaterAnalytics/EPANET-Matlab-Toolkit] for use in MATLAB. It is an open-source software that provides programming interface for EPANET within MATLAB framework. It is easy to modify, simulate and plot the result produced by EPANET ~~libraries~~libraries (Eliades et al., 2016). Figure ~~5~~ 9 reveals that 493 nodes were defined to simulate leaks with different emitter coefficients: 0.8, 1.6, 2.4 and 3.2, which corresponds approximately to leak rates of 5, 10, 15 and 20 l/s as per Eq. (2)

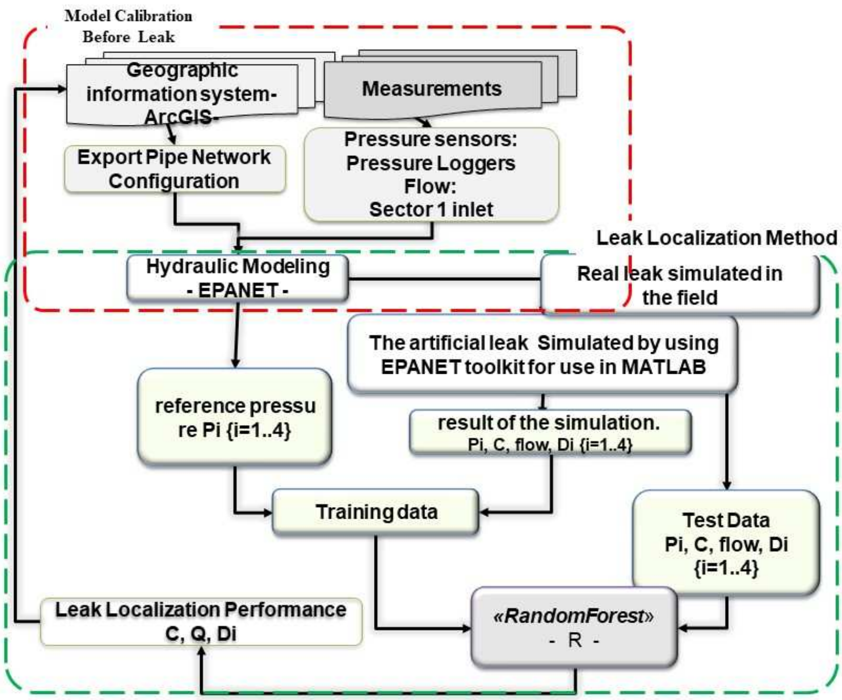



**Figure ~~4~~ 8 Leak pre-localization procedure**

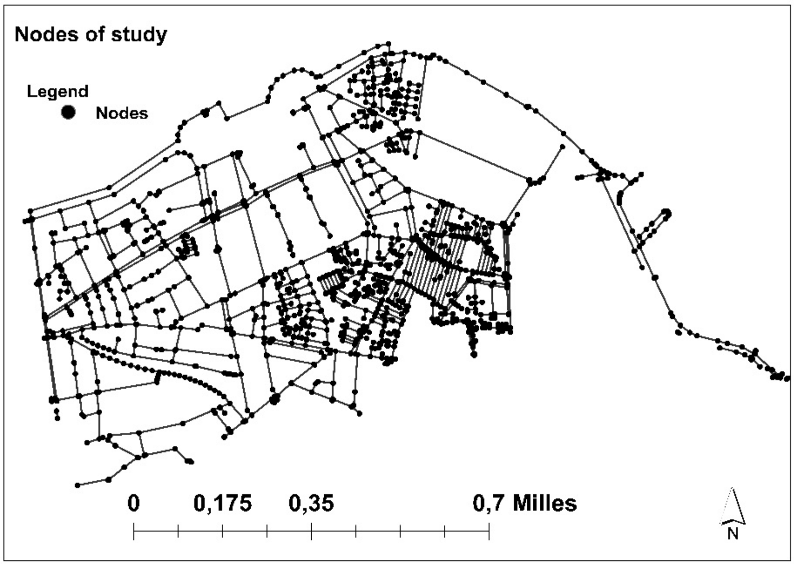



**Figure ~~5~~ 9 Leak simulation nodes in sector 1**

Thus, at each node, we simulated 4 leaks with emitter coefficients equal to 0.8, 1.6, 2.4 and 3.2, for a total of 1972 simulations. The purpose of this 1972 simulations was to stimulate the pressure behavior at each node, the area contains 493 nodes, thus, we simulated 4 leaks with emitter coefficients equal to 0.8, 1.6, 2.4 and 3.2. This makes a total of 1972 simulations. Each time, the leakage rate, the emitting coefficient, the location of the leak, the distances from the four sensors P14, P57, P58 and PC are noted, as well as the maximum, minimum and average pressures at these measuring points. the authors would like to record the maximum data of pressure variations in the case even if the leaks are triggered in the looped far part on the network. A completely new base for data ~~Each time, we note the leakage rate, the emitter coefficient, the location of the leakage through the hydraulic distances of the simulation node with respect to the four sensors P14, P57, P58 and PC, as well as the maximum, minimum pressures. and average at these measurement points, the~~learning. The results are reported in Table 2.

**Table 2 Result of Model Leak Simulations**

| Data | Node 1 | Node 2 | Node 3 | Node 4 | Node 5 | Node 6 | Node 7 | Node 8 | …… |
|---|---|---|---|---|---|---|---|---|---|
| Pmax1 | 38,91 | 38,85 | 38,78 | 38,70 | 38,91 | 38,85 | 38,78 | 38,70 | …… |
| Pmin1 | 37,33 | 37,16 | 36,98 | 36,80 | 37,33 | 37,16 | 36,98 | 36,80 | |
| Pmoy1 | 38,39 | 38,29 | 38,17 | 38,04 | 38,39 | 38,29 | 38,17 | 38,04 | |
| Pmax2 | 37,48 | 37,43 | 37,36 | 37,29 | 37,48 | 37,43 | 37,36 | 37,29 | |
| Pmin2 | 35,66 | 35,50 | 35,34 | 35,16 | 35,66 | 35,50 | 35,34 | 35,16 | |
| Pmoy2 | 36,87 | 36,77 | 36,65 | 36,53 | 36,87 | 36,77 | 36,65 | 36,53 | |
| Pmax3 | 36,89 | 36,84 | 36,78 | 36,71 | 36,89 | 36,84 | 36,78 | 36,71 | |
| Pmin3 | 34,91 | 34,75 | 34,59 | 34,42 | 34,91 | 34,75 | 34,59 | 34,41 | |
| Pmoy3 | 36,20 | 36,11 | 35,99 | 35,87 | 36,20 | 36,11 | 35,99 | 35,87 | |
| Pmax4 | 34,51 | 34,46 | 34,40 | 34,33 | 34,51 | 34,46 | 34,40 | 34,33 | |
| Pmin4 | 32,17 | 32,02 | 31,86 | 31,69 | 32,17 | 32,02 | 31,86 | 31,69 | |
| Pmoy4 | 33,66 | 33,56 | 33,45 | 33,33 | 33,66 | 33,56 | 33,45 | 33,33 | |
| C | 0,8 | 1,6 | 2,4 | 3,2 | 0,8 | 1,6 | 2,4 | 3,2 | |
| Q | 4,96 | 9,90 | 14,83 | 19,73 | 4,96 | 9,90 | 14,83 | 19,73 | |
| D1 | 478,21 | 478,21 | 478,21 | 478,21 | 475,51 | 475,51 | 475,51 | 475,51 | |
| D2 | 399,55 | 399,55 | 399,55 | 399,55 | 483,06 | 483,06 | 483,06 | 483,06 | |
| D3 | 486,43 | 486,43 | 486,43 | 486,43 | 483,06 | 483,06 | 483,06 | 483,06 | |
| D4 | 729,73 | 729,73 | 729,73 | 729,73 | 726,19 | 726,19 | 726,19 | 726,19 | |

