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Assessment of Water Loss in the Water Distribution Network of Bendjerrah Using a Combination Approach of Fixed Area Variable Area Discharge, Minimum Night Flow, and Epanet Calibrator

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Abstract

Water losses due to leakage are a pernicious problem for water utilities. Understanding and quantifying Non-Revenue Water (NRW) and water loss components is the first step in the management of urban water losses. Hydraulic modeling is a powerful tool to predict the impacts of different management scenarios on the hydraulics of the Water Distribution Network (WDN). The water distribution network (WDN) can be divided into a number of District Meter Areas (DMAs) with suitable sizes in order to apply pressure management. In this study, the Fixed Area Variable Area Discharge (FAVAD) concept and the number of leaks were analyzed for a number of water network pressure management areas in the city of Bendjerrah – the district of Guelma, Algeria. The analysis identified some anomalies concerning the parameters of some networks; especially those related to leakage exponent N_1 values greater than 1.5. The approach used in this framework is based on the estimation of the leakage from the Minimum Night Flow (MNF) and the burst frequency of Average Zonal Pressure (AZP). After the use of this approach and the calibration procedure using the Epanet-calibrator on real District Meter Areas, the obtained results are very close to the real state of the network. In addition, this paper studies the possibility of explicitly incorporating the variation of the leakage zone in the hydraulic modeling of the water distribution systems. The results show that the power equation leakage exponent N_1 estimates the total system leakage with an error of up to 20%. From the Minimum Night Flow, obtained by using the South African Night Flow (SANFLOW) practical tool, it was found that the actual losses calculated for sectors 1, 2, and 3 are respectively 25%, 45%, and 30%.

Keywords: Minimum Night Flow (MNF), Fixed Area Variable Area Discharge (Favad), South African Night Flow (Sanflow), water losses, leakage, modulation of pressure

1 Introduction

Water is not a product or business asset; this is a resource that should be valued by mankind. The water shortage issue is put into the spotlight over most of the world and pushes many nations to re-planning their water resources in various aspects. Providing data on water's economic value assists policymakers to make informed decisions regarding water distribution. Additionally, addressing the increasing demand for all uses and building a sustainable future of agricultural and water policies [1].

Non-revenue water in Algeria is estimated between 40 and 50% and is divided into two categories: technical losses and commercial losses. In fact, because of technical and economic reasons, a leak-free network is not realizable, but the amount of water loss should be kept as low as possible. The distribution network undergoes degradation over time, which can easily lead to leaks. A whole range of factors is, to varying degrees in space and time, responsible for water loss.

Sustaining water services is challenging for every water utility. The goal of this effort is to make sure that water losses are kept at a minimum. Water losses, non-revenue water, and unaccounted-for water are the most commonly used terms to address the wastage occurring in the supply network. The term nonrevenue water has substituted the term 'Unaccounted for Water as suggested by International Water Association (IWA), and as recommended by American Water Work Association “AWWA, (2014)” [2]. Generally, NRW is an indicator of the operational efficiency of WDS. Precise knowledge of water consumption allows for quantifying the water lost volumes on the network. But even an exact assessment of losses is still not enough to eliminate all the leaks on the network.

Due to the huge economic impact of water losses, several approaches, that deal with this problem, have been proposed. Many water loss management studies assess non-revenue water without evaluating the contribution of leakages to total water losses. Consequently, total water losses are not partitioned accordingly. Therefore, there is an urgent need for specialized application tools for assessing partitions of non-revenue water. One such tool is the Pressure management scheme.

Pressure pipelines with a variable flow rate of fluid along the path are widely used in many industrial processes - pipeline-collector (PC) and distribution pipeline (DP). PCs are widespread in water supply (water-intake structures with tubular heads), amelioration (drainage systems), water supply, etc. [3].

Pressure management can be defined as “the practice of managing system pressures to an optimum level of service ensuring sufficient and efficient supply to legitimate users and consumers, while eliminating or reducing pressure transients and variations, faulty level controls and reducing unnecessary or excess pressures, all of which cause the distribution system to leak and break unnecessarily” [4], [5].

There are several methods for regulating pressure in the WDNs [6], [7]. In addition, regulating the water pressure in distribution networks is usually achieved by partitioning the

complex networks into smaller sub-networks known as the District Meter Areas (DMAs) [8], [9]. The water pressure in these areas is regulated by installing network elements such as control valves at the inlet of the zones. Ryma Fares [10] developed a theoretical approach linking the reduction in leak flow rate with the pressure reduction in the network. The proposed approach counts explicitly and separately the leaks and rigidity of the pipe materials in the network. The pressure management proposed by Liberatore and Sechi [11] is carried out by means of control valves. This method consists of the pressure constraint at (pseudo-valves) nodes and determines the valve optimum calibration value. Another powerful tool is the South African Night Flow (SANFLOW) Analysis Model. The SANFLOW analysis model is an alternative tool, relevant and highly adaptable to the developing world. This model [12] uses the Minimum Night Flow (MNF) method based on the inflow measurement at the MNF time.

