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Analysis of the effect of pressure control on leakages in distribution systems by FAVAD equation and field applications

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Abstract

Pressure has an important effect on the occurrence of failures/leaks in water distribution systems (WDSs) or the change of leakage in existing leakages. For this reason, monitoring the pressure is important especially for analyzing the changes in the day and night, determining the fluctuations and applying pressure management (PM) to ensure normal operating conditions. In this study, the effect of pressure on water losses and minimum night flow (MNF) was carried out according to the Fixed and Varied Area Discharge (FAVAD) approach, which allows the amount of leakage to be calculated based on the change in pressure and field tests. The minimum flow rate and potential leakage were determined under the network operating conditions before the pressure control in a region. Then, considering the features of the region, pressure was reduced with the pressure control system and MNFs and leaks were monitored. By reducing the pressure from 9.10 bar to 3.2 bar in the region, the MNF rate was reduced from 6.95 l/s to 3.29 l/s. The daily water savings in the system inlet volume is 78.44 m^3/day and the annual saving is 28,624 m^3/year. The results obtained are very important for practitioners in terms of implementing PM in the field.

Key words: FAVAD equation, leakage, minimum night flow (MNF), pressure control, water distribution system

Highlights

- The effect of pressure on water losses and minimum night flow rate was analyzed.
- The pressure was reduced with the help of the pressure control system.
- The minimum night flows were monitored after pressure management.
- The theoretical leakage level was analyzed according to the FAVAD equation.
- The results of field data and FAVAD equation were compared.

INTRODUCTION

The amount of leakage in current failures in water distribution systems (WDS) increases under high operating pressure or high pressure changes. Kleiner & Rajani (2002) stated that effective planning for the renewal of water distribution systems requires accurate quantification of the structural deterioration of water mains. The high fluctuations in day and night pressures in the system are very effective in the formation of new leaks and failures (Lambert *et al.* 1999). A general diagnosis of

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the actual structural state of these systems is needed, as are tools to assess their rate of deterioration based on the characteristics of water pipes and on their breakage histories (Pelletier *et al.* 2003). The total cost of a failure also increases with time to implement a repair and fast detection of failures is an essential part of a pipeline network management system (Rajani & Kleiner 2004). For this reason, controlling the system pressure, reducing fluctuations, and reducing high pressure at night when consumption is low will reduce the occurrence of new breakdown as well as the leakage volume lost in unit time in existing failures. The FAVAD (Fixed and Variable Area Discharges) equation, proposed by the IWA Task Force, which is the most commonly used approach to express the relationship between pressure leakage and failure, and explains the change in leakage or failure due to pressure change (Lambert *et al.* 1999; Lambert 2002; Lambert & McKenzie 2002; Farley *et al.* 2008). In this equation, while the pressure leakage relationship is expressed depending on the pipe material and the N1 leakage exponent coefficient. Moreover, the failure frequencies in service connections and mains before and after PM are examined to analyze the pressure-failure relationship, and the change in fault frequency is expressed in terms of pressure change and N2 exponent defined depending on pipe material (Pearson & Trow 2005). In the system, where the effect of the pressure is so high, it is essential to apply the most appropriate pressure control system to reduce failure rates, reduce leaks and thus reduce operating and maintenance costs. In studies conducted in the literature, it was seen that various studies have been carried out to reduce the effect of pressure in failures and leakage management (Fanner *et al.* 2007; Fanner & Lambert 2009; Nazif *et al.* 2010; Wu *et al.* 2010; Gomes *et al.* 2011; Bieupoude *et al.* 2012; Karadirek *et al.* 2012; Dai & Li 2014; Schwaller & van Zyl 2015; Creaco *et al.* 2016; Martínez-Codina *et al.* 2016; Vicente *et al.* 2016; Giustolisi *et al.* 2017). On the other hand, besides the benefits of pressure control management, components such as automation system, room construction, device and equipment selection-placement and monitoring of data are important costs and it was emphasized that detailed analysis and evaluation should be performed before PM is applied (Charalambous & Kanellopoulou 2010).

