Determination of the most economical leakage level in the district-metered area with the optimization algorithm

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Abstract. Failures and breaks occurring in water distribution networks (WDSs) create significant leakage volumes annually. System operating conditions deteriorate due to the increase in the rate of failure and leakage. Therefore, the failure rate and leakage volume should be reduced by applying the most appropriate methods. For this, the most economically suitable level must first be defined in each system or district-metered area. This study aims to define the most economical leakage level with the optimization algorithm in the district-metered area in water distribution systems. For this, network characteristics, subscriber information and water consumption, water production cost, failure rates, and other data in the isolated measurement area are considered. Ant lion optimization algorithm was used as the optimization algorithm in the study. The definition of the methods to be applied to reach the defined ELL level constitutes a reference for the implementers. Water utilities can continue their loss reduction strategies in the most economically efficient way with the help of this method. In the selected regions of the study area, pressure management application and active leakage method application were economical. Thus, it is possible to create a more effective and efficient leakage management plan in the isolated measurement area. It is thought that the results obtained from the study will serve as a reference for practitioners and technical personnel, especially in terms of determining the appropriate leakage target level for each isolated region.

1 Introduction

Non-revenue water in WDNs can be observed at different levels depending on network characteristics and hydraulic data (pressure and pressure fluctuation). Water losses basically consist of two main components: apparent losses and real losses (leakages). Leaks occurring in distribution systems have a very high rate of total losses. Annual leakage rates in distribution systems are between 25 and 30%. The non-revenue water rate is approximately 30% [1].

A significant portion of water is lost due to leaks in WDNs. In developed countries, the volume of these leaks is between 3 and 7% of the water provided, while in developing countries there is more than 50% leakage . In Turkey, the average water loss rate is 42%, (between 22% and 67%) [2]

The basic components are the system operation pressure control, leak detection with acoustic equipment, pipe material management, and improvement of fault repair quality, which have been applied in order to manage, reduce, and control leaks [3]. It is not possible to reduce water losses and leaks in WDNs to zero economically. Leak management can be likened to the patient-doctor relationship. Based on this logic, the current situation of the administration should first be revealed, and suitable/achievable goals should be determined accordingly [4]

In Turkey, water loss targets were defined in the "Prevention and Reduction of water losses/non-revenue water" regulation published in 2014. According to this regulation, water administrations are required to reduce water loss rates to 25% by 2028. Since the dynamic structure and existing infrastructure conditions of the distribution system and water utilities will differ, it may not be realistic to set the same target for all administrations. Therefore, administration-specific water loss rate targets should be set [5]. Many factors such as the current loss rate in the distribution system, the network features (pipe age, diameter, material condition), system pressure, technical team and personnel status in utility, and equipment infrastructure are important parameters in the management of water loss management processes [6,7].

Molinos-Senante et al. (2016) introduced the definition of sustainable economic leakage (SELL) in their study, unlike the ICS. The environmental and water resource costs will be assessed within the ICS. In determining the costs, the number of employees and the number of maintenance, called shadow costs, were calculated [8]. [9] investigated the effects of repairing leaks on water production and operation costs. It was emphasized that after repairing the leaks in DMA, the

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isolated area inlet flow rate decreased by 9%, and accordingly, an 8% decrease in system input energy was detected, and system efficiency improved with the application of active leakage control. [10] argued that it is impossible to reduce water loss to 0 (zero) economically and that a loss reduction policy should be created by accurately analyzing water loss components. They argued that in the analyses carried out for methods accepted in the literature, different results were obtained in the same regions for different methods, and therefore, at least 2 methods should be compared with each other in future studies [10].

The methods and processes applied to combat water losses create direct economic costs for administrations, such as water losses. For four primary methods to reduce physical water losses (pressure management, pipe material management, active leakage control, and fault management), it is necessary to have detailed information about the current network conditions and technological tools are needed for each method [11]. Pressure-breaking valves are to be placed in various parts of the network for pressure management or new drinking water tanks to be built and state-of-the-art equipment such as acoustic listening devices and regional monitoring devices for active leakage control is needed. In this case, a new problem arises for water administrations; "Will the expenditures to reduce water loss have a financial return to the administration?" Administrations need to determine the ideal water loss rate according to current network conditions to answer this question.