Apart from the MNF data, the SANFLOW model also uses basic infrastructure variables such as length of mains, number of connections, number of properties, estimated population, average zone night pressure, and major water users. It is important to note that if there was no data such as leakage coefficients and pressure correction factors, some assumptions were made and SANFLOW default values which were recommended by McKenzie [12] were used. The SANFLOW model is based directly on the BABE (burst and background estimate) with Fixed and Variable Area Discharges (FAVAD) principles and is written in DELPHI computer language for the Windows operating system [13].

The present work focuses on the development of an approach to WDN using Rossman's Epanet software and the South African Night Flow (SANFLOW) Analysis Model. This study proposes the use of a calibration technique to assess the leaks in each network sector. In addition, the results of the calibration model were compared with the results estimated from the MNF method targeting the validation of the computational approach. A calibration with (Epanet Calibrator) was particularly used as a calculation tool. Field measurements were carried out in a real system in order to collect the pressure and flow rate data. The scarcity of data is a real problem in network modeling. In an attempt to overcome this difficulty, a new approach has been proposed. One of the simplest ways of tackling this problem is to develop a model that can be used for pressure management rather than for assessing the background leaks in the networks. This study has been conducted by considering the frequency of burst pipes caused by high pressure at the most unfavorable points (critical points), based on the minimum night flow rate, in order to quantify the leak flow rate at specific locations.

2 Materials and Methods

2.1 Real Loss Assessment Using Minimum Night Flow (MNF) Rate

The scarcity of measured data is a real obstacle to network modelers. To overcome this difficulty, a new approach is proposed. The steps are described in the detailed flowchart below (Figure 1).

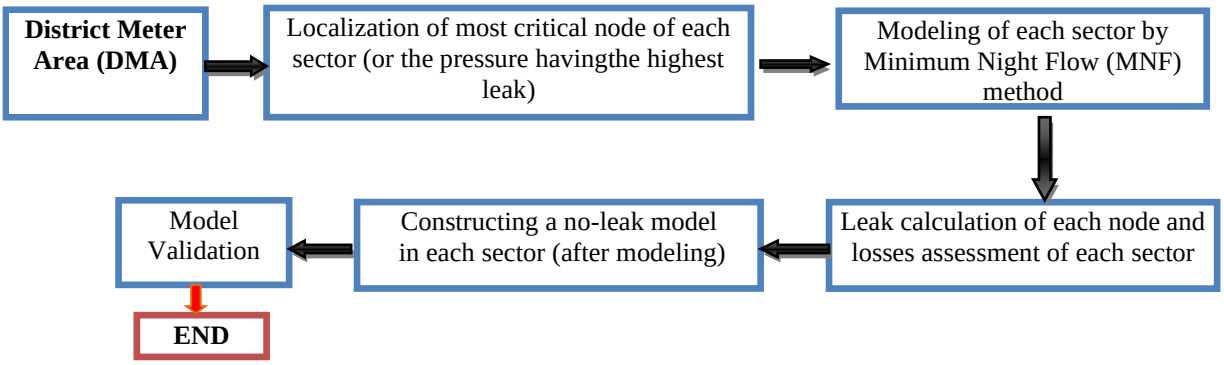


Figure 1: Flowchart of the proposed approach

The idea is to develop a model that can be used for pressure management rather than for assessing the background leaks in the networks. The study was conducted considering the frequency of pipe bursts caused by high pressure at the most unfavorable points (critical points), and by using the minimum night flow rate, to quantify the leak flow rate at specific locations.

The MNF is the lowest flow entering a water supply area during 24-hours, assuming that the availability of water during this period is sufficient to meet the required demands [14]. Since the pressure during the night is usually the largest and the pressure varies throughout the day, the real loss value of the whole day cannot be determined by extrapolating the real loss value measured during the MNF. According to the study carried out by Marzola et al. [15] the MNF analysis can only be performed in the District Meter Area.

During the analysis of MNF, the flow is considered to consist of three main components namely: normal legitimate night use, background leakage, and burst leakage (or excess night flow) as mentioned by AL-Washali et al. [16]. Utility managers should also determine a pressure factor that creates a true average 24-hour leakage value when applied to the Net Night Flow (NNF). "Morrison et al.[17] proposed that the Minimum Night Flow (MNF) should comprise the Legitimate Night Flow (LNF) of household and non-household and abnormal night flow on account of background losses and bursts, i.e., the physical losses. As leakage is proportional to pressure, the average leakage can be represented throughout the day and the Utility Net Night Flow (UNNF) should be corrected with respect to the pressure factor. Typical values of the Night Day Factor (NDF) range from 20 or less in gravity fed systems to over 30 hours per day in pressure management areas with flow modulated systems [18].
A leak in a pipe can be considered an orifice. The hydraulics of orifices is well understood and clearly described by Torricelli's Law. Experimental research has shown that the discharge in orifices varies greatly with pressures depending on the pipe material, called the Fixed and Variable Area Discharges (FAVAD) principle, as described by the following relationship [19]:

$$\frac{Q_i}{Q_{MNF}} = \left(\frac{P_i}{P_{MNF}}\right)^{N_1} \quad (1)$$

where,

Q_i, leakage rate in DMA at time *i* [m^3/h], Q_{MNF}, leakage rate in DMA at time *MNF* [m^3/h], P_i, average zonal pressure (AZP) in DMA at time *i* [m], P_{MNF}, average zonal pressure (AZP) in DMA at time *MNF* [m]; N_1, leakage exponent [-].