Farley *et al.* (2008) emphasized that pressure and pressure change are highly effective on failures, leakages and physical losses and PM contributes significantly to reducing this effect. McKenzie *et al.* (2004) carried out an application in the Khayelistha distribution system in South Africa to analyze the impact of PM on leakage prevention. For this purpose, the system was analyzed and pressure reduction valves were installed and started to be monitored. At the end of the work, it was stated that PM provides significant benefits in reducing existing leaks, and that new failures in pipes can be prevented significantly. In addition, it is stated that 9 million m^3 of leakage was saved annually by using pressure reducing valves in the system. Araujo *et al.*(2006) aimed to develop and implement the pressure control system based on the hydraulic model. For this purpose, authors used the EPANET to create and simulate the hydraulic model of the system, and applied the genetic algorithm (GA) technique for pressure control. In this way, it was provided to optimize the opening amount, number and positions of the control valves for optimization of leakage amounts. By analyzing scenarios with different number and position control valves, the most ideal one was determined. Marunga *et al.* (2006) aimed to apply PM in pilot areas (Mutare city, Zimbabwe) where operating pressure is high. It was determined that the operating pressure in the selected pilot regions is between 75 and 80 m, and the rate of non-revenue water at these pressure levels is 47 and 32%. As a result of the work done in the field, if the outlet pressure is 50 m, a 25% saving in MNF was achieved. Thornton & Lambert (2007) stated that while applying PM in water distribution networks in general, preventing water losses and preventing pipe breaks are associated with maximum pressure, but pressure changes are extremely important in solving PM problems. Charalambous (2007) created 15 sub-regions in Lemesos to reduce losses in water networks, and carried out PM work. A fixed outlet pressure reducing valve was installed in the created sub-regions and as a result of decreasing the pressure, a 38% reduction in water losses has occurred. At the same time, 41% reduction was observed in the bursts of pipes. Giustolisi *et al.* (2008) proposed a steady-state network simulation model considering the pressure-driven demand and leakage at pipe level and analyzed based on a case study from real system. Authors stated that the model has the high robustness of the proposed pressure-driven demand and leakage simulation model. Cinal (2009) aimed to define the relationship between pressure and leakage and to analyze the effect of PM in reducing leakage rates. For this purpose, in a pilot isolated zone with an inlet, the measurement unit and a control unit with the features of recording flow meter, pressure reduction valve (PRV) and data logging are placed. In the study, the current data was firstly recorded without using the pressure reducing valve, then the output pressure of the PRV was set to a fixed value, and the third condition, the output pressure of the PRV was adjusted two times. With the use of PRV, the water supplied to the network has decreased by 18% as a result of the decrease in pressure in the work area by 30%. Pressure control, which is sensitive to flow rate, has decreased up to 21%.

Alkasseh *et al.* (2013) applied statistical modeling to predict water losses in a city in Malaysia, taking into account many factors affecting water losses and using the minimum night flow (MNF). They stated that the PM to be applied to reduce water losses for a WDS depends on the good calibration of hydraulic modeling. An approach has been developed to solve the Genetic Algorithms and Integer-Mixed Nonlinear Programming (MINLP) problem in order to optimize the region where PRVs will be applied to minimize leaks in WDS. Creaco & Walski (2017) implemented an active pressure control strategy to reduce leaks and losses and examined economic results. The results were compared by using conventional pressure reduction valves and pressure reduction systems, which are controlled remotely in real time. As a result of the studies, it was revealed that active pressure control is not required in regions with low leakage levels, low maintenance and operating costs and remote-controlled pressure breakers should be used in complex and large systems. Fontana *et al.* (2018) recommended a real-time pressure control system to prevent and reduce leaks and emphasized that real-time pressure control provided significant gains in minimizing pressure fluctuations and regulating pressure as a result of field experiments. Foglianti *et al.* (2020) proposed two methods for the solution of water distribution networks equipped with pressure-control valves based on the global-gradient algorithm (GGA). The performance of the methods was analyzed and compared based on field case studies to test the hydraulic accuracy and efficiency.

In this study, the effect of pressure on water losses, water balance and MNF rate was analyzed and evaluated according to field data and tests. For this purpose, the MNF and potential leakage amount, which is measured in the network operating conditions (current pressure and network physical properties) before pressure control in the pilot isolated region, has been determined. Then, considering the features of the region, the pressure was reduced with the help of the pressure control system and the MNFs were monitored in the new conditions that occurred. The theoretical leakage level was analyzed according to the FAVAD equation and the evaluation was made by comparing with the real results obtained from the field. This comparison is particularly important for practitioners in terms of implementing PM in the field, evaluating gains achieved and technically determining the level at which the leak level can be reduced.

