Analyzing the Effect of Pressure Management on Infrastructure Leakage Index in Distribution Systems based on Field Data

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Abstract

In this study, the relationship between pressure management (PM) and infrastructure leakage index (ILI) in distribution systems was investigated based on the field data. Before PM, non-revenue water (NRW) rates were calculated as 48.44%, 76.49% and 36.57% and ILI indicators were determined as 16.97, 22.90 and 26.88, in three DMAs. The leakage volume is also calculated by the FAVAD equation and compared the field data. With the implementation of PM, although NRW ratios decreased, the ILI did not improve in the same rate. ILI class was improved in 3 regions, ILI class dropped from A to B in one region. Although the ILI class did not change in the 5 regions, the loss rates decreased. Using the ILI alone in regions where PM is used can create misleading results in performance analysis. It is thought that it would be more accurate to evaluate losses with performance indicators in PM areas.

Introduction And Theoretical Background

The most serious problem encountered in WDSs is high leakages. Based on increasing water demands and leakages and decreasing water resources, leakage reduction strategies should be developed for the continuation of sustainable water services (Liemberger et al. 2006; Vairavamoorthy 2011). The basic methods in leakage management are PM, improving the repair speed and quality, material management and active leak control (ALC) (Islam and Babel 2013; Lambert et al. 1999; Lambert and McKenzie 2002; Nicolini and Zovatto 2009; Venkatesh 2012). The repair speed and quality, ALC and material management make a significant contribution to preventing and reducing leaks. Moreover, PM makes significant contributions in reducing leakage rates in existing failures, minimizing the risk of new failures and extending the economic life of the pipe (May, 1994; Lambert et al., 1999; Farley & Trow 2003; Lambert & Fantozzi 2010; Lambert & Thornton 2012; Lambert et al. 2014; Schwaller & van Zyl 2015). Although the relationship between leakage and pressure was tested and tried in many field applications, it is mainly explained by the orifice equation (May, 1994). Liemberger and McKenzie (2005) developed the targets for the daily leakage level per connection in various pressure classes for developed and developing countries. Limit values defined for developed countries are 5 l/connection/day/ pressure, 150 l/connection/day at 20-40 meters pressure. In developing countries, two times of these values are directly targeted. (Tabesh et al. 2008) assessed leakages for different pressure levels based on the water balance and minimum night flow (MNF), the network hydraulic model and showed that leakage reduction can be achieved with PM. Nicolini and Zovatto (2009) addressed the problem of optimal pressure management in water distribution systems through the introduction and regulation of pressure reducing valves by applying the multiobjective genetic algorithms. Wegelin & McKenzie (2010) developed a PM and reduction strategy to reduce leaks in the city of Cape Town by using pressure reducing valve (PRV) and analyzed the changes in MNF rates. According to field measurements, significant reductions in MNF rates have occurred and significant gains were achieved in preventing leaks by controlling the pressure. Thornton (2011) stated that pressure zones should be created first and the most suitable PRV should be selected to obtain the expected benefits from PM in the network. Page et al. (2017) proposed the remote real-time pressure control methodology to reduce the failures, leakages and decrease the excessive consumption. Reducing pressure in a water distribution system leads to a decrease in water leakage, decreased cracks in pipes, and consumption decreases. Creaco and Walski (2017) presented an economic analysis of PM method to reduce leaks and burst reduction and applied conventional and real-time controlled PRVs. Authors emphasized that there is no need for PM in areas with low leakage levels and low operating costs. Fontana et al. (2018) applied the real-time control of pressure for leakage reduction in WDSs by regulating the pressure level as nearly constant at critical point. The results showed that pressure controller is effective in optimizing and managing the pressure over the entire WDS. Latifi et al. (2018) expressed that the number of failures, leakage rate and consumption increase in distribution systems by the effect of high pressure. It was stated that the pressure management is an effective strategy for improving the system operating condition. Monsef et al. (2018) denoted that the pressure management in urban water distribution networks is one of the options that can significantly reduce water loss. The results showed that by applying PM, the network background leakage and the energy consumption have been reduced by 41.72% and 28.4%, respectively, compared to a non-management mode. Haider et al. (2019) stated that water loss control actions, including ALC, passive leakage control, pressure management, and infrastructure asset management, are performed by the municipalities up to the service connections until the cost of these actions becomes equal to the cost of the water lost. Moslehi et al. (2019) proposed a methodology for estimating the short-run economic leakage level with respect to ALC by considering the field data.

The results revealed that the economic leakage level is significantly affected by the operating pressure and infrastructure condition. Garcia et al. (2020) examined the influence, extent, and impacts of pressure on the physical integrity of water mains. Authors reported that stronger correlations between two variables, which reflects the role of pressure on increased failure rates Areas with a consistently high failure rates.

