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Comparison of Cost and Benefit Analysis of Active Leakage Control Applications in Water Distribution Systems

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Abstract

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The fight against leaks and failures in water distribution systems has gained a serious importance with the increasing drought, the inefficient use of water resources and the rapid contamination of existing water resources. These studies are generally carried out with two different approaches, active leakage control and passive leakage control. Although the passive control method, which covers the repair of the reported faults, is less costly and easier, the vast majority of the faults that occur in the system are caused by unreported faults. It is possible to detect, repair and control such faults with active leakage methods. In order to gain the expected efficiency from these methods, it is very important to regularly monitor the networks by dividing them into isolated areas, to estimate the amount of preventable leakage, and to determine the leak location with devices and equipment such as ground microphone, regional recorder, regional correlator within the framework of a certain systematic program. The regular maintenance of these systematic studies in the implementation of the active leakage method also creates serious costs for water administrations. In addition to the costs of creating and monitoring measurable regions, the costs of devices and equipment with different characteristics, sensitivities and costs to be used for the determination of the fault location should also be considered in the studies to be carried out. In this study, a standard calculation structure is defined for the benefits and costs of the ground microphone and regional correlator methods used to locate unreported leaks. By using the defined calculation methodology, the benefits and costs for both methods are analyzed and compared in a sample network. The method to be selected according to the general characteristics of the networks plays an important role for the most efficient operation.

Keywords: Water distribution system, leakage, active leakage control, leakage detection

1. Introduction

Water distribution systems are one of the most important urban infrastructure systems. Ensuring normal operating conditions in water distribution systems is quite important for water supply safety. However, failures, breaks and leaks occur in water distribution systems depending on various factors that are the physical properties of network (pipe length, pipe material, pipe diameter etc.), environmental (traffic loads, groundwater variation etc.) and hydraulic parameter (high pressure, pressure change) [1]. A certain portion of these leakages rise to the surface and constitute the reported leakages. On the other hand, a significant portion does not rise to the surface and constitutes unreported leakages [2]-[3]. Annual leakage rates in distribution systems are between 25 and 30% [4], and the NRW rate is approximately 30% [5]. A significant part of water resources is lost due to leaks in water distribution networks. In developed countries, the volume of these leaks is seen to be between 3 and 7% of the water provided, while in developing countries there is more than 50% leakage [6]. In our country, according to the data of 25 administrations in the report published by the Turkish Water Institute (SUEN); The average GGS rate is 42%, and the lowest and highest values are 22% and 67%, respectively [7].

In water distribution systems, an active leak control strategy, which includes the activities of recognizing, locating and repairing unreported leaks, which constitute a significant portion of leaks, plays an important role in reducing the volume of physical losses [2], [8]. Active leak control includes minimum night flow in district metered areas, performing night flow analysis, identifying potential recoverable leaks, and locating unreported leaks with acoustic methods. However, in order to obtain the expected benefits of the active leak control approach, creating district metered areas and defining boundaries is quite important step. The volume of recoverable leaks increases as the time it takes to detect and locate unreported leaks increases [5], [9-11]. Moslehi et al. emphasized that leaks constitute the most important component of water losses. It was stated that in many administrations, high-cost methods are applied to minimize leaks, but economic criteria should be taken into account in leak management in order to ensure efficiency in all aspects of the system [12].

Active leak control covers the detection, reduction and prevention of non-surface (unreported) leaks in district metered areas. For active leakage control, it is necessary to district metered areas in the water distribution system, perform minimum night flow analysis, monitor flow-pressure changes, detect detected leakage locations and carry out leak repairs [13]. In addition, the flow-pressure change in the isolated measurement area should be constantly monitored and new leaks should be intervened immediately. Active leak control is applied to locate and prevent potential preventable leaks determined by minimum night flow analysis. This method has no effect on reducing and preventing uncertain leaks. In order to reduce the volume of preventable leakage detected by monitoring the minimum night flow rate in a district metered areas, studies are carried out to detect the leak location with devices and equipment such as ground microphone, regional recorder, regional correlator. It has been emphasized in the literature that the aim is to detect and repair pipe bursts faster as a result of active leak control studies [14]. In this way, it has been argued that the benefits of reducing both possible damage to the environment and water loss will be achieved. Leak detection team refers to the technical team formed to locate non-surface faults detected by minimum night flow analysis in distribution systems. This team is of critical importance in combating leaks. Detecting the leak location late or not detecting it causes the leak volume to increase. The field experience of the leak detection team is very important in accurately detecting the leak location [15],[16].

