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Analyzing the economic water loss level with a discrete stochastic optimization algorithm by considering budget constraints

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ABSTRACT

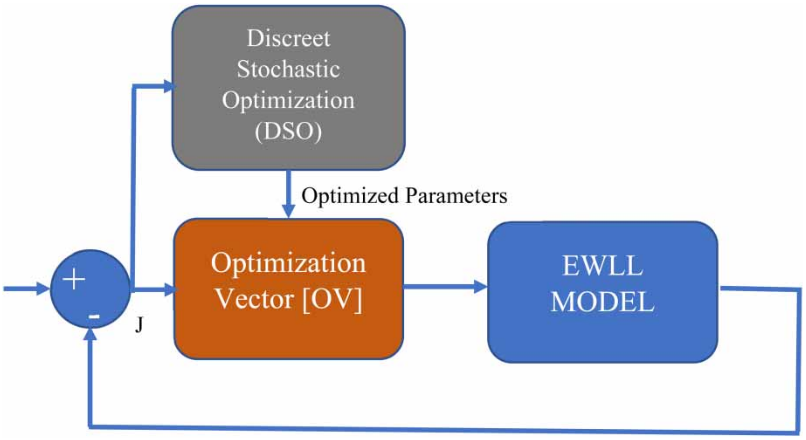
Water losses in water distribution systems (WDSs) cause inefficiency of water resources and increase operating costs. Water loss management (WLM) methods generally have high initial investment and operating costs. However, the budget planned within the scope of WLM in administrations is generally limited. Therefore, the most appropriate method should be determined by considering the budget conditions and cost–benefit analysis. The aim of this study is to propose a new economic water loss level (EWLL) model in WDSs with the different budget constraints of 5, 15 and 20% of the annual income. This EWLL model was developed by the discrete stochastic optimization algorithm. The EWLL and economically recoverable leakage volumes were determined by considering the budget constraints. Moreover, the most appropriate methods were determined to reach the EWLL values defined according to the budget constraints. The EWLL was calculated as 8.62% by the optimization model without budget constraints. Moreover, the EWLL values with budget constraints of 5, 15 and 20% of the annual income were determined as 56.82, 21.14 and 18.02%, respectively. This EWLL model will make a significant contribution to the annual planning in WLM depending on the budget constraints of the administrations.

Key words: budget constraint, economic loss level, optimization model, water losses, water loss management

HIGHLIGHTS

- A new economic loss level model was developed with the optimization algorithm.
- The budget constraints for water loss management practices were considered.
- The economically recoverable loss volume was determined.
- The economic loss levels were defined with different budget constraints.
- The developed model was tested with field data.

GRAPHICAL ABSTRACT



INTRODUCTION

Non-revenue water (NRW) includes the leakages in water distribution systems (WDSs), apparent losses due to meter inaccuracies and illegal connections and authorized unbilled consumptions (Farley & Trow 2003; Farley & Liemberger 2005; Pearson 2019). Globally, the amount of leakage and apparent losses in developing countries is around 45 million m^3/day and 30 million m^3/day, respectively (Liemberger *et al.* 2006). Water utilities in developing countries face significant challenges and adverse effects of water losses in WDSs. The most appropriate water loss management (WLM) strategy should be defined in order to provide reliable water supply to customers and to establish an efficient operation plan (Mutikanga *et al.* 2010; Syed *et al.* 2021). NRW has significant adverse effects on economic losses, water resource and energy inefficiency, and safety of water service in WDS. Therefore, the NRW rate in WDSs should be reduced and a sustainable urban water management plan should be established (Aboelnga *et al.* 2018). Water losses and leaks in WDSs cause significant operational, environmental and financial problems (Duan *et al.* 2020). Therefore, an appropriate WLM strategy should be defined by considering the current state of the WDS in order to reduce these negative effects (Bozkurt *et al.* 2022).

The fundamental methods that are the district metered area (DMA) design (Bonthuys *et al.* 2019; Creaco & Haidar 2019; Liu & Lansey 2020), minimum night flow (MNF) analysis (Choi *et al.* 2015; Amoatey *et al.* 2018; Negharchi & Shafaghat 2020), pressure management (PM) (Creaco & Walski 2017; Monsef *et al.* 2018; Giudicianni *et al.* 2020), improvement of leak repair quality and speed (Salguero *et al.* 2019; Savic & Kapelan 2019; Guo *et al.* 2021), network renewal and material management (Aşchileana *et al.* 2017; Lakehal & Laouacheria 2017; Bishop *et al.* 2019; Wang *et al.* 2020), have been applied within the scope of WLM. However, the costs of the equipment and installation, construction, labor, data monitoring and transfer and system operation arise with the implementation of these methods in the field. Therefore, the current status of systems should be known and the technical and equipment capacity of the administration should be sufficient (Liemberger & Frauendorfer 2010; Sechi & Zucca 2017; Guo *et al.* 2021). Creaco & Walski (2017) presented an economic analysis structure for pressure control and leakage management. The cost components (installation, operating, data transfer, maintenance) of pressure management and control systems were analyzed. The results pointed out that no pressure controls are needed if leakage and the variable O&M cost of water are low.