As can be seen, benefits such as reduction of existing leaks and failures are obtained from PM. However, significant costs such as room construction, device and equipment selection and placement, and automation system are incurred (Charalambous and Kanellopoulou 2010). Therefore, cost-benefit analysis should be done by considering the data obtained by analyzing the cost components (Kanakoudis and Gonelas 2014). The physical, operational and environmental factors are effective in the occurrence of new leakages in WDSs (Farley et al. 2008). Pressure can be at high levels depending on the topographic conditions and the location of the water tanks. In such cases, PM is applied to regulate the pressure and reduce fluctuations (Creaco and Walski 2017; Farley et al. 2008; Lambert and Mckenzie 2001; Tabesh et al. 2011). Pressure management is becoming an important technique for reducing leakages in the water networks (Gupta and Kulat, 2018). Moreover, PM provides significant contributions such as decreasing the risk of new failures and extending the economic life of the pipe (Lambert et al. 1999; Creaco & Walski 2017). May (1994) proposed the Fixed and Varied Area Discharge (FAVAD) method (equation 1), which describes the relationship between leakage and pressure for pipes of different diameters and conditions. The parameters of the power equation are not constant but vary with pressure, which is a problem especially for water distribution pipe networks where pressure varies with time, for example, due to diurnal demand variation. An empirical power equation (N1) is widely used to model the pressure–leakage relationship in practice (Kabaasha et al., 2020).

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

L_0: Leakage at pressure P_0, L_1 : Leakage at regulated pressure P_1, P_0 is : average pressure, P_1: average pressure regulated in the zone. N_1 is the leakage exponent (ranges between 0.5 and 1.5). This exponent is directly related to the analysis of the effect of pressure change in the system on leakage. N1 coefficient should be determined according to the weighted pipe type of the network in the studies examined in order to define the relationship (Lambert 2001, Salinas-Vazquez et al. 2006, Mora-Rodríguez et al. 2014). In the case of pipes with flexible material (PVC and PE) in a WDS, the N1 coefficient is defined between 1 and 1.5 (for varied area leakages). In these pipes, the crack expands with the effect of pressure and the amount of water lost per unit time increases. Similarly, as the crack will narrow more by decreasing the pressure, the leakage will decrease more. On the other hand, in distribution systems with pipes with hard material, the N1 is determined between 0.5 and 1 (for fixed area leakages). In these systems, there will be no change (expansion or contraction) in the crack due to the pressure change. It has been suggested that the N1 will be taken as 1 in systems with unknown pipe material type or with mixed materials (Lambert and Thornton 2012). Considering the main line and service connections in the pilot areas, mixed pipe material is available in DMA1 (mostly Cast type), DMA5 (predominantly Steel) and DMA6 (predominantly Cast type). Therefore, N1 coefficient was chosen as 1 in these regions.

The effect of pressure change on leakage has been explained in detail in the literature. However, in the implementation of PM, there are many cost items such as field manufacturing, device supply, labor and data transfer. Therefore, it is very important for efficiency to calculate the expected benefits correctly and evaluate the leakage level according to the correct indicators before applying PM. In the following sections, the effect of PM on leakage and performance change has been analyzed based on real field data.

The most appropriate performance analysis should be carried out to test the effectiveness of leakage prevention methods and monitor efficiency by using applicable indicators (Lambert et al. 1999; Liemberger et al. 2006). The indicators based on the percentage of system input volume, network length and number of service connections is used (Lambert 2002; Lambert et al. 1999). However, these indicators do not consider the pressure or network physical known effects on leakage. The NRW rate (although the leakage volume remains constant) changes depending on the regular measurement of the inlet volume and authorized consumptions. Therefore, using an indicator that considers the data representing the system and operating conditions will provide a more accurate assessment. Lambert (1997) emphasized the need for a performance indicator that will allow the network to be evaluated according to many variables and to be compared at an international level. Moreover, the ILI which is the ratio of "Current Annual Real Losses (CARL)" and " Unavoidable Annual Real Losses (UARL)", is frequently used indicator for evaluating performance and comparing systems (equation 2) (Lambert et al. 1999). UARL (liter/day) representing the technically lowest leakage level in a system, is calculated by equation (3) (Lambert et al. 1999). UARL is sensitive to system operating pressure and network characteristics and is directly affected by changes in pressure.

$$ILI = {}^{CARL}/_{UARL} \quad (2)$$

$$UARL = \left(18 * L_m + 0.8 * N_c + 25 * L_p\right) * P \quad (3)$$

P: the average pressure (m), Lm: the main length (km), Nc: the number of the service connection, Lp: the length of service connection on private property (km).

Since UARL considers the physical and operational data of the system, the ILI offers a more objective evaluation than other indicators (Lambert and McKenzie 2002; Liemberger et al. 2007). The ILI shows how much leakage is present in a system than the lowest technically possible leak. Because of its ability to represent the system better, ILI was considered in this study for the analysis of performance change due to PM. Limit values were proposed to evaluate ILI results and to compare the current state of the system (Lambert et al. 1999; Lambert and McKenzie 2002).