Leak detection devices refer to acoustic devices that are based on sound waves and their propagation and change along the pipeline-connectors in determining the exact location of the leak. These devices can basically be given as ground microphone (local listening), regional correlator, regional recorders, hydraulic model-based monitoring systems. Local leak detection involves monitoring the street-based step-by-step change of sound waves by using acoustic devices, referred to as ground microphones, to locate leaks that do not surface in the distribution system. Pipe material type, fault location, fault diameter, soil cover thickness on the pipe, experience of the personnel using the device and inspection time are effective in detecting this type of leak. In order to perform leakage inspection more accurately, night hours when ambient noise is the least should be preferred. Regional leak detection aims to determine the location of potential leak points with the help of sensors placed at valve points in the region in order to prevent potential preventable leaks detected by MNF analysis in isolated measurement areas. In this method, potential streets that may leak are determined based on the frequency changes received from sensors in the region. Then, local detection work is carried out on the street with leakage potential using local leak detection equipment.

The regular maintenance of these systematic studies in the implementation of the active leakage method also creates serious costs for water administrations. In addition to the costs of creating and monitoring measurable regions, the costs of devices and equipment with different characteristics, sensitivities and costs to be used for the determination of the fault location should also be considered in the studies to be carried out. In this study, a standard calculation structure is defined for the benefits and costs of the ground microphone and regional correlator methods used to locate unreported leaks. By using the defined calculation methodology, the benefits and costs for both methods are analyzed and compared in a sample network. The method to be selected according to the general characteristics of the networks plays an important role for the most efficient operation.

2. Material and Method

2.1. Non-Revenue Water and Components

Non-revenue water refers to water that is supplied to the distribution system but cannot be charged for. Non-revenue water basically consists of three main components: apparent losses, real losses and unbilled authorized uses. This component should be minimal to ensure operational efficiency in the system. In its simplest form, the non-revenue water ratio is obtained as the ratio of the non-revenue water volume to the inlet volume. According to the water balance table, the non-revenue water volume is calculated as the difference between the system inlet volume and the revenue-generating water volume. Real losses occur as a result of malfunctions (reported/unreported) in water distribution systems due to various factors or overflows and cracks in water tanks. This component is lost as leakage before the water supplied to the system reaches the subscribers and constitutes a significant part of the volumetric water losses. One of the most basic tools used to determine the amount and rate of water loss at a certain standard and to monitor its change is the "standard water balance" recommended by International Water Association (IWA) and American Water Works Association (AWWA) (Table 1). In the next stage of this method, Administrative and Physical losses and their sub-components are calculated or estimated based on legal consumptions and input volumes. The standard water balance table, filled in using real data to represent the system, provides the opportunity to access information about the subcomponents of water losses as well as the non-revenue water rate.

Table 1: IWA Standard water balance [2]

(1) System Input Volume	(10) Authorized consumption	(4) Billed authorized consumption	(2) Billed metered consumption	(5) Non-revenue water
			(3) Billed unmetered consumption	
		(9) Unbilled authorized consumption	(7) Unbilled metered consumption	
			(8) Unbilled unmetered consumption	
	(11)Water losses	(15)Apparent losses	(12)Illegal consumption	(6)Revenue water
			(13) Losses due to meter inaccuracies	
			(14) Losses due to reading errors	
		(16)Real losses	(17) Leakages in transmission and distribution systems	
			(18) Leakages in reservoirs	
			(19) Leakages in service connections	

In order to monitor the water loss performance of administrations and municipalities in Turkey and to carry out water loss management studies effectively, systematically and at a certain standard, the "Control of Water Loss in Drinking Water Supply and Distribution Systems" regulation was issued by the Ministry of Agriculture and Forestry in 2014.The most basic methods applied in the management of leaks in the international literature are suggested as active leak control, pressure management, fault repair speed and quality and pipe material management (Figure 1).

