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Review Article

DISTRICT METERED AREAS FOR WATER LOSS MANAGEMENT IN DISTRIBUTION SYSTEMS

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ABSTRACT

Reducing and managing the leaks and identifying the most appropriate strategy could be seen as the most fundamental problem for water administrations. The aim of this study is to discuss the importance of DMA for the management, reduction and control of water losses based on the system components and to evaluate the advantages of the DMA and the expected benefits. The answer to the question of *"Why is DMA necessary in water management?"* has been investigated based on the results emphasized from the literature studies and the field application. It may be emphasized that DMA could be an important tool in terms of accurate and sustainable measurement of data required for monitoring the system performance. It could be said that DMA is necessary to provide customer management, to recognize, detect the unreported leaks, to determine the most appropriate pressure management and to define the most appropriate strategy in water management.
Keywords: Non-revenue water, water loss management, DMA, leakage detection.

1. INTRODUCTION

Non-revenue water (NRW) could be explained as "water that entered the system however not billed [1,2]. The most important component of this NRW is the leakages occurring based on reported or unreported failures in the system [2]. In the water distribution systems (WDSs) where rates of the pipes that old and completed the economic life are high, the leakages are generally high, which increases the operating cost of the system. In general, the following problems arise in such systems; (i) delaying the transmission of water to the customers in time, (ii) inefficiency use of water and energy resources, (iii) increasing the cost of the network maintenance and repairs, (iv) increasing the replacement cost of pipes in local and/or street, (v) non-economic operating conditions. For this reason, it is important to determine the location and amount of unreported leakages, to analyze the main factors that cause leakage and to reduce their impact, to prevent apparent losses in the system, and to determine the most appropriate network operation strategies. In particular, in big WDS where pipe length or customer numbers are high, the planning and implementation of water loss management strategies throughout the system in order to reduce the failure rate and water losses simultaneously results in time-consuming and expensive results.

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Considering the problems experienced in this type of WDS, instead of evaluating the whole system at the same time as a whole and taking it into consideration, dividing it into smaller and manageable systems will make a significant contribution to reaching the result in a shorter time. Therefore, in order to provide a more effective strategy in water loss management and to manage the system better, it is thought that the dividing the system into smaller and measurable sub-regions (District Metered Area, DMA), separate evaluation of flow rate, number of customers, consumptions, water thief and leakages in each system will provide an important advantage. The main purpose of this study can be given as; (i) detailed discussion of the importance of DMA planning and creation in urban water management for identification, reduction, prevention and control of water losses, (ii) the advantages of creating DMA, expected benefits, analysis and evaluation of design criteria, (iii) DMA planning, implementation and discussion of the benefits and benefits obtained from real field applications in study area.

2. DISTRICT METERED AREA

The DMA can be expressed as a system whose boundaries are defined, isolated from other networks, with single or multiple inputs [2,3]. In the DMA approach, the entry flow rate of the system, the network pipeline and its components, customers in the system, authorized billed, authorized-unauthorized unbilled consumptions, reported and unreported leakages, customer water management etc. are evaluated separately in each system. However, due to the highly complex and uncontrollable nature of the system, significant operational problems are experienced and in many cases it is not possible to develop and implement the same solution methodology for the overall system. The basic problems in WDS with complex structure can be given as;

- Differences in pressure strength of pipes constructed at different times depending on environmental and operating factors,
- The location of the valves and the areas where the feed regions are not known clearly, implementation of a region-based water interruption strategy for maintenance and repair,
- The data to be used in analyzing the system performance and in determining the most appropriate water loss management strategy and the data representing the system cannot be obtained in a correct, sustainable manner,
- Difficulties in the implementation of the same method for the overall system in reducing and controlling the failure rates and water losses
- Problems in correct implementation of water loss detection, prevention, mitigation and control methods and difficulties in achieving expected benefits.

For this reason, it could be said that the DMA approach will provide significant contributions and advantages in order to minimize the problems mentioned above in water loss management and to present an effective strategy [4, 5]. However, the design and implementation of the DMA covers not only highly detailed planning, but also important stages of installation and equipment which can be costly. Therefore, it is necessary to determine the target in the DMA design, to analyze whether it is necessary, to take into account the technical and personnel conditions and to be applicable in the field.

In addition, before DMA planning is carried out, it is important to find answers to the following questions in terms of efficient use of resources;

- Is DMA needed?
- What are the expected benefits of DMA?
- What are the DMA design criteria?
- What are planning, project planning and fieldwork to create DMA?

2.1. Why is DMA required in Water Loss Management?

It is thought that the DMA will make important contributions to reduce the problems mentioned in the previous sections, to ensure customer satisfaction, to increase system efficiency and to reduce costs. The reasons why DMA is needed in effective and sustainable water loss management, advantages and expected benefits are listed as follows [2, 3,6,7,8];

- Establishing an observable and controllable system whose boundaries are clearly defined and isolated from other networks
- Measuring, monitoring, controlling and conducting the current condition analysis of all physical, hydraulic, environmental and structural components in each DMA
- Filling the standard water balance table more correct and effectively with the measured data to monitor system performance regularly
- Identifying and monitoring the input flow and volume with single or multiple entry point defined, determining the volume entering the system at the least consumption time
- Determining the number, type and consumption characteristics of the customers, correlating with the night flow rate and performing the loss analysis,
- Analyzing the current situation of the customer water meters in the region, planning the meter renewal programs, reducing the apparent losses caused by the meter errors,
- Determining and preventing potential leakages by monitoring the night flow rate,
- Instantaneous flow and pressure measurement, monitoring of changes, performing leakage analysis,
- Implementation of a more effective pressure control management strategy in such systems, as the topographic conditions are taken into account in DMA,
- Determining the weaknesses and strengths of each DMA, development and implementation of the most appropriate strategy for improvement

In literature, DMA design, establishment and implementation of optimization based models, reduction, controlling, determining and evaluating the water losses, and monitoring the system performance, implementation of the most appropriate pressure management strategy, estimation of leak location and amount, reduction and management of apparent losses, application of active leakage control have been carried out (Table 1). In the light of the results of these studies conducted in the network and water loss management and the results obtained from the pilot study area, the above mentioned benefits are discussed and detailed in the following sections.

Table 1. Studies related to the DMA application or design

Aim	Reference	Design (D) Application (A)	NRW, Reduction, Detection, Estimation, Control, Operation	Method used in Design
Pressure management	Nazif et al. [30]	A	R	
	Karadirek et al. [42]	A	HM, C	
	Wu et al. [43]	D, A	D,R	GA
	Wu et al. [44]	A	C	
	Xu et al. [28]	A	R	
	Babic et al. (2014)	A	C, R	
	Gomes et al. [38]	A	WD	
	Kanakoudis and Gonelas [45]	A	R	
	Meirelles et al. (2017)	D	HM	PSO
	De Paola et al. [46]	D, A	R	HS, GA
	Samir et al. [54]	A	R	
NRW management	Fantozzi et al. [29]	A	E, O	
	Tabesh et al. [21]	A	E,R	
	Cheung et al. [22]	A	E	
	Alkasseh et al. [26]	A	E, R	
	Verde et al. [27]	A	E, R	
	Latchoomun et al. [16]	A	E, R	
	Choi et al. [18]	A	R	
	Kanakoudis et al. [15]	A	R	
	Mazzolani et al. [47]	A	E	
	Mazzolani et al. [48]	A	E	
	Farah and Shahrour [23]	A	E	
	Christodoulou et al. [49]	A	D	
	Wu et al. [50]	A	D,E	
DMA Design	Di Nardo and Di Natale [51]	D	O	GT
	Diao et al. (2013)	D	O/R	CS
	Laucelli et al. [5]	D	R	
	Liu and Han [52]	D	O	MCDA
	Rahmani et al. [53]	D	O	GT
	Gilbert et al. [33]	D	O/R	SO
	Meirelles et al. (2017)	D/A	O/R	
	Hajibandeh and Nazif [39]	D	D/E	ACO, MACO
	Rahman and Wu [12]	D	O/R	GT, GA
	Brentan et al. (2018)	D	O/R	PSO

HS: Harmony Search, GA: Genetic Algorithm, MCDA: Multi-criteria decision analysis, ACO: Ant Colony Algorithm, MACO: Multi-objective Ant Colony Algorithm, SO: Swarm Optimization, PSO: Particle Swarm Optimization, GT: Graph Theory, SA: Simulated Annealing, CS: Community Structure.