The high-cost investments are made in order to achieve the targets defined without considering the system characteristics. However, the investments made are not generally economical because cost and benefit (C&B) analysis is not considered. In this case, a new problem arises for water administrations; will the expenditures to reduce water loss be financially returned to the administration? The most appropriate loss level in systems where the operating and production costs of water are quite high is different from the level in gravity-fed systems that do not require energy consumption or treatment. Therefore, the C&B standard and economic analysis model should be defined by considering the operational components (Mutikanga *et al.* 2013; Ezbakhe & Foguet 2019; Tsanov *et al.* 2020; Eissa *et al.* 2022). The factors that are regional-based assessment, current status of system, financial capacity, C&B of methods should be considered in defining the most appropriate loss level in WDS (Deidda *et al.* 2014). Therefore, the economic water loss level (EWLL) should be defined based on the current network conditions (Wyatt & Alshafey 2012; Islam & Babel 2013; Haider *et al.* 2019). Giudicianni *et al.* (2020) proposed a novel method for network partitioning in order to manage the leaks and save the water and energy with optimization algorithm. The financial analysis standard was defined to calculate the optimal period of the pumps.

The EWLL could be defined as the point where the unit cost to reduce losses is equal to the water sales price (Firat *et al.* 2021). Reducing water losses in WDS to less than the EWLL value would not be economical as the operating costs outweigh the benefits. A short-term EWLL methodology is proposed based on field data for active leakage control (ALC) in WDS. In this methodology, the EWLL target is defined using flow and pressure data and marginal cost (Moslehi *et al.* 2021). Moreover, four different methods, namely total cost, marginal cost, total cost–benefit method and component-based method, were used to estimate the economically recoverable losses. Planning the investments for WLM practices based on the EWLL target is quite important in terms of ensuring efficiency, especially in administrations experiencing financial difficulties (Heryanto *et al.* 2021). The C&B components for the ALC were defined and the EWLL was calculated in order to determine the economically recoverable leakage volume (Yilmaz *et al.* 2021).

The EWLL based on the network characteristics, the requirements and costs of the methods is a real-time optimization problem (Firat *et al.* 2021). Defining the most appropriate level of pressure, which has a significant effect on failure and leakage, and defining the most appropriate number of leakage detection teams to improve the speed of failure repair, constitute the most important optimization components. Therefore, it is necessary to consider the factors affecting the failure and leakage, to define the cost components, to make a C&B analysis and to develop an optimization-based model. Firat *et al.* (2021) proposed a novel EWLL model based on optimization algorithm by considering the system components, the requirements, constraints and cost components of methods. In this model, the most appropriate pressure level and the number of leak detection teams were determined to analyze the EWLL.

However, the budget allocated within the scope of WLM in administrations is not unlimited. The budget in the administration is firstly allocated for the most basic expenses such as network operation, personnel, energy and new investments. Therefore, a certain part of annual budget may be planned in order to reduce water losses in administrations. The budget constraints were not considered as a parameter in the model proposed by Firat *et al.* (2021). Therefore, there is a need for a new EWLL model that considers the budget constraints for WLM. The aim of this study is to propose a new EWLL model in WDSs with the different budget constraints of 5, 15 and 20% of the annual income. This EWLL model was developed by the discrete stochastic optimization (DSO) algorithm. The EWLL and economically recoverable leakage volumes were determined by considering the budget constraints. Moreover, the most appropriate methods were determined to reach the EWLL values defined according to the budget constraints. The novelty of this study is that the current characteristics of the network and the budget constraints planned by the administration annually for WLM are considered in the EWLL analysis. It is thought that this study will make a significant contribution to the annual planning and roadmap in WLM, especially depending on the current situation, capacity and budget constraints of the administrations.

EWLL ANALYSIS WITH BUDGET CONSTRAINTS

The fundamental hydraulic parameters such as flow and pressure in WDSs should be regularly monitored with the Supervisory Control and Data Acquisition (SCADA) system in order to manage water losses (physical and administrative losses) in a sustainable way. In addition, system performance should be monitored by performing cost–benefit analysis for WLM practices (Sechi & Zucca 2017; Firat *et al.* 2021; Guo *et al.* 2021). Therefore, the EWLL model was developed by considering system characteristics and budget constraints in administration to define the economically recoverable loss volume. This model includes the system and water loss components, cost components of reduction methods. In this model, cost–benefit analysis standards for fundamental methods of DMA design, PM, ALC, water meter management, network renewal and team management for leak detection were considered (Figure 1; Firat *et al.* 2021).

The EWLL model basically includes the following analyses: (i) remaining useful life in the network, (ii) unit cost for DMA creation, (iii) economically recoverable loss volume with PM, (iv) economically recoverable loss volume with the ALC method, (v) leak detection team optimization and (vi) economically recoverable loss volume with meter rehabilitation (Firat *et al.* 2021). The PM and ALC methods are critical in WLM, and the variables of pressure level and the number of team are optimized to calculate the EWLL value. The NRW amount and rate are calculated using Equations (1) and (2),

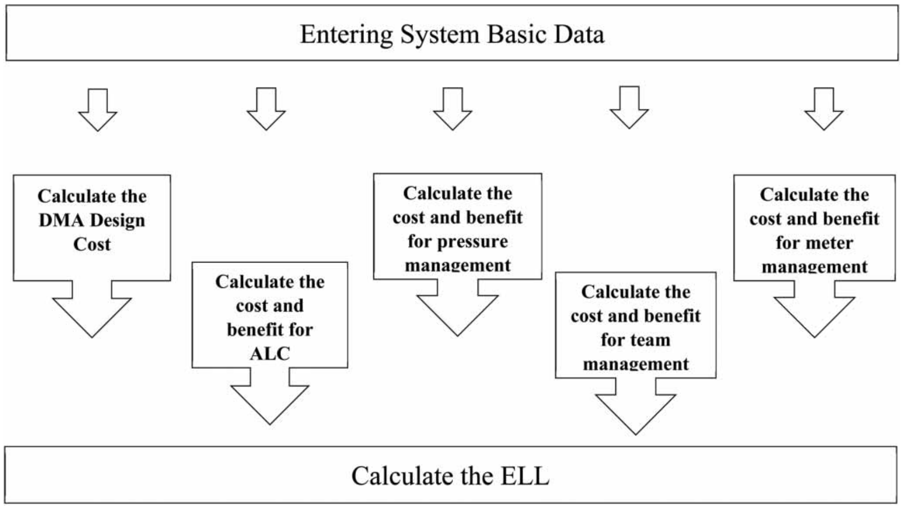


Figure 1 | System model for cost analysis of WLM methods.