ILI is known to make a significant contribution to monitoring the effects of methods (improving pipe material, failure repair speed and quality, reducing leaks) (McKenzie and Seago 2005). To reduce the failures and leaks, the WDS should be analyzed in detail, the most appropriate prevention and monitoring methods should be used, and system performance should be monitored with ILI and UARL indicators. One of the important points here is that ILI calculates without considering any economic condition. This indicates that it may cause uneconomic consequences, especially if only ILI is taken into account in defining leakage targets. Moreover, a decrease in ILI may not always be observed depending on PM since the PM has an effect on reducing UARL and CARL values (Liemberger et al. 2007). Especially in systems where NRW rates are relatively low, it provides significant benefits in determining which of the active leakage methods give more effective results (Darsana and Varija 2018). The ILI is a performance indicator quantifying how effectively a water utility controls the level of real loss by implementing leakage control measures like PLC, asset management, and ALC at the current operating pressure (Moslehi et al., 2019). Klosok-Bazan et al. (2021) stated that ILI accommodates the fact that real losses will always exists, even in the very best and well managed system. As the current pressure regime may not be optimal, ILI should always be interpreted with some measure of pressure and only used for tracking progress if all justifiable pressure management has already been completed. Especially in systems where PM is applied, an indicator that provides objective evaluation of the change in system performance should be used. For this reason, ILI indicator should be analyzed according to field data in PM applied systems. That is, the applicability of these indicators alone in PM should be tested according to field data. Thus, it will be possible to evaluate the PM performance more accurately in leakage management. In this study, the relationship between PM and ILI in WDSs was investigated and the effectiveness of ILI in monitoring system performance was analyzed. For this purpose, PM was applied in 3 pilot areas in the application area, process indicators and ILI were calculated based on field data in conditions before and after PM to analyze the effect of PM on the ILI. In this way, the positive or negative effect of the decrease in leakage on the ILI due to PM was evaluated. Moreover, a total of 6 DMAs where PM is not applied were selected and possible changes in ILI and other indicators in case of PM application in these regions were analyzed. Thus, reference information was generated in testing the applicability of PM by analyzing possible benefits before applying PM. In addition, the effect of the selection of the N1 according to different pipe material types in the FAVAD equation, which reveals the effect of PM on leaks, on the results was also analyzed and discussed.

Study Area And Data

In this study, Malatya (Turkey) WDS with length of approximately 2,000 km network and number of customers 350000 was chosen for field applications (MASKI, 2020). ALC activities DMA design were carried out between years 2016–2020 and water balance, flow pressure monitoring and MNF monitoring are performed in DMAs. A total of 9 DMAs were taken into consideration and the areas with and without PM were determined (Fig. 1, Table 1). The network lengths, customer densities, water production / operation costs and water loss amounts differ were selected. Inlet flow rates are regularly measured and monitored instantly with the SCADA system in DMAs. Network length, number of customers, service connection length and total consumption were determined for each region by using customer management and GIS databases. The average pressure of the system was obtained by measuring with pressure gauges placed in each isolated area at the average zone point. Since all isolated zones are integrated into the SCADA system, instantaneous pressure changes are monitored. Monthly data were taken into account in establishing the water balance in isolated regions.

Table 1
Characteristic data of pressure management areas

Parameters	Unit	DMA1	DMA2	DMA3	DMA4	DMA5	DMA6	DMA7	DMA8	DMA9
Main length	m	15533	27850	9700	4780	5800	13480	12800	15620	13200
Number of customers	No.	4663	2270	2872	1046	3391	7032	2895	4208	1514
Number of service connections	No.	1160	1751	510	315	500	1386	427	526	689
Average service connections length	m	8	8	8	8	7.8	7.04	7.98	7.83	8.24
Billed metered consumption	l/s	24.45	11.61	23.14	7.89	15.21	32.45	13.15	3.82	8.22
Average Pipe Type	-	Cast	PVC	HDPE	Asbestos	Steel	Cast	PVC	HDPE	Asbestos
N1	-	1	1.5	2	0.5	1	1	1.5	2	0.5
Before Pressure Management										
Average pressure	m	65	50.8	50.1	45	38	55	60	51	50
Average input volume	l/s	47.42	49.39	36.48	12.93	30.76	36.48	17.82	13.52	10.88
Non-revenue water volume	l/s	22.97	37.78	13.34	5.04	15.56	4.03	4.68	9.70	2.66
Non-revenue water rate	%	48.44%	76.49%	36.57%	38.98%	50.56%	11.05%	26.23%	71.75%	24.47%
Real loss volume (CARL)	l/s	18.376	30.224	10.672	4.03	12.44	3.22	3.74	7.76	2.13
UARL	l/s	1.08	1.32	0.40	0.21	0.26	1.02	0.46	0.47	0.54
ILI	-	16.97	22.90	26.88	19.20	46.99	3.18	8.20	16.56	3.97
ILI	-	D	D	D	D	D	A	C	D	A
After Pressure Management										
Average pressure	m	36	40	40	30	25	30	30	20	30
Non-revenue water volume (Calculated)	l/s	12.72	26.4	8.5	4.12	10.23	2.2	1.65	1.49	2.06
Non-revenue water volume (measured)	l/s	12.5	27.65	5.07	12.01	25.44	34.65	14.80	5.31	10.28
New Average input volume	l/s	36.95	39.26	28.21	12.01	25.44	34.65	14.80	5.31	10.28

Parameters	Unit	DMA1	DMA2	DMA3	DMA4	DMA5	DMA6	DMA7	DMA8	DMA9
Non-revenue water volume	l/s	12.5	27.65	5.07	4.12	10.23	2.2	1.65	1.49	2.06
Non-revenue water rate	%	33.83%	70.43%	17.97%	34.30%	40.21%	6.35%	11.15%	28.06%	20.04%
Real loss volume (CARL)	l/s	10	22.12	4.056	3.29	8.18	1.76	1.32	1.19	1.65
UARL	l/s	0.60	1.04	0.32	0.14	0.17	0.55	0.23	0.18	0.32
ILI	-	16.67	21.27	12.80	23.54	46.99	3.18	5.78	6.49	5.12
ILI	-	D	D	C	D	D	A	B	B	B
Change in flow	l/s	10.47	10.13	8.27	-0.92	-5.33	-1.83	-3.03	-8.21	-0.60
Change in flow	%	22.08%	20.51%	22.67%	-7.12%	-17.31%	-5.02%	-16.98%	-60.72%	-5.53%