Reducing the water loss level in distribution systems to a lower level will not be economical for water utilities since the cost of the activities is higher than the benefits to be obtained. Various mathematical and statistical methods approaches have been applied to analyze the economic level [12–15]. However, these methods do not evaluate all water loss reduction methods holistically. The originality of this study is that it evaluates all the methods used in a holistic manner, makes cost-benefit analyses, and selects the ideal methods accordingly. Thus, with the help of the established algorithms, it is possible to analyze networks under different conditions.

In this study, it is aimed to define the most economical loss level by the optimization algorithm in the DMA in WDNs. For this, network characteristics, subscriber information and water consumption, water production cost, failure rates and other data in the isolated measurement area are considered.

2 Material and Method

2.1 Non-Revenue Water and Leakage Management

A significant rate of the water supplied to the WDN is consumed and paid for by authorized billed customers. However, the remaining part consists of water losses in the form of transmission and distribution system leaks, illegal uses, and losses resulting from meter inaccuracies [3]. Although the failure rates in transmission lines are low, the amount of unit water loss due to a fault is relatively high due to the large pipe diameter and the amount of water transmitted. However, in distribution networks, failure rates reach very high levels depending on many factors, such as the main line length, number of customer connections, current physical condition of the network, and system operating pressure. Due to the high failure rate, the leakage volumes also increase.

Real losses (leakages) constitute a significant part of the total NRW rate in terms of volume, and the increase or decrease of this volume varies depending on the awareness of unreported leaks, detection of their location, or active leak control strategy [16] Leaks occurring in distribution systems are classified as reported leaks (leaks to the surface), unreported leaks (non-surface), and undetermined or unavoidable leaks (non-surface) [17]. Since unreported and unspecified leaks do not come to the surface, it is impossible to detect and repair them unless active leak control is implemented or monitored with other automation and analysis systems.

These leaks cause inefficient use of water and energy resources due to the search for new resources and increased pump operating times, as well as increased operation and maintenance costs due to increasing malfunction and leakage rates, decrease in service quality due to continuous water outages, increase in subscriber complaints, It creates a wide range of negative effects, such as the system becoming technically unmanageable and water quality changing depending on the intensity of the fault. Combating unreported leaks depends on the current status of the network, the technical-economic and technical staff infrastructure of the Administration, recognizing the leaks, determining the amount according to field measurements or calculating it mathematically, detecting the location of the leak, detecting it with equipment with different features and costs, or mathematically-determining the leaks. prediction using statistical or optimization-based methods, etc. It can involve quite complex, difficult, and costly processes. Therefore, the most appropriate, most economical, and achievable loss rate targets must be defined, taking into account the existing conditions in the distribution system and/or isolated measurement areas.

When drinking water distribution systems are examined, defining the economic leakage level by taking into account the network components (failure and leakage rate, number of teams, pressure limits, current situation), the requirements and constraints of prevention methods, and their cost analyses in leakage management appears as a real-time optimization problem [2], [7], [15], [18]. Defining the economic leakage level, analyzing the pressure, which significantly affects failure and leakage, defining the optimal pressure level according to the system characteristics, and defining the optimal number of teams to improve the fault repair speed constitute the most important optimization components. Therefore, to define the economic leakage level, it is necessary to consider all the factors that cause failure and leakage, analyze their effects, define the cost components, perform a cost-benefit analysis, and develop an optimization-based model. Therefore, within the scope of the study, optimization-based models were developed to define the economic leakage level, to determine the most appropriate pressure level and the number of teams to reach this level, taking into account the system and water loss components, the requirements, constraints, and cost components of the prevention methods [2], [7], [19].

2.2 Optimization Method: Ant Lion Algorithm

In this study, ant lion optimization method was used to define the most economical leakage level. The antlion optimization (ALO) algorithm is a nature-inspired algorithm proposed by Mirjalili (2015)[20]. Antlions (scribble bugs) belong to Myrmeleontidae and the order Neuroptera (web-winged insects). The ALO algorithm mimics the interaction between antlions and ants in the trap.

$$x(t) = [0, kumtop(2r(t_1) - 1), kumtop(2r(t_2) - 1), \ldots kumtop(2r(t_n) - 1)] \quad (1)$$

In the equation, sandball cumulative sum n represents the maximum number of iterations and t represents the random motion step. r(t) is a stochastic function. The position of the ants is recorded and used in the following matrix during optimization [20]

$$M = \begin{bmatrix} A_{1,1} & A_{2,1} & \cdots & \cdots & A_{1,d} \\ A_{2,1} & A_{2,2} & \cdots & \cdots & A_{2,d} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_{n,1} & A_{n,2} & \cdots & \cdots & A_{n,d} \end{bmatrix} \quad (2)$$