Or :

- D1: the distance from the simulation node to the P14
- D2: the distance from the simulation node to the P57
- D3: the distance from the simulation node to the P58

- D4: the distance from the simulation node to the PC
- Q: the leakage
- C: emitter coefficients
- Pmax 1: The maximum pressure during low consumption period at P14
- Pmin 1: the minimum pressure in rush hour period at P14
- Pmoy 1: average daily pressure at P14
- Similarly, for the indices 2,3 and 4 which correspond respectively to the P57, P58 and PC,

The table thus constructed constitutes the input data of our algorithm

### 2.3 Location and simulation of leaks on the ground

#### 2.3.1 leak pre-locating

In this section we remind the existing techniques of leak ~~The~~detection. The technique used to search preventive leakage on distribution networks is organized around three distinct but complementary operations: sectoring, pre-location, followed by localization. These methods must be adapted according to the dimensions and the degree of knowledge of the targeted. The following figure 10 summarizes the existing pre-localization stages, these stages make it possible to go from hundreds of km of network to tens of m, by proceeding by elimination: In the identified leaky zones, the night flow of sectors is measured then sub-sectors to identify leaking sections and precisely guide acoustic detection and then the location of leaks.

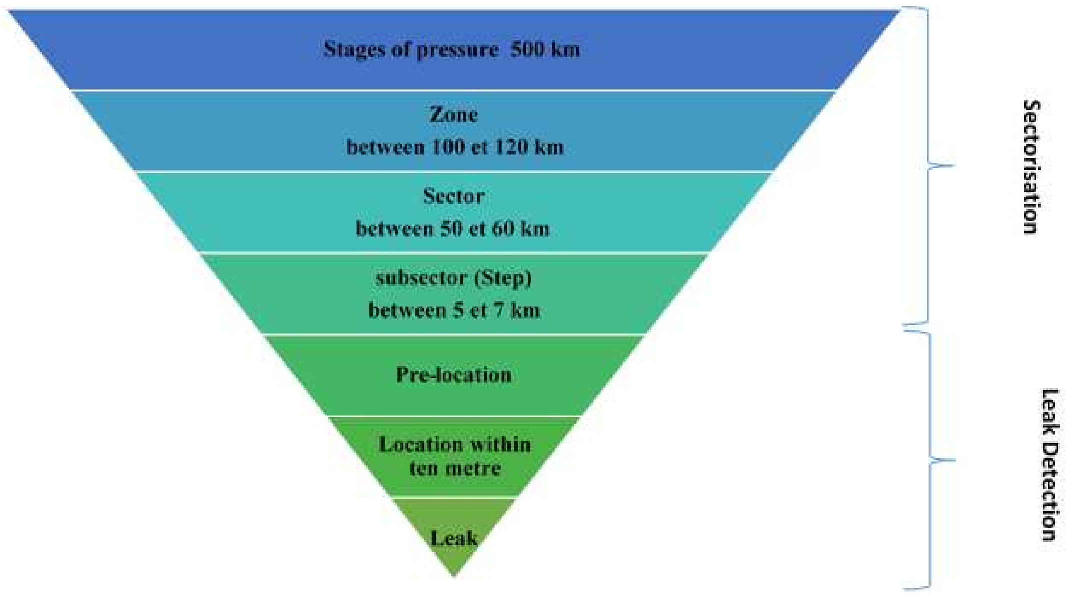



**Figure 10 Stages of sectorization**

The objective of sectorization is to define priorities between different sectors and to estimate or even quantify the level of leakage. It defines fugitive areas larger than the linear kilometer;

The objective of the pre-location is to check the presence of leaks in a given sector and to determine their position with a precision of the order of magnitude of the hundred ~~meters;~~

meters. The correlation is sometimes used to confirm leak position. It consists in positioning 2 sensors on access points of the network (if possible on both sides of the leak) and to seek the similarities between the noises which they record.When a leak noise is identified, it is possible to calculate its position, knowing:

- the distance between the two sensors.

The objective of this correlation is to define the position of a leak with a precision of the order of one meter, to avoid extra cost of earth work without leak.

The objective of this research was to skip some of the steps, especially all the steps of sectorization, presenting a high day operation cost of the network and achieve directly the last step of prelocalization. The purpose was to pre localise a leak within a hundred meters radius~~The objective of the location is to define the position of a leak with a precision of the order of one meter.~~

### 2.3.2 Pre-localization of leaks by learning data

- Random Forest

The type of learning we apply to anomaly detection in this article is a supervised learning. In Zhang et al., (2008), decision tree forests are used to detect intrusions from the network.

To execute the anomaly detection method by supervised learning, we used the statistical software -R (Zhang et al. 2008).

Random Forest is a type of tree based supervised learning algorithm (Ho, 1995). It uses many decision trees to aggregate the answer. In this paper, the supervised Random Forest algorithm was used as technique to detect the leaks (Breiman, 2001). In addition to its efficiency, this algorithm is famous for its ability to treat big-data.

The random forest optimization principle is based on the combination of multiple decision trees, to extract different classes from the original raw dataset. Then, the average classes are determined based on the classes outputted by the decision trees used. Thus, the performance of the resulting model is enhanced, compared to one decision tree model, and the ability to apply the resulting model in other datasets is acquired. Figure ~~6~~ 11 illustrates the principle of running a random forest algorithm.