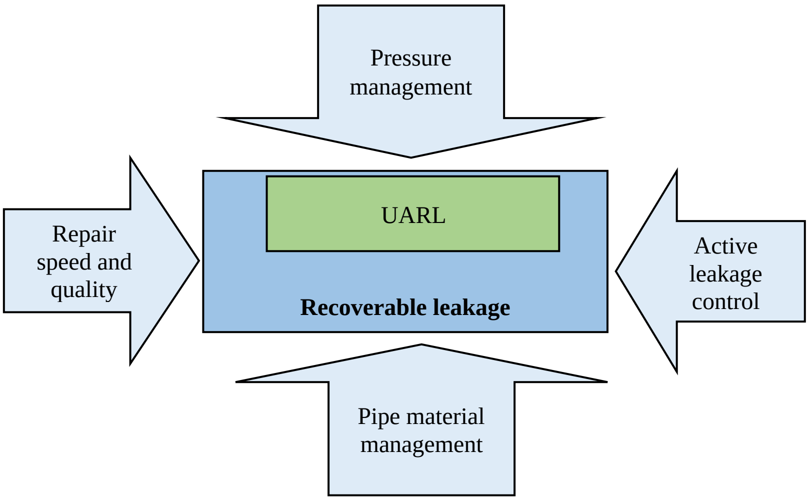

Figure 1: Basic reduction components of real losses [2]

In this figure, the unavoidable annual real loss (UARL) volume is the lowest value of leakages as technical in a water distribution system. This volume is not the economical level. Therefore, the economical leakage level should be defined based on the network characteristics and water utility properties. Pipe material management is defined as the most difficult and costly process in reducing, managing and controlling leaks [17-18]. Therefore, less costly methods such as active leak control, fault repair speed and quality, and pressure management should be applied primarily in the distribution system. Two different intervention methods such as passive leakage control and active leakage control are applied to control and manage malfunctions and leaks occurring in the water distribution system. Active leakage control covers the detection, reduction and prevention of non-surface (unreported) leaks in district metered areas. For active leakage control, it is necessary to create isolated measurement zones in the water distribution system, perform MNF analysis, monitor flow-pressure changes, detect detected leakage locations and carry out leak repairs. This method has no effect on reducing and preventing uncertain leaks. Passive leak control includes the process of repairing and managing surface (reported) faults in distribution systems. This method only covers the management and repair of faults that surface. Leak location detection refers to the determination of the location of potential preventable leaks in the network (in which pipe on a street basis) detected by MNF analysis in district metered areas. Local, regional and instant monitoring systems are used to detect the leak location. Detecting the leak location is very important to reduce the leak volume and ensure water efficiency. Local leak detection involves monitoring the street-based step-by-step change of sound waves by using acoustic devices, referred to as ground microphones, to locate leaks that do not surface in the distribution system. Pipe material type, fault location, fault diameter, soil cover thickness on the pipe, experience of the personnel using the device and inspection time are effective in detecting this type of leak. In order to perform leakage inspection more accurately, night hours when ambient noise is the least should be preferred.

2.2. Leak Detection with Ground Microphone and Cost-Benefit Analysis

Ground microphones refer to local detection devices used to listen from the ground on the pipeline using the acoustic method. This device similarly detects leaks by monitoring acoustic signals. In this context, it should be protected from external sounds such as traffic and wind, and listening should be done step by step at 1- or 2-meters intervals on the pipe. Listening to and locating faults with a ground microphone is one of the most frequently used methods in active leak management. In this method, when the location of the existing network is known, an operator tries to detect the sound of the leaks by listening sensitively on the route of the network. The unreported leaks can be detected and leakage losses can be prevented with this equipment [2], [19] (Figure 2).