Empirically N_1 values are 0.5 for metallic pipes and between 1.5 to 2.5 for plastic pipes [19]. There is a relative abundance of data concerning the associated leakage exponents of individual leaks tested under laboratory conditions compared to field data of District Metered Area (DMA) level leakage exponents [19]. In order to calculate a daily leakage rate, a NightDay Factor (NDF) is introduced by Equations 2 and 3.

$$Q_{RL} = NDF * Q_{MNF} \tag{2}$$

$$Q_{RL} = NDF * Q_{MNF} \tag{3}$$

$$NDF = \sum_{i=1}^{i=24} \left(\frac{P_i}{P_{MNF}}\right) * P^{N_1} \tag{4}$$

where,
Q_{RL}, Real losses inside DMA [m^3/day]
QNNF, Net Night Flow in DMA [m^3/h]
NDF, Night Day Factor [h/day]
Apparent losses can be written as follows:

$$Q_{AL} = NRW - Q_{RL} \tag{5}$$

where,
Q_{AL}, Apparent losses inside DMA [m^3/day]
NRW, Non-revenue water inside DMA [m^3/day]
Q_{RL}, Real losses inside DMA [m^3/day]

2.2 Calibration Model

The Epanet Calibrator allows for establishing regressive models aimed to correlate the invisible leaks and pressures. In order to assess the real losses from Epanet Calibrator, first, the DMA sector should be modeled, and then the flow rate and pressure data observed would be entered into the software with regard to calibrating the network. Based on this research, it is important to take into consideration the frequency of burst pipes of high pressure for the most critical points of the area of study, along with the minimum Night Flow Rate in order to quantify the leakage rate at specific locations.

3 Case Study

The methodology is applied to a real network located northeast of Algeria (Guelma district); it is the WDN of the Bendjerrah municipality. It comprises 270 nodes. The total connection number is 1 923, with a network length of 36 km. The system of average flow rate is about

2174 m^3/day. The DMAs synoptic in the latter case is composed of 03 sectors, each one fed by an HDPE supply pipe of 150, 200, and 200 mm in diameter, collected from a 1500 m^3 semi-buried reservoir supplied by pumping. Using the AWWA-WAS-v5-09152014 software a water balance calculation is carried out. The overall results are summarized in Table 1. Over the past two years, which are 2018 and 2019, the real loss has averaged out to around 0.73, indicating a high proportion of the NRW, therefore, there is an urgent need to reduce leakages. The increase in the levels of NRW could be related to a number of factors such as: the age of the supply infrastructure, increased number of illegal connections, inaccurate billing, reservoir overflows, and vandalism of pipelines.

Table 1: Results of the water balance obtained by using the AWWA-WAS-v5-09152014 software

Year	**2017**	**2018**	**2019**
System Volume Input	181 189	198 609	210 060
Authorized Consumption	159 579	163 050	168 539
Billed Authorized Consumption	157 439	160 567	166 399
Unbilled Authorized Consumption	2 140	2 483	2 140
Billed Metered Consumption (inc. water exported)	157 439	160 567	166 399
Non-Revenue-water	23 750	38 042	43 661
Unauthorized Consumption	453	497	525
Apparent Losses	10 453	10 497	10 525
Real Losses	11 157	25 063	30 996
Water Losses	21 654	35 560	41 512
(Real Losses / Water Losses)	0.51	0.71	0.75

The district metering areas (DMAs) are shown in Figure 2. The DMA contains a total of 1020 residential connections, where three sectors were created, namely: sector 1, 450 residential connections, sector 2, 350 residential connections, and 220 residential connections in sector 3. Figure 2 represents the model EPANET for the three sectors as well as the locations of the monitored points (critical point/sector).