Analysis And Discussion

Field Application of PM

PM was applied in the field by using PRV in DMA1, DMA2 and DMA3. First of all, the current situation assessment was made for all regions based on field data. The possible leakage level according to PM is calculated with the FAVAD equation based on the network and operational data of each region. The changes in the ILI were analyzed using the real data obtained by the applying PM in the field and the leaks calculated according to the FAVAD equation.

The different types of PRVs that are "fixed output" and "time adjusted and flow sensitive", have been used to increase system efficiency in WDSs (Vicente et al. 2016). Flow sensitive PRV adjusts the output pressure according to the flow demand (Berardi et al. 2015; Creaco et al. 2019). In this study, the necessary data was obtained by using the SCADA and customer management systems. Data of the network length, number of the service connections, average length of service connection on private property and average pipe type in DMAs were obtained by using GIS database. In addition, pressure management was implemented by placing pressure control valves at the inlets of the isolated zone. Inlet flow rates and pressure data in each isolated zone are regularly measured and monitored with a SCADA system. In this study, fixed output PRV for DMA1, and flow sensitive PRV for DMA2 and DMA3 are used. Flow rates and pressures occurring before and after PM in DMA are monitored by SCADA (Fig. 2).

Before applying PM in DMA1, the inlet flow was measured as 47.2 l/s and the pressure was 65 m (Fig. 2). Considering the leakage-pressure relationship, the high pressure in the region is expected to cause new leakages or increase in leakages in existing failures. In DMA2, the initial pressure was 51 m and the inlet flow rate was about 50 l/s. Finally, the pressure was 50 m and the inlet flow rate was 36.48 l/s before PM in DMA3. Although the pressure in DMA2 and DMA3 is lower than DMA1, the possible effects of pressure on leakage/failure should be monitored. PM was applied in DMAs to reduce the effect of pressure on existing and new leakage. As a result of field measurements, NRW rate, UARL, CARL and ILI were calculated for three regions before and after PM.

NRW rates in DMAs before PM were calculated as 48.44%, 76.49% and 36.57%, respectively. It is seen that these rates are higher than the limit values (> 25%) recommended in the international literature. As it is known, it is not enough to evaluate the NRW percentage alone, so UARL and ILI were calculated for each region. The ILI in DMA1, DMA2 and DMA3 were determined as 16.97 (D), 22.90 (D) and 26.88 (D), respectively. It can be said that the NRW rates and ILI classes in each region are at a very poor level. For this reason, it seems that the system should be intervened in order to reduce leakage and improve system performance in the regions. With PM, the pressures were reduced from 65 m to 36 m in DMA1, from 50.8 m to 40 m in DMA2 and from 50.1 m to 40 m in DMA3 (Fig. 3). ILI changes in the regions where PM is applied are shown in Fig. 3.

Although there were significant reductions in NRW rates (average 21.75%), the ILI did not improve at the same rate. In DMA1, although a gain of approximately 10.47 l/s (22.08%) is obtained in the input flow by reducing the pressure from 65 m to 36 m, the ILI has decreased from 16.97 to 16.67. Similarly, in DMA2, the loss of 10.13 l/s (20.51%) was reduced by reducing the pressure from 50.8 m to 40 m, but the ILI decreased from only 22.9 to 21.27. Regulations in pressure similarly change the UARL value as the pipe type is rigid in this region. Therefore, due to the decrease in the values of the CARL and UARL, no significant improvement was observed in the ILI. In DMA3, pressure variations cause significant decreases in CARL value due to the flexible material of the network pipe. In parallel with this decrease, a significant change was observed in the ILI in this region. NRW rates were reduced from 36.57–17.97% by reducing the pressure from 50.1 m to 40 m in this region.

Berardi et al. (2015) analyzed that how hydraulic models are relevant to support pressure control strategies at both planning and operation stages on the real WDN. Moreover, the effectiveness and changes of the ILI indicator was presented for tracking progresses in leakage management. The results demonstrated that using the ILI to assess the leakage reduction achievements is not consistent with the expected hydraulic WDN behavior. Consequently, the use of ILI for regulation purposes in the WDN sector would be misleading without the support of appropriate hydraulic modelling. In more detail, the analysis reported herein shows that, depending on the current leakage rate and pressure control scheme, the ILI might be invariant or even increase in the face of a large reduction of leakage volume from the controlled network.

As a result of this decrease in NRW value, the ILI has decreased from 26.88 (D) to 12.80 (C) (Fig. 3). As can be seen, the type of pipe material affects the NRW ratio and the ILI in the region where the PM was applied. Especially in areas with flexible materials, the crack narrows due to the decrease in pressure and the leakage rate and total leakage volume per unit time decrease. It was determined that these decreases in leakage due to PM in regions with flexible material density are reflected in the ILI.