Figure 2: Sample Fault Detection Process with ground microphone

In the cost-benefit analysis of this method, after obtaining the data on the total line length and subscriber numbers of the network to be studied, the total water loss in the network must be calculated in l/km/hour (Yilmaz et al., 2023). The current average network pressure of the system and unit water costs should also be defined as variables. The benefits and possible costs that can be obtained were calculated using the following data, while making the cost benefit analysis of this method.

Table 2: Data used in analysis

No	Parameters	Unit
1	Total length of main line	m
2	Average length of service connetions	m
3	Unit cost of water produced	Turkish Liras (TL) /m3
4	Total number of failures in a year	No.
5	The volume of real losses	m^3/month
6	The volume of leakages in water tanks	m^3/month
7	The rate of unreported failures to total failures in water distribution netwokr	%
8	System operation pressure	m

2.3. Leak Detection with Regional Correlator and Cost-Benefit Analysis

Acoustic (zonal) recorders can be considered as a compact unit containing acoustic sensors and programmable data loggers, which can be mounted on a valve-fire hydrant or metal pipe with a magnetic structure. Its size and features enable it to be easily placed and used at points suitable for monitoring sound frequencies in the distribution system. These devices are generally placed at suitable points to listen to the sound of leaks between 02:00 and 04:00 at night, which is the most suitable time for monitoring sound changes. After the recorders are correctly programmed and placed, the propagation of sound waves along the pipeline is recorded and the collected data is analyzed to determine the potential leak line.

Acoustic (regional) correlators are shown to be one of the most effective tools used in locating leaks. In the application of this tool, a mathematical-based relationship is established between the frequency curves of two signals coming from the same leak (potential leak), and the location of the leak is determined. Therefore, instead of looking for the highest noise point, the potential leak point is determined by applying cross-correlation based on the frequency curves between two sensors.

In studies conducted in the literature, this method/tool detects the leak location with high accuracy (generally with an error of less than 1 m). When planning the placement of recorders, two basic elements must be taken into account as they affect the propagation of sound waves. These factors are the type of pipe material to be listened to, the operating pressure present in the system. Another method most frequently used in the active leakage method is to detect faults with a regional correlator. In this method, a constant sound and vibration is listened to with the help of correlators placed at certain distances, and accordingly, the location of the leak is aimed to be determined.

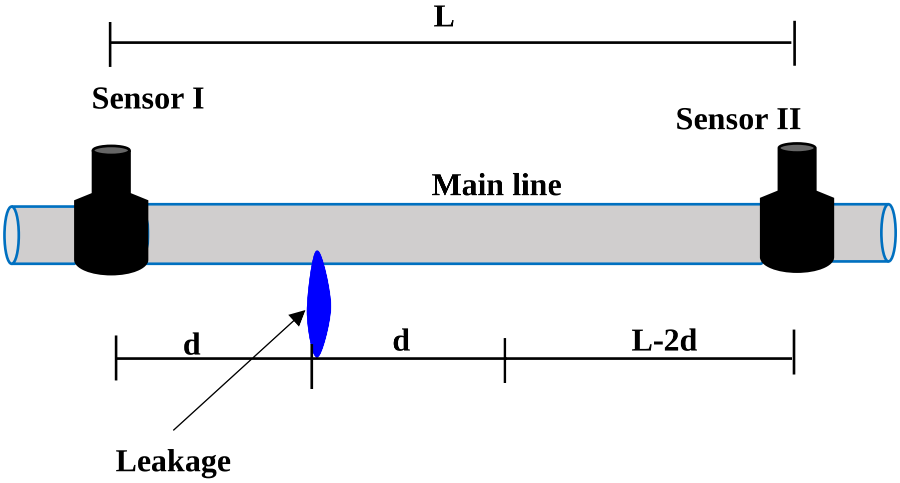

Figure 3: Regional Correlator working structure

The acoustic leak sound correlation method aims to compare the leak sound determined by sensors (monitoring the exit sound frequency of water coming out of the fault crack point) placed at two valve points (in a pipeline) in order to detect leaks that do not come to the surface in the isolated measurement area and to determine the potential leak point accordingly. In this method, it is assumed that the leak sound velocity in the pipe is constant and the leak sound moves from the leak note in both sensor directions. If the crack (leak) in the pipe is at an equal distance from both sensors, the sensors detect the leak simultaneously. If the crack (leak) in the pipe is not at an equal distance from both sensors, the sensors detect the leak at different times, in which case the difference between the time the leak sound reaches the sensors is measured by the correlation process [19].