2.1.1. Data Management

In water loss management, accurate and continuous measurement of the data that is effective on the problem, representing the system and the problem can be shown as the most basic step in order to correctly diagnose and manage the problem and to develop the best strategies. The standard water balance was proposed by IWA for monitoring, assessing and comparing water loss rate and system performance, and for comparison with other systems [1, 9, 10]. Also in Turkey, for controlling and management of water losses, a regulation was published in May 8th, 2014. It is emphasized that Water Utilities should reduce water loss rates to 30 % in 5 years and to 25 % in the following 4 years based on the date published. It is clear that significant investments have to be made in order to reduce water losses to the rates given in the regulation. In order to make these investments, to fill the water balance in a correct and sustainable way, to put forward the most appropriate strategy, it is important to provide the following conditions in WDS [5,11,12];

- Analyzing the current condition of the system
- Knowing the components under the main factors such as hydraulic, physical, environmental and operating of the system,
- Accurate, sustainable measurement of data
- A clear understanding of the water loss rate through continuous and accurate monitoring of the system

Network features, profile and characteristics of the customers, environmental and operating conditions, failure rates, pipe material properties and other components of the system do not have similar characteristics in all of the WDS and may vary from region to region. Therefore, the measurement and monitoring of all system components throughout the WDS with complex structure becomes difficult due to the following reasons;

- The measurement way, frequency and priority of the data vary from region to region
- Factors affecting the rates of failure and leakage have different impact level between regions in complex systems
- The nature, type and frequency of the data required for the methods to be applied in reducing the rate of failure depending on the characteristics of the effective factors
- Since the ratio of physical and apparent losses components vary from region to region, the frequency of data collection according to the strategy to be applied in reducing and preventing these ratios varies.
- Obtaining data for all components in the more accurate filling of the IWA standard water balance table

On the other hand, in DMA, obtaining measurable, applicable and sustainable data will be faster and more effective, depending on the requirements or weakness of the system. In this way, water loss analysis in DMA can be carried out by collecting system data without any further investment in equipment and technical personnel.

2.1.2. Sustainable Network and Leakage Management

In a WDS, some of the leakages appear on the ground surface (reported), however a significant part of leakages (unreported) do not rise to the ground surface due to various factors [1,9,13]. In complex WDSs, the establishment of appropriate network operating conditions becomes difficult due to various factors and significant problems arise. It is quite difficult to develop a systematic and planned operation and maintenance strategy in such systems where the density of the old network pipe is high, the pipe characteristic varies, the intensity of the failure differ throughout the network and the pressure regulation is not possible depending on the irregular topography. For this reason, it is not possible to perform long-term programs in network operating and planning works in such systems, to reduce failures and the water loss rate, to minimize the number of water interruptions in a systematic and plan manner. In the WDS, the failure rate is calculated as the ratio of the number of failures occurring in the system annually to the line length [14]. The failure rate occurs due to factors such as various physical, environmental and operating and significant differences are observed between regions. In WDS with too long line lengths, the development of the maintenance-repair-pipe replacement or renewal strategy for the whole system, the analysis of the factors that cause the failures and leakages, the planning and studies to reduce the rate of failure results uneconomic consequences. Because in general, leakage characteristics (occurrence, location, type, time, frequency), factors affecting the failure and performance of pipes and fittings vary from region to region and in most cases there are significant differences between regions. Therefore, in WDS to reduce the failure rate and leakages, to make the DMA-based assessment and failure analysis, to detect factors affecting on failures and to minimize the effects of the these factors, to develop the most appropriate failure management model, to plan the best pipe replacement or renewal strategy for each DMA will be a more effective and sustainable approach and will make significant contributions to network management [15,16]. In order to decide on network rehabilitation in a DMA, it may be more appropriate to prioritize network rehabilitation according to various factors [17, 18]. Thus, each DMA is evaluated in itself, the factors affecting the failure are analyzed separately for each region and the failure rate can be effectively reduced in a shorter time. Loureiro et al. [19] applied the DMA approach to monitoring and detecting unexpected flow changes and failure events in WDS and emphasized that this method can be applied and effective in determining such events.

Water interruptions applied for maintenance and repair of leakages can be considered as one of the major operational problems in complex systems. In such systems, it is often not possible to make water interruptions at the closest point to the point of failure due to the fact that the valves remain under the road surface and their location and feeding areas are unknown. However, in an DMA, determining the location of all pipe and other control elements of the system, transferring to the digital environment, establishing the appropriate operating plans, determining the location of the valve closest to the point of failure in case of failure, is easier and offers important contributions in the sense of operating [11,20]. As a result, in the event of a failure in a DMA, only the closest valve to the fault point on the relevant street will be closed so that at least the customer will be affected.

2.1.3. Night Flow Monitoring and Leak Detection

The reduction of unreported leaks in water loss management is basically composed of 3 steps: (i) awareness, (ii) locating the point, and (iii) repairing [2, 3]. However, due to the complex nature of the large WDSs, it is very difficult to know the location of the potential leakages or to recognize the leakages. In such systems, only the total loss rate is calculated and it is not possible to make separate evaluation for the physical and apparent loss components [21]. In addition, with IWA water balance for assessing water losses, the water volume of the system is determined and provides information on the total loss percentage. However, it is not possible to reach clear information about the volume of losses caused by unreported leaks. It is not possible to implement effective water loss management strategies in such systems, especially due to the fact that the flow rate is not monitored regularly, the day and night flow and pressure changes cannot be analyzed or the evaluation of potential leaks due to the monitored flow is not possible for the whole system. On the other hand, in an DMA, the volume of water entering the system, the input flow changes occurring for 24 hours, the water consumption characteristics depending on the customers type in the system and the pressure values taken from the pressure gauges at the critical points in the system are taken into consideration, and the night flow analysis is performed and by monitoring the night flow rate, it is possible to recognize unreported leaks in the trace system [22, 23, 24, 25,26].

In order to prevent the leakages, the passive leakage control that involves the maintenance and repair of the reported leakages and the active leakage control cover the determination of the unreported leakages with the detection equipment [1,9,13]. With the implementation of minimum night flow and active leakage control methods in a DMA, it will be possible to know the potential leakage in the streets and only to scan on the relevant street and to locate the point of leakage in a shorter time, and will provide significant gains in terms of time, and cost [2,7]. In a DMA according to given the above, the benefits such as less water transferring into the system due to the detection of leakages, the prevention of pressure drops with the repair of the detected failures, the more efficient use of the water supply and the reduction of the customer complaints will be obtained. As a result, in a DMA, as the simultaneous determination, monitoring and control of customer consumptions, volume of the system, night consumption changes, pressure changes, and determination of the leakage of the system are easier and more feasible than large systems.