PRESSURE-LEAKAGE RELATIONSHIP: THEORETICAL BACKGROUND

Network features, environmental factors, and most importantly, system operating conditions are very effective in new failures or breaks in distribution systems. One of the most important reasons for the formation of new failures in a network can be shown to be sudden pressure change and fluctuation in the system. In addition, the amount of water lost per unit of time in current unreported failures and background leaks increases due to pressure change (Lambert *et al.* 1999; Lambert & McKenzie 2002; Farley *et al.* 2008). Because the pressure causes stress on the inner surface of the pipe and according to the material properties, the wall thickness of the pipes and thus the compressive strength changes. Factors that may affect the change in pressure: (i) the consumption characteristic between day and night, (ii) the water use status of high consumption subscribers during the day, (iii) the frequency of water interruptions, (iv) the irregular pressure condition in the systems fed directly to system. In water loss and leakage management, the type of pipe material has a huge impact on the pressure-leak relationship. Depending on the characteristics of the pipe material, different pipe types can behave differently against pressure and external influences and their response is different (Lambert *et al.* 1999; Lambert & McKenzie 2002; Farley *et al.* 2008). In literature, it was seen that the FAVAD equation, which was developed based on the basic orifice equation, was used extensively to explain the relationship between pressure and leakage (May 1994). This equation theoretically provides the opportunity to evaluate the level of leakage that can be observed in the system at any pressure level (Lambert *et al.* 1999; Lambert & McKenzie 2002). The failure frequencies in service connections and mains are examined before and after PM to analyze the pressure-failure relationship, and the change in fault frequency is expressed in terms of pressure change and N2 exponent (Pearson & Trow 2005). Equation (2) calculates the change in the number of failures according to the N2 coefficient and pressure change is used to define the pressure-failure relationship.

$$L_1 = L_0 * \left(\frac{P_1}{P_0}\right)^{n1} \tag{1}$$

$$\frac{B0}{B1} = \left(\frac{P0}{P1}\right)^{N2} \tag{2}$$

where, L_0 is the first leakage flow at P_0; L_1 is the leakage at regulated pressure P_1, P_0 is the average pressure at initial condition, P_1 is the average pressure regulated, n1 is the leakage exponent ($n1 = 0.5$ for fixed area leaks, $n1 = 1.5$ for variable area leaks) (May 1994; Lambert & Morrison 1996). As can be seen from the FAVAD equation, the leakage level decreases or increases due to the pressure change in the distribution system. In this study, theoretical leakage levels were calculated according to the pressure levels occurring before and after PM in the pilot application area and an evaluation was made according to the results obtained from the field. This comparison is particularly important for practitioners in terms of implementing PM in the field, evaluating gains achieved and technically determining the level to which the leak level can be reduced.

STUDY AREA

To determine the pressure-leakage theoretically and to implement the pressure control system in the field, an isolated region located in the service area of Kayseri Water and Sewerage Administration (KASKİ) was chosen as a pilot application area (Figure 1). In Kayseri WDS, in the beginning of 2019, DMAs have been created within the scope of combating water losses and 140 sub-regions have been planned in this context. In the central distribution system, 30 regions have already been isolated, SCADA integration has been carried out, flow and pressure changes have begun to be monitored and water loss analysis studies are carried out. Flow rate changes are monitored regularly in the pilot isolated region created in the central distribution system and selected as the pilot region. In the pilot isolated region, there are generally small facilities with commercial activities and the density of housing is limited. It is known that the businesses operating in this region do not have night consumption. Characteristic features of the region are given in Table 1 (KASKİ 2020).