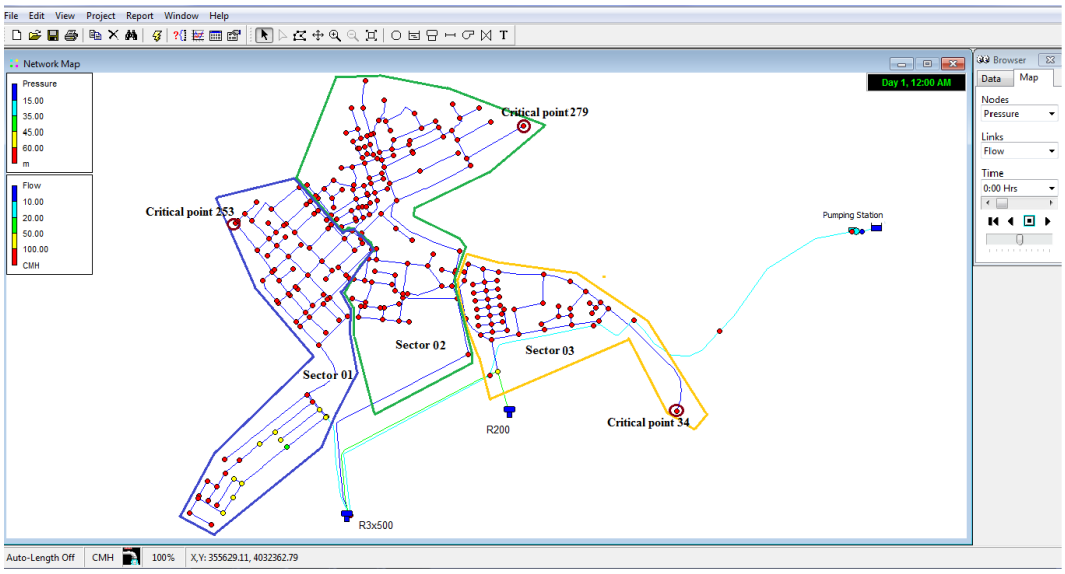


Figure 2: Parameterized model of Bendjerrah municipality WDN using Epanet Calibrator

Minimum night flow rate measurements (MNF) were carried out between 01:00 am and 05:00 am at the monitored points in each sector. In order to obtain the variations in flow rate and pressure, the computed values vary every 30 minutes. Figure 3 illustrates the excel spreadsheet charts of pressure versus leakage and they were plotted by using all the available chart types such as power, exponential, and polynomial (best fit) so as to establish a chart type with a good correlation coefficient (R^2). The follow-up of the weekly average night flow rate, *Q night(s)* clearly highlighted the correlation between the leak flow rate and pressure. Additionally, the pressure impact on the occurrence of the leak was confirmed by a strong flow rate increase, related to one or many new leaks, when the pressure was significantly increased.

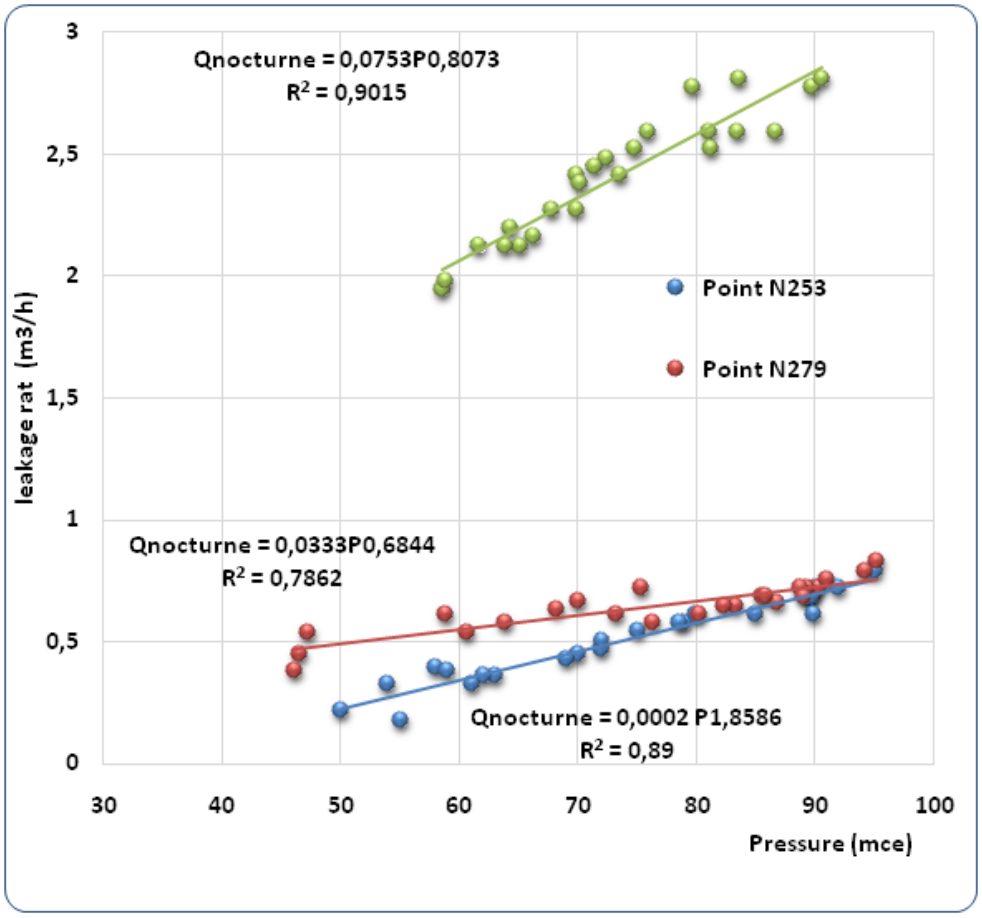


Figure 3: Night flow rate model of the 3 sectors critical points

4 Results and Discussion

The minimum Night Flow Rate methodology (MNF) was applied to the system of the network studied on Epanet as shown in Figure 2. After the valve (downstream) has been installed and handled which is located at the inlet of each sector, in order to urge small disruptions in the system, it was possible to assess the N_1 value as shown in Table 2 and to use the hourly pressure values according to the studied points (critical points) from data recorders.