2.1.4. Pressure Management

In literature, it is emphasized that leakages and failures in pipes and fittings in the WDS are sensitive to pressure and pressure fluctuation [2,7,8,9,10,27]. For this reason, it is very important to determine and apply the pressure management to minimize the fluctuations in pressure between the day and night hours and to reduce the existing leakages or new potential leakages [28]. The main purpose of pressure control could be emphasized as; (i) reducing the existing losses in the network; (ii) preventing and reducing the new potential leakages that may occur in the future; (iii) reducing the frequency of failure. However, before the pressure management is applied in a WDS, the network and customer characteristics, urban topography should be accurately determined and analyzed. In addition, the critical points should be determined taking into account all factors and, the minimum pressure limit values required to transmit water to the critical points in the network must be defined [7,8,9,28,29,30,31,32]. However, in a WDS with very complex topographically, establishing the same pressure conditions, defining the upper and lower pressure limits for the overall system, defining the critical points to represent the overall system and providing a standard pressure control method according to these points is not feasible [2,33]. Therefore, one of the basic criteria for determining the boundaries of DMA is that as far as possible, topography does not change much and a homogenous structure is formed topographically. In this context, it is possible to define the pressure lower and upper limit values, determine the critical point to represent the region and to define the most appropriate pressure control strategy. Thus, a feasible and sustainable solution that represents the DMA requirements, provides the most benefit with minimum investment reduction of the number of failures with the most appropriate pressure strategy, will be put forward [2,7].

2.1.5. Customer Management and Apparent Losses

In the WDS, the component, which is consumed by the customers but cannot be charged, is caused by illegal usage, all kinds of meter and accounting errors and the loss of direct income is expressed as apparent losses [1,2,9]. Losses caused by meters (lack of measurement or no measurement) may be considered as the most important component of apparent losses [32,34]. Xin et al. [25] stated that one of the most important components of water that does not generate revenue in a WDS is apparent losses and the struggle against these losses is very complex and invisible. It was emphasized that the DMA contributed significantly to the identification, estimation of apparent losses. Knowing the characteristics of authorized customers (customer type, number, water consumption characteristics, meter accuracy and calibration) in the region served by the WDS, knowing the authorized unbilled consumptions, knowing the unauthorized unbilled water consumptions is very important for effective apparent loss management [34,35,36]. For example, in determining the leakage by monitoring the minimum night flow rate, the customer characteristic within the region and the night consumption of commercial customers should be known and taken into consideration. On the other hand, it is necessary to know customer consumptions and water losses due to meter errors in order to accurately fill the IWA standard water balance table and to evaluate performance of the water losses in the WDS [1,2]. However, it is not possible to collect, monitor and control these data for a complex WDS. On the other hand, it could be said that the establishment of a customer management system in an isolated DMA, verification of data with field works, monitoring of meter errors, determination of the characteristics of customers and water consumptions, collection of accurate data for the methods used to detect leaks will be easier and more advantageous than the bigger systems.

2.2. DMA Design: Criteria

It was already emphasized that the DMA approach will be an important tool in achieving the expected benefits in water loss and network management, failure and leakage management and strategy development. However, it is very important to ensure that the DMA design in the WDS is properly performed and the necessary tests are carried out in the distribution system in order to achieve the objectives and expected benefits and to provide an effective water loss management strategy. In recent years, it was seen that various studies were carried out in the scope of DMA applications, design, benefits and field studies for effective water loss management, different methods, various design criteria and field tests are proposed. In order to increase efficiency in terms of energy, water, personnel and economic parameters in sustainable water loss management, it is considered that the following questions should be answered carefully [2,3,5,6,8,11,31,33,37,38,39];

- Is there a current condition analysis in terms of water losses, operating and other parameters?
- Are the physical, environmental, hydraulic and operational data of the network? Is there sufficient facility for measurement?
- Is the hydraulic model made under the current network conditions? Is the model calibrated?
- Is there a need for DMA design in existing network conditions? Is it possible to design?
- Are the technical infrastructure, personnel, equipment and technology, and economic facilities sufficient to carry out the required tests and implement the DMA design in the field?
- What should be the network boundaries and size of the DMA?
- What should be the network length, the number of service connections and customers?
- What should be the number of entries?
- Are there significant structures (Hospitals, schools, military area, industrial plant)?
- What should be the flow rate and the required pressure limits?
- Are there a railway, main road, stream and natural channel within DMA boundaries? Can it be defined as a natural DMA boundary?
- Is there sufficient information on the customer profile and their water consumption characteristics?
- What is the location and number of the isolation valves?
- What should be the pressure requirement and the lower and upper pressure limits based on topographic conditions?
- What are the location and the number of critical points to be measured and monitored?
- Is there economic analysis carried out for the DMA in the short, medium and long term for approximate investment costs and the expected benefits for the identified objectives?

In order to decide the DMA design, it is also important to carry out the current condition analysis, the disadvantages and problems in the current system, the requirements, and the targets, the expected benefits and the comparative cost analysis [2,5,33,37]. For this purpose, components such as failure rate, water loss rate, system operating cost, frequency of water interruptions, customer satisfaction should be analyzed by supporting and collecting the field data. In addition, after making this analysis, whether the DMA planned to be performed can be applied in the field, whether it is possible to conduct tests and works in the field should be analyzed. On the other hand, in order to determine the critical points in terms of pressure and operating, it is very important to perform hydraulic modeling of the system, to perform the hydraulic analysis of the pipes serving in the streets and to calibrate with the field data, to establish the operation plan, to locate the isolation valve points [2,37]. One of the most important works in DMA design is to define the boundaries; therefore, the river, the natural canal, the main road and the railway can be defined as the natural boundary to the DMA [6].

Rahman and Wu (2018) implemented a DMA design in a WDS, proposed that the DMA size should not be chosen too large to obtain the expected benefits in water loss management, to ensure efficient network management and to keep the night consumption at an acceptable level. In a WDS, the size of the DMA should be determined depending on the number of connections, network length, number of people living, and initial investment and operating costs. Especially in areas with low customer density or number of service connections, the network length can be considered as a measure in determining DMA size. On the other hand, it is more appropriate to use the number of service connections as the main criterion rather than the network length in the regions with a high number of service connections. It was proposed to take the number of service connections between 500 and 3000 [2,6,7,37]. If the number of service connections in the DMA is more than 3000, it will be difficult to detect, prevent and control the unreported leaks occurring in the pipelines as well as to manage apparent losses, and it will be difficult to achieve effective water loss management and the expected benefits.

On the other hand, although the very small planning of the DMA size gives a great advantage in determining the new leakages, the number of devices to be used for monitoring the components and the number of isolated valves and the initial investment and operating costs of the system will increase [5,12]. In systems where the current network is very bad, the density and frequency of the failures will increase as the strength of the pipe material will decrease. It is stated that the number of service connections can be kept small (fewer than 500) in order to manage the failures and leakage more effectively [7,8]. On the other hand, it is emphasized that the length of the pipe line can be taken between 4 km and 30 km, but it can be average around 15 km [2,55]. In DMA design, it is important to limit the number of entry point to reduce the installation cost of the flow-meters used to monitor the water volume entering the system and the night flow analyzes and the water balance [12].

Moreover, it is important to take into consideration the significant structures, the determination of their water demands, the special consumptions and the night consumption and the effect on the operating pressure of the system. Because, in the analysis of water loss, the customer profile, water consumption characteristics, night water usage knowledge are effective on the accuracy of the results [38]. As already mentioned, it is important that the topography does not change too much in order to reduce the effect of pressure in an isolated DMA or to manage the effective pressure control. For this reason, land elevation variation in the region should be considered when determining DMA boundaries [2,6,7]. If the topography in the DMA is not considered, it will be very difficult to define the critical point in pressure management, keeping the pressure within the minimum and maximum limits. Thus, the expected benefits from the DMA and pressure control management applications cannot be achieved and non-economic results will be obtained.