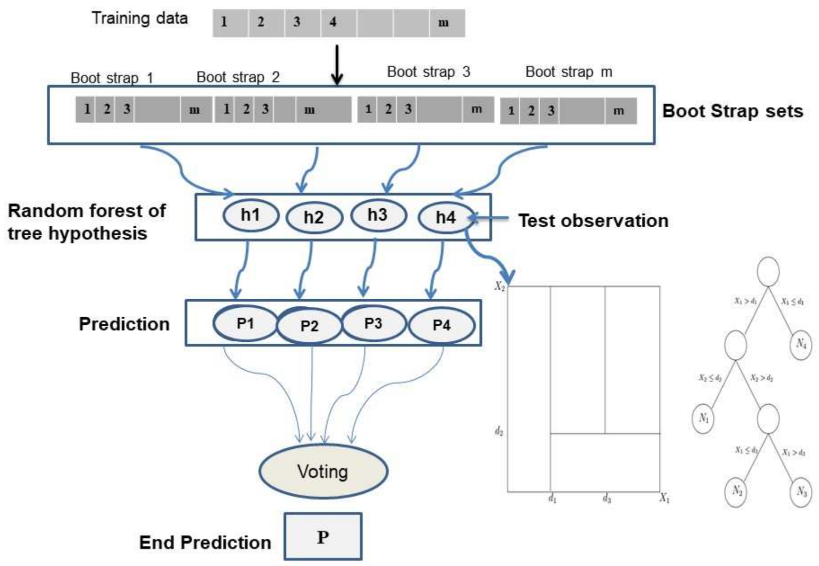



**Figure ~~6~~ 11 Random Forest Tree**

- Leakage Detection Algorithm:

The input data are: Training data td, (sensor node number~~number of sensor node~~, the distance between simulation node and the sensor, the leakage flow Emitter Coefficient and Pressure at the sensors).

The process engaged in the proposed leak detection is concisely discussed in the following Algorithm:

Algorithm:

1: Start {

2: Load Training data network parameters

3: Read network parameters and initialise

4: for node i= 1 to nt, (nt: The number of nodes in the network)

Run hydraulic analysis and compute leakage Qleak

5: if Qleak < tolerance (relatively low)

6: Print “L= 0” No leaking node”

7: else

8: i: Print “Leaking node ID”

9: if Qleak > tolerance

10: Print “L= 1” leaking node”

11: else

12: i: Print “Leaking node ID”

13: Display “Distance from sensor, pressure node, Qleak ...”

14: end if

15: end if

16: end for i

17: Stop}

### 2.4 Preparation of input data for the algorithm

Several pressure profiles for reference (without leaks) are required to attain satisfactory level of prediction from the data analysis algorithms. This pressure profiles are obtained by using EPANET. Around 7 references cases are added to the table 1. A first case is the pressure reference that has been simulated, the others constitute a translation of the reference curve of +0.1, +0.2, +0.3, -0.1, -0.2, and 0.2 meters, forming envelope with 0.6m amplitude as shown in Fig. ~~7~~ 12 below case of P14 measuring point.

we imposed this error range to avoid false results. According to the field tests we carried out, a leak of 6 l/s implies a minimum pressure drop of 0.3 m. the band is a translation of +/- 0.3m, those 7 references cases are added to pressure profiles without leak.

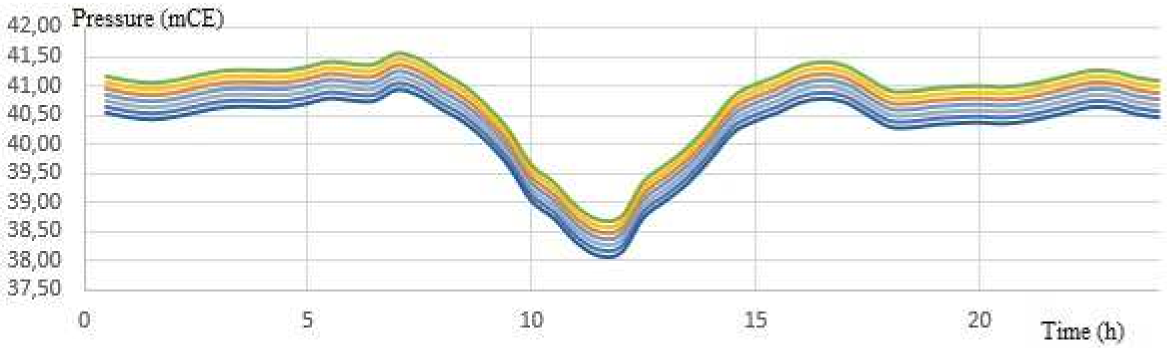



**Figure ~~7~~ 12 The reference pressures profile at P14**

For each measurement point we considered seven reference curves. This envelope is the area of variation of the daily pressure, it was calculated from several measurements of pressure spread over several days.

To simulate the artificial leaks in the study area, the leakage rate was created by opening fire hydrants on three locations at three times (during night-time hours, peak time and during off-peak periods of the day) with a leak size of 6 l/s and 17 l/s. The artificial leaks are measured with fire hydrant controller (FHC).

Using 3 artificial leaks and one real leak, the leak localization method is validated.

During the leaks simulation, the results are recorded and localized with four pressure measurement sensors placed on fire hydrants.

We then simulated these leaks on EPANET model by taking stock of the time interval of real simulations, taking a time step of 5 min equal to the recording step of the sensors in the field.

A total of 4 leaks were simulated by opening fire hydrants rated A, B and C, the artificial leaks locations are shown in Fig. 813.

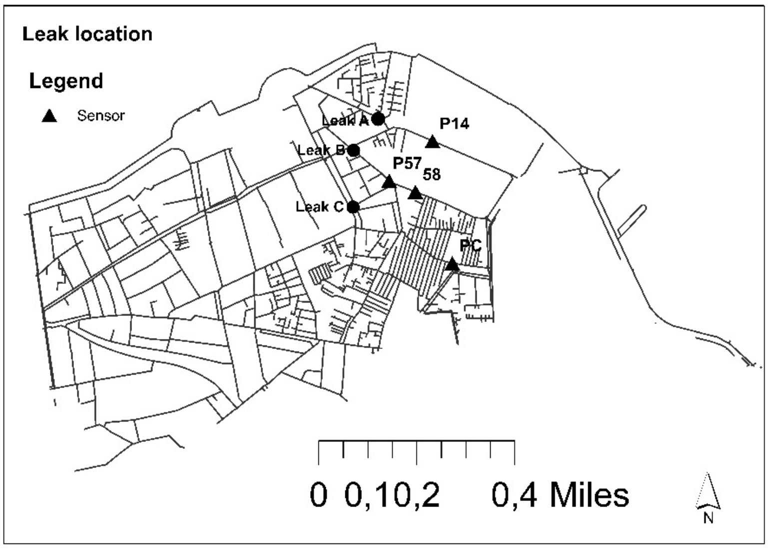



**Figure 8 13 Sensors and leaks locations**

The leak localization method depends on the head loss, itself depends, among other factors, on the size of the leak. Thus, if we have a limited leak, the sensors could not detect the small head loss, a leak of 6 l/s is chosen as a lower simulation limit. As upper limit, we chosen the 17 l/s leak, and we presume that those bypassing this limit finish by surfacing, and therefore do not require any localization process. (Pérez et al., 2014a).