Depending on the PM, the possible leakage volume is calculated according to the FAVAD equation in case the pressure is reduced to the desired level. The evaluation was made by comparing the field data and the results of the FAVAD approach (Table 1). The N1 was selected according to the pipe material in DMA. Considering the main line and service connections in the pilot areas, mixed pipe material is available in DMA1 (mostly Cast type), DMA5 (predominantly Steel) and DMA6 (predominantly Cast). Therefore, N1 was chosen as 1 in these regions (Table 1). The N1 was chosen as 1.5 for DMA2 (PVC) and for DMA3 (HDPE) the coefficient was determined as 2. It is seen that the loss levels calculated according to the FAVAD equation depending on the PM in DMAs are very close to the loss levels measured in the field (Table 1). Considering the effect of the N1 on the FAVAD equation, it is very important to choose the most appropriate N1 value for the pipe type in the region. For this reason, it is thought that the gain to be obtained by using the relevant equation and N1 for the regions where PM is planned can be calculated in a way that is very close to the reality by knowing the weighted pipe type of the network exactly.

Application Of Favad Approach To Other Dmas

In the previous section, it was determined that the leakage rates calculated with the FAVAD equation in DMAs are compatible with the field data. For this reason, in the second stage, 6 DMAs without PM were selected. The results obtained in case of applying PM in these regions were evaluated and possible benefits (leakage reduction, ILI change) were estimated. For this purpose, the characteristic data of the regions were collected and, the GGS volume and ratio, UARL, CARL and ILI were calculated.

The NRW rates in DMAs under current conditions vary between 11.05% (DMA6) and 71.75% (DMA8). In the current situation, DMA6 is at a very good level, and the rates in DMA7 and DMA9 are at an acceptable level. Based on ILI classification, DMA 6 and DMA9 are in class A, DMA7 is in class C (DMA7) and DMA 4, DMA 5 and DMA8 are in class D. When the NRW rates and ILI in DMAs are compared, the NRW rates in the A-class regions are generally lower than 25%. However, in DMA7 and DMA9, although leakage and NRW volumes are very close to each other, the ILI is 8.20 (C) in DMA7 and 3.97 (A) in DMA9. As can be seen, although the leakage volumes are close to each other, the differences in the inlet volumes proportionally ensure that the performance of the system is good or bad.

In the second stage, the changes in leakage and ILI in case of PM were analyzed (Fig. 3). The leakage can be reduced between 0.6 l/s (DMA9) and 8.21 l/s (DMA8) in 6 regions. The gain flow rate to be obtained is directly related to the weighted pipe type of the network as well as the pressure change. In DMA4 and DMA5 where pressure reduction rates are very close to each other, significant decreases in leaks (7.12–17.31%) are expected depending on the pipe material.

On the other hand, NRW rates in DMA6, DMA7 and DMA9 are at relatively acceptable levels (11.05%, 26.23% and 24.47%), while ILI indicators are at good and intermediate levels (A, C and A). Although these areas are not considered as the priority area in theoretical intervention, they are very suitable for PM due to high pressures. It was observed that serious gains will be achieved by pulling the pressure to ideal levels. Useful flow rates will be added to the system by applying PM. The expected changes in ILI and NRW by adding these beneficial flow rates to the system are shown in Fig. 3.

When the possible changes in the NRW rates are examined, a decrease is expected in all DMAs. It is seen that there will be a serious decrease in the GGS ratio in regions where the current loss rate and pressure change is high (DMA8). Especially in DMAs where N1 is greater than 1, the change reaches serious levels compared to other regions (DMA7 and DMA8). The main reason for this is that elastic pipes are highly sensitive to pressure. In flexible pipes, it is thought that the crack diameter will expand more than rigid pipes with high pressures. In regions with more rigid pipe types (DMA4 and DMA9), the changes in losses due to pressure remain at a lower level.

Moreover, the reduction of the NRW rate depending on the pressure was also examined with the ILI and quite important results were obtained. The decrease in NRW rates with the reduction of pressure does not always cause a positive change in the ILI. As a result of PM, leakage rates prevented in DMA4 and DMA9 are 0.92 l/s and 0.60 l/s, respectively. Moreover, the decrease in NRW rates is about 4% (38.98–34.30% and 24.47–20.04%). However, although the NRW rates decreased, an increase was observed in the ILI indicator. In DMA4, the initial ILI was 19.20 (D), while it was calculated as 23.54 (D) at the end of the PM. Similarly, in DMA6, the ILI increased from 3.97 (A) to 5.12 (B). The main reason for this is that the pressure variable affects differently depending on the N1 in the calculation of FAVAD and UARL.

When the UARL used in ILI analysis is examined, the pressure is a direct factor and the change in pressure will change the ILI linearly. However, the N1 is used as the exponent of the pressure change in the FAVAD equation. The new leakage amount will change in a nonlinear way according to the value of the N1. In DMA4 and DMA9 where there are rigid pipes in the network, the UARL and ILI decreases and increases at the same rate with the rate of change in pressure. However, in DMAs, the leakage will be affected by the N1 (0.5) of the change in pressure. As a result, pressure variation in these regions can have a negative effect on ILI, although it causes a decrease in leakage volume. Likewise, since the N1 is selected as 1 in DMA5 and DMA6, the change in pressure affects ILI and NRW at the same rate, even though the flow rate has benefited in these regions, ILI will not change or will be affected very little (Fig. 3). As a result, ILI class was improved in 3 regions (DMA3: D > C, DMA7: C > B, DMA8: D > B), in one region (DMA9) ILI class dropped from A to B. Although the ILI class did not change in the other 5 regions, it was observed that the loss rates decreased. For this reason, using the ILI alone in the regions where PM is used can create misleading results in performance analysis. It is thought that it would be more accurate to evaluate losses with performance indicators in PM areas.