Considering the criteria, DMA size, boundaries, number of customers, entry point, critical points and number and location of isolated valves should be determined and field tests should be carried out whether DMA is fully isolated from other networks [2]. For this purpose, the most fundamental method applied in the field is the Zero Pressure Test method in which the system is closed and the water is prevented from entering the system and the pressure in the system is expected to be zero [2,3,37]. To ensure this; (i) the DMA boundaries should be very well defined and the system must be fully isolated from other network elements, (ii) there should be no water entry from other points to the system, (iii) The number and location of valves should be very well defined, (iv) the isolation valves should be monitored to see whether there is water inlet and outlet [12,38]. If these tests and controls are not performed, the DMA will not be fully isolated from other networks, in case of water entry from other points; the system input volume will be calculated incorrectly. Therefore the standard water balance and night flow analysis will not be calculated correctly and the expected benefit from DMA will not be obtained. The application principles, field works and processing steps of the zero pressure test are detailed in the studies conducted in the literature [2,3,37].

3. DMA Application

3.1. Study Area

Based on the DMA design criteria given in detail in the previous section, DMA planning and the field application works were carried out in Malatya WDS (Figure 1) by the MASKİ General Directorate. In the Malatya WDS, water demands of approximately 179 districts (approximately 65% of the population) are supplied from a single source (Pınarbaşı source) which is groundwater source and in 1210 m elevation. There are approximately 1.700 km of water distribution network in the city center. From the source to the city in the last 3 years (2015-2017) average 2.900 l/s water was transferred. In application area, according to 2018 data, the average water loss is calculated as 55% [40,41]. The need flow rate is estimated as 1800 l/s according to the maximum consumption day if the loss leakage rate is reduced to 25% [41].

3.2. Current Status and DMA Design in Study Area

Aydogdu and Firat [14] analyzed the reported leakage records in Malatya WDS between years 2007-2012 and evaluated its spatial distribution. It was emphasized that a significant part of the failures in WDS were observed in the settlements with old pipe material. Similarly, Boztaş [40] analyzed the service connection failures (reported and unreported leakages) observed in Malatya WDS between years 2007-2016 and the spatial distribution of the records was examined. It was found that the leakage density in service connections is high in the regions where there are old settlements in the city center. It was also emphasized that the annual service connection failure density in the areas with old pipes is 0.0417 breakdowns/connection/year, and that one of the average 24 service connections failures every year [40]. According to the reports of MASKI, the annual loss-leakage rate in the Malatya WDS is in the range of 65% however this rate is estimated to be approximately 55% at the end of 2017 [41]. As previously mentioned, in Turkey, a regulation was published in May 8th, 2014 to use water resources more effectively and to reduce water losses and monitor the performance of Water Utilities. According to the reports, it is very important to reduce water losses, prevent and control the systems especially in old pipe material systems. However, as given above in detail, the implementation of the same water loss management strategy for the overall system where failure density varies, is quite difficult, time consuming and costly. For this reason, DMA planning was carried out and field application was performed in order to control and reduce water losses in the application area where two different ways were followed for DMA design. The first of which is in the form of isolated zones with the pipe material completely rehabilitated regions, in the other, only the outer boundaries are determined without changing the pipe material. Defining the boundaries of the region, determining the number and location of the isolation valves and completely isolating the region from other regions are the most important and the most difficult works. In application area, 15 of the DMAs (non-rehabilitated) were created by converting the existing network into an isolated system, while 18 DMAs (rehabilitated) were created by renewing the existing network and service connections (Figure 1) and descriptive information of DMAs was given in Table 2 [11,41].

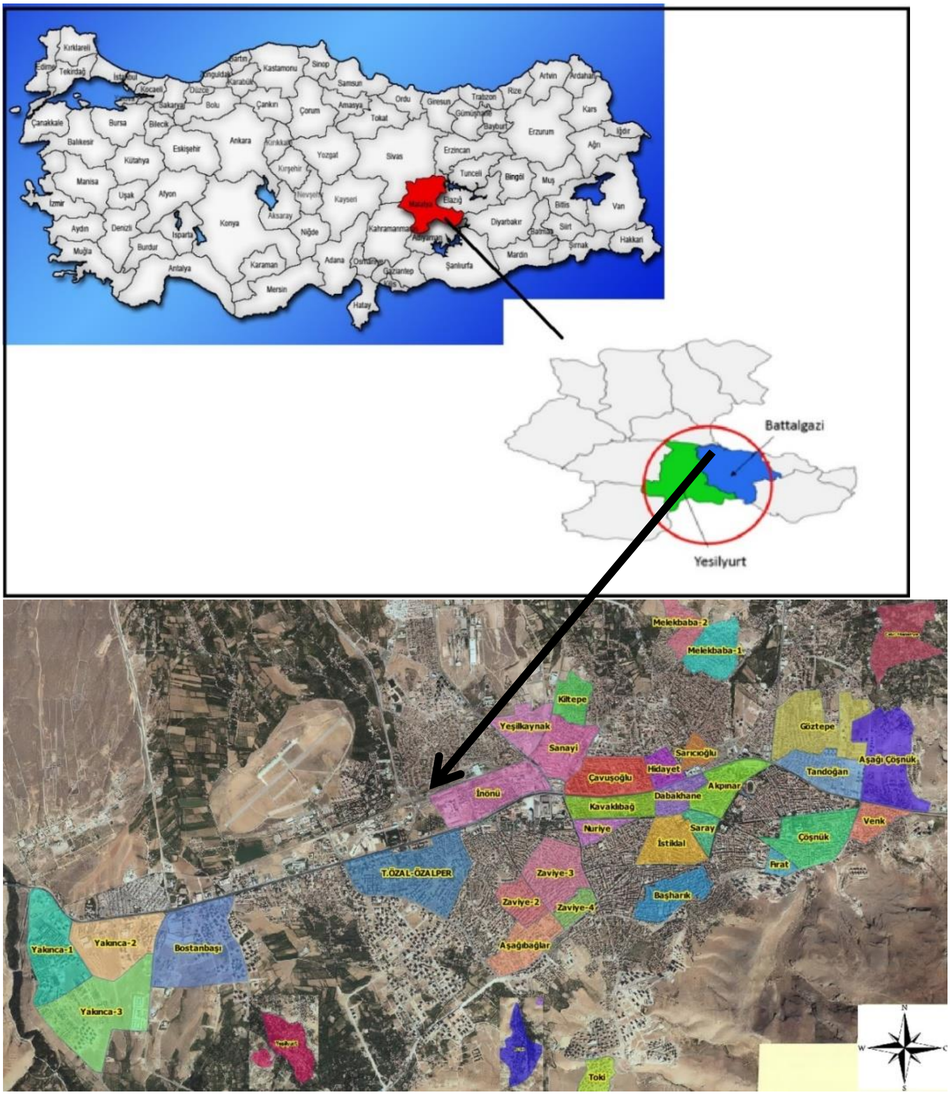


Figure 1. DMAs in study area [11, 41]

Table 2. The descriptive information of DMAs [11, 41]

DMA ID (non-rehabilitated)	The number of entry	Pipe Length (km)	The number of service connections	The number of customers	Percentage of residence customers (%)	The number of isolation valve
DMAs (non-rehabilitated)						
DMA1	2	5.65	510	2.872	35	2
DMA2	2	8.70	522	2.832	58	-
DMA3	2	14.00	1.179	5.655	79	3
DMA4	2	9.61	678	4.507	62.25	1
DMA5	2	3.227	454	2.515	47.99	1
DMA6	1	3.413	301	1.405	64.55	-
DMA7	2	4.58	315	1.321	70.77	-
DMA8	1	15.62	526	1.300	82.6	-
DMA9	1	19.48	1.47	2.836	85.78	1
DMA10	1	4.68	384	2.446	73.95	-
DMA11	1	20.91	1.05	1.510	3.04	2
DMA12	1	6.94	697	760.0	78.94	1
DMA13	1	12.63	949	1.183	78.02	-
DMA14	1	11.11	575	604.0	88.41	-
DMA15	1	7.43	537	770.0	80.77	-
DMA16	1	11.09	829	2.38	97.24	-
DMAs (rehabilitated)						
DMA17	1	11.20	834	3.067	90	-
DMA18	1	17.75	980	5.603	96	-
DMA 19	1	5.60	428	3.049	97	1
DMA 20	1	12.97	1.03	7.650	96.29	1
DMA 21	1	2.59	251	3.140	71.87	1
DMA 22	1	9.81	517	2.695	78.59	1
DMA 23	1	8.89	774	4.470	82.59	2
DMA 24	1	17.61	367	2.451	88.75	1
DMA 25	2	4.752	99	1.090	95.81	1
DMA 26	1	13.72	286	2.213	97.92	1
DMA 27	2	9.84	205	3.364	96.97	1
DMA 28	1	3.00	152	1.640	94.58	-
DMA 29	1	3.65	413	2.891	95.33	-
DMA 30	1	21.15	1.12	5.040	98.95	-
DMA 31	2	14.01	1.06	1.198	94.82	1