Table 2: N_1 calculated for each point monitored during minimum night flow rates

		Critical points 253 in sector 1		**Critical points 279 in sector 2**		**Critical points 34 in sector 3**	
	Time	Pi/P_{MNF}	Qi/Q_{MNF}	Pi/P_{MNF}	Qi/Q_{MNF}	Pi/P_{MNF}	Qi/Q_{MNF}
	01:00-01:30	0.011	1.364	1.25	1.86	1.02	1.20
	01:30-02:00	0.013	1.889	1.26	1.82	1.01	1.36
	02:00-02:30	0.017	3.333	1.27	1.73	0.96	1.26
Day 1	02:30-03:00	0.013	1.810	1.00	1.45	0.90	1.07
	03:00-03:30	0.010	1.151	0.78	1.17	0.80	0.97
	03:30-04:00	0.011	1.600	0.84	1.23	0.75	0.86
	04:00-04:30	0.009	1.240	0.85	1.19	0.71	0.80
	04:30-05:00	0.008	1.083	0.91	1.14	0.73	0.83
	01:00-01:30	0.010	1.500	0.95	1.30	0.83	0.94
	01:30-02:00	0.013	3.400	0.80	1.34	0.93	1.22
	02:00-02:30	0.014	2.222	0.69	1.42	0.76	1.05
Day 2	02:30-03:00	0.011	1.462	0.65	1.24	0.70	0.94
	03:00-03:30	0.009	1.094	0.69	1.23	0.67	0.89
	03:30-04:00	0.008	0.941	0.66	1.14	0.69	0.92
	04:00-04:30	0.007	0.816	0.62	0.95	0.74	0.89
	04:30-05:00	0.006	0.650	0.61	0.79	0.81	0.90
	01:00-01:30	0.008	0.882	0.65	0.98	0.86	1.03
	01:30-02:00	0.009	1.063	0.68	1.20	1.02	1.32
	02:00-02:30	0.012	1.429	0.72	1.44	1.03	1.28
Day3	02:30-03:00	0.009	1.000	0.74	1.45	1.06	1.31
	03:00-03:30	0.008	0.875	0.77	1.46	0.96	1.18
	03:30-04:00	0.007	0.727	0.71	1.26	0.88	1.05
	04:00-04:30	0.007	0.816	0.65	1.09	0.84	0.92
	04:30-05:00	0.006	0.765	0.64	0.87	0.80	0.86
		N_1=1.54		N_2 = 0.73		N_3 = 1.05	
		R^2=	0.88	R^2=	0.76	R^2=	0.81

At the network inlet, the data recorder presents the average flow rate of each of the three sectors respectively 12.82 m^3/h, 8.23 m^3/h, and 5.51 m^3/h. From the minimum night flow rate (MNF), the average night-day factor NDF is calculated for each sector by means of Equation 3 and Q_{RL} by using equation 2. The results are presented in Table 3. Regarding the values obtained from the recorder, the N_1 values are satisfactory (according to the correlation factor R^2).

Table 3: Real losses and NDF factor calculated for each point monitored during minimum night flow rates

	Real losses m^3/24h	**Real losses %**	**NDF**
Sector 1	2373.51	25	0.79
Sector 2	4300.74	45	0.97
Sector 3	2828.46	30	0.94

5 Intervention Tools for Water Losses Management

Figure 4 presents the EPANET model for each sector and the location of the monitored points. The equipment was set up in residential flow meters aiming to continuously measure the network pressure.

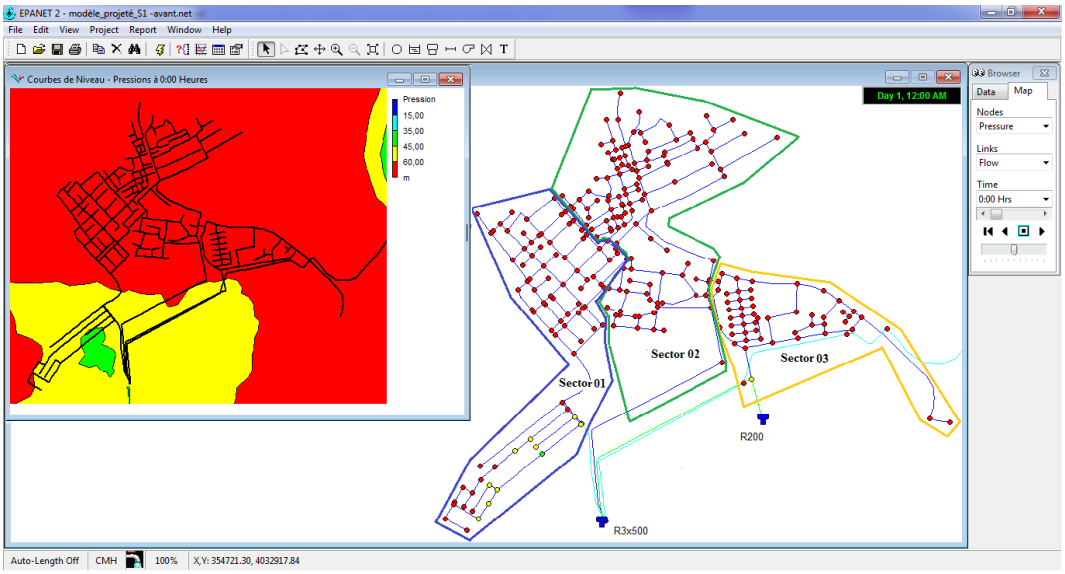


Figure 4: Pressure representation before modulation of valve less network

Continuous pressure sensors were set up for each pipe group (see Figure 3) in order to collect the real data system. The observed flow rate and pressure were used as input data for Epanet as illustrated in Figure 5.

