Pamukkale Univ Muh Bilim Derg, 32(3), 562-574, 2026

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

Assessment of current implementation levels of apparent loss management components with current status evaluation system

Mevcut durum değerlendirme sistemi ile idari kayıp yönetimi bileşenlerinin mevcut uygulama düzeylerinin değerlendirilmesi

Cansu Bozkurt[1*], *Mahmut Fırat*[2]

[1]Department of Construction, Technical Sciences Vocational School, Ardahan University, Ardahan, Türkiye.
cansubozkurt@ardahan.edu.tr

[2]Department of Civil Engineering, Faculty of Engineering, Inönü University, Malatya, Türkiye.
mahmut.firat@inonu.edu.tr

Received/Geliş Tarihi: 19.04.2025 Revision/Düzeltme Tarihi: 18.08.2025 doi: 10.5505/pajes.2025.28661
Accepted/Kabul Tarihi: 27.08.2025 Research Article/Araştırma Makalesi

Abstract

Water demand and difficulty in accessing clean water resources increase the importance of effective and sustainable management of water losses in utilities. Regular measurement of data, analysis of effective factors and efficiency of methods and tools are quite important for sustainable management of losses. The aim of this study is to develop a current status assessment system for analyzing the data quality and monitoring the current implementation levels of apparent loss management components. The system consists of 45 components under main headings of the technical, operation and maintenance, commercial and economic based on literature and field experience. A scoring system is proposed to evaluate these components between 0 and 5 (quite good, good, insufficient, poor and quite poor). The system is tested with using field data in three utilities. The data quality and current status of apparent loss management practices in utility II (generally good) is better than other utility I (insufficient) and III (poor). The components that need improvement within the scope of apparent loss management are defined in utilities based the scoring results. This system provides the opportunity to question in detail the quality, measurement frequency and accuracy of the data used in the apparent loss management in utilities. However, the main problem experienced in the implementation of this system is the lack of sufficient report, data and records for apparent loss prevention, reduction and detection methods in utilities. This assessment system will help more realistic data for apparent loss management in the utility and to allow the field implementations more accurately.

Keywords: Apparent losses, Apparent loss management practices, Current status analysis, Data quality assessment, Scoring structure.

Öz

Su talebi ve temiz su kaynaklarına erişim zorluğu, kamu hizmetlerinde su kayıplarının etkili ve sürdürülebilir yönetiminin önemini artırmaktadır. Verilerin düzenli ölçümü, etkili faktörlerin analizi ve yöntem ve araçların verimliliği, kayıpların sürdürülebilir yönetimi için oldukça önemlidir. Bu çalışmanın amacı, veri kalitesini analiz etmek ve idari kayıp yönetimi bileşenlerinin mevcut uygulama düzeylerini izlemek için güncel bir durum değerlendirme sistemi geliştirmektir. Sistem, literatür ve saha deneyimlerine dayalı olarak teknik, işletme ve bakım, ticari ve ekonomik ana başlıkları altında 45 bileşenden oluşmaktadır. Bu bileşenleri 0 ile 5 (oldukça iyi, iyi, yetersiz, zayıf ve oldukça zayıf) arasında değerlendirmek için bir puanlama sistemi önerilmektedir. Sistem, üç kamu hizmetinde saha verileri kullanılarak test edilmiştir. İdare II'deki (genellikle iyi) görünür kayıp yönetimi uygulamalarının veri kalitesi ve güncel durumu, diğer İdare I (yetersiz) ve III'ten (zayıf) daha iyidir. İdari kayıp yönetimi kapsamında iyileştirilmesi gereken bileşenler, puanlama sonuçlarına göre su idarelerinde tanımlanmaktadır. Bu sistem, su idarelerinde idari kayıp yönetiminde kullanılan verilerin kalitesini, ölçüm sıklığını ve doğruluğunu ayrıntılı olarak sorgulama olanağı sağlamaktadır. Ancak bu sistemin uygulanmasında yaşanan temel sorun, su idarelerinde görünür kayıp önleme, azaltma ve tespit yöntemleri için yeterli rapor, veri ve kayıtların bulunmamasıdır. Bu değerlendirme sistemi su idarelerinde idari kayıp yönetimi için daha gerçekçi veriler elde edilmesine ve saha uygulamalarının daha doğru yapılmasına yardımcı olacaktır.

Anahtar Kelimeler: İdari kayıplar, İdari kayıp yönetimi uygulamaları, Mevcut durum analizi, Veri kalitesi değerlendirmesi, Puanlama yapısı.

1 Introduction

Water losses cover the leakages and apparent losses (AL). The non-revenue water (NRW) is one of the most fundamental problems encountered in the water distribution systems (WDSs) and mainly includes apparent, real losses and unbilled authorized consumptions [1]-[4]. AL cause the loss of revenue. Authors analyzed the illegal use, meter inaccuracies and reading errors to estimate the apparent loss rate in South America [5]-[11]. Globally, the annual volume of water losses reaches significant levels and is estimated to be around 126 billion cubic meters, with an economic impact of approximately 39 billion dollars [12]. Turkish Water Institute (SUEN) reported that the NRW rate in Türkiye in 2020 was 42%. The sustainability of water management depends on detecting and managing the leakages and AL due to metering inaccuracies, billing accuracy, utility management, and resource planning [13]. In the literature, there are a lot of studies within the scope of determining meter inaccuracies, economic analysis of AL, analyzing the effect of meter type and class, environmental and operating factors on meter inaccuracies [14]-[21].