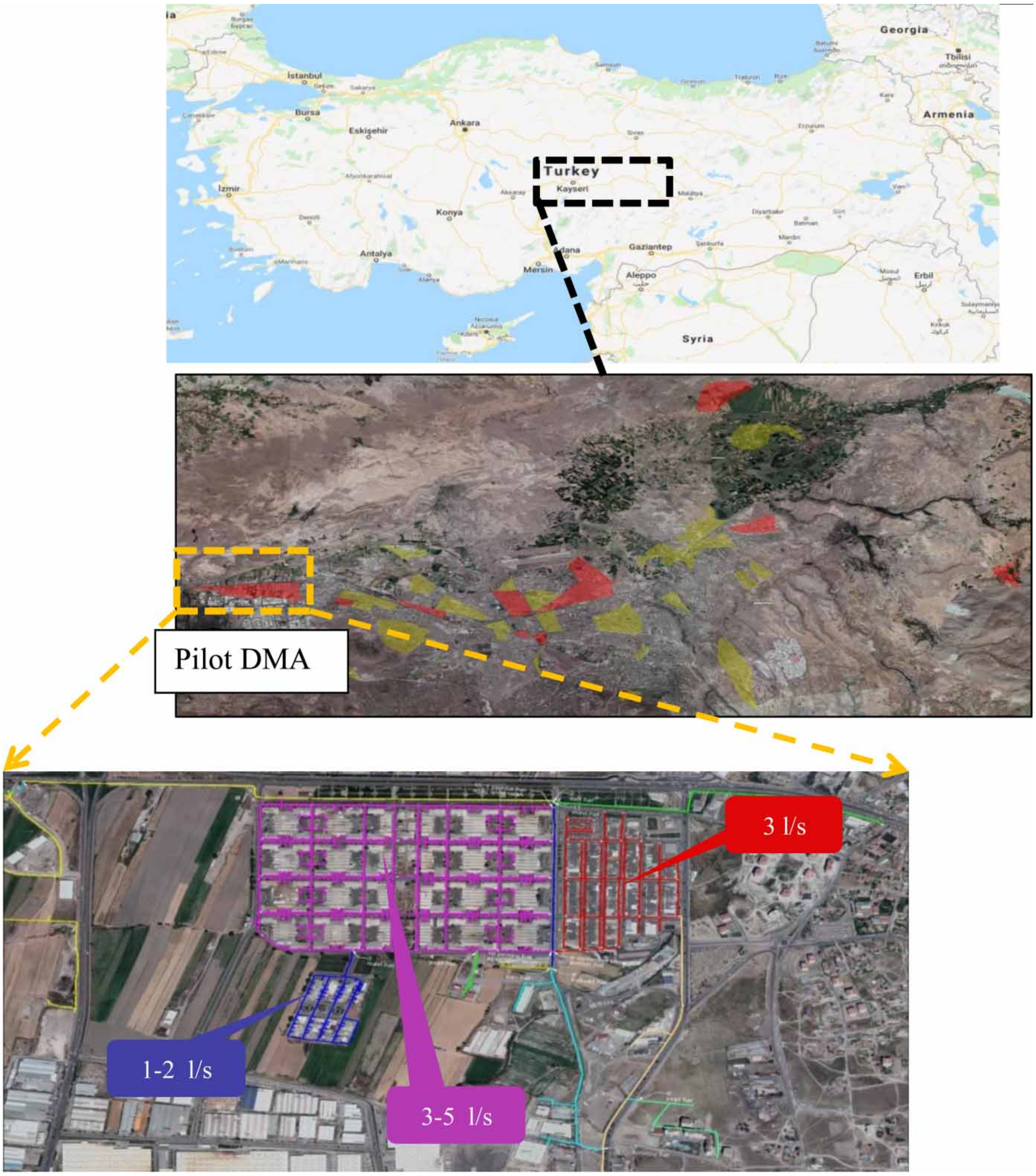

Figure 1 | Pilot isolated measuring zone (KASKİ 2020).

ANALYSIS AND DISCUSSION

Minimum night flow analysis

In a DMA, the system flow is monitored during the hours when the customer consumptions are lowest (between 02:00 and 4:00 at night) and potential leakages are evaluated in the region. By applying the MNF method, the components can be monitored daily and it is possible for the practitioners to be aware of potential leaks. For this, nightly customer consumptions and background leaks are subtracted from the system inlet flow, which is measured at the MNF rate and the potential leakage

Table 1 | Analysis parameters in the pilot region

Components	Symbol	Value	Unit
Main length	LM	32.23	km
Number of service connections	Nc	931	No.
Total length of the private service connections	Lp	9.53	km
Number of the Customers		2,500	No.
Number of non-residential customers		2,200	No.
Number of residential customers		300	No.
Number of isolation valves		1	No.
Ground level difference in the region		15	m
Network condition	Moderate		
Data transfer	SCADA		
System pressure before pressure management	AZNP0	91	m
System pressure after pressure management	AZNP1	31	m
Night–Day Factor (NDF) at before pressure management	NDF0	22.5	Hours/day
Night–Day Factor (NDF) at after pressure management	NDF1	23.8	Hours/day
Minimum night flow before pressure management	MNF0	6.95	l/s
Minimum night flow after pressure management	MNF1	3.29	l/s
Night customer consumption (BABE equation)	Qcons.	0.28	l/s
Background leaks (BABE equation) before pressure management	Qleak-0	2.38	l/s
Background leaks (BABE equation) after pressure management	Qleak-1	0.56	l/s
Change in pressure	ΔP	60	m
Change in minimum night flow	ΔMNF	3.66	l/s
Rate of change in pressure	ΔP	65.9	%
Rate of change in minimum night flow	ΔMNF	52.7	%
N1 power (for PE and PVC pipes)	N1	1.50	

amount is determined. In this context, the Bursts And Background Estimates (BABE) equation proposed by IWA is used to calculate nightly legal consumption and background leaks in the region. The BABE approach considers the background leakages in mains, service connections (main to edge of the street) and service connections on private property. The main length, number of service connections, length of the service connection on private property and average zone night flow is required to calculate the background leakage in DM. Background leakage for a system in good condition could be calculated by using the BABE approach (Equation (3)) (Lambert 1994, 2002; Lambert & Morrison 1996; Lambert *et al.* 1999).

$$BL = (20 * L_m + (1.25 + 0.033 * L_p) * N_c) * (50/AZNP)^{1.5} \tag{3}$$

L_m is the main length (m), N_c is the number of service connections, L_p is the length of the service connection private property (m), $AZNP$ is the average.