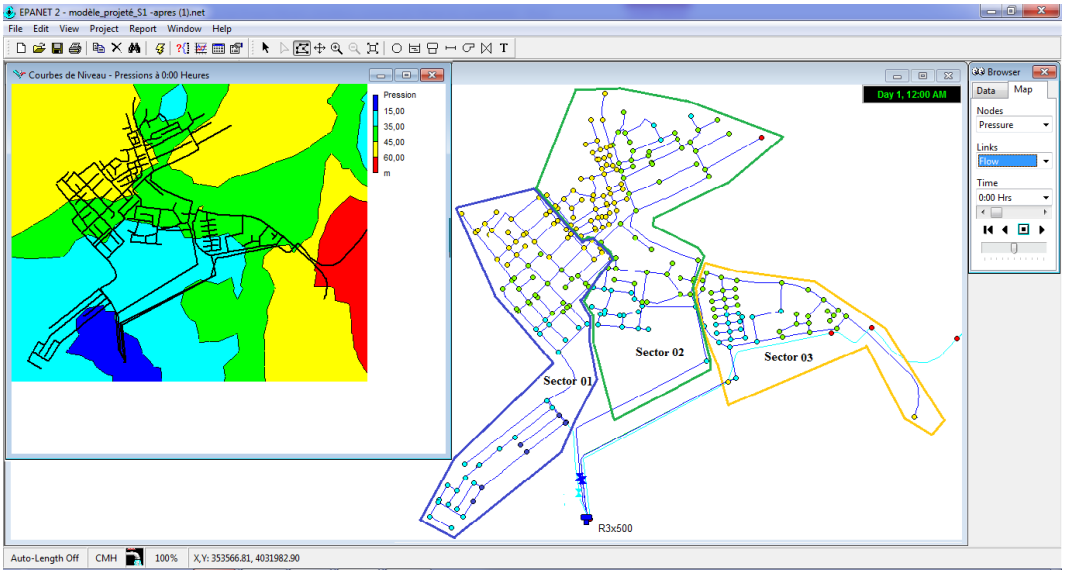


Figure 5: Pressure representation after modulation of network with pressure-reducing stab valve

From the flow rate diagram in Figure 5, the results of the 3 values ((**a**) observation, (**b**) simulation, an (**c**) calibration) can be represented. The operational roles seem to be inverted such as:

(a) the observed flow rates during 4 days at the 3 critical points for each sector;
(b) the simulated flow rates during 4 days at the 3 critical points for each sector;
(c) the calibrated flow rates during 4 days at the 3 critical points for each sector.