An objective function is used during optimization to evaluate each ant and the fitness value of all ants is recorded in the following matrix [20]

$$M_{amaç} = \begin{bmatrix} f([A_{1,1}, A_{1,2}, \ldots . A_{1,d}]) \\ f([A_{1,1}, A_{1,2}, \ldots . A_{1,d}]) \\ \vdots \\ \vdots \\ f([A_{n,1}, A_{n,2}, \ldots . A_{n,d}]) \end{bmatrix} \quad (3)$$

Random walks are performed according to Equation (1). Ants update their positions with a random walk at each step of the optimization. The random step is calculated according to Equation 4 [20].

$$X_i^t = \frac{(X_i^t - a_i) x (d_i - c_i^t)}{(d_i^t - a_i)} + c_i \quad (4)$$

ai i. is the minimum random step of the variable, bi i. is the maximum random step of the variable, ci t. in iteration i. is the minimum value of the variable and d is t. in iteration i. is the maximum value of the variable. In this way, ant lions can set traps proportional to their condition and cause the ants to move randomly. To model this behavior mathematically, the radius of the hypersphere of the ants' random walks is adaptively reduced. The following equations have been suggested for this [20].

$$c^t = \frac{c^t}{I} \quad (5)$$

$$d^t = \frac{d^t}{I} \quad (6)$$

The final stage of the hunt is when the ant reaches the bottom of the pit and is caught in the antlion's jaws. In this context, the following equation has been proposed.

$$Antlion_j^t = Ant_i^t iff(Ant_i^t) > f(Antlion_j^t)) \quad (7)$$

In the equation, t is the current iteration, and the Antlion variable is t. j in iteration. It shows the position of the ant lion. Ant variable is t. in iteration i. It shows the position of Ant. Elitism is an essential feature of evolutionary algorithms that allows them to maintain the best solution or solutions obtained at any stage of the optimization process. In this method, the best antlion obtained so far was recorded and considered elite in each iteration.

$$Ant_i^t = \frac{R_A^t + R_E^t}{2} \quad (8)$$

RA t. The ant selected by the Roulette wheel in the iteration walks randomly around the lion, RE ist. It shows the random walk around the elite solution in the iteration. The Pseudo Code of the Antlion Optimization Algorithm is as follows.

- Randomly initialize the initial population of ants and antlions
- Calculate the fitness value of ants and antlion
- Find the best antlions and consider them elite
- While end criterion is not met
- for every ant
- Choose an ant lion using the roulette wheel
- Equation. Update c and d using 5 and 6.
- Create a Random walk using Equations 1 and 4
- Update the ant's position according to Equation 8.
- If it becomes more efficient, replace an antlion with the corresponding ant (Eq. 7).
- If an antlion becomes more efficient than the elite, update the elite.
- End While

3 Analysis and Results

Two district metered areas were chosen as application areas to define the most economical loss level with the Ant Lion algorithm. For this purpose, real field data from district metered areas were taken into account. In order to start the analysis process, the data from the study area must be collected accurately and sustainably. In this context, firstly, network data were transferred to geographical information systems (GIS) in the study areas. Thus, many parameters were obtained, such as network lengths, diameters, number of subscribers, and number of subscriber connections. At this stage, it was possible to obtain location information during the construction stages of the regions. Then, the areas planned to be studied were transformed into DMA regions. In this context, network boundaries were determined, boundary valves were closed, and measurements were started by installing flow meters in the water inlet areas. In addition, pressure gauges were placed at different points to determine the average pressure in the region, and records were taken. Subscribers in the regions were transferred to the GIS system, and monthly water bills were recorded. In addition, the number of faults in the regions and fault resolution operations are also recorded with fault information systems. In this process, the number of failures and the repair and intervention times of these failures are also kept.

In order to produce an effective water loss strategy, firstly, the existing network data must be obtained wholly and healthily. In this way, the problems of the existing network can be identified, and cost-benefit analyses can be made for each water loss reduction method. Using such advanced methods in networks where primary data cannot be collected will not be possible. The data used within the scope of the study are presented below.