In this study, the benefits and ILI changes to be obtained in case of different pipe types in the isolated zone were also calculated (Table 2). For this purpose, an application has been carried out for the cases of different pipe material in DMA 8. Although DMA 8 consists entirely of HDPE pipes under current conditions (N1 = 2), the change in losses was calculated in the case of asbestos, steel and PVC pipes respectively (N1 = 0.5, 1.0, 1.5). In this context, if the current pressure level is reduced from 51 meters to 20 meters, the rate of NRW decreases from 71.75–28.06% under current conditions. Moreover, according to the initial value, it has been calculated that a significant reduction will be achieved by decreasing the ILI parameter from 16.56 to 6.49. If the same region consists of asbestos pipes, it is expected that there will be a 10% reduction in NRW ratio, while it is seen that the ILI parameter will increase from 16.56 to 26.43. Similarly, if the line consists of steel pipes, although a 22% decrease is predicted in NRW, it is seen that the ILI parameter does not change (16.56 - Class D). As can be understood from the examples, the network pipe type has a quite important place in pressure management. It is seen that more benefits can be obtained in flexible pipes compared to rigid pipes. In addition, it has been observed that if the N1 is chosen 1 or less than 1, the ILI parameter may be insufficient to evaluate the performance of the pressure management application. As a result, although losses in the network have been reduced by pressure management, the ILI indicator may remain stable or increase.

Table 2
Analysis of the impact of pipe material type on pressure management performance

Parameters	**Unit**	**DMA8**	**DMA8**	**DMA8**	**DMA8**
Main length	m	15620	15620	15620	15620
Number of customers	No.	4208	4208	4208	4208
Number of service connections	No.	526	526	526	526
Average service connections length	m	7.83	7.83	7.83	7.83
Billed metered consumption	l/s	3.82	3.82	3.82	3.82
Average Pipe Type	-	HDPE	Asbestos	Steel	PVC
N1	-	2	0.5	1	1.5
Average pressure	m	51	51	51	51
Average input volume	l/s	13.52	13.52	13.52	13.52
Non-revenue water volume	l/s	9.70	9.70	9.70	9.70
Non-revenue water rate	%	71.75%	71.75%	71.75%	71.75%
Real loss volume (CARL)	l/s	7.76	7.76	7.76	7.76
UARL	l/s	0.47	0.47	0.47	0.47
ILI	-	16.56	16.56	16.56	16.56
ILI	-	D	D	D	D
Average pressure	m	20	20	20	20
Non-revenue water volume (Calculated)	l/s	1.49	6.07	3.8	2.38
New Average input volume	l/s	5.31	9.89	7.62	6.20
Non-revenue water volume	l/s	1.49	6.07	3.8	2.38
Non-revenue water rate	%	28.06%	61.38%	49.87%	38.39%
Real loss volume (CARL)	l/s	1.19	4.86	3.04	1.904
UARL	l/s	0.18	0.18	0.18	0.18
ILI	-	6.49	26.43	16.56	10.36
ILI	-	B	D	D	C
Change in flow	l/s	-8.21	-3.63	-5.90	-7.32
Change in flow	%	-60.72%	-26.85%	-43.64%	-54.14%

As it is known, the ILI performance indicator offers significant benefits in terms of evaluating the initial performance of WDSs and comparing them with other networks. The current performances of the networks are calculated with basic data such as main length, number of service connection, and length of the service connection on private property and pressure, which provides serious insight into the loss status of the network. For this reason, the ILI indicator provides a significant advantage in determining the priority region where water losses should be intervened primarily. In addition, the performance of leakage reduction methods that are acoustic listening method, fault repair management and network rehabilitation can be monitored with the ILI indicator. In pressure management, it can be used to evaluate the performance of the ILI method in cases where the N1 is selected greater than 1 (if the line is mainly composed of flexible pipes).

Conclusions

In this study, the relationship between PM and the ILI in WDS was analyzed and the effectiveness of the ILI in monitoring system performance was investigated. Before PM, NRW rates were calculated as 48.44%, 76.49% and 36.57%, respectively, and ILI indicators were determined as 16.97 (D), 22.90 (D) and 26.88 (D), in DMA1, DMA2 and DMA3, respectively. With the implementation of PM in these regions, the ILI did not improve in the same proportion, although NRW rates decreased (average 21.75%). In DMA1, although a gain of approximately 10.47 l/s (22.08%) was obtained in the input flow, the ILI value just decreased from 16.97 to 16.67. The loss of 10.13 l/s (20.51%) was reduced in DMA2, however the ILI value decreased from only 22.9 to 21.27. In this region, no significant improvement was observed in the ILI indicator due to the decrease in the CARL and UARL parameters as a result of the change in pressure, as the predominant pipe type is rigid pipes. In DMA3 with flexible pipe material, NRW decreased from 36.57–17.97% and ILI improved from 26.88 (D) to 12.80 (C). Moreover, possible benefits are calculated if PM is applied in 6 isolated zones where PM is not applied. It was observed that leakage can be reduced between 0.6 l/s (DMA9) and 8.21 l/s (DMA8) with PM in DMAs. In DMA4 and DMA9, there was a decrease in GGS rates (from 38.98–34.30% and from 24.47–20.04%). However, in DMA4, the initial ILI was 19.20 (D), while it was calculated as 23.54 (D) at the end of PM. In DMA6, the ILI value increased from 3.97 (A) to 5.12 (B). As a result, the ILI parameter, which has a very important place in performance analysis using PM, is insufficient to evaluate the performance of PM alone. For this reason, it is thought that the system should be evaluated with various performance indicators together with ILI in PM studies.

Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material (The authors confirm that the data supporting the findings of this study could be requested from the corresponding author, upon reasonable request**)**

Code availability

In this study custom code was used.

Ethics approval (Not Applicable)

Consent to participate

All authors agreed with the content and that all gave explicit consent to submit.

Consent for publication

All authors agreed with the content and that all gave explicit consent to publish.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Salih YILMAZ], [Mahmut FIRAT], [Abdullah ATEŞ] and [Özgür ÖZDEMİR]. The first draft of the manuscript was written by all authors and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

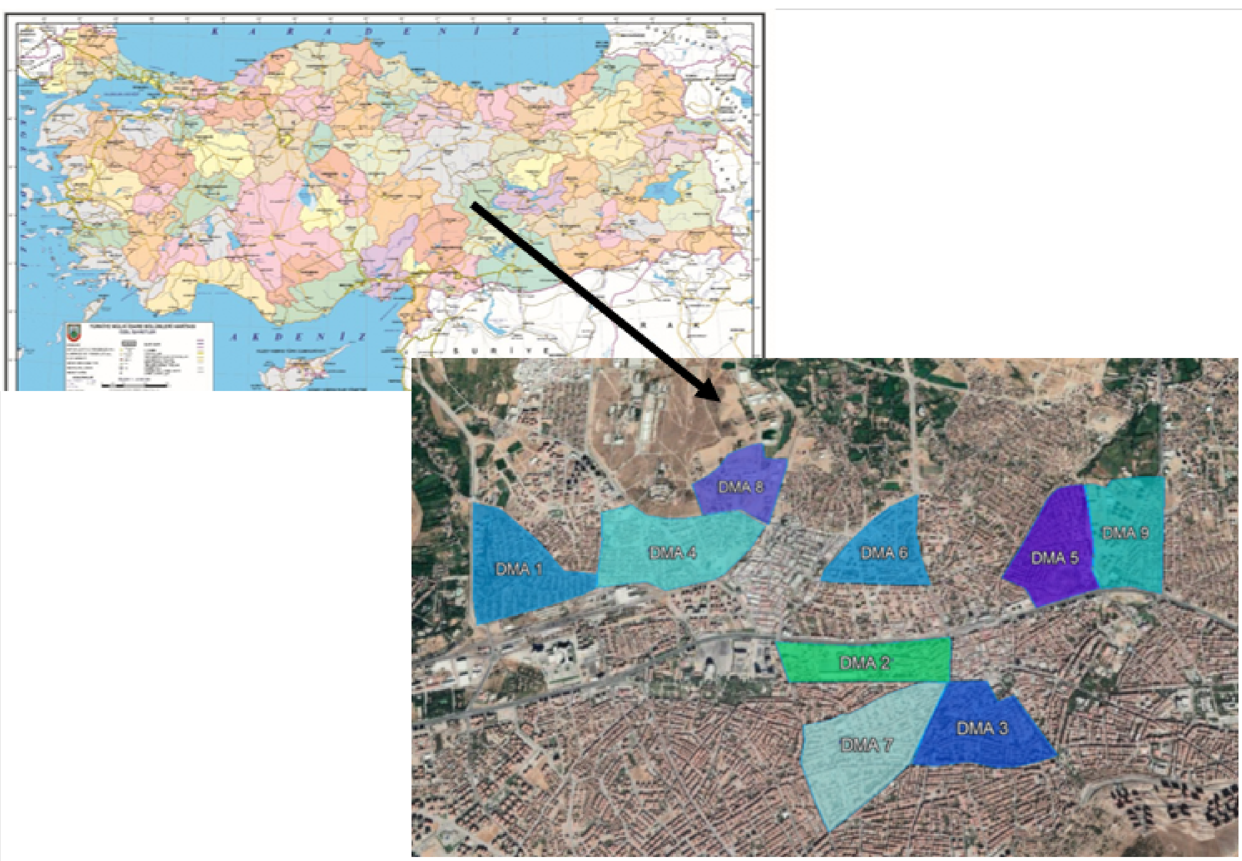
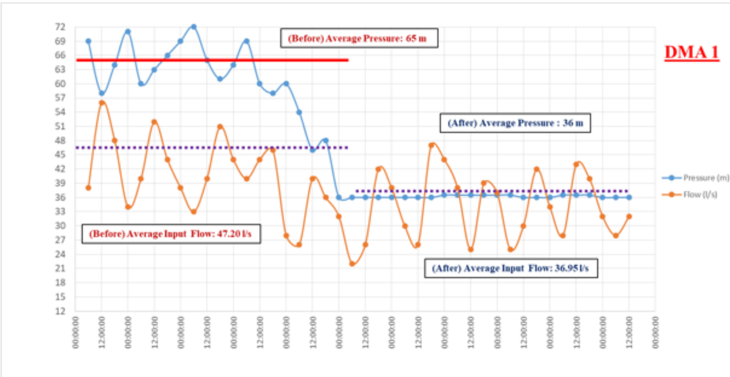
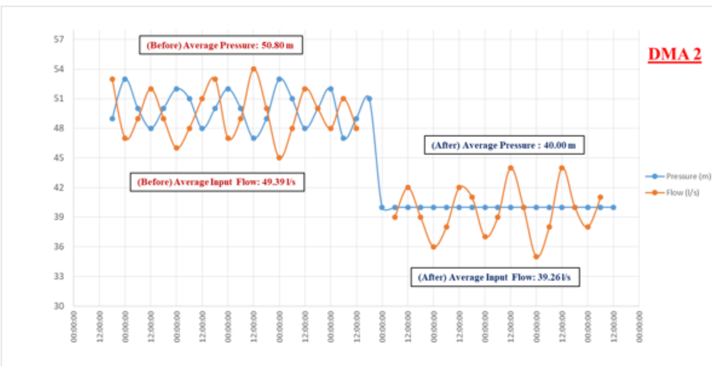