respectively, considering the system inlet volume (V_{Input}), and the authorized consumptions (V_{cons}).

$$V_{\text{Loss}} = V_{\text{Input}} - V_{\text{cons}} \tag{1}$$

$$\text{Non} - \text{revenue water rate} = \frac{V_{\text{Loss}}}{V_{\text{Input}}} \tag{2}$$

where V_{Loss} is the non-revenue water volume in the system, V_{Input} is the system input volume and V_{cons} is the authorized billed consumptions. The system input volume should be regularly measured with the electromagnetic/ultrasonic flow meters. Moreover, the authorized billed consumptions are obtained from the customer information management system in utility. Two objective functions are used in the EWLL model. The percentage of total loss is minimized and the recovered loss volume (the amount of water saved to the system) is maximized (Equations (3) and (4)).

$$\text{Total Benefit} = \text{Benefit}_{\text{pressure}} + \text{Benefit}_{ALC} + \text{Benefit}_{\text{team management}} + \text{Benefit}_{\text{meter management}} \tag{3}$$

$$\text{EWLL} = \frac{V_{\text{Loss}} - \text{Total Benefit}}{V_{\text{Input}}} \tag{4}$$

In these equations, the EWLL is the economic water loss level, the *total benefit* refers to the maximum useful flow rate (economically recoverable flow rate) that can be obtained from the applied methods. The $Benefit_{pressure}$ is the economically recoverable flow rate with pressure management, the $Benefit_{ALC}$ is the economically recoverable flow rate with the ALC method, the $Benefit_{team\ management}$ is the economically recoverable flow rate with team management strategy and the $Benefit_{meter\ management}$ is the economically recoverable flow rate with meter management strategy.

The objective function in this optimization model is actually a multi-objective function that is defined by Equation (5) to solve both minimization and maximization problems simultaneously.

$$J = w_1 * (\text{Total Benefit})^{-1} + w_2 * \text{EWLL} \tag{5}$$

In this equation, w_1 and w_2 are the weights that balance between the two variables. Weight values are defined according to which variable is more effective during optimization. For example, if the effects of both variables are equal, it is taken as $w_1 = w_2 = 0.5$. These parameters are adjusted during the optimization. The total benefit is maximized and the EWLL value is minimized in the optimization model. The point where these two levels overlap is defined as the EWLL. It is extremely difficult to find the appropriate pressure value and to determine the most appropriate number of teams. Therefore, the values of these parameters should be obtained with optimization algorithm by considering all constraints. A DSO algorithm is used to

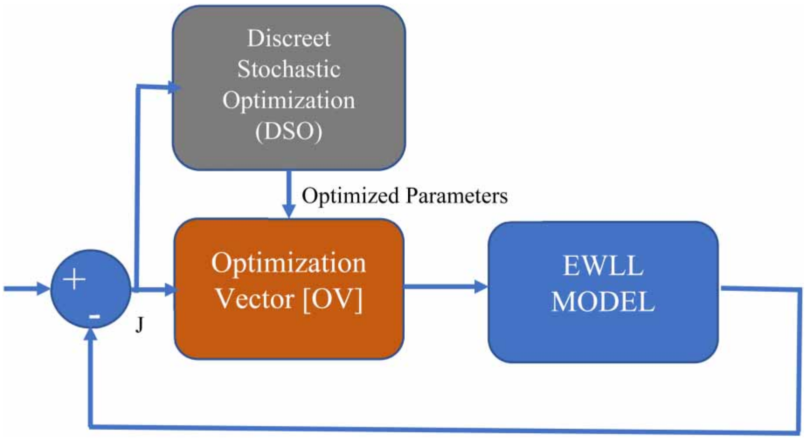


Figure 2 | Diagram applied for the proposed EWLL model using the DSO algorithm.

find the optimal values of parameters. Pressure and number of teams are simultaneously optimized to optimize the optimization vector (OV), which is part of the proposed EWLL model and includes pressure level and number of team (Figure 2).

OV vector can be defined as follows: $OV = [P \cdot NW]$, where P is the pressure and NW is the number of the worker. The pseudo code of the algorithmic structure used during the study is as follows. During the optimization, the following steps were followed. According to these steps, the algorithm first calculates the model parameters. Then the initial solution is proposed. Candidate solutions are determined according to the initial solutions. These candidate solutions are in the form of back and forth motion with a random coefficient in the parameter vector space. Candidate solutions are suggested as $P_{new} = P_{old} \pm$ rand or $NW_{new} = NW_{old} \pm$ rand. According to the candidate solution obtained, the objective function J is calculated. The algorithm works in a way that minimizes the multi-objective function whose parameters were presented in the previous sections until it reaches the maximum number of iterations or the threshold value (e) determined at the beginning of the optimization. The maximum number of iterations is completely determined by the user, according to the dynamics of the problem. The threshold value was used to prevent the algorithm from entering an infinite loop as a result of the tests performed according to the problem dynamics.