The DMA should be established by taking into account the current network conditions and the minimum initial investment cost and the existing network plan in the field. The network length could be stated as another important design criterion. Therefore, it is seen that the network length is between 3 and 21 km in DMAs and the upper limit of 30 km given in the literature is not exceeded. The DMA 11, which is not rehabilitated, has the maximum network length and industrial facilities in this region and it is spread over a wide area, therefore, pipeline length is taken as the basis for planning this region (Table 2). In this region, the rate of residence customers is 3%, which is an important data that should be taken into consideration especially in the analysis of minimum night flow. In DMA 30 (rehabilitated), the line length is high as it covers a large area. On the other hand, in the literature, it was emphasized that the number of service connections and customers are very important in DMA design. In this study, it is seen that the number of service connections in DMAs (non-rehabilitated) varies between 300 and 1450 items.

In addition, based on the number of customers, it is seen that only DMA 3 has 5655 customers. The fact that the number of customers in this DMA is high is due to the fact that the DMA contains the old residential area of the city. However, although the number of service connections in the DMA 25 (rehabilitated) appears to be very low, the number of customers and pipe length remain within the limit values. This situation has arisen due to the developmental characteristics of the region originating from the geographical structure and the number of high-rise buildings. In order to make a more detailed evaluation about the DMAs, data of the operating parameters were collected (Table 3).

Table 3. The operating data in DMAs (non-rehabilitated) [11]

DMA ID	Elevation (min-max.)	Critical point	The number of failures	Water loss rate (%)		Pipe replacement (%)	Average age of network (year)
				Before	After		
DMAs (non-rehabilitated)							
DMA1	957- 973	1	47	52.26	36.87	0	18.7
DMA2	946- 970	1	52	64.43	39.00	2	25.1
DMA3	966-1001	1	143	61.63	56.44	0.5	19.5
DMA4	956-977	1	138	42.8	34.69	4.89	14
DMA5	960-984	1	55	62.05	45.29	12.14	11.02
DMA6	943-952	1	19	44.86	33.29	8.17	16.7
DMA7	948-960	1	14	82.69	76.27	3.8	18.2
DMA8	938-999	1	21	63.09	60.12	7.2	12.5
DMA9	933-971	1	91	27.91	13.69	6.15	15.4
DMA10	953-991	1	129	49.82	35.42	4.54	16.9
DMA11	922-938	1	40	71.24	57.24	0	18.2
DMA12	914-940	1	5	56,32	29.48	0	18.3
DMA13	928-994	1	8	78.52	68.29	3.32	10.9
DMA14	924-977	1	19			7.25	11.9
DMA15	917-946	1	25	65.34	56.22	6.17	14.4
DMA16	964-990	1	39	61.6	32.81	22.54	6
DMAs (rehabilitated)							
DMA17	936- 953	1	108	90.05	15.22	100	2
DMA18	970-1004	1	83	-	15.24	100	1
DMA 19	998-1050	1	141	-	32.79	100	1
DMA 20	963-1003	1	70	-	20.03	100	1
DMA 21	999-1027	1	42	-	26.87	100	1
DMA 22	992-1022	1	71	-	25.62	100	1.5
DMA 23	993-1031	1	49	-	25.31	100	1
DMA 24	938-963	1	17	-	-	100	1
DMA 25	932-966	1	26	-	-	100	1
DMA 26	964-993	1	35	-	-	100	1
DMA 27	926-972	1	28	-	-	100	1
DMA 28	1019-1049	1	14	-	17.37	100	1
DMA 29	935-942	1	36	54.31	18.74	100	1
DMA 30	1058-1196	3	35	-	-	100	1
DMA 31	977-1059	3	40	83.2	-	100	1

As mentioned previously, it is very important to know the parameters such as the topography of the region, the number of critical points in the region, the difference between the maximum and minimum ground elevations depending on the topography, and to consider the DMA design [6,7,8]. The topography was also considered in the DMAs planned and applied in the field and it was taken into consideration that the elevation difference did not exceed these limit values defined between 2.5 and 6.5 bars given in a regulation. It is seen that the network pipe age is generally more than 10 years. Considering the effect of pipe age on the failure rate, network operation should be carried out by maintaining the existing network conditions and rehabilitating the minimum pipe material. Water loss rates are very high in regions where the network pipe is not rehabilitated and the pipe age is more than 10 years. In addition, water loss rates in the first measurement period in DMA (rehabilitated) are generally in the range of 40-80% (Table 3). It is observed that water loss rates have decreased in the regions where DMA design has been done and the field works were completed [11,41]. On the reduction in water loss rates, it could be said that the water loss reduction method applied for each DMA is effective. Since the water loss rate, pipe age, compressive strength, soil property and water consumption characteristics of each DMA will vary in the application area, it is possible to apply a water loss strategy specific to each region with DMA design. For instance, in DMA30 and DMA 31 (rehabilitated), the topography is highly in difference elevation with about 14 and 8 bars respectively. It is seen that pressure management strategy should be implemented in these regions. As the boundaries of these regions are determined and isolated from other regions, it is possible to develop the most appropriate pressure management in region, thus; the pressure problem will be solved in less time with less cost [11]. On the other hand, in regions where there is no pressure difference or in areas where there is no need for pressure management, the rate of loss of water is reduced by applying only active leakage control method. The explanatory statements in the table show that the physical and operational parameters of the system in a WDS vary from region to region. These parameters are known to be effective on the rate of failure and the rate of non-revenue water and are also seen from the table.

The performance of water loss in DMAs (rehabilitated and un-rehabilitated) was monitored (Table 3). It was observed that the rate of water loss decreased significantly in the regions which were not rehabilitated and formed with low initial investment cost. At the beginning of the study, while the water loss rates in general were around 40-80 %, this value was reduced to 30-40% after the construction of the DMAs. With the DMA approach, it can be said that the components of the system are more easily and effectively monitored and controllable. In addition, it is possible to determine the amount of potential leakage by monitoring the minimum night flow rate and thus to concentrate the active leakage control activities in the field. On the other hand, the most important component of the water loss analysis was easier management of the customers.

3.4. Flow Monitoring in DMA

In this section, DMA1 (Dabakhane DMA) with pipe length of 5817 m was selected as pilot area for monitoring flow and pressure and discussing the benefits obtained (Figure 2). The length of the service connections in the region is 3867 m and a total of 3391 customers are supplied with water pressure with an average pressure of 50.69 m.