Sensors are placed at two valve points (points I and II) as shown in the figure. The distance of the leak point that occurs at the bottom of the pipe between the two sensors to sensor no. I is (d), and the distance from the leak point to sensor no. II is marked (d). In this example, the distance (L-2d) between the point (d) away from the leak point and sensor no. II causes the delay time (t) for the leak sound speed to reach sensor no. II. This distance (L-2d), which causes the delay time, can be written as V*t.

Here, V; The speed of sound created by the leakage coming out of the crack, L; horizontal distance (m) between two sensors.$L = (2 * d) + (V * t)$

$$L = (2 * d) + (L - 2d) \tag{1}$$

In this case, the distance of the leak point to the sensor can be written as follows;

$$d = \frac{L - (V * t)}{2} \quad (2)$$

In this method, the correlation process determines the delay time (t) of the leak sound between two sensor points. In this method, the distance (L) between the two sensors must be measured accurately. The speed of the sound of the leak caused by the leak coming out of a crack varies depending on the pipe material, pipe diameter, pipe wall thickness and the characteristics of the ground around the pipe. In general, theoretical values for the speed of sound are used in many cases and are acceptable for the initial assumption of the leak location. However, since the sound speed varies depending on these factors, if there are previous repairs on the pipe (different pipe material, etc.), then the assumption made for the sound speed may change. In this method, the performance of the correlators depends on the system operating pressure and the level of acoustic noise in the network. While making the cost benefit analysis of this method, the benefits and possible costs that can be obtained were calculated using the following data.

Table 3: Data Used in Analysis

No	Parameters	Unit	Value
1	Total Network Length	m	
2	Unit Water Cost	TL/m3	
3	Existing Weighted Pipe Type of the Network	-	
4	Network Failure Repair Cost	TL/piece	₺3.200,00
5	Correlator Cost	TL/piece	₺5.500,00
6	Correlator System and Transmitter Cost	TL/piece	₺120.000,00
7	Estimated Number of Network Failures	pieces/month	Calculating
8	Calculation of Interceptable Flow	m3/month	Calculating
9	Calculation of Benefit Flow Rate to be Obtained with Microphone	m3/month	Calculating
10	Number of Correlators Required	piece	Calculating

Network main line length refers to the length of the pipeline that passes through the street or street in the distribution system and is under the responsibility of the water administration. Unit water production cost refers to the production cost of water obtained from the sources feeding the distribution system. In order to calculate this cost, first of all, all resources feeding the system must be measured continuously and accurately. Energy expenses should be monitored regularly in the promotion system for water production costs. Unit fault repair cost refers to the cost incurred by repairing one reported or unreported fault that occurs in the distribution system. This cost especially has a direct impact on operating cost and efficiency. This cost basically includes components such as excavation, pipe material, labor, filling, road covering, and the cost of unsold water. In systems with a high number of malfunctions, fault repair costs increase linearly, causing the water sales price to reach high levels. Correlator System and Transmitter Cost includes the initial investment cost of the regional correlator used for leak detection in the distribution system.

Table 4: Data Used in Analysis (comt.)

No	Data Name	Unit	Value
11	Determination of Method Performance	%	Calculating
12	Calculation of Interceptable Flow	m3/month	Calculating
13	False Detection Cost	TL	Calculating
14	Detected Fault Repair Cost	TL	Calculating
15	Calculation of the Benefit Flow Rate to be Obtained with Correlator	m3/month	Calculating
16	Correlator Total Cost	TL/year	Calculating
17	Economic Gain to be Obtained with Correlator	TL/year	Calculating

3. Results

In order to compare the costs and benefits of fixed correlator and ground microphone methods, calculations were made for a network whose values are given below.