Step 1: START
Step 2: Calculate model parameters
Step 3: Set initial values of OV vector. Define P^0 and NM^0
Step 4: Generated candidate solution of OV.
Step 5: Calculate objective function $J = w_1 * (Total\ Benefit)^{-1} + w_2 * EWLL$
Step 6: if $f(OV_c{}^n) - f(OV^n) < 0$
$n = n + 1$
  Update $OV^n = OV_c{}^n$
    else
$n = n + 1$ if $f(OV^n) < e$ || Maximum Number of the iteration $= n$ Optimization completed.
Go to Step 7.
Else   Go to Step 4
End
End
Step 7: END

A new problem arises in the EWLL model; will the total budget foreseen by the administrations for water loss reduction be sufficient for the entire study? The budget allocated within the scope of WLM in administrations is not unlimited. In general, a certain part of annual budget (limited) may be planned to reduce water losses in administrations. However, budget constraints were not considered as a parameter in the model proposed by Firat *et al.* (2021).

The annual budget for WLM practices may vary at a certain rate (for example, between 5 and 25%) of the annual total budget according to the current situation, the existence of water resources, technical and financial capacity of the administrations. Therefore, in this study, the EWLL analysis with the optimization algorithm according to the budget constraints in the administrations was performed. The methods that will provide maximum benefit are determined by applying the EWLL model. In this context, a total of seven different C&B scenarios for the budget constraints were defined using the fundamental methods such as PM, ALC, meter management and team management applied in WLM.

Scenario 1. Implementation of PM

In this scenario, the optimum pressure level is not optimized since PM and ALC methods are not used together. There is no need to define the appropriate level for pressure, since ALC is not implemented. The minimum pressure requirement defined in the regulation (the minimum pressure is determined in the range of 20–30 m in Turkey) or by the user according to the network feature was considered in analyzing the benefits. The DMA should be planned in order to implement PM. Therefore, the DMA creation cost is the cost component that should be defined for this scenario.

The reduction in leakage rate (benefits) or new leakage level (L_1) at regulated pressure (P_1) due to PM is calculated on the basis of Equation (6). The costs for this scenario are analyzed based on cost standard of DMA design defined by Firat *et al.* (2021).

$$L_1/L_0 = (P_1/P_0)^{N_1} \tag{6}$$

where L_0 is the initial leakage at P_0 pressure, L_1 is the new leakage at the regulated pressure, P_0 is the initial pressure, P_1 is the regulated pressure and N_1 is the leakage exponent (Lambert & Morrison 1996).

Scenario 2. Implementation of ALC

The PM will not be performed in the system in this scenario. The ALC method will be applied for detection of leakages. Therefore, it was thought that the pressure value would be constant in the analysis and the leak inspection quality would remain constant at the initial conditions. C&B should be recalculated according to these conditions. The cost components are the cost of DMA design and leak detection activities in the field. The leakage inspection quality values are defined by assuming that the leakage inspection quality does not change according to the pressure (Table 1; Firat *et al.* 2021).

Scenario 3. Implementation of ALC and PM methods

In this scenario, the simultaneous implementation of PM and ALC methods that affect each other is considered. The most appropriate pressure level should be defined in the EWLL model to get the most benefit from ALC and PM methods. The quality of leak inspection and detection is adversely affected by acoustic methods in ALC in case the pressure is reduced too much. In this scenario, the cost components are the cost of creating the DMA. The PM and ALC methods could be applied together after DMA is established. Thus, the C&B to be obtained for the implementation of these methods together will be calculated.

Scenarios 4–5 and 6. Meter calibration and renewal

C&B in this scenario were analyzed by considering a total of three different calibration possibilities for authorized customer meters. Firstly, the C&B are calculated in case of the first and second calibrations of the meters over 10 years old. Finally, the option to renew the meters was considered and the C&B are defined in case of replacing the meters over 10 years old.

Table 1 | Defining the leakage inspection quality

Variable	Unit	Value
Failure rate detected by the first inspection activity	%	40%
Failure rate detected by the second inspection activity	%	25%
Failure rate detected by the third inspection activity	%	14%
Failure rate detected by the fourth inspection activity	%	9%
Failure rate detected by the fifth inspection activity	%	7%
Failure rate detected by the sixth inspection activity	%	5%

Scenario 7. Team management

In this scenario, the C&B are analyzed according to the condition of increasing the number of teams, considering the number of teams available in the management of failures.

The budget constraints should be defined to the algorithm in addition to the cost–benefit standard for seven different scenarios. The revenue budget is calculated based on the amount of authorized billed consumptions. Then, how much of annual income proportionally will be used in WLM is defined as a variable to the algorithm. Thus, the total C&B variables with budget constraints are calculated and defined in the algorithm.

$$\sum_{1}^{n} \text{Total Benefit} = \text{Benefit}_n \tag{7}$$

$$\sum_{1}^{n} \text{Total Cost} = \text{Cost}_n \tag{8}$$

There are three basic limitations in the algorithm defined in this study. The first is that the total cost to be spent is less than the constrained budget. Another constraint is that the cost and benefits of one of the alternatives that are PM, ALC and 'ALC and PM' are selected by the algorithm. These alternatives cannot be applied at the same time. For this reason, only one of these three cases is selected by the algorithm. Similarly, the same constraints are also valid for alternatives of the first calibration of meters; the second calibration of meters and meter renewal. Therefore, the algorithm is expected to choose only one of these three cases.

$$\text{Budged Rate for WLM} = \text{Total Volume of Authorized billed consumptions} * n \tag{9}$$

In this equation, the budget constraint (n) is defined as a percentage of the total annual revenues (due to authorized billed consumptions). In this case, how much of the revenue will be used in WLM (can vary between 5 and 20%) should be selected in the algorithm. The created algorithm revises the solution matrix according to the constraints after calculating all the probabilities. Finally, the algorithm chooses the combination with the highest benefit in the solution matrix that provides all the constraints, and presents the EWLL value and the methods to be implemented with budget constraints.