After the pilot zone was isolated, it was integrated into the SCADA system and the flow and pressure changes were monitored (Figure 2). According to the BABE equation and the physical characteristics of the network given in Table 1, background leaks (2.2 liters per second) and nightly legal consumption (0.45 liters per second) were calculated in the region before PM (Table 1). In the DMA, observation started from 24.11.2019 and the MNF rate was measured as 12.5 liters per second. Considering the customer profiles and network features in the region, it is predicted that a significant part of this flow, which is quite high, is potentially preventable leakage.

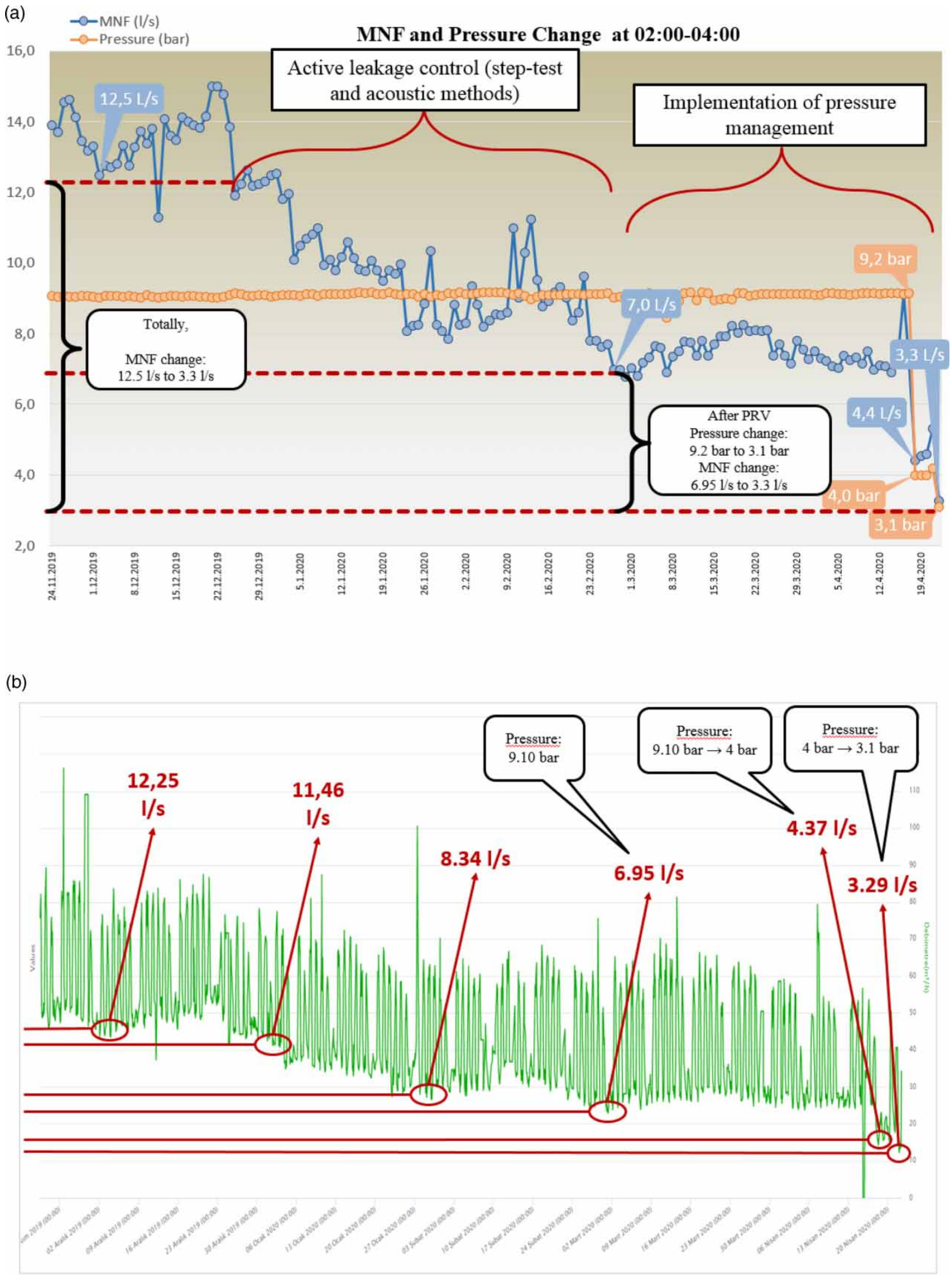

Figure 2 | (a) The change in minimum night flow in pilot region; (b) flow rate variation in the region according to active leak control works.