Table 5: Network Data used in analysis

Parameters	Unit	Value
Total Network Length	km	15
Total Number of Customers	No.	1000
Total Number of Commercial Subscribers	No.	250
Total Number of Housing Subscribers	No.	750
Average Night Pressure	atm	55
System Inlet Flow	m^3/month	125000
Amount of Water Accrued	m^3/month	100000
Average Unit Water Cost	TL/m^3	6.5
Average Unit Water Sales Price	TL/m^3	8
Annual Breakdown Amount	No.	200

As a result of the analyses, different amounts of water were recovered depending on the method chosen in the ground microphone and correlator studies. Additionally, differences were observed in the application costs of the methods. The benefit to be obtained is calculated in direct proportion to the water sales price.

Table 6: Results of cost benefit analysis

Method	Benefit Flow (m^3/month)	Cost (TL)	Benefit (TL)	+ / - (TL)
ALC Ground Microphone	3,075	146,420	184,530	38,110
ALC Correlator	6,430	270,320	385,930	115,610

According to the results, the method is seen as a factor that seriously affects the benefit to be obtained in ground microphone and correlator studies. The benefits to be obtained from the methods also vary depending on the current characteristics of the region and the different values of the network and operating conditions. Therefore, before developing water loss reduction strategies, the current conditions of the region must be analyzed and appropriate methods must be selected.

Conclusions

In this study, a standard calculation structure is defined for the benefits and costs of the ground microphone and regional correlator methods used to locate unreported leaks. By using the defined calculation methodology, the benefits and costs for both methods are analyzed and compared in a sample network. The average non-revenue water rate in Turkey is 42%, and the lowest and highest values are 22% and 67%, respectively. These data show that non-revenue water rates in Turkey are very high and urgent measures must be taken to reduce these rates. It can be concluded that the total annual economic loss due to water loss and leakage in our metropolitan cities exceeds 7 billion TL at 2017 prices. This economic loss is undoubtedly; This is a valid reason in itself to combat water loss and leakage. Technological tools are needed for each method in combating water loss. For pressure management, pressure breaking valves to be placed in various parts of the network or new drinking water tanks to be built, and state-of-the-art equipment such as audio listening devices and magnetic listening devices are required to perform active leakage control. Long-term strategies should be put forward by water utilities to prevent losses and keep the system under control. This strategy should be based on the following studies;

- Continuous and active monitoring of the system
- Constantly combating leaks and administrative loss of components
- Implementation of active leak control approach
- Implementation of subscriber, meter management, pressure management, pipe material management, fault management applications

Although the approach based on active leakage control seems costly, it provides a long-term solution in terms of resource efficiency, subscriber satisfaction and network management. Obtained results; It has been concluded that the method to be chosen according to the general characteristics of the networks plays an important role for the most efficient operation.

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Contribution of Researchers

All authors contributed to the preparation of the article. Abdullah ATEŞ contributed to the writing and editing of the article, Salih YILMAZ contributed to the analysis of the data and evaluation of the results, Mahmut FIRAT contributed to the interpretation of the results and writing the article.

Conflicts of Interest

The author declares no conflict of interest.

References

[1]. Berardi, L., Laucelli, D., Ugarelli, R., ve Giustolisi, O. (2015). Leakage management: Planning remote real time controlled pressure reduction in Oppegård municipality. Procedia Engineering, 119 (1), 72–81.

[2]. Lambert, A. O., Brown, T. G., Takizawa, M., and Weimer, D. (1999). "A review of performance indicators for real losses from water supply systems." Journal of Water Supply: Research and Technology - AQUA.

[3]. Yılmaz, S., Fırat, M., Ateş, A., Özdemir, Ö. (2021). Analysis of Economic Leakage Level and Infrastructure Leakage Index Indicator by Applying Active Leakage Control. ASCE's Journal of Pipeline Systems - Engineering and Practice. 10.1061/(ASCE)PS.1949-1204.0000583.