STUDY AREA AND DATA

In this study, the Kayseri province located in the Central Anatolian region of Turkey was chosen as the study area (Figure 3). In the study area, the total network length is 4,200 km and the total number of customers is around 550,000 (KASKİ 2020). The WLM activities have been performed since 2018. The analysis of the water balance, flow-pressure monitoring and MNF monitoring are performed in DMAs. The system input flow rates in the pilot area are regularly monitored by the SCADA system. In addition, geographical information system (GIS) and customer management systems are used and regularly updated for the systematic monitoring of network and operational data in the region. Network, service connection, customer and other operational data in the region were obtained by using these databases (Table 2).

ANALYSIS AND DISCUSSION

In this section, the most appropriate loss rate and amount that can be reduced economically are analyzed using the EWLL model with budget constraints. Firstly, the economically recoverable losses and the EWLL were analyzed without the budget constraints. Moreover, the economically recoverable losses are determined separately depending on the implementation of PM, ALC, team management and meter management methods. Then, the EWLL and economically recoverable losses were determined by considering the various budget constraints for WLM practices in the administration.

EWLL ANALYSIS BASED ON NETWORK CHARACTERISTICS

The most appropriate NRW rate in the current conditions was calculated by defining the basic data to the algorithm. The current NRW rate in the region is quite high as 61.98% (15.47 l/s). The most appropriate NRW rate and volume was calculated as 8.62% (2.15 l/s) by the optimization model. Thus, a significant amount of loss (13.32 l/s) can be reduced economically with on-site activities in the region. Thus, the NRW rate can be economically reduced below the 10% level.

Moreover, the most appropriate pressure level and the number of teams were determined by the optimization algorithm according to the network characteristics. The pressure in the region was measured as 66 m. The optimum pressure level

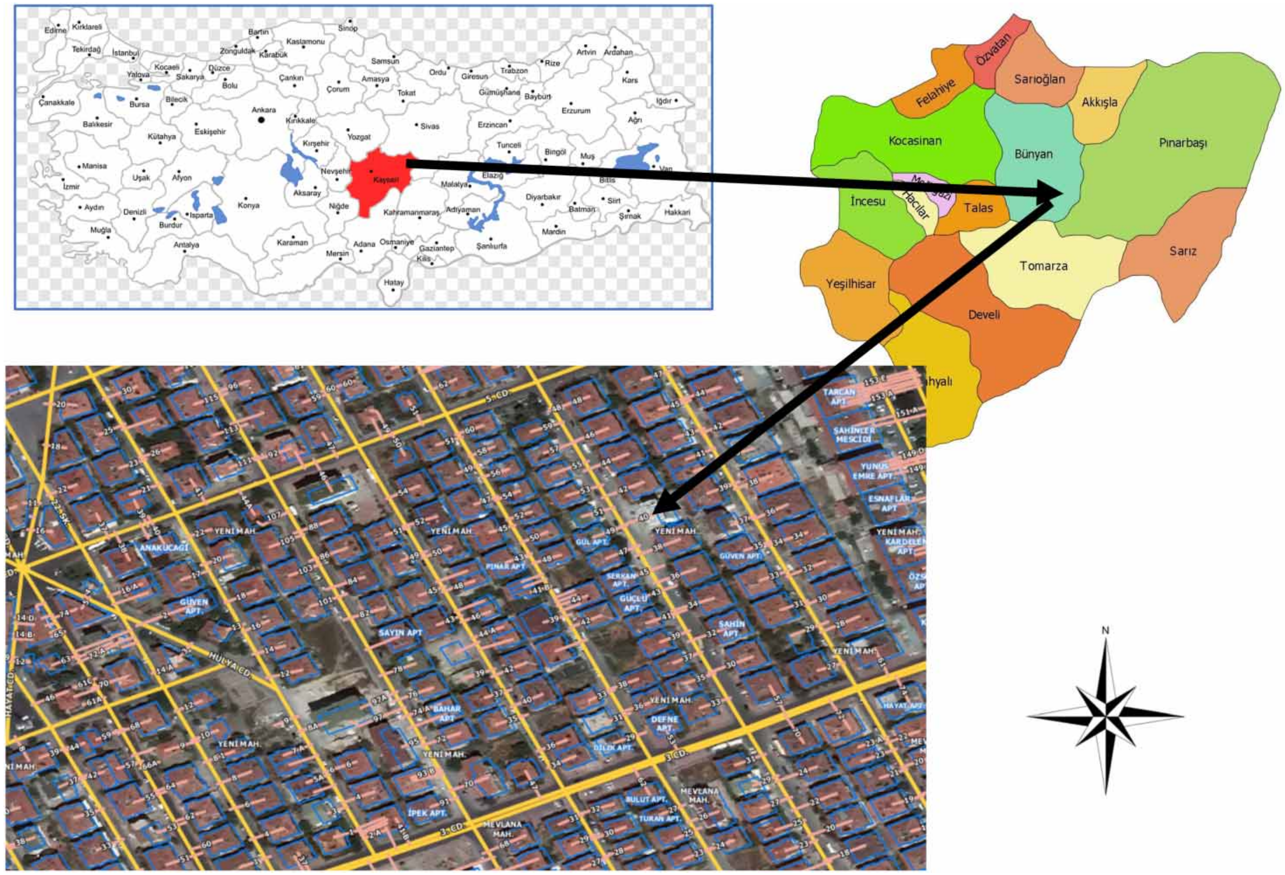


Figure 3 | The location of the study area.

in the system was determined as 38.08 m. In addition, the most appropriate number of teams was defined as three in order to manage leaks more effectively and economically.