The factors causing meter deterioration were analyzed by considering meter age, system pressure, user behavior, and water tanks in houses. It was also stated that the complexity of AL has significant effects on subscribers' water use and the revenue losses of utilities [22].

*Corresponding author/Yazışılan Yazar

It was emphasized that sustainable management, control and reduction policies of water losses causing the operational costs and constrain the revenue, are important for utilities [23]. Therefore, a simplified methodology was proposed by authors to assess the economic level of AL in utilities. Although the International Water Association (IWA) water balance table is widely used in water loss management (WLM), there are significant difficulties in applying this methodology [1]. In particular, determining customer's consumption profiles and testing meters is difficult in many utilities. The challenges of water sector reform and NRW reduction in Malaysia were investigated to identify possible drivers that can accelerate NRW management reform. A systems thinking approach, in which key systemic relationships were represented using causal loop diagrams, was used in the analysis [24]. Planning and implementation of leakage or AL practices should be prioritized, and the data quality of loss management practices should be systematically checked [25].

The effect of meter type on measurement accuracy was analyzed by testing a total of 50 water meters in the laboratory under different flow rates and operating pressures. It was determined that flow rates and consumption characteristics have a significant effect on meter inaccuracies [21]. The accuracy of water meters was evaluated based on various factors such as operational conditions and equipment properties, and it was emphasized that the sustainability of measuring customer consumption should be ensured [26]. It was also stated that strategies should be developed to reduce excessive water consumption, manage losses due to water meters, and improve operational performance [27]. The factors influencing non-revenue water volume and rate were analyzed, and it was highlighted that customer water meters causing fluctuations in billed water consumption should be improved to reduce AL and manage non-revenue water [28]. In addition, inaccuracies in customer water meters were estimated using novel methods, including laboratory experiments and gene expression programming algorithms, for the sustainable management of AL [29]. The results showed that the various factors such as water mater's position and installation angle and flow and operation conditions, affect the rate of inaccuracies in water meters.

The various studies have been made for determination and management of AL due to water meter inaccuracies using different methodologies in general. However, the management of AL require the detail planning and field works. Reducing and sustainable management of AL generally requires detailed field work. Therefore, the current situation and capacity (technical, economic, technological and staff) of the system should be considered. Moreover, suitability and practicality of methods and current status of methods should be assessed with measurable and appropriate criteria.

The gaps have been identified in the literature within the scope of the administrative losses. Firstly, in the literature, inaccuracies in customer meters have been generally determined in pilot regions or experimental setups. Moreover, a holistic approach for the identification, reduction and effective management of AL has not been proposed. In addition, there is no approach that questions the implementation levels of the methods or tools currently applied in the management of administrative losses in administrations or the quality of the data (measurement status, frequency). A system was proposed to evaluate real loss management practices in water distribution networks by considering 60 components [30]. Moreover, a novel water loss management strategy model that consisting of the current status assessment, performance monitoring, target definition and methods matrices [31],[32].

This study aims to develop a current status assessment system for analyzing the data quality, querying and monitoring the current implementation status of apparent loss management (ALM) components. IWA water balance is used to calculate the volumes and rates of apparent and real losses based on the system input volume and authorized consumptions. The water balance table does not provide detailed information about the current situation of ALM methods and data management. However, the main purpose is not to analyze the key performance indicators (KPIs) or not to define the level of AL. The current status assessment system proposed in this study provides a detailed current situation analysis within the scope of ALM. The weaknesses and strengths in ALM are revealed in a comprehensive manner based on the current situation analysis. This assessment system will help more realistic data for ALM management in the utility and to allow the field implementations more accurately. The assessment system consists of 45 ALM components under main headings that are the data measurement and management, meter and customer management, reduction of meter inaccuracies, and management of illegal usage determined based on the literature and field studies. A scoring system is proposed to evaluate these components in a measurable criterion between 0 and 5 (poor and quite poor, insufficient, good, quite good). The assessment system is tested with using field data in three utilities in Türkiye by external experts. The main problem experienced in the implementation of this system is the lack of sufficient report, data and records for apparent loss prevention, reduction and detection methods, on the units in scoring the components. Incomplete or inadequate recording of reports in units makes scoring difficult.

2 Methodology

The main problems encountered in ALM are: (i) the lack of reliable and accurate customer and water meter data, (ii) the absence of a guide for data management, (iii) the lack of an assessment model for evaluating the current status of AL practices, (iv) the lack of a system that identifies the components that need improvement, and (v) the lack of a target definition system [1],[21],[26],[27]. It is quite important to keep regular and analyze customer and meter data and to determine annual meter inaccuracy rate and illegal connections. Moreover, priority areas in meter replacement and meter management plan should be defined based on economic analysis. Therefore, a comprehensive assessment system that considers all components within the scope of ALM is required for sustainable WLM. This evaluation structure should consider all the components and factors in the system. The best fit methodologies and roadmaps for sustainable apparent loss management should be defined based on the current status.

2.1 Assessment framework for apparent loss management practices

This study proposes an assessment system to evaluate the current status of the ALM practices (Figure 1). This system consists of the current status assessment system, the data matrix including the data used in performance analysis, the gap analysis and the target definition.