[4]. European Commission (2014) LEAKCURE project, focus on reducing urban water leakage. http://cordis.europa. eu/news/rcn/36134_en.html. Access 3 May 2021

[5]. Liemberger R, Wyatt A (2019) Quantifying the global non-revenue water problem. Water Supply 19(3):831– 837. https://doi.org/10.2166/ws.2018.129.

[6]. Moslehi, I., Jalili Ghazizadeh, M.R., ve Yousefie Khoshghalb, E. (2019). Economic analysis of pressure management in water distribution networks. Journal of Water and Wastewater, 31 (2), 100–117.

[7]. SUEN. (2020). Türkiye Su Kayıp İstatistikleri.

[8]. Fırat, M., Yılmaz, S., Ateş, A., Özdemir, Ö. (2021). Determination of Economic Leakage Level with Optimization Algorithm in Water Distribution Systems. Water Economics and Policy. 7(3):1-38. 2150014. DOI:10.1142/S2382624X21500144.

[9]. Haider, H., Al-Salamah, I.S., Ghazaw, Y.M., Abdel-Maguid, R.H., Shafiquzzaman, M., ve Ghumman, A.R. (2019). Framework to establish economic level of leakage for intermittent water supplies in arid environments. Journal of Water Resources Planning and Management, 145 (2), 1–12.

[10]. Ahopelto, S. ve Vahala, R. (2020). Cost-Benefit Analysis of Leakage Reduction Methods in Water Supply Networks. Water, 12 (1), 195.

[11]. Choi, G.W., Geun Jo, H., Park, H., ve Jang, D. (2020). Application of decision making model for leakage reduction to economic project in water distribution systems. Journal of Ambient Intelligence and Humanized Computing.

[12]. Moslehi, I., Jalili-Ghazizadeh, M. Yousefi-Khoshqalb, E. (2021). 'Developing a Framework for Leakage Target Setting in Water Distribution Networks from an Economic Perspective'. Structure and Infrastructure Engineering 17(6): 821–37. https://doi.org/10.1080/15732479.2020.1777568.

[13]. Aboelnga, A., Saidan, M., Al-Weshah, R., Sturm, M., Ribbe, L., Frechen, F-B. (2018). Component analysis for optimal leakage management in Madaba, Jordan. Journal of Water Supply: Research and Technology-Aqua 1 June 2018; 67 (4): 384–396. doi: https://doi.org/10.2166/aqua.2018.180.

[14]. Berardi, L., and O. Giustolisi. 2021. 'Calibration of Design Models for Leakage Management of Water Distribution Networks'. Water Resources Management 35(8): 2537–51.

[15]. Ye, G. ve Fenner, R.A. (2011). Kalman Filtering of Hydraulic Measurements for Burst Detection in Water Distribution Systems. Journal of Pipeline Systems Engineering and Practice, 2 (1), 14–22.

[16]. He, S., Wu, Q.H., ve Saunders, J.R. (2009). Group search optimizer: An optimization algorithm inspired by animal searching behavior. IEEE Transactions on Evolutionary Computation, 13 (5), 973–990.

[17]. AL-Washali, T., Sharma, S., Lupoja, R., AL-Nozaily, F., Haidera, M., ve Kennedy, M. (2020). Assessment of water losses in distribution networks: Methods, applications, uncertainties, and implications in intermittent supply. Resources, Conservation and Recycling, 152 (September 2019), 104515.

[18]. Yılmaz, S., Fırat, M., Ateş, A., Özdemir, Ö. (2022). Analyzing the economic water loss level with a discrete stochastic optimization algorithm by considering budget constraints. *AQUA - Water Infrastructure, Ecosystems and Society* 1 July 2022; 71 (7): 835–848. doi: https://doi.org/10.2166/aqua.2022.060

[19]. Pearson, D. ve Trow, S.W. (2005). Calculating the Economic Levels of Leakage. Leakage 2005 Conference Proceedings, 1–16.