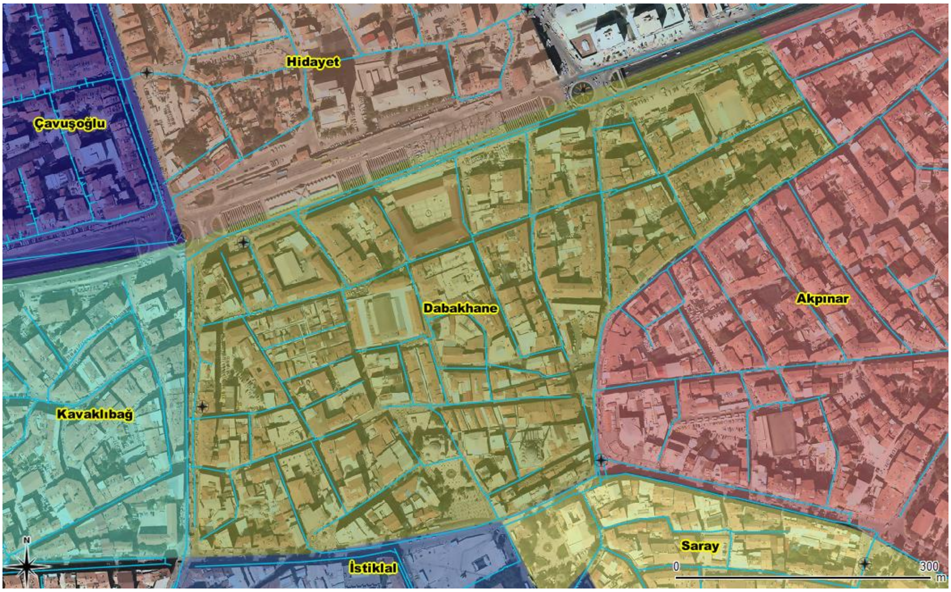
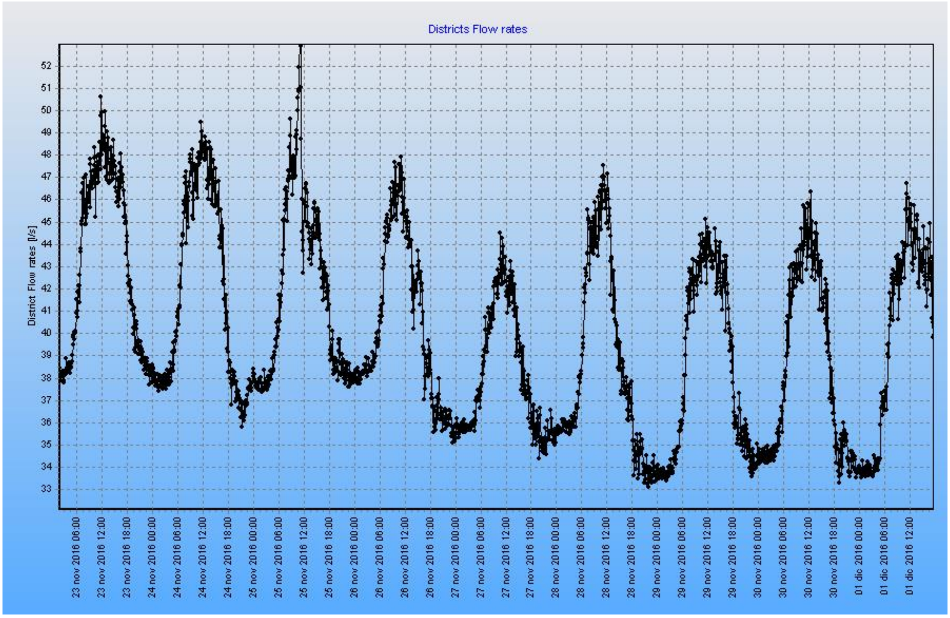
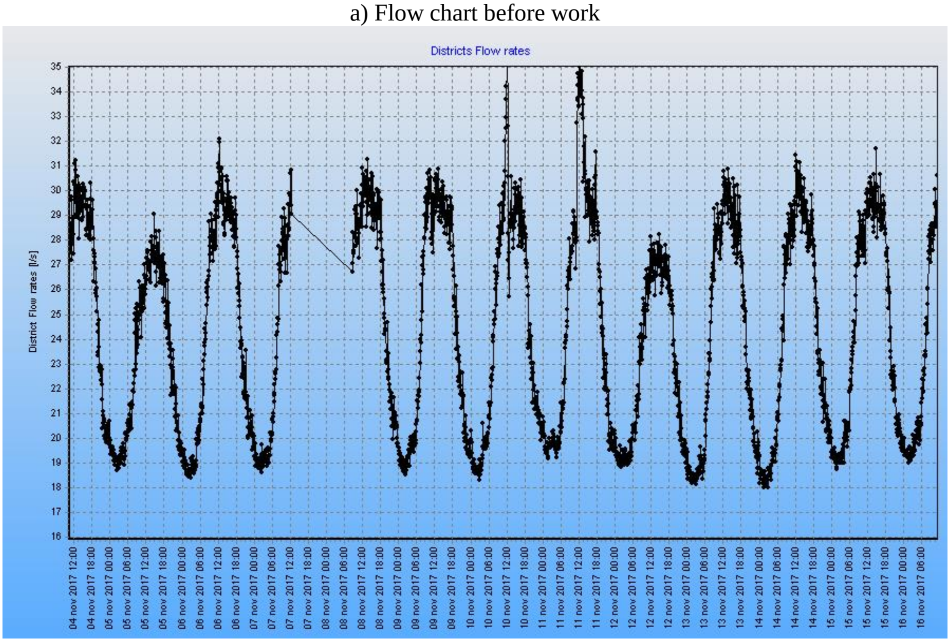


Figure 2. DMA1 (Dabakhane DMA) for monitoring flow and pressure [11, 41]

After isolating the DMA 1 zone, system inlet and outlet flow rates and pressures are monitored. In DMA 1 zone, the minimum flow rate was 38 l/s at the start of flow monitoring and the peak flow rate was 51 l/s at the maximum consumption hour (Figure 3a).



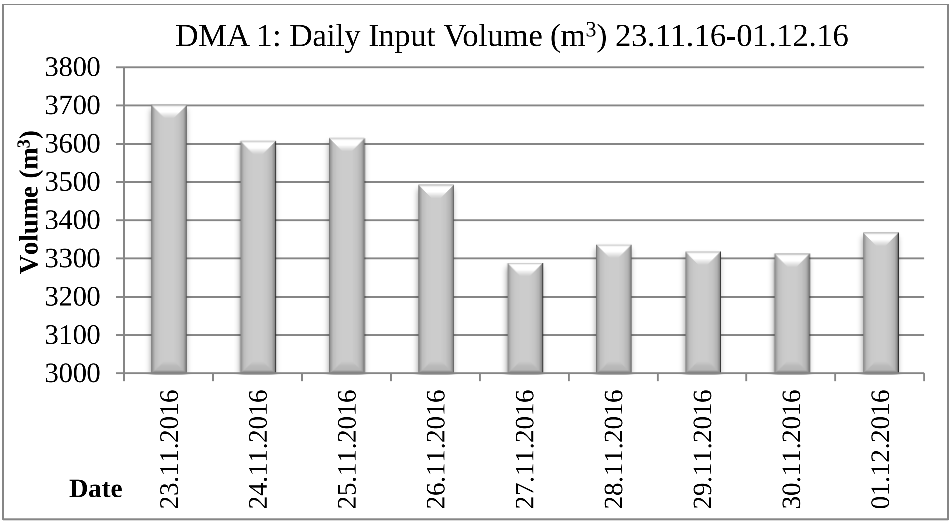
a) Flow chart before work



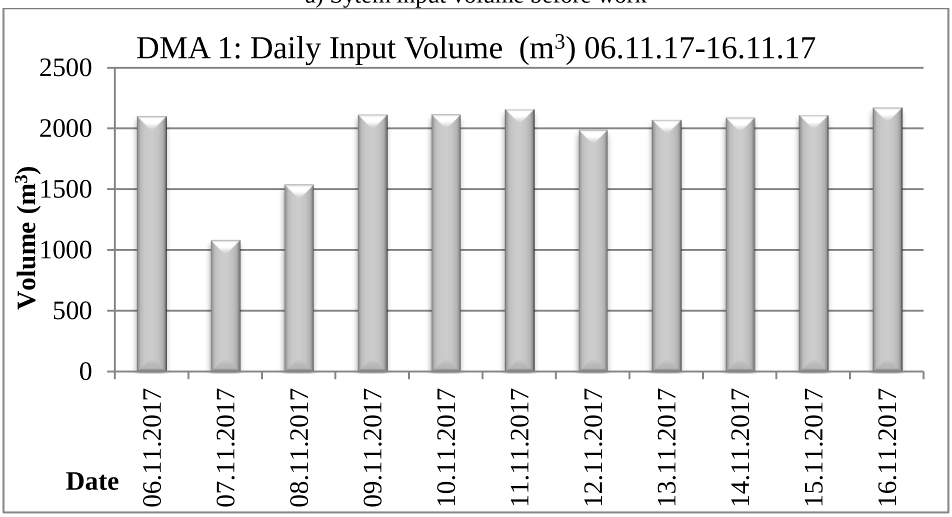
b) Flow chart after work

Figure 3. Inlet Flow Change in DMA1 [11, 41]