Figure 1

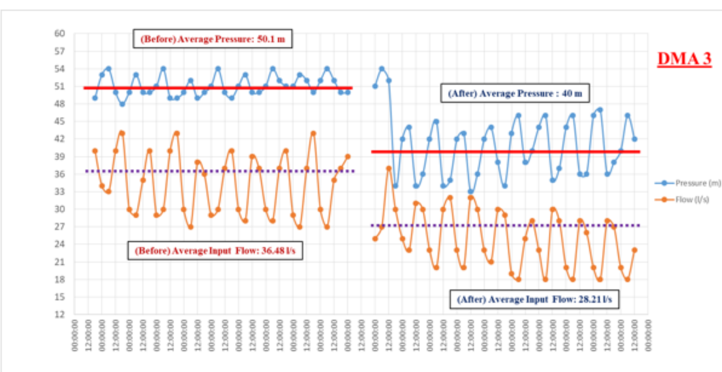
General view of the study area and isolated areas (Source: https://www.harita.gov.tr/urun/map-of-turkeys-administrative-boundries/266)



a) DMA1



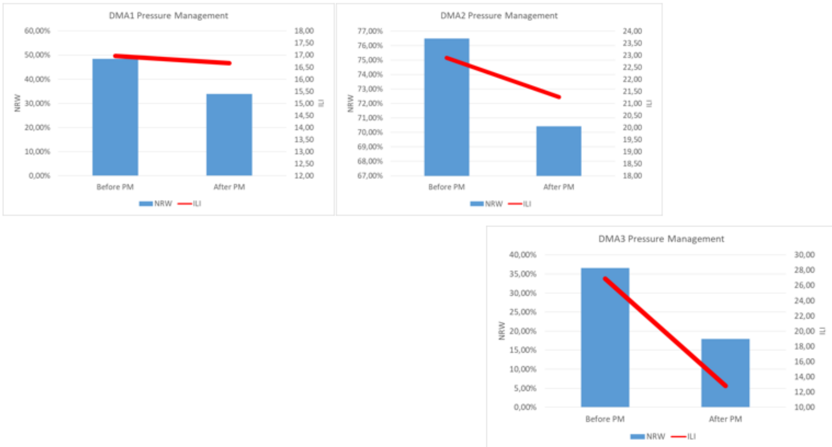
b) DMA2



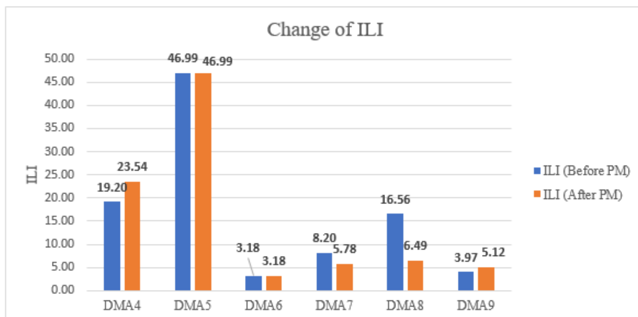
c) DMA3

Figure 2

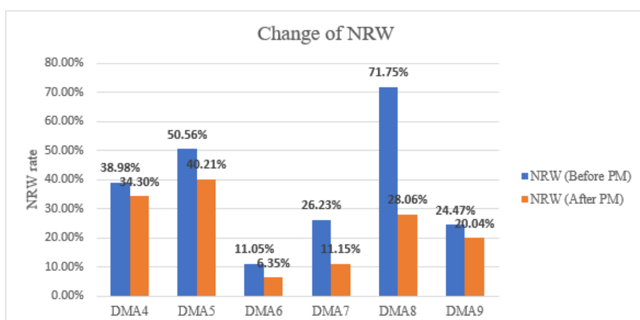
Flow-pressure graphs in isolated areas



a) ILI and NRW changes in PM applied areas



b)ILI changes in 6 pilot regions



c)NRW changes in 6 pilot regions

Figure 3

Effects of Pressure on ILI and NRW in pilot areas