Table 1. Data used in the analysis

Parameters	DMA1	DMA2
Main line length (km)	44.08	10.79
Number of billed customers (No.)	9,740	800
Number of non-domestic customer (No.)	328	40
Number of domestic customers (No.)	9,412	760
Number of customer connections (No.)	2,387	533
Average length of service connection (m)	2	5.34
Pressure at MNF time (m)	44.24	42.62
System input flow (m3/month)	146,536	49,083
Billed consumption(m3/month)	80,623	20,457
Average Unit Water Cost (TL/m3)	5	5
Average Unit Water Sales Price (TL/m3)	12.66	8.09
Number of failures (No.)	292	251
Number of failure repair teams (No.)	1	1
Cost of repair team TL/team/month)	35,000	35,000
Average failure repair time (hour/No.)	39.2	64.8
Pipe type	PVC	HDPE

Basic performance parameters in DMAs were calculated (Table 2). It is seen that the region has an NRW rate of approximately 44% and 58%, respectively. Since this rate is well above the desired levels and poses a severe economic difficulty, it is clear that water loss reduction studies are necessary for the region.

Table 2. Basic performance parameters for DMAs

Parameters	DMA1	DMA2
System Flow Rate (m3/month)	146,536	49,083
Billed Consumption (m3/month)	80,623	20,457
Non-Revenue Water (m3/month)	65,913	28,626
Non-Revenue Water (%)	44.98%	58.32%
Unbilled Authorized Consumption (m3/month)	838	0
Apparent Loss ((m3/month)	242	61
Leakage (m3/month)	64,833	28,565

The economic loss level in DMAs was determined. As a result of the optimization, economic analyses were made for 6 essential leakage reduction and control methods, and the economic benefits of methods were calculated as m³/unit. The optimization convergence chart is given below.

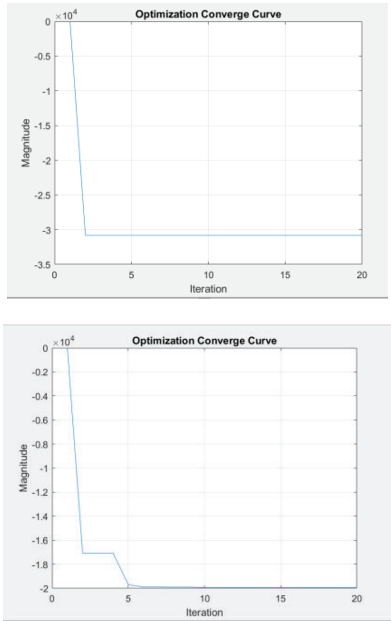

Fig. 1. Convergence Graph for Optimization

Table 3. The results optimization model in DMAs

Parameters	DMA1	DMA2
Pressure (m) after optimization	30	34
Number of Repair Teams (No.)	1	1
Network Renewal	1st option	1st option

It was calculated that at the optimal values calculated for DMA1, the system operation pressure should be controlled and reduced from 44.24 m to 30.00 m, and the optimum number of failure repair teams for the sample DMA1 was 1. At the same time, “1. Option (Do Not Work)” values were found. Moreover, it was calculated that at the optimal values calculated for DMA2, the operation pressure should be controlled and reduced from 42.62 m to 34.00 m. Moreover, the optimum number of failure repair teams for the DMA1 was 1. At the same time, network rehabilitation “1st Option (Do Not Work)” values were found. The network's current and optimum loss amounts and percentages are obtained depending on the calculated optimum values.

Table 4. The ELL values for DMAs

Parameters	***DMA1***		***DMA2***	
	Current	**ELL**	**Current**	**ELL**
Non-Revenue Water (m3/month)	65,913	37,800	28,620	14,930
Non-Revenue Water (%)	44.98	25.8	58.32	30.42

Thus, the economic leakage levels for the DMA1 and DMA2 were calculated as 37,801 and 14,931 m³/month in volume and 25.79% and 30.42% in percentage, respectively. The studies required to obtain the optimum value in the DMA in question have been determined.

Table 5. Basic performance parameters for DMAs

Method	***DMA1***	***DMA2***
Pressure Management (m3/month)	584	5,973
Active Leakage Control (m3/month)	26,502	7,722

In DMA 1;

- The amount of loss can be reduced from 65,913 m³/month to 37,801 m³/month with loss reduction methods.
- by reducing the system average pressure value from 44.24 meters to 30 meters with pressure management, approximately 584 m³/month of water can be added to the system. As a result of repairing the faults detected by the regional correlator listening in the field, 26,502 m³/month of water can be added to the system.