It is seen that the minimum night flow rates are quite high in the region before the study (Figure 3a). For this reason, active leakage control was applied and flow changes were monitored for detection and repair of unreported leaks. As a result of the works, the minimum night flow rate was reduced to 18 l/s and the peak flow rate for the maximum consumption hour was reduced to 33 l/s. Based on flow data in the region, input volumes were recorded at the beginning and after the study and their changes were monitored (Figure 4).



a) Sytem input volume before work



b) Sytem input volume after work

Figure 4. System input volume change in DMA 1 [11, 41]

After the isolation of the DMA 1 region, an average of 3600 m3 water inflow per day was determined. With the intervention at the beginning of the study, this flow was reduced to an average of 3300 m3 per day and the water flow entering the region in the long term was reduced to an average of 2000 m3 per day. Accordingly, 1600 m3 of water was saved daily in the region. According to the results given in tables and graphs, it is possible to detect, locate and repair leaks that are not reported in the system by creating isolated zones in a shorter time. This provides significant gains in terms of more efficient use of water, energy and personnel resources.

4. CONCLUSIONS

The aim of this study was to discuss the importance of DMA for the management, reduction and control of water losses in water management based on the system components. The advantages of the DMA, the expected benefits, design criteria were evaluated, and the benefits from the DMA applied in Malatya water distribution system were discussed. The answer to the question of "*Why is DMA necessary in water management*?" was investigated based on the studies in the literature and the results obtained from the field application. In order to make a more detailed evaluation about the DMAs, data of the operating parameters were collected. It was determined that the water loss rates in the first measurement period in DMAs (rehabilitated) are generally in the range of 40-80%. At the beginning of the study, while the water loss rates in general were around 60%, this value was reduced to 30-40% after the defining the DMAs. With the DMA approach, it can be said that the components of the system are more easily and effectively monitored and controllable. It was observed that water loss rates have decreased in the regions where DMA design has been done and the field works were completed.

The benefits of the DMA approach in water loss management could be listed as follows;

- Measuring, monitoring, controlling, conducting the current condition analysis of all physical, hydraulic, environmental and structural factors in each DMA for an effective water loss management
- Determining the number, type and consumption characteristics of the customers, correlating with the night flow rate and performing the loss analysis,
- Regular measurement of all components of the system and accurate monitoring of system performance,
- Implementation of each region-specific method to reduce the rate of non-income water
- Implementation of a more effective pressure control management strategy in such systems as the topographic conditions are taken into account when determining DMA,
- Determining the weaknesses and strengths of each DMA, development and implementation of the most appropriate strategy for improvement of weaknesses.
- Analyzing the current situation of the customer water meters, planning the meter renewal programs, reducing the apparent losses caused by the meter errors,
- Determining potential unreported leakages and preventing new leaks by monitoring the night flow rate,
- Implementation of active leakage control in narrower area, determination of leakage location with high accuracy rates
- Implementation of water interruption program on street basis for maintenance and failure repair

As a result, in a DMA, as the simultaneous determination, monitoring and control of customer consumptions, volume of the system, night consumption and pressure changes, and determination of the leakages are easier and more feasible than large systems.

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REFERENCES

[1] Farley M., (2003) Non Revenue Water - International Best Practice for Assessment, Monitoring and Control. 12th Annual CWWA Water, Wastewater & Solid Waste 1–18.

[2] Farley, M. Wyeth, G. Ghazali, ZBM. Istandar, A. and Singh S., (2008). The Manager's Non-Revenue Water Handbook. A Guide to Understanding Water Losses. (Editors: van Dijk, N., Raksakulthai, V., Kirkwood, E.). 110.

[3] Simbeye I., (2010) Managing Non-Revenue Water: Non-Revenue Water Sourcebook for Trainers. WAVE Pool. InWEnt. Germany, pp101.

[4] Karathanasi, I and Papageorgakopoulos C., (2016) Development of a leakage control system at the water supply network of the city of Patras. Procedia Engineering. 162: 553-558.

[5] Laucelli, DB, Simone, A, Berardi, L and Giustolisi O., (2017) Optimal Design of District Metering Areas for the Reduction of Leakages. Journal of Water Resources Planning and Management. 143(6): 04017017.

[6] Morrison, J, Tooms, S and Rogers D., (2007) District metered areas: Guidance notes, IWA Publishing, London.

[7] Mutikanga, HE, Sharma, SK and Vairavamoorthy K., (2013) Methods and Tools for Managing Losses in Water Distribution Systems. Journal of Water Resources Planning and Management. 139(2): 166-174.

[8] Vicente, DJ, Garrote, L, Sánchez, R and Santillán D., (2016). Pressure Management in Water Distribution Systems: Current Status, Proposals, and Future Trends. Journal of Water Resources Planning and Management. 142(2): 04015061.

[9] Lambert A., (2003) Assessing non-revenue water and its components : a practical approach. Water21. 5(4): 50–51.

[10] Farley, M and Trow S., (2003) Losses in water distribution networks : a practitioner's guide to assessment, monitoring and control. IWA Publishing. pp296.

[11] Durmuşçelebi FM., (2018) Rehabilitation of Water Distribution Systems For Water Loss Reduction And Cos-Benefit Analysis. MSc Thesis. Inonu University. p 113.

[12] Rahman A, Wu ZY., (2018) Multistep Simulation-Optimization Modeling Approach for Partitioning Water Distribution System into District Meter Areas. Journal of Water Resources Planning and Management, 144(5), 04018018.

[13] Liemberger, R and Farley M., (2004) Developing a Non-Revenue Water Reduction Strategy, Part 1: Investigating and Assessing Water Losses. In: Proceeding of IWA WWC 2004 Conference. Marrakech, Morocco.

[14] Aydogdu, M and Firat M., (2015). Estimation of Failure Rate in Water Distribution Network Using Fuzzy Clustering and LS-SVM Methods. Water Resources Management. 29: 1575-1590.

[15] Kanakoudis, V, Tsitsifli, S and Demetriou G., (2016) Applying an integrated methodology towards Non-Revenue Water reduction: the case of Nicosia, Cyprus. Desalination and Water Treatment. 57(25): 11447-11461.

[16] Latchoomun, L, Ah King RTF and Busawon K., (2015) A new approach to model development of water distribution networks with high leakage and burst rates. Procedia Engineering. 119: 690-699.

[17] Tabesh, M and Saber H., (2012) A Prioritization Model for Rehabilitation of Water Distribution Networks Using GIS. Water Resources Management. 26: 225-241.

[18] Choi, T, Han, J and Koo J., (2015). Decision method for rehabilitation priority of water distribution system using ELECTRE method. Desalination and Water Treatment. 53: 2369-2377.