The system pressure at the time of MNF may be different from the pressures observed due to the changes in water demand in a 24-hour period in the region. In systems fed with gravity, it is observed that the pressure at the time of MNF is higher than the average pressure per day or during the day. On the other hand, in case of pressure control (especially in flow-sensitive or time-sensitive systems), the pressure during nighttime is lower than that in the daytime. In flow-sensitive or time adjusted pressure control systems, more pressure is reduced by PRV due to low demand at nighttime.

The leakage volume varies depending on the pressure in the area. In many systems, the pressure changes in a 24-hour period, and therefore the leakage rate, varies accordingly. Therefore, leakage rates (l/s) detected by MNF cannot simply be multiplied by 24 hours and the daily leakage volume (m^3/a) cannot be calculated. For this reason, in the MNF analysis, the 'Day and night factor (NDF)' parameter determined according to the conditions of the system should be calculated and taken into consideration instead of taking 24 hours to find the daily, monthly or yearly volumetric value of the flow that was determined and saved by the active leakage control methodology. Night-Day Factors typically could be varied from 18 to 23 hours/day (for systems supplied with gravity) and from 24 to over 30 hours/day (in case of pressure control) (Lambert 2002; Tabesh *et al.* 2005; Cheung *et al.* 2010).

This factor is calculated in the system taking into account the pressures measured in each 7-day period (Lambert & Thornton 2012). Also, to calculate gains from PM in the area where PM is applied, the NDF parameter should be to be calculated both for the conditions before PM and for the condition that occurs after PM is applied (Lambert & Thornton 2012). Therefore, in this study, this factor was calculated as $NDF0 = 22.5$ hours/day according to the system conditions prior to PM and $NDF1 = 23$ hours/day for the conditions after PM to calculate the water volume saved at the end of PM (Table 1).

It seems that the MNF shows oscillation especially in the pilot area before pressure control (Figure 2). Considering that a significant part of the region is in PE and PVC pipe density (expressed as variable area leaks in the literature), the crack is widened and the leakage increases with the effect of pressure. In addition, pipes under constant stress can produce new failures over time due to the high pressure observed in the region, which causes leakage to increase. For this reason, in order to reduce the existing leaks in the region, active leakage control and acoustic methods have been applied to identify unreported leaks.

For this purpose, leak detection (by ground microphone) and step-test works were carried out in the region between 24.11.2019 and 24.02.2020 (Figure 1). However, the main problem encountered in the implementation of the step test can be shown to be that the valve points are generally under the asphalt layer, and the most appropriate shut-off valves are determined. In addition, especially in regions without a GIS database, considering the situations where the valve delivering water to the pipes is not known, field studies are extended and labor costs increase. Despite these difficulties, as a result of these studies carried out in the pilot region, it is thought that there may be potential leakage to a total of 8–10 liters per second in three different sub-regions (Figure 1).

By applying a step-test, local listening areas in the region were narrowed and the leakage location was found in a shorter time. Point detection works were carried out using the ground microphone to detect and repair leakage locations in three different sub-regions, which are located in the map given in Figure 2 and are thought to have potential leakage. Within this scope, unreported leaks at five different points were identified and repaired. As a result of the 3-month field tests applied in the region, the MNF rate, which was 12.5 liters per second, was reduced to 6.95 liters per second (Figure 2).

As a result, approximately 5.45 liters per second of leakage was saved in the region. Considering the NDF value (22.5 hours/day) determined according to the physical, topographic and operational conditions of the region, as a result of this study, a total of 441 m^3 per day and 161,130 m^3 per year water saving was achieved in the region. Although significant gains have been achieved in the region as a result of these works, it is observed that the MNF rate is still at high levels considering that there are generally commercial customers (no night consumption) and the number of houses is very low. Considering that water supply to the region is provided by pumps from the wells, reducing the level of leakage in the system to the economically and technically possible level will provide important economic contributions. When acoustic methods and step-test studies were carried out in the field, after the detected leaks were repaired, a decrease in MNF value was observed and accordingly an increase in the MNF value was determined due to the increase in system pressure, (Figure 2). The main problem here is that operating pressure tends to increase as leakage is prevented in the system, existing cracks in PVC and PE pipes expand with the effect of increasing pressure, and the amount of leakage increases. It is seen that this situation was repeated often during the period when these studies were carried out. As a result, leaks that are not reported are detected and repaired by applying active leakage control and other field studies, but increases or fluctuations in system pressure lead to new failures and increased leaks in existing faults, resulting in discontinuity and fluctuations in the MNF value. These results revealed that management of system operating pressure is very important in leak management, preventing fluctuations and increase in leak level and implementing a sustainable strategy. For this reason, in the second phase of the pilot work, a pressure control system was installed and the system was monitored in order to reduce the effect of high pressure, to decrease the MNF rates, to reduce leaks, to provide the pipes with less pressure and to extend their economic life. While doing this, the pressure leakage relationship was analyzed according to the FAVAD equation, the values that the leakage could take were calculated according to the pressure levels formed in the field and the pressure control system was compared with the real results obtained by applying the pressure control system in the field. Within the scope of this study, the basic analysis and evaluations to reveal the relationship between theoretical and field application and pressure and leakage can be given as follows: (i) MNF analysis (separately before and after PM according to the BABE method), (ii) analyzing and monitoring the relationship between pressure and MNF, (iii) analysis of leakage level due to pressure change (separately for FAVAD and field applications), (iv) gains according to PM and comparison with theoretical equation results, (v) calculation of day and night factors and (vi) comparison of the results.