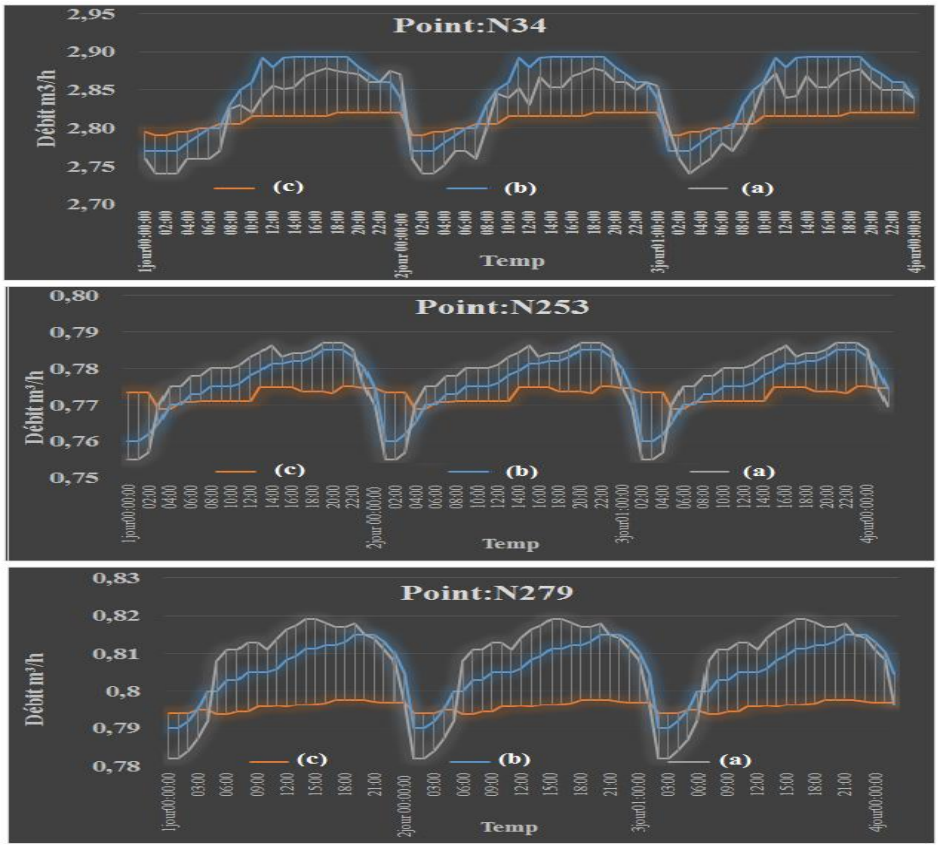


Figure 6: Flow rate (cubic meter per hour) at a critical point in each sector (a) valve less sector, (b) sector with valve fitted to outlet, (c) sector with valve modulated over time (pressure reducer)

From the data in Figure 6, it can be concluded that the demand at the critical points of the 3 sectors is decreased and is satisfactory at the calibrated sector (c), compared to other models (a) observed and (b) simulated where the demand and pressures are high. This indicates that the pressure is detected at the critical point and conveyed to PRV (pressure-reducing stab valve) which, in turn, adjusts the inlet pressure in order to keep the minimum pressure during the day.

Table 4 presents the coefficient calibration of Hazen-Williams. As long as the Epanet Calibrator simulates the leaks, as a result, the flow rates increased with respect to the observed values by the Epanet Calibration process.

Table 4: Hazen-Williams calibration coefficient

	Sector 1	**Sector 2**	**Sector 3**
Before calibration	160	160	160
After calibration	83.2	85	87.9

6 Zone Pressure Management

Reducing the pressure at a critical point either in a sector or in a network at a certain level triggers a significant pressure reduction at the network inlet. The tool does not depend on the network hydraulic representation; it rather compromises the MNF analysis and the most in-depth analysis of pressure measures, friction factors, and head losses at 3 DMA key points: inlet point, average zone point (elevation), and critical point, point(s) of the sector, the pressure of which is the lowest during the day as illustrated in Figure 7.

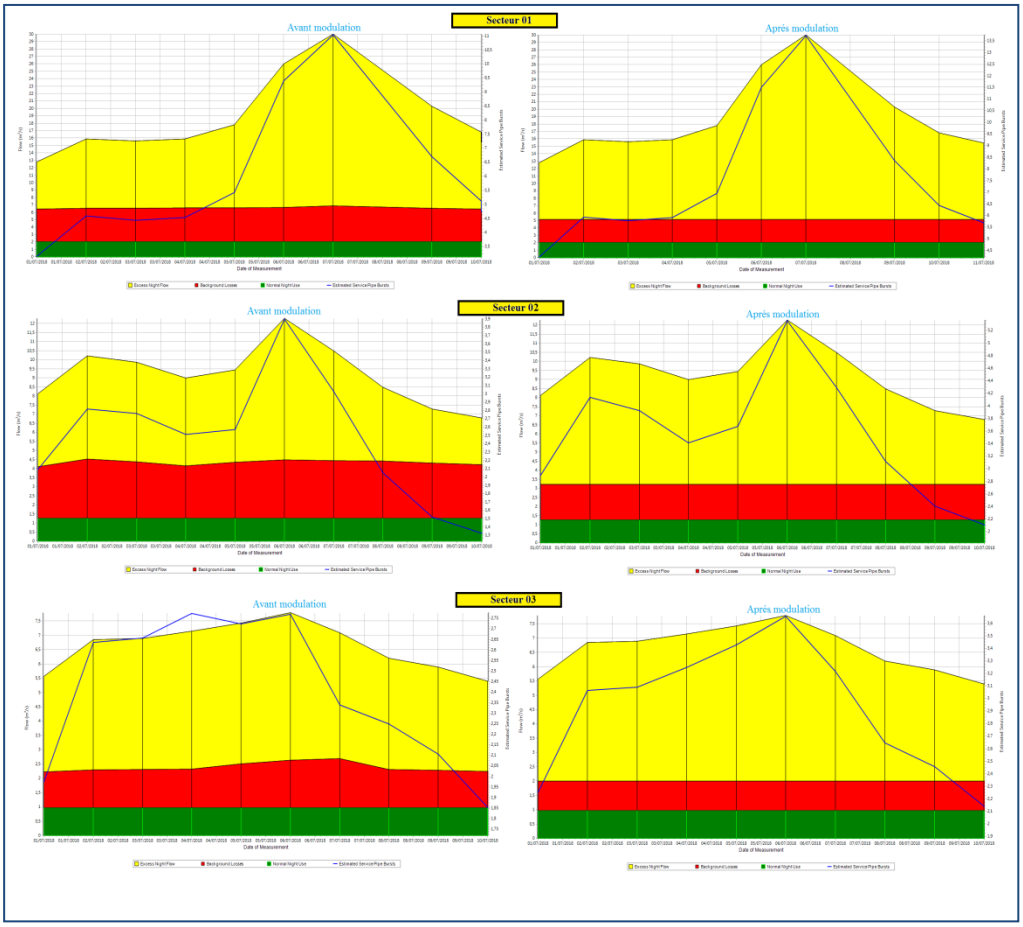


Figure 7: Leak, background losses and night use of the 3 sectors, Source: Sanflow v4.6