As a result, the loss amount of the system can be reduced from 15.47 to 2.15 l/s by implementation of reduction methods. Therefore, four fundamental methods should be implemented in the field in order to reach the most appropriate NRW rate. The benefit of each method is calculated separately depending on the application of these methods in the EWLL model. It was determined that four basic methods are economically viable in WLM in the region. Approximately 5.94 l/s part of the losses in the system can be reduced economically by reducing the pressure from 66 to 38 m with applying the PM. Similarly, the economically recoverable losses were determined as 4.76 l/s in case of leak detection activities with acoustic methods. In addition, the loss rate of 1.34 l/s will be economically reduced by replacing all meters over 10 years old. It was seen that approximately 1.28 l/s of water can be saved into the system by increasing the number of teams. Thus, a total of 13.32 l/s loss can be economically reduced depending on the application of these fundamental methods.

It is not technically and economically possible to reduce the losses to zero in distribution systems. The analysis of the EWLL value and economically recoverable loss volumes contributes to the achievement of economic efficiency. It is a well-known fact that system pressure affects leaks and failures. In addition, the most basic methodology applied in the management of unreported failures is the ALC method. According to the results of the analysis, it is seen that the most benefit in reaching the EWLL level will be obtained from the PM and ALC methods, respectively.

EWLL ANALYSIS WITH BUDGET CONSTRAINTS

In the previous section, the EWLL value and economically recoverable loss volume were determined without the budget constraints. In this section, the budget constraints are considered for the EWLL analysis. For this purpose, benefits and costs were analyzed in the budget constraints of 5, 15 and 20% of the annual income in the administration. Then, the new EWLL values and economically recoverable loss volumes with the different budget constraint rates were determined. The results of the EWLL

Table 2 | Basic network data in DMA

Variables	Unit	Value
Population	No.	1,603
Main length	km	18
Number of customers	No.	2,225
Number of commercial customers	No.	225
Number of residential customers	No.	2,000
Number of service connections	No.	360
Average of service connection length	m	8
Operation pressure at MNF	m	66
Minimum operation pressure	m	20
Maximum operation pressure	m	66
System input flow rate	l/s	24.97
Authorized billed consumption volume	l/s	9.5
Unit water production cost	TL/m^3	2.91
Unit water sales price	TL/m^3	3.68
Ratio of meter over 10 years old to total meters	%	47
Is there a DMA approach in the region?	e/h	e
If DMA is available total DMA network length	m	18,000
How many DMA zones are there?	No.	1
Total number of reported failures	No.	31
Total number of failure repair teams	No.	2
Team creation cost	TL/team/month	₺19.500,00
Average failure resolution time	hour/No.	30
Current weighted pipe type of the network	–	HDPE

model for each budget constraint are compared and discussed with the EWLL value calculated without the budget constraints. Moreover, the methods that should be applied in each budget constraint are determined in order to reach the EWLL value defined with budget constraints. Then, the economically recoverable loss rates by the implementation of these methods are analyzed separately. Thus, a road map was created for effective and sustainable WLM within the budget constraints planned annually in the administration. The benefit and costs calculated according to budget constraints are given in Table 3.

It was revealed that the methods of PM and ALC (scenario 3), meter management (meter renewal) and team management should be applied and a total of 449,235.00 Turkish Liras (TL) should be spent in order to reach the EWLL value defined in Table 3.

Table 3 | Benefits and costs for basic methods under budget constraints

Methods	Scenario	Benefit (l/s)	Total cost (TL)
Pressure management (PM)	1	8.91	₺103,900.00
ALC	2	6.24	₺281,250.00
PM and ALC	3	10.7	₺278,105.00
Meter management (the first calibration)	4	0.78	₺10,541.00
Meter management (the second calibration)	5	0.62	₺10,541.00
Meter management (meter renewal)	6	1.34	₺151,630.00
Team management	7	1.28	₺19,500.00
Total		10.97	449,235.00

Another issue that needs to be determined in order to analyze the EWLL value under the budget constraints is the determination of the budget constraint rates. Therefore, it should be defined how much of the revenues in the administrations will be used for WLM practices. The EWLL values and economically recoverable losses are analyzed by assuming the different budget constraints (20, 15 and 5% of the revenues) (Table 4).

The EWLL analysis was performed for the budget constraint rate of 20% and the budget was determined as 174,419.00 TL by considering the total revenue of administration (Table 4). The methods of PM, meter management (the first calibration) and team management should be applied within these budget constraints in order to reach the EWLL value determined in the table. It has been determined that a total of 10.97 l/s of water can be saved to the system with this budget (the budget constraint is 20%).

On the other hand, it is no longer possible to implement the ALC method and replace all meters over 10 years old in administration due to the budget constraints. Therefore, it is recommended to apply the PM method in the system, calibrate the meters (the first calibration) and increase the number of team to 4. The total cost of the methods to be applied was calculated as approximately 133,941.00 TL. The EWLL value was calculated as 18.02% (4.5 l/s) under the budget constraint (20%, 174.419.00 TL).