Estimation of leakage level according to FAVAD equation

The level of leakage that can be reached technically according to the pressure change in the pilot region is estimated. Since the pipe material characteristic is PE and PVC in the isolated region, the

Table 2 | The level of leakage that may technically occur in the pilot region according to the FAVAD equation

Components	Symbol	Value	Unit
System pressure before pressure management	AZNP0	91	m
System pressure after pressure management	AZNP1	31	m
Night–Day Factor (NDF) before pressure management	NDF0	22.5	hour/day
Night–Day Factor (NDF) after pressure management	NDF1	23.8	hour/day
Total leakage level before pressure management	Lo	6.67	l/s
Total leakage level after pressure management	L1	1.33	l/s
Change in total leakage level	ΔL	5.34	l/s
Rate of change in total leakage level	ΔL	80.1	%
Potential recoverable leak level before pressure management	Potential Lo	4.29	l/s
Potential recoverable leak level after pressure management	Potential L1	0.77	l/s
Change in recoverable leakage level	ΔL(Potential)	3.52	l/s
Rate of change in recoverable leakage level	ΔL(Potential)	82.1	%
Water saved by total leakage level (daily)		118.5	m3
Water saved by total leakage level (monthly)		3,555.3	m3
Water saved by total leakage level (annual)		43,256.7	m3
Water saved by recoverable leakage level (daily)		78.3	m3
Water saved by recoverable leakage level (monthly)		2,348.7	m3
Water saved by recoverable leakage level (annual)		28,575.7	m3

N1 power coefficient is taken as 1.5 and the calculation is made (Table 2). Leakage level for 91 m pressure is 6.95 liters per second under initial conditions and, according to the FAVAD equation, the leakage level that can occur for 31 m pressure has been calculated as 1.33 liters per second (Table 2). The amount of the background leakage, which was 2.38 liters per second before PM in the region, was calculated as 0.56 liters per second after PM. Here, it is seen that there is a significant decrease in uncertain leakages only due to the change of pressure in the system.

It is observed that the value calculated in the region according to the FAVAD equation, which indicates the level of leakage technically (1.33 liters per second), is quite low, and it is possible to achieve significant savings due to the decrease in pressure (Table 2). At the end of the study, the change in the total leakage level was calculated as 5.34 liters per second (the rate is approximately 80.1%) and the change for the potential recoverable leakage was calculated as 4.29 liters per second (82.1%) (Table 2). In addition, the volumes saved were calculated by considering the NDF_0 parameters calculated for the region before the PM and NDF_1 parameters for the subsequent conditions. Accordingly, it is observed that there is a potential to save 118.5 m^3 per day according to the total leakage level and 78.3 m^3 for the recoverable leakage value. When these rates are taken into consideration, it is obvious that it will provide significant gains in terms of reducing energy costs, especially in pumped systems. Here, it is thought that leakage levels calculated by using the theoretical equation and technically indicating the value that leakage can take, will be a reference especially for practitioners, contributing and guiding in setting targets in the field. In the second stage of the study, based on these calculated leaks, leakage levels in real conditions were determined; gains were calculated and compared with theoretical values.

Implementation of pressure management in the field

After the pilot was monitored for a certain period of time, the isolated zone was found to have a high level of pressure in the system and a pressure breaker valve was installed to implement PM. The isolated region has a single inlet point and the inlet pipe diameter is 200 mm. Here, in order to improve the operating conditions of the system, a 150 mm diameter bypass line was created from the 200 mm diameter line and the 150 mm diameter pressure control valve, which can be controlled remotely, was placed on this line. The pilot region was determined as the critical point, and the pressure limit required to prevent the subscribers from experiencing low pressure problems during maximum hours was determined. Based on field works, the system outlet pressure was initially set at 4 bar and then at the 3.1 bar level (Table 3). After the pressure breaker valve was placed, the pressure flow changes obtained from the SCADA system started to be monitored. It is known that the physical condition of the network is generally at an average level in the region.