At "PI A" we simulated two leaks of 6 l/s and 17 l/s; for the "PI B" a small leak of 6 l/s and for "PI C" a leak of 17 l/s (Table 3).

The flow rate at each fire hydrant was controlled by using a pressure measurement and flowmeter for fire post (PFP). The hydrants were kept opened for around 30 minutes to collect data. The time of simulation was limited to 30 minutes for reasons of water conservation and safety considerations.

**Table 3** Leaks information in the study area~~The artificial leaks that were created for each location~~

| ID of hydrants | Emitter Coefficient | leak flow rate at 04:00 am | Duration of simulation (min) | leak flow rate at 11:16 am | Duration of simulation (min) | leak flow rate at 05:00 pm | Duration of simulation (min) |
|---|---|---|---|---|---|---|---|
| PI A | 0.8 | 6 L/s | 30 | 6 L/s | | 6 L/s | |
| PI A | 3.0 | 17 L/s | 20 | 17 L/s | 30 | 17 L/s | 30 |
| PI B | 0.8 | 6 L/s | 20 | 6 L/s | | 6 L/s | |
| PI C | 3.0 | 17 L/s | 30 | 17 L/s | | 17 L/s | |

| ~~ID Leaks~~ | ~~fire hydrants~~ | ~~Flow~~ |
|---|---|---|
| ~~LA 1~~ | ~~PI A~~ | ~~6 L/s~~ |
| ~~LA 2~~ | ~~PI A~~ | ~~17 L/s~~ |
| ~~LB~~ | ~~PI B~~ | ~~6 L/s~~ |
| ~~LC~~ | ~~PI C~~ | ~~17 L/s~~ |

## 3. Results and Discussion

### 3.1 Data-reading pressure at sensor

The performance of the pressure for the artificial leak simulation during May the 3rd is shown in Fig. 9. The blue line in Fig.~~9~~ 14 shows the daily pattern of pressure at P14.

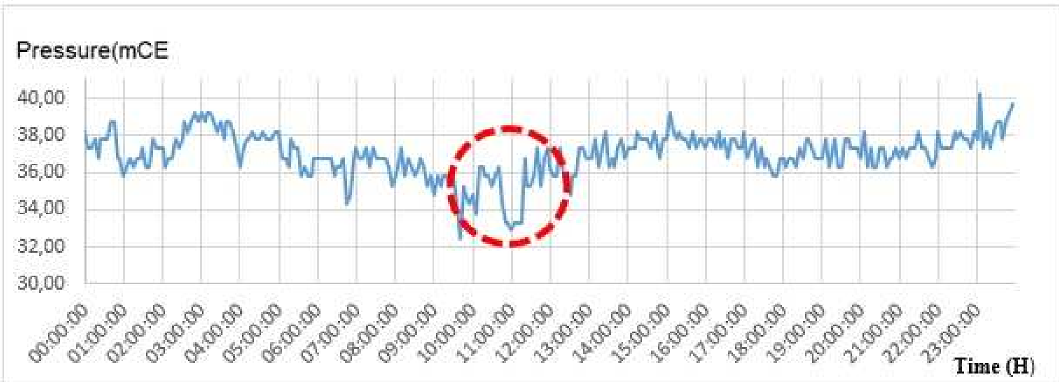


**Figure ~~9~~ 14 Pressure profile of 3/5/17 at P14**

The red circle shows the decrease of the pressure during the real simulation.

These leaks were simulated on the EPANET model by choosing the same time slot of the real simulations.

The model was calibrated without errors. It was tested and validated by comparing the measured and simulated pressures.

The results ~~of the simulation~~ are ~~very close to what is measured as~~ shown in Fig. ~~10~~ 15 and ~~11~~16.