These analyses were performed separately for 15 and 5% budget constraints (Table 4). The total budget was obtained as 130,814.25 TL in the case of the 15% budget constraint rate. The EWLL analysis was performed with this budget constraint.

Table 4 | Benefits and costs for different budget constraints

Methods	Scenario	Benefit (l/s)	Total cost (TL)
Budget constraint is 20%			
PM	1	8.91	₺103,900.00
ALC	2	6.24	₺281,250.00
PM and ALC	3	10.7	₺278,105.00
Meter management (the first calibration)	4	0.78	₺10,541.00
Meter management (the second calibration)	5	0.62	₺10,541.00
Meter management (meter renewal)	6	1.34	₺151,630.00
Team management	7	1.28	₺19,500.00
Total		10.97	₺133,941.00
Budget constraint is 15%			
PM	1	8.91	₺103,900.00
ALC	2	6.24	₺281,250.00
PM and ALC	3	10.7	₺278,105.00
Meter management (the first calibration)	4	0.78	₺10,541.00
Meter management (the second calibration)	5	0.62	₺10,541.00
Meter management (meter renewal)	6	1.34	₺151,630.00
Team management	7	1.28	₺19,500.00
Total		10.19	₺123,400.00
Budget constraint is 5%			
PM	1	8.91	₺103,900.00
ALC	2	6.24	₺281,250.00
PM and ALC	3	10.7	₺278,105.00
Meter management (the first calibration)	4	0.78	₺10,541.00
Meter management (the second calibration)	5	0.62	₺10,541.00
Meter management (meter renewal)	6	1.34	₺151,630.00
Team management	7	1.28	₺19,500.00
Total		1.28	₺19,500.00

It was determined that the methods of PM and team management are economically applicable in this budget constraint defined. The losses can be reduced to the EWLL value in the system by applying PM and increasing the number of team. The EWLL value was calculated as 21.14%. Thus, a total loss of 10.19 l/s was reduced with a total expenditure of 123,400 TL in this budget constraint.

Finally, the total budget was obtained as 43,604.75 TL in the case of the 5% budget constraint rate. The EWLL analysis was performed with this budget constraint. It was determined that the method of team management is economically applicable in this budget constraint defined. The losses can be reduced to the EWLL value by increasing the number of teams to 4. The EWLL value was calculated as 56.82%. Thus, a total loss of 1.28 l/s was reduced with a total expenditure of 19,500 TL in this budget constraint. The comparison of analysis results for different budget constraints is given in Table 5 and Figures 4 and 5.

It is seen that some water loss reduction techniques cannot be applied anymore in case the budget planned for reducing water losses is reduced (Figures 4 and 5). It was observed that EWLL levels can vary between 2.15 l/s (8.62%) and 14.19 l/s (56.82%) depending on the budget constraints in the study areas. It is seen that every water loss reduction method is applicable and in this case, the amount of loss can be reduced to 2.15 l/s in the case that the budget constraint is not taken into account. In the absence of budget constraints, the total amount to be spent on loss reduction can be met with the benefit of the amount of water to be added to the system. However, water utilities may not always be able to cover the necessary costs to carry out the entire study. It is quite important to calculate the maximum efficiency with which water loss reduction works in the budget conditions allocated for water losses. In addition, determining the economic leakage level of the system in case of this budget constraint makes a significant contribution to a sustainable WLM.

Table 5 | Comparison of analysis results for different budget constraints

Methods	Unit	EWLL (without budget constraint)	EWLL (with 20% budget constraint)	EWLL (with 15% budget constraint)	EWLL (with 5% budget constraint)
PM	l/s	5.94	8.91	8.91	0
ALC	l/s	4.76	0	0	0
Meter management	l/s	1.34	0.78	0	0
Team management	l/s	1.28	1.28	1.28	1.28
Total		13.32	10.97	10.19	1.28
NRW	l/s	2.15	4.50	5.28	14.19
EWLL	%	8.62	18.02	21.14	56.82

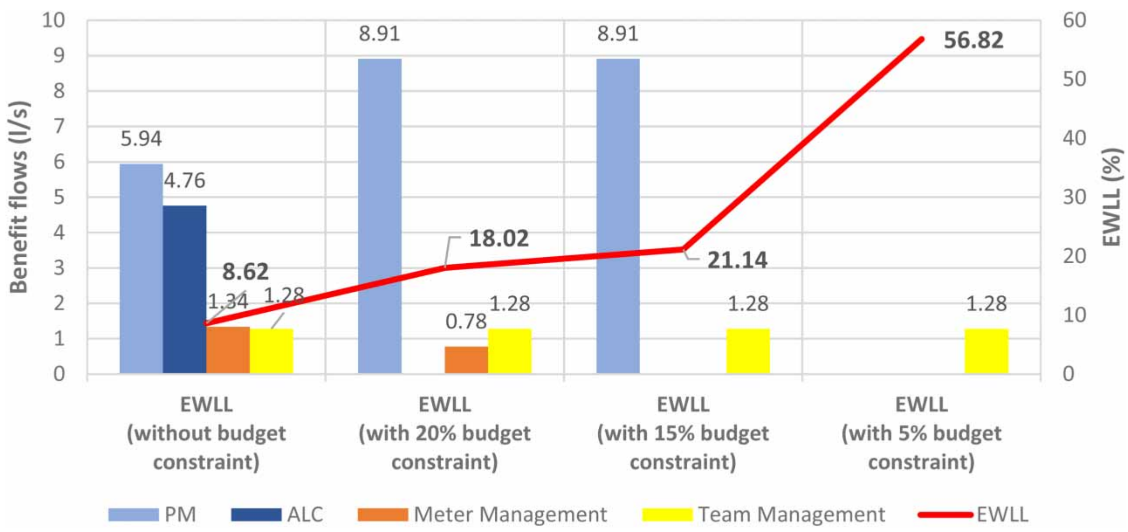


Figure 4 | Comparison of analysis results for different budget constraints.