It has been observed that these two methods are not suitable for these regions because there is no known warehouse leak in the region and the network renewal costs are too high compared to the benefits to be obtained. It has been observed that the ground microphone method, which is another active leakage method, will be much less helpful than the regional correlator, which is another active leakage method, due to its relatively longer region length and higher scanning costs.

In DMA 2;

- the amount of loss can be reduced from 28,626 m³/month to 14,931 m³/month with loss reduction methods.
- by reducing the system average pressure value from 42.62 meters to 34 meters with pressure management, approximately 5973 m³/month of water can be added to the system. As a result of repairing the faults detected by the regional correlator listening in the field, 7722 m³/month of water can be added to the system.

It has been observed that these two methods are not suitable for these regions since there is no known warehouse leak in the region and the network renewal costs are too high compared to the benefits to be obtained.

Within the scope of the study, cost-benefit calculations were made for each of the PM, ALC, team management, and meter management methods. While making these analyses, the study areas' main characteristics were considered. In addition, the effects of water loss reduction methods on each other were also taken into consideration. For example, as it is known, pressure reduction has a direct positive effect on water losses. However, reducing the pressure too much reduces the performance of acoustic listening methods such as ground microphones. For this reason, the pressure in the DMA2 area was reduced to 34 meters rather than the minimum value allowed by the regulations (30 m). Because below this level, acoustic listening in that area no longer produces uneconomical results. Active leakage control has an essential place in the fight against water losses. Significant amounts of water can be saved to the system by detecting and repairing faults and monitoring the operations carried out due to acoustic listening by field teams. On the other hand, the costs of listening equipment and repairing faults after their detection cause severe costs for the administrators. In these methods, many parameters, such as the type of pipes in the network (sound transmission conditions), pressure level, network length, subscriber density, unit water cost, and search and repair costs, directly affect the method's performance [7]. The established algorithm calculates the possible benefits of applying these methods. If the benefit to be obtained is more than the amount to be spent, it is concluded that the method is suitable. A similar cost-benefit analysis is performed for each water loss reduction method.

The results obtained reveal the water management plan that decision-makers should follow. Each study area has its problems and solutions. For this reason, while developing water loss reduction strategies, the regions' existing characteristics should be considered, and the cost-benefit analyses of the methods should be recalculated according to the network conditions. In this study, the results are compared for two sample regions. The results argue that regional analyses should be made to develop regional water management plans. Making universal assumptions in the studies may reduce the success of the strategy.

4 Conclusions

In this study, the optimization algorithm defined the most economical leakage level in the district-metered area in water distribution systems. Water network features, subscriber information and water consumption, water production cost, failure rates, and other data in the isolated measurement area are considered for this. Ant lion optimization algorithm was used as the optimization algorithm in the study. Tests were carried out based on field data for pilot-isolated measurement areas. The most economical loss rates were calculated based on region characteristics, team status, current pressure, and loss rates. According to the optimization results, it has been seen that significant leaks can be reduced by applying pressure management in the regions. By applying pressure management in the regions, a total of 584 m^3/month and 5973 m^3/month and leakage can be prevented. Similarly, it has been determined that significant leaks can be reduced in isolated measurement areas by applying the active leakage method. Thus, it is possible to define the most suitable target based on the current conditions of each isolated measurement area. It also determines the methods that must be implemented to achieve this goal. It is thought that the methodology proposed in this study will significantly contribute to technical personnel and decision-makers regarding the economic management of water losses.

Water utilities are earnestly trying to reduce water loss levels in the fight against drinking water losses. The organizations usually set their target water loss levels by the regulations and laws in their region. Such practices are uneconomical for water utilities and lead to many problems, with severe problems in practice. Nowadays, the ELL concept that changes this understanding is put forward. With the ELL approach, it is possible to develop the most appropriate water loss strategy for water utilities. As a result of the study, cost-benefit calculations were made for each of the PM, ALC, team management, and meter management methods and which methods should be selected for each budget situation, the estimated amounts to be spent for the implementation of these methods, and the possible benefits to be obtained were calculated.

Data security is one of the most critical factors in the application of the method. For the calculations to be accurate, the primary network data in Table 1 must be accurately measured by SCADA, GIS, and corporate subscriber systems.

The definition of the methods to be applied to reach the defined ELL level constitutes a reference for the implementers. Water utilities can continue their loss reduction strategies in the most economically efficient way with the help of this method. The scope of the study can be extended by adding new water loss reduction methods to the algorithm to be developed in the future.

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