7 Model Validation

Sanflow deals with the analysis of each sector before and after calibration (reducing stab). The obtained results are summarized in Table 5. It is worth noting that the loss reduction (background losses) after calibration is observed; thereby allowing the protection of each network sector and minimizing the leaks. After having measured (assessed) the different components of normal night use, figures were added and then subtracted from the minimum night flow rate measured. The difference lies in the unexpected losses attributable, either to unreported bursts or to errors in the hypotheses made during the calculation. The probability of errors in the hypotheses will be treated separately and the remainder of this section considers the difference as a leak.

Table 5: Background loss assessment for night flow rate, Source: Sanflow v4.6

	S1	**S2**	**S3**
network losses (m^3)	0.34	0.22	0.16
connection losses (m^3)	1.35	1.05	0.66
property losses (m^3)	0.48	0.37	0.24
Total background leakage P =50 m	2.17	1.64	1.06
correction factor	2.08	1.86	1.33
Final total background leakage (m^3/h) P = 50 m	4.52	3.06	1.41

The use of different loss parameter values in the analysis is shown in Table 6. It is based on the previous experiment, which can be taken into account, when the loss parameters determination comprises pipe material, age, soil conditions, implementation quality, etc. A pressure correction factor is then necessary to assess the background losses since the loss parameters are always specified at the standard pressure of 50 m. In this research, the average zone night pressure is located at 63 m, which requires a correction in order to reduce the losses. After assessing the two components, the connections background leak and network (BLCONN/ BLMAIN) and the installation background leak (BLINST)) can be determined. It is then possible to calculate the difference between the Minimum Night Flow rate measured and the legitimate use assessed with the results are presented in Table 6.

Table 6: Bursts assessment of each sector/night flow rate. Source: Sanflow v4.6

	S1	**S2**	**S3**
Unaccounted loss	6.4	4.7	2.6
Standard service pipes burst	0.80	0.76	0.48
Pressure correction factor	1.28	1.23	1.10
Burst equivalent service Pipes leak	1.02	0.93	0.53
Bursts expected number of equivalent service pipes	6	4	1

Based on the results obtained in Table 6, the majority of leaks are assumed to be of fixed zone type. In addition, the losses and bursts are not as pressure dependent as the background leak. From this Table, it can also be deduced that the bursts expected number of the service pipes, corresponding to the first sector is in the order of 6 bursts, with respect to the second and third sectors which have 4 and 1 burst, respectively.

8 Conclusion

Finding approaches toward water sustainability is crucial for national economic and social development. To reach water sustainability, water losses represented in Non-Revenue Water should be reduced. Many attempts have been made to reduce water losses in water distribution systems and as such many methodologies and tools have been applied to minimize water losses. These tools range from computational approaches, legal and policy implementation, economic approaches, and infrastructural rehabilitation approaches. A water balance is the best practice approach that can be used to partition various components of Non-Revenue Water. However, a water balance approach would not be able to forecast leakage as it only gives a general overview of water loss. Therefore, there is a need for specialized application tools for assessing partitions of non-revenue water. One such tool is the South African Night Flow (SANFLOW) analysis model, for analyzing flows and pressure within district-metered areas. In this study, the SANFLOW analysis model was found to be suitable for partitioning water leakages. The water losses that result only from leakages were determined by identifying the minimum night flow in the district metered areas.
The introduced case study represents an example of a high water loss area with, poor data availability. The semi-urban Municipality of Ben Djerrah has recorded in recent years an increasing Non-Revenue Water. The pressure impact on the occurrence of the leak was confirmed by a strong flow rate increase, linked to one or many new leaks when the pressure was significantly increased. A combination approaches of Rossman's Epanet software and the South African Night Flow (SANFLOW) Analysis Model and the minimum Night Flow Rate methodology were applied to the system of the network studied on Epanet. It was possible to determine the N_1 value from data records after having installed and managed the valve (downstream), situated at the inlet of each sector, to encourage minor disruptions in the system. The calculated N_1 values ranged between 0.5 and 2.5 (two outliers were determined as N_1=8.9 and N_1=10.77 but these are not impossible and can be explained through physical issues with the pressure management zone). The relationship between the calculated Leakage Exponent (N_1) and the Leakage Number (LN) was determined to be consistent with theoretical studies. The variation in N_1 values shows that leakage in water distribution systems is more sensitive to pressure than conventionally assumed. The importance of N_1 is demonstrated through de calculation of the percentage of the reduction in leaks. The obtained values for the latter ranged from 29% to 82%. At the network inlet, the data recorder, respectively, presents the average flow rate of each of the three sectors respectively 12.82 m^3/h, 8.23 m^3/h, and 5.51 m^3/h. From the minimum night flow rate, the average night-day factor is calculated for each sector. Regarding the values obtained from the recorder, the N_1 values are satisfactory (according to determination factor R^2).

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