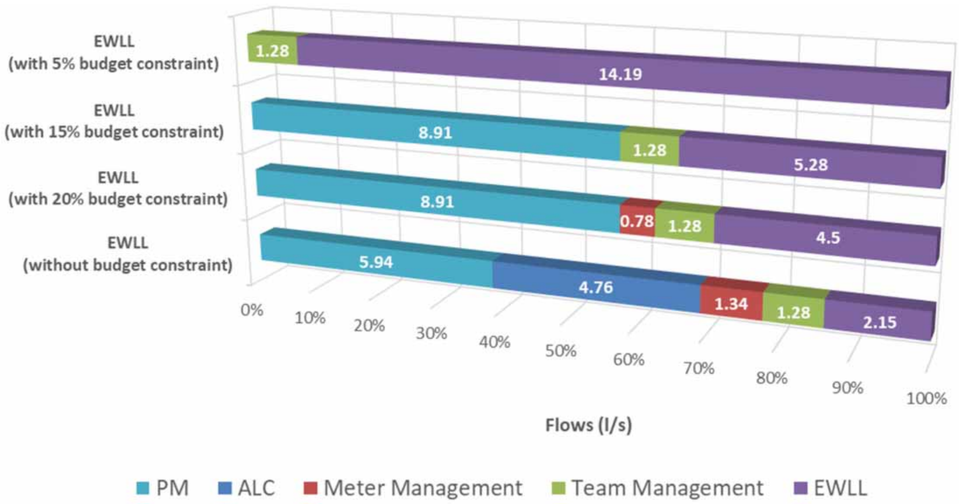


Figure 5 | Comparison of analysis results for different budget constraints.

As is known, the WLM practices are time-consuming and costly. Therefore, the budget planned within the scope of WLM in administrations should be used efficiently. It is quite important to apply the method that provides the most benefit in a short time in the current budget conditions. As can be seen in the results of the analysis, the developed model suggested the most appropriate methods for the most efficient management of the current budget. Thus, both the budget constraints planned by the administration within the scope of WLM were considered and the method that provides the most benefit according to this budget was defined.

In general, the PM method has been proposed to reach the EWLL level in the analysis made according to the budget constraints. PM also provides significant contributions to preventing the occurrence of new failures. Thus, the method that provides the most benefit according to the budget conditions is recommended by the model as a priority.

The definition of the methods to be applied to reach the EWLL level, which is defined depending on the budget constraints, constitutes a reference for the practitioners. It was determined that the EWLL value increases as the budget planned for WLM in the administration decreases (as the budget constraint ratio increases). In other words, the lack of WLM activities due to the low budget has a negative effect on the economically recoverable losses in the system.

CONCLUSION

In this study, a new EWLL analysis model was developed with the budget constraints. Firstly, the EWLL was calculated by defining the costs and benefits for WLM practices without budget constraints. Then, the budget constraints as a certain part of the annual revenue in administration for WLM were defined in the EWLL model. The current NRW rate in the region is quite high at 61.98% (15.47 l/s). The EWLL value was calculated as 8.62% (2.15 l/s) without the budget constraint. Thus, a significant amount of losses (13.32 l/s) can be reduced economically with on-site activities. Then, the costs and benefits and EWLL values were analyzed with different budget constraints in the administration. The EWLL values were determined as 56.82, 21.14 and 18.02%, respectively, by considering the budget constraints of 5, 15 and 20%, respectively.

Water utilities are making serious efforts to reduce water loss rates in the WLM. Utilities usually define the NRW targets according to the regulations and laws in their region. Such practices have uneconomical results for water utilities and cause significant problems in the implementation of methods in the field. Today, the EWLL approach, which changes this understanding, is put forward. However, the most important factor in the EWLL approach is that the unit cost of the loss reduction method is not higher than the unit cost of water production. Although it is a correct approach in theory, sometimes there may not be enough budget for the whole study, especially in developing countries. Therefore, in this study, a new EWLL analysis was made in the case of a limited budget for water loss reduction works. In this study, cost–benefit calculations were made for each of the PM, ALC, team management and meter management methods. It was also ensured that appropriate methods were selected for each budget constraint. The cost–benefit analyses of each of these methods in a limited budget situation have not been examined in the literature before.

One of the most important factors in the implementation of the method is data security. In order for the established algorithm to give accurate results, the basic network data given in Table 2 must be measured completely and accurately.

In general, the PM method has been proposed to reach the EWLL level with the budget constraints. PM also makes a significant contribution to prevent new failures. For this reason, the method that provides the most benefit according to the budget conditions is recommended by the model. The determination of the methods to be applied to reach the EWLL level defined depending on the budget constraints constitutes a reference for the practitioners.

It is thought that water utilities can determine the most appropriate and efficient loss reduction strategies by considering this method. In future studies, the scope of this work can be expanded by adding new water loss reduction methods (regional leak detection, remote reading of customers, etc.) to the algorithm.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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