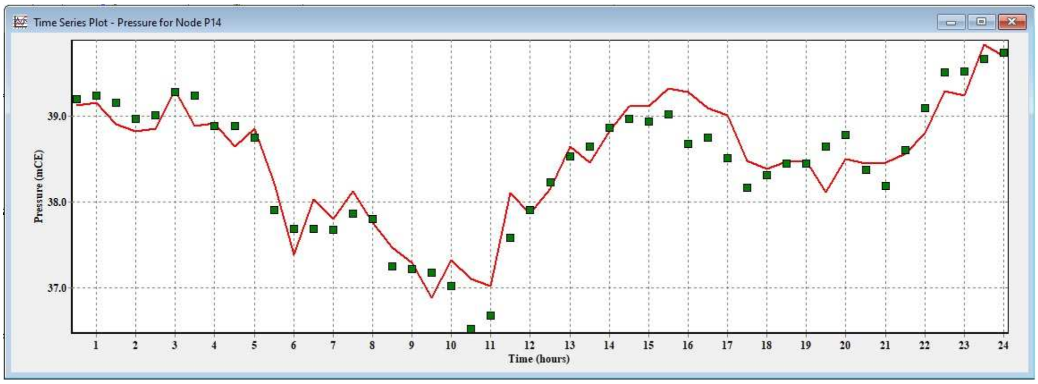



**Figure ~~10~~ 15 Pressure profile at P14**

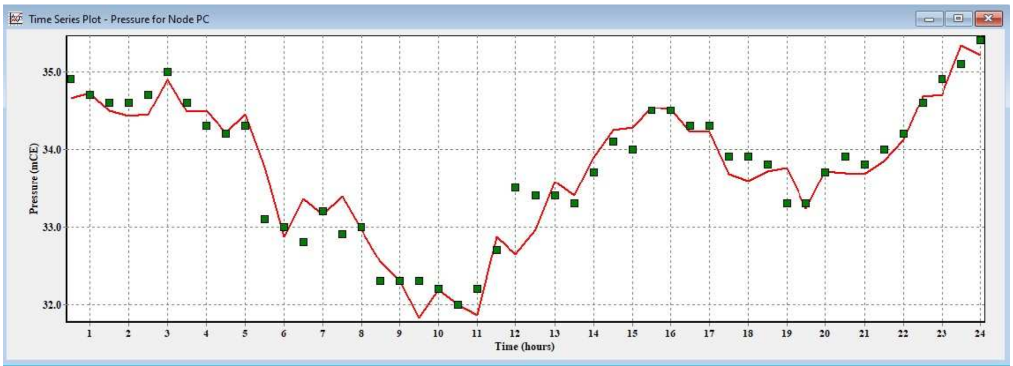
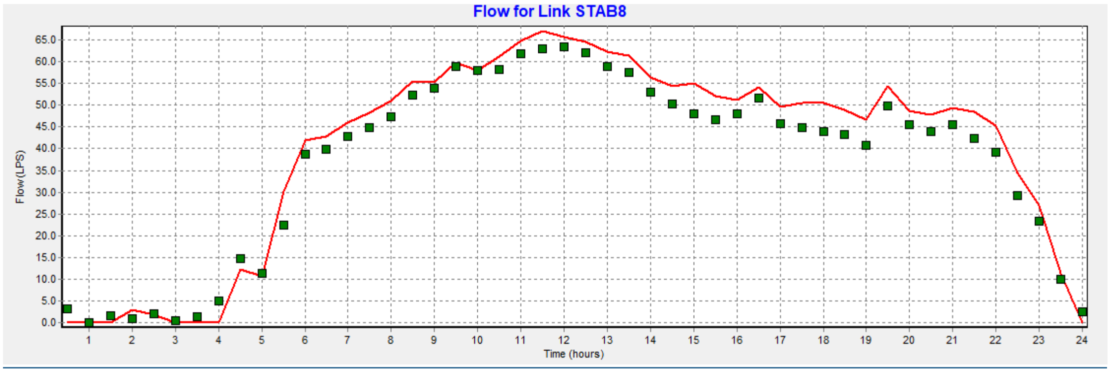



**Figure ~~11~~ 16 Pressure profile at PC**

The figures show an example of comparison between modeled pressure and measured pressure in the study area at sensor P14 and PC. The red line is the simulated pressures in Epanet and the green squares is the measured pressure.

The comparison shows that the results of the simulation are very close to what is measured, the model is calibrated and is ready for simulation.

The calibration is also made against the flow at the three inputs of the study area, the result of the flow simulation (red line) are very close to what is measured green squares as shown in Fig.17.




[**Figure 17 flowrate calibration**]

~~The red line corresponds to the simulation within EPANET and the green nodes to the pressures measured by the sensors.~~

To calculate the magnitude of the leak for each time and node, Eq.2 was used. The following Table shows the emitter coefficients simulated on each network node (Sebbagh et al., 2017~~.~~).

**Table 4 Emitter coefficients corresponding to simulated leaks**

| ID Leak | Flow | Emitter coefficient |
|---|---|---|
| LA-1 | 6 l/s | 1 |
| LA-2 | 17 l/s | 2,2 |
| LB | 6 l/s | 1 |
| LC | 17 l/s | 2,4 |

Table 5 resumes where the leaks are spatially spotted and the value of leakage flow at each node of the network, ~~. u~~using the Random Forest algorithm.

**Table 5 Quantification of the leaks.**

| Date | L | Emitter coefficient | Flow rate | D1 | D2 | D3 | D4 |
|---|---|---|---|---|---|---|---|
| 22/04 | 0 | 0,41 | 2,47 | 91 | 45 | 39 | 84 |
| 23/04 | 1 | 2,21 | 13,77 | 529 | 362 | 336 | 358 |
| 24/04 | 0 | 0,33 | 2,62 | 122 | 47 | 41 | 86 |
| 25/04 | 0 | 0,34 | 2,31 | 48 | 53 | 44 | 148 |
| 26/04 | 1 | 2,99 | 17,89 | 525 | 344 | 320 | 332 |
| 27/04 | 0 | 0,32 | 2,10 | 65 | 37 | 46 | 45 |
| 28/04 | 0 | 0,01 | 0,04 | 4 | 0 | 0 | 2 |
| 09/05 | 0 | 0,01 | 0,03 | 3 | 0 | 0 | 2 |
| 10/05 | 0 | 0,01 | 0,03 | 3 | 0 | 0 | 2 |
| 11/05 | 0 | 0,03 | 0,27 | 37 | 16 | 14 | 18 |
| Leak LA-1 | 1 | 2,35 | 14,12 | 229 | 239 | 291 | 591 |
| Leak LA-2 | 1 | 2,60 | 16,04 | 201 | 214 | 259 | 517 |
| Leak LB | 1 | 2,62 | 16,25 | 253 | 207 | 271 | 464 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Leak LC | 1 | 3,00 | 18,34 | 288 | 110 | 164 | 345 |

Note that for the 4 last leaks we have L = 1 which means that the algorithm classified them as leaks. However, the leak is over-estimated. The algorithm shows the days of 23/04 and 26/04 as being cases of leaks.

The results of these two days are not used because the change in pressure profile during these days was not because of a leak but because there was closure of some valves in the area to do some work,

For other days we have indeed L = 0

The data analysis confirms that, for an emission coefficient of at least 2, the leaks pre-localization via the adopted method is possible in particularly for flows passing 10 l/s. Indeed, these values of flow provoke important “head loss” easily detected by the pressure sensors implemented within the acting zone, which confirms the hypothesis made at the beginning of this study.

Two phenomena can explain the limits of the current method in terms of its capacity to detect leaks with low flow values. First of all, according to Jarrige et al., (2011) several factors may influence the leak noise propagation til the sensors, such as: the material type, the pipe diameter, and more importantly the pipe roughness. In fact, the misevaluation of this last factor influences the reference pressure calculation. According to Paquin et al., (2000) the results prove that it is necessary to measure the real roughness in order to interpret correctly a simulated and a measured pressure.

The second reason beyond the limited performance of the proposed method to spot leak characterized by low flow was highlighted by a study of Mirats-Tur et al., (2014). In their paper the authors demonstrated that a mis-calibrated hydraulic model (in terms of the topographic structure and its parameters), the precision regarding the estimation of the spatial water need distribution within the sector of application and the precision of the sensors embedded in the network are all eventual causes of the mentioned detection issues.

In fact, like the Mirats-Tur et al. (2014) study, our proposed method is mainly relying on the sensitivity analysis of the pressure measures to the water demand fluctuation in the network nodes. The only difference is that we simulated leak flow series at the level of fire hydrant according to different buffer (radius of 100m, 200m, 300m..), and the only aim is to study the influence radius of each sensor to detect the real flow simulated. This analysis permitted an optimal distribution of sensors in the network. For Mirats-Tur et al (2014), although the sensors were narrowly installed, the leak position was determined within a 150 m radius, compared to the 100 m radius of our method.