[19] Loureiro, D, Amado, C, Martins, A, Vitorino, D, Mamade, A and Coelho ST., (2014) Water distribution systems flow monitoring and anomalous event detection: A practical approach. Urban Water Journal. 13(3): 242-252.
[20] Salomons, E, Skulovich O and Ostfeld A., (2017) Battle of Water Networks DMAs: Multistage Design Approach. Journal of Water Resources Planning and Management. 143(10): 04017059.
[21] Tabesh, M, Asadiyani, AH and Burrows R., (2009). An Integrated Model to Evaluate Losses in Water Distribution Systems. Water Resources Management. 23: 477–492.
[22] Cheung, PB, Girol, GV, Abe, N and Propato M., (2010). Night flow analysis and modeling for leakage estimation in a water distribution system. Integrating Water Systems. Taylor & Francis Group, London, ISBN 978-0-415-54851-9. 509-513.
[23] Farah, E and Shahrour I., (2017) Leakage Detection Using Smart Water System: Combination of Water Balance and Automated Minimum Night Flow. Water Resources Management. 31: 4821-4833.
[24] Peters, EJ and Ben-Ephraim Y., (2012) System leakage by night flow analysis: A case study in Guyana. Water Management. 165(8): 451-457.
[25] Xin, K, Tao, T, Lu, Y, Xiong, X and Li F., (2014). Apparent Losses Analysis in District Metered Areas of Water Distribution Systems. Water Resources Management. 28: 683-696.
[26] Alkasseh, JMA, Adlan, MN, Abustan, I, Abdul Aziz, H and Hanif ABM., (2013). Applying Minimum Night Flow to Estimate Water Loss Using Statistical Modeling: A Case Study in Kinta Valley, Malaysia. Water Resources Management. 27: 1439-1455.
[27] Verde, D, Cima, E, Ferrante, M, Brunone, B and Meniconi S., (2014). The Dependence of District Minimum Night Flow on Pressure Head: The Case Study of Lenola. Procedia Engineering. 89: 1224-1230.
[28] Xu, Q, Chen, Q, Ma, J, Blanckaert, K and Wan Z., (2014). Water Saving and Energy Reduction through Pressure Management in Urban Water Distribution Networks. Water Resources Management. 28: 3715-3726.
[29] Fantozzi, M, Calza, F and Lambert A., (2009). Experience and results achieved in introducing District Metered Areas (DMA) and Pressure Management Areas (PMA) at Enia utility (Italy). IWA Specialist Conference 'Waterloss 2009', South Africa.
[30] Nazif, S, Karamouz, M, Tabesh, M and Moridi A., (2010) Pressure Management Model for Urban Water Distribution Networks. Water Resources Management. 24: 437-458.
[31] Wu, ZY, Sage, P and Turtle D., (2010). Pressure-Dependent Leak Detection Model and Its Application to a District Water System. Journal of Water Resources Planning and Management. 136(1): 116-128.
[32] Mutikanga, HE, Sharma, SK and Vairavamoorthy K., (2010) Assessment of apparent losses in urban water systems. Water and Environmental Journal. 25: 327-335.
[33] Gilbert, D, Abraham, E, Montalvo, I and Piller O., (2018). Iterative Multistage Method for a Large Water Network Sectorization into DMAs under Multiple Design Objectives. Journal of Water Resources Planning and Management. 143(11): 04017067.
[34] Rizzo, A and Cilia J., (2005) Quantifying meter under-registration caused by the ball valves of roof tanks (for indirect plumbing systems). Proceedings of the Leakage 2005 Conference, Halifax, Canada.
[35] Arregui, F, Cabrera, Jr E and Cobacho R., (2006). Integrated water meter management. London: IWA Publishing.
[36] Criminisi, A, Fontanazza, CM, Freni, G and La Loggia G., (2009). Evaluation of the apparent losses caused by water meter under-registration in intermittent water supply. Water Science & Technology—WST. 60.9. 2373-2382.

[37] Fallis, P, Hübschen, K, Oertle, E, Ziegler, D, Kingel, P, Baader, J, Trujilo, R and Laures C., (2011). Guidelines for water loss reduction: A focus on pressure management. Deutsche Gesellschaft für Internationale Zusammenarbeit. Germany, 228.
[38] Gomes, R, Sousa, J and Sa Marques A., (2014). Influence of future water demand patterns on the district metered areas design and benefits yielded by pressure management. Procedia Engineering. 70: 744–752.
[39] Hajibandeh, E and Nazif S., (2018) Pressure Zoning Approach for Leak Detection in Water Distribution Systems Based on a Multi Objective Ant Colony Optimization. Water Resources Management. 32: 2287-2300.
[40] Boztaş F., (2017) Analysis of Leakages on Building (Service) Connections at Water Distribution Systems. MSc Thesis. Inonu University. p 92.
[41] MASKİ (2018) Malatya Water and Sewerage Administration General Directorate.
[42] Karadirek, IE, Kara, S, Yilmaz, G, Muhammetoglu A and Muhammetoglu H., (2012) Implementation of Hydraulic Modelling for Water-Loss Reduction Through Pressure Management. Water Resources Management. 26: 2555-2568.
[43] Wu, S, Yang, L, Zhou, C, and Zhang J., (2013a). Analysis of Benefits Yielded by Pressure Management in the Area based on Temperature Revision. ICPTT 2013 ASCE, 127-140.
[44] Wu, S, Yang, L, Zhou, C, and Zhang J., (2013b). Leakage Modeling And Leakage Control Analysis By Pressure Management In Water Supply System Of DMA. ICPTT 2013 ASCE, 141-150.
[45] Kanakoudis, V and Gonelas K., (2014) Applying Pressure management to reduce water losses in two Greek cities' WDSS: Expectations, Problems, Results and Revisions. Procedia Engineering. 89: 318-325.
[46] De Paola, F, Giugni, M and Portolano D., (2017). Pressure Management Through Optimal Location and Setting of Valves in Water Distribution Networks Using a Music-Inspired Approach. Water Resources Management. 31: 1517-1533.
[47] Mazzolania, G, Berardi, L, Laucelli, D, Martino, R, Simone, A and Giustolisi O (2016) A methodology to estimate leakages in water distribution networks based on inlet flow data analysis. Procedia Engineering. 162: 411 – 418.
[48] Mazzolania, G, Berardi, L, Laucelli, D, Simone, A, Martino, R and Giustolisi O., (2017) Estimating Leakages in Water Distribution Networks Based Only on Inlet Flow Data. Journal of Water Resources Planning and Management. 143(6): 04017014.
[49] Christodoulou, SE, Kourti, E and Agathokleou A., (2017). Waterloss Detection in Water Distribution Networks using Wavelet Change-Point Detection. Water Resources Management. 31: 979-994.
[50] Wu, Y, Liu, S, Smith, K and Wang Y., (2018). Using Correlation between Data from Multiple Monitoring Sensors to Detect Bursts in Water Distribution Systems. Journal of Water Resources Planning and Management. 144(2): 04017084.
[51] Di Nardo, A and Di Natale M., (2011). A heuristic design support methodology based on graph theory for district metering of water supply networks. Engineering Optimization. 43(2): 193-211.
[52] Liu, J and Han R., (2018) Spectral Clustering and Multicriteria Decision for Design of District Metered Areas. Journal of Water Resources Planning and Management. 144(5): 04018013.
[53] Rahmani, F, Muhammed, K, Behzadian, K and Farmani R., (2018). Optimal Operation of Water Distribution Systems Using a Graph Theory–Based Configuration of District Metered Areas. Journal of Water Resources Planning and Management. 144(8): 04018042.
[54] Samir, N, Kansoh, R, Elbarki, W and Fleifle A., (2017) Pressure control for minimizing leakage in water distribution systems. Alexandria Engineering Journal. 56: 601-612.

[55] MacDonald, G and Yates CD., (2005) DMA Design and Implementation, a North American Context. Leakage 2005 - Conference Proceedings. 1-8.