According to field works, it is observed that the MNF measurement value has decreased to 3.29 liters per second after pressure control, and the total leakage is 3.01 liters per second after subtracting the nightly legal uses (according to the BABE equation) from this measurement value. Initially, the total leakage value was 6.67 liters per second, and after PM, the leakage reduction was calculated as 3.66 litres per second (rate of change is about 54.9%). It can be seen that despite the considerable gains achieved by the application of PM, the preventable leakage is still high. This leakage flow is thought to be caused by unreported leaks occurring in the region, especially in service connections. In order to prevent these leaks, leakage points should be found again with step-test and acoustic methods. When the FAVAD method and field data are compared, it is seen that there is a difference of 1.70 liters per second between the theoretically calculated total leakage level and the measurement results obtained from the field. This difference is particularly likely to arise from new leaks due to pressure changes. According to field data, it is observed that the total leakage level is 78.4 m^3 per day, and 38.2 m^3 for potentially recoverable leakage. When these rates are taken into consideration, it is obvious that it will provide significant gains in

Table 3 | Leakage level in the pilot region according to field data

Components	Symbol	Value	Unit
System pressure before pressure management	$AZNP0$	91	m
System pressure after pressure management	$AZNP1$	31	m
Night–Day Factor (NDF) before pressure management	NDF0	22.5	Hours/day
Night–Day Factor (NDF) after pressure management	NDF1	23.8	Hours/day
Total leakage level before pressure management	L_0	6.67	l/s
Total leakage level after pressure management	L_1	3.01	l/s
Change in total leakage level	ΔL	**3.66**	l/s
Rate of change in total leakage level	ΔL	**54.9**	%
Recoverable leak level before pressure management	Potential L_0	4.29	l/s
Recoverable leak level after pressure management	Potential L_1	2.45	l/s
Change in recoverable leakage level	ΔL(Potential)	1.84	l/s
Rate of change in recoverable leakage level	ΔL(Potential)	42.9	%
Water saved by total leakage level (daily)		78.44	m^3
Water saved by total leakage level (monthly)		2,353	m^3
Water saved by total leakage level (annual)		28,629	m^3
Water saved by recoverable leakage level (daily)		38.2	m^3
Water saved by recoverable leakage level (monthly)		1,146	m^3
Water sved by recoverable leakage level (annual)		13,948	m^3

terms of reducing energy costs especially in pumped systems. Here, it is thought that leakage levels calculated by using the theoretical equation and technically indicating the value that leakage can take, will be a reference especially for practitioners, contributing and guiding in setting targets in the field.

CONCLUSIONS

In this study, the effect of system operating pressure on water losses and MNF rate was analyzed and evaluated according to field data and the FAVAD equation. In this context, flow pressure changes were observed in the pilot isolated region and it was determined that the MNF rate was high when the regional characteristics were taken into consideration. Firstly, a step-test was applied to reduce the level of recoverable leakage in the region. Then potential leaks were detected in three sub-regions and site inspections with a ground microphone were carried out to determine the locations of the leak points in the narrowed areas. With the step-test, a potential leak in the range of approximately 8–10 l/s was detected, and five unreported leakage locations were identified and repaired at the end of the inspections made with the ground microphone. The NDF parameter was calculated as $\mathrm{NDF0} = 22.5$ hours/day according to the system conditions prior to PM and $\mathrm{NDF1} = 23$ hours/day for the conditions after PM to calculate the water volume saved at the end of PM. As a result of these studies, the MNF rate of 12.5 l/s was reduced to 6.95 l/s. In addition, 441 m^3/day and 161,130 m^3/year of water are saved in the inlet volume daily. In the second stage, pressure control was applied in the region to reduce the effect of pressure. With the pressure control in the field, the pressure value was reduced from 9.10 bar level to 3.1 bar level accordingly; the MNF rate was reduced from 6.95 l/s to 3.29 l/s. After pressure control, the daily and annual prevented leakage volume is calculated as 78.44 m^3/day and 28,629 m^3/year. A difference of approximately 1.70 l/s occurred between the values obtained from the field and the values calculated according to the FAVAD equation. This may be due to many factors such as field conditions, network features, subscriber behavior, and the presence of unknown leaks in the service connections in the system. This comparison is particularly important for practitioners in terms of implementing PM in the field, evaluating gains achieved and technically determining the level at which the leak level can be reduced.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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