The presented results are outputted from a model established using measures from the network. Some of these measures are considered to have a good precision, and other have a certain level of uncertainty. For instance, the roughness and the nodes' elevations measures are highly impacted by uncertainties. Another factor that impact the precision of the proposed method is the measuring devices in terms of their recording interval (the pressure is measured each 5 minutes). In order to optimize the detection, and to focus on the leaks with high head losses spotted by standard sensors, it is recommended to use sensors with high frequency, capable of recording a high number of samples. This will help detect the small pressure variation caused by low leak flow.

### 3.2 Displaying results

The proposed method outputs are not always reliable. In fact, instead of a deterministic mapping of the leaks, there is a probabilistic output that maps the probability of occurrence of leaks in space (Pérez et al., 2014b).

If the forecast indicates a leak, which is estimated, to locate it on the map, we have 4 distances from the 4 pressure sensors, around each sensor we draw a circle of radius corresponds to the given distance by the prediction Fig. ~~12~~18, the ideal would then be that these four circles intersect at a single point which corresponds to the leak point,

The intersection of these 4 circles will then be at the maximum at 12 points if all the circles intersect with each other at two points, considering two circles, there are three cases:

- The circles intersect at two points, one corresponds to the leak point and the other is his symmetrical with respect to the line passing through the centers of the two circles,
- Circles tangent to each other intersect at a single point that corresponds to the leak point
- The circles do not cross, but if the forecast is good, they can get closer in the leaking zone

By drawing all the points of intersection, around each of them, the leakage location is identified within a 100 m radius.

A good performance with highest probability of having the location of leak when there is a big agglomeration of circle that has a more intersect point. This agglomeration corresponds to the cumulative probability of the given nodes to experience a leakage (Fig. ~~13~~19).

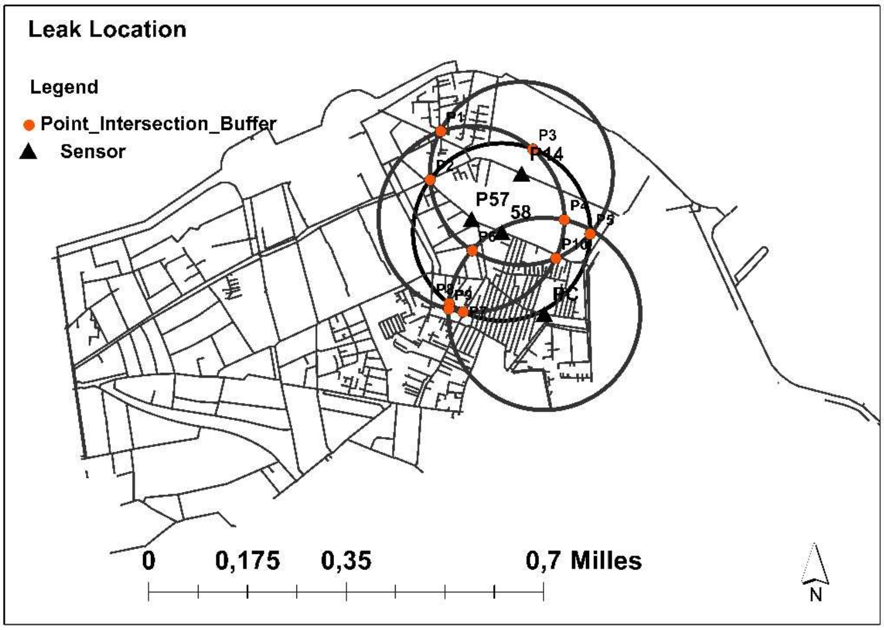



**Figure ~~12~~ 18 The spatial intersection of circles**

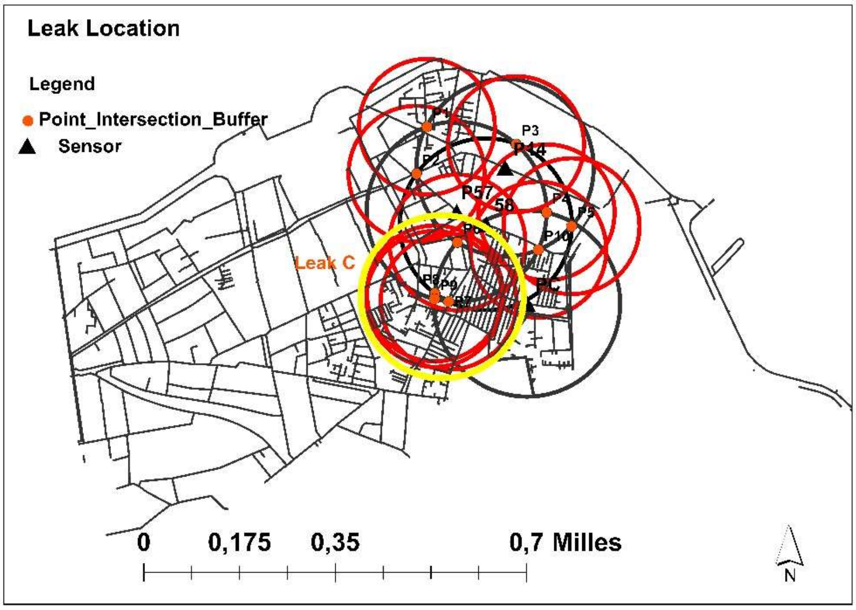



**Figure ~~13~~ 19 Spatial location of the leak LC**

Our research objective was the purpose of discovery appropriate solution for detection and localization of leakages and estimation of the size of leakages for a water distribution system.

The results obtained using this approach is satisfying. The leak is identified within a 100 m radius.

That said, the detection of a leak is extremely related to its location within the network. For instance, one located in the looped section of the network is less likely to be spotted in night time. In the mesh part of the network the pressure fallen at the sensor levels are too low, which could lead to disturb by uncertainties in the model, the measured pressures obviously involve significant errors, which reduces, in the analysis, the possibility of detecting leaks of lesser importance.

## 4 Conclusions and perspectives

Our research objective was ~~the purpose of _discovery~~ discovering appropriate solution for detection and localization of leakages and estimation of the size of leakages for a water distribution system. The FAVAD parameters were optimized via a prediction algorithm, to constitute the core of our adopted procedure. The adopted approach necessitates a coupled hydraulic-GIS interface by mean of the random forest algorithm.

This work helped to spot critical leaking points, and therefore contribute in the effort of physical loss reduction. Although, the detection results were not always accurate in term of space localization, the radius of search is reduced substantially, which make the detection rates during field campaigns more successful and less time-consuming.

Conflicts of interests: the authors declare that they have no conflict of interest.

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## Point-by-point reply to the comments

**We thank the Editor-In-Chief, reviewer 1 and Pr Said RHOUZLANE for their helpful comments. The comments from reviewers were constructive and helped to improve the quality of the manuscript. We have taken the comments on board to improve and clarify the manuscript. Please find below a detailed point-by-point response to all comments.**

**reviewer 1 comments:**

**Referee comment:** "water drinking distribution network (WDDN)"??? Should be "drinking water distribution network (DWDN)".
Author response: (marked up manuscript lines 10,14,47, and 55)

We have replaced the phrase 'water drinking distribution network (WDDN)' with 'drinking water distribution network (DWDN) (line 140).

**Referee comment:** "on the field" must be "in the field
Author response: (marked up manuscript line 14)

This change was made.

**Referee comment**: don't use CC for Climate Change
Author response: (marked up manuscript lines 26, 28,29 and 31)

We have removed the citation from the manuscript.

**Referee comment**: don't use capitol after comma
Author response: (marked up manuscript line 40)

this remark is integrated in the revised paragraph

**Referee comment**: "DHS" must be "DHS'"

Author response: (marked up manuscript line 40)

This change was made.

**Referee comment**: So there is no flow meter at each inlet??
Author response: (marked up manuscript lines 64-65)

Each of the three inlet of the zone has its own flow meter in diameter 300, and the hydraulic model was calibrated at each inlet.

**Referee comment**: End with "

Author response: (marked up manuscript line 93)

This remark is integrated in the revised version of the manuscript.

**Referee comment**: What is N
Author response: (marked up manuscript lines 97-108,455-457)

Empirical research has repeatedly shown that the Fixed and Variable Area Discharges (FAVAD) principle, which demonstrates the fact that most discharges from pressurized pipelines vary with pressure to a greater or lesser extent. This concept, via the definition of an exponent N1, defines the relationship between the leakage rate and the pressure in case of pressure modulation.

According to (Lambert, 2000) and (Rozental, 2010~~) the leakage exponent N1 varies from 0.5 for a fixed area in rigid pipes as metallic pipes and 1.5 for a flexible area in plastic pipes as shown in Equation below~~

$L1/L0=\times(P1/P0)^{N1}$

where L1 and P1 are respectively the leakage rate and the average pressure in the DHS during the day, L0 and P0 are respectively the leakage rate and average pressure at the minimum night flow (MNF) time, between 2:00 AM and 4:00 AM.

The number of references were increased to 1.

Lambert, A.: What do we know about pressure-leakage relationships in distribution systems. In Proceedings of the IWA Conference in Systems Approach to Leakage Control and Water Distribution System Management, Brno, Czech Republic, 16–18, 2001.

**Referee comment**: No, this is not dynamic simulation; this is consecutive static simulations. Epanet can only do static calculation, no dynamic calculation including dynamic aspects of accelerating and slowing down of water
Author response: (marked up manuscript lines 135-142)

~~The authors agree that this aspect needs more explanation . What we would like to mention in this section is that, Epanet~~ It predicts the dynamic hydraulic behavior within a drinking water distribution system operating over an extended period of time. the pressure changes due to discharge, pressure calculating and changes according to base demand and daily consumption patterns at each node. The pressure drop during a peak period of consumption is due to higher consumption patterns in the DHS (The pattern provides multipliers that are applied to the Base Demand to determine actual demand in a given time period).
**Figure 4 daily consumption patterns in the study area**

**Referee comment**: I don't understand. How can you vary the Emitter Coefficient? Do you suggest that you keep pressure constant and leak size constant, and let Emitter Coefficient determine the leak flow? Why did you choose this method? How do you model a leak in Epanet?

Author response: (marked up manuscript lines 175-189)

There are two ways to model a water leak in a hydraulic network model EPANET (i) as an additional nodal demand, and (ii) by adding a leak valve to each node Fig 2a and 2b.

**Figure 5 Ways to model a water leak in a hydraulic network model**

where QDi is the node base demand (consumption), QADi is the node additional demand, Pi is the node pressure, Ci is the leak valve coefficient and Qi is the leakage flow.

According to Cobacho et al., 2014 the best way to represent leakage in a hydraulic network model is not by means of an additional demand, but rather by adding a leak valve to each node, the dynamic behavior of leakage is appreciated in this case rather than the case as an additional demand.

In Epanet, the closest element to a leak valve is the emitter, which presents an open valve to the atmosphere, the emitter behaviour equation ~~is~~ as shown above in equation 2 ~~below~~:

~~Qleak j = C x Pj $^{N}$~~

~~where Qleak is the leakage flow rate at node j, Pj is the pressure, C is the emitter coefficient, and N is the pressure exponent.~~

The emitter coefficient is placed at the junctions, 4 emitter coefficients ( 0.8, 1.6, 2.4 and 3.2) were used in this simulation step at each node, which correspond respectively to approximate flow leaks: 5, 10, 15 and 20 l/s, the objective of this simulation step is to vary the leak rate at nodes, to calculate and generate the new profile of pressures at each changes in flow rate.

The simulation results obtained constitute the training data for our machine learning model~~. But before launching the simulations, the model must therefore be calibrated against measured data of pressure and flow rate (as mentioned in line 240).~~

**Referee comment**: Why 1972 simulations?

Author response: (marked up manuscript lines 201-208)

The purpose of this 1972 simulations was to stimulate the pressure behavior at each node, the area contains 493 nodes, thus, we simulated 4 leaks with emitter coefficients equal to 0.8, 1.6, 2.4 and 3.2. This makes a total of 1972 simulations. Each time, the leakage rate, the emitting coefficient, the location of the leak, the distances from the four sensors P14, P57, P58 and PC are noted, as well as the maximum, minimum and average pressures at these measuring points. the authors would like to record the maximum data of pressure variations in the case even if the leaks are triggered in the looped far part on the network. A completely new base for data learning.

**Referee comment**: Did you also simulate leaks at different times? E.g. at 6 am; at 3 pm; et cetera

Author response: (marked up manuscript lines 298-305)

To simulate the artificial leaks in the study area, the leakage rate was created by opening fire hydrants on three locations at three times (during night-time hours, peak time and during off-peak periods of the day) with a leak size of 6 l/s and 17 l/s. ~~The Table below illustrate the leakage information.~~

Table ~~1~~3 Leaks information in the study area

During the leaks simulation, the results are recorded and localized with four pressure measurement sensors placed on fire hydrants.

We then simulated these leaks on EPANET model by taking stock of the time interval of real simulations, taking a time step of 5 min equal to the recording step of the sensors in the field.

**Referee comment**: This seems very precise. How large is the area the you researched?
Author response: (marked up manuscript lines 228-233, 238-246)

The following figure 10 summarizes the existing pre-localization stages, these stages make it possible to go from hundreds of km of network to tens of m, by proceeding by elimination: In the identified leaky zones, the night flow of sectors is measured then sub-sectors to identify leaking sections and precisely guide acoustic detection and then the location of leaks.

**Figure 8 Stages of sectorization**

The correlation is sometimes used to confirm leak position. It consists in positioning 2 sensors on access points of the network (if possible on both sides of the leak) and to seek the similarities between the noises which they record.When a leak noise is identified, it is possible to calculate its position, knowing:

- the distance between the two sensors.

The objective of this correlation is to define the position of a leak with a precision of the order of one meter, to avoid extra cost of earth work without leak.

~~in view of the cost of this approach mentioned above, we worked on this approach of virtual leaks research, without the closure the valves in the field, without sectorization, only through a well-calibrated hydraulic model, the data of pressure due to the conditions of the leakage experiments, are compared to the pressure of the previous day without leakage, this data will be associated with an algorithm that predict the location of the leak.~~

The objective of this research was to skip some of the steps, especially all the steps of sectorization, presenting a high day operation cost of the network and achieve directly the last step of prelocalization. The purpose was to pre localise a leak within a hundred meters radius

**Referee comment**: Change “number of sensor node” to “sensor node number”
Author response: (marked up manuscript line 263)

This change was made

**Referee comment**: Why is this? Why simple linear band?
Author response: (marked up manuscript line 291-293)

we imposed this error range to avoid false results. According to the field tests we carried out, a leak of 6 l/s implies a minimum pressure drop of 0.3 m. the band is a translation of +/- 0.3m, those 7 references cases are added to pressure profiles without leak

**Referee comment**: What is the average demand in the area? Can you show a graph of an average day of measured water demand?
Author response: (marked up manuscript line 68-70)

The following figure 2 shows the daily average of measured water demand

**Figure 2 Daily average water demand of the study area.**

**Referee comment**: For how long was de leak simulated? 15 minutes? 1 hours? ??
Author response: (marked up manuscript line 316-318)

the flow rate at each fire hydrant was controlled by using a pressure measurement and flowmeter for fire post ~~CPI~~ (PFP) ~~or flow rate and pressure tests on fire hydrants~~. The hydrants were kept opened for around 30 minutes to collect data. The time of simulation was limited to 30 minutes for reasons of water conservation and safety considerations.

**Referee comment**: What is simulated (red line?) and what is measured (green squares?)? Please explain
Author response: (marked up manuscript line 337-340)

The Figures show an example of comparison between modeled pressure and measured pressure in the study area at sensor P14 and PC. The red line is the simulated pressures in Epanet and the green squares is the measured pressure.
The comparison shows that the results of the simulation are very close to what is measured, the model is calibrated and is ready for simulation.

**The comments from reviewer 2 Pr Said RHOUZLANE were constructive and helped to improve the quality of the manuscript. The comments are addressed below.**

**Referee comment**: you have mentioned “Concerning the instrumentation, the network flow and pressure are monitored through flowmeter” the study area is it moduled, micro-moduled, how many critical points, measurement points ?? all this is not clear in your article
Author response: (marked up manuscript line 63)

The study area is a micro modulated sector with a single critical pressure point that is continuously monitored.

**Referee comment**: « The average age is 40 years, increasing vulnerability and promoting leaks » you have to descreibe more scientifficaly. You have to write and talk to selection criteria: (you need to talk about the performance indicators for this area, MNF, ILP for example)
Author response: (marked up manuscript line 71-72)
The figure above shows a significant minimum night flow around 40 LPS between 2:00 and 4:00 AM, with a linear loss index (LLI) of 54 m3/day/km which implies a high probability of the presence of physical losses.

**Referee comment**: "Roughness coefficient of materials" Physical modeling of your network requires the roughness of the pipes. It should be noted that there is great uncertainty about the values considered. How did you minimize these uncertainties and their impact on the results given by EPANET

Author response: (marked up manuscript line 149-163)

Different factors are attributable to the uncertainty of the pressure measured on the network, the most important of which is the fluctuation of the pressure in the network. According to the pressure differences observed on the ground when determining roughness, according to the work of Paquin et al., (2000) this error is estimated at 0.3 mCE. Regarding the error in modeling the reference pressures, a value of 0.2 mCE is considered realistic. The total uncertainty related to the pressure difference between the measured pressure and the reference pressure is therefore 0.5 mCE.

Various factors including the measuring devices and the state of equilibrium of the network can influence the accuracy of the value of the roughnesses measured in the field, as well as for the estimation of roughness for the other conduits of the network. The following figure 6 presents 3 curves which correspond to the pressure drop caused by a leak in the middle of a pipe without a junction, one with roughness as measured in the field, and two others with limit values taking into account a +/- 10% error related to this parameter ($\varepsilon$ + 10%, $\varepsilon$ –10%).

**Figure 6 Influence of the error on the roughness of the pipe**

When the roughness is increased, the pressure difference caused by a leak is greater. Conversely, when the pipes are smoother (plastic), the pressure difference decreases. Leak detection by the method studied therefore seems more promising on networks whose hydraulic capacity is weakened by corrosion rates.

**Referee comment**: you have mentioned ". Dynamic simulation is used to describe the operation of the network during a given period, while considering the variation in customers' consumption over time." Physical modeling of your network requires consumption at nodes. It is important to indicate how you estimated this parameter. It should be noted that there is great uncertainty about the nodal distribution of the study area. How did you develop your consumption patterns for dynamic modeling?

Author response: (marked up manuscript lines 135-142)

Author response: (marked up manuscript line 68-70)

**Referee comment**: you have mentioned that you have used the Matlab-software, For EPANET code, please find a better reference

Author response: (marked up manuscript line 193, 440-442,468-470)

For EPANET code, the original work based on:

D.G. Eliades, M. Kyriakou, S. Vrachimis and M.M. Polycarpou, "EPANET-MATLAB Toolkit: An Open-Source Software for Interfacing EPANET with MATLAB", in Proc. 14th International Conference on Computing and Control for the Water Industry (CCWI), The Netherlands, Nov 2016, p.8. (doi:10.5281/zenodo.831493).

Sebbagh, k., Abdelhamid, S., Zabot, M. : Démarche de prélocalisation des pertes physiques sur un réseau de distribution d'eau potable par l'optimisation du modèle hydraulique via un algorithme évolutionnaire, La Houille Blanche., 59-66, doi.org/10.1051/lhb/2016062,2017

The number of references were increased to 2.

**Referee comment**: you have mentioned “The model was calibrated without errors” What are the calibration data for your model? Discuss them clearly

Author response: (marked up manuscript line 337-343)

**Referee comment**: the calibration results of pressure are presented, you need to complete with the flow calibration

Author response: (marked up manuscript line 341-344)

The calibration is also made against the flow at the three inputs of the study area, the result of the flow simulation (red line) are very close to what is measured green squares as shown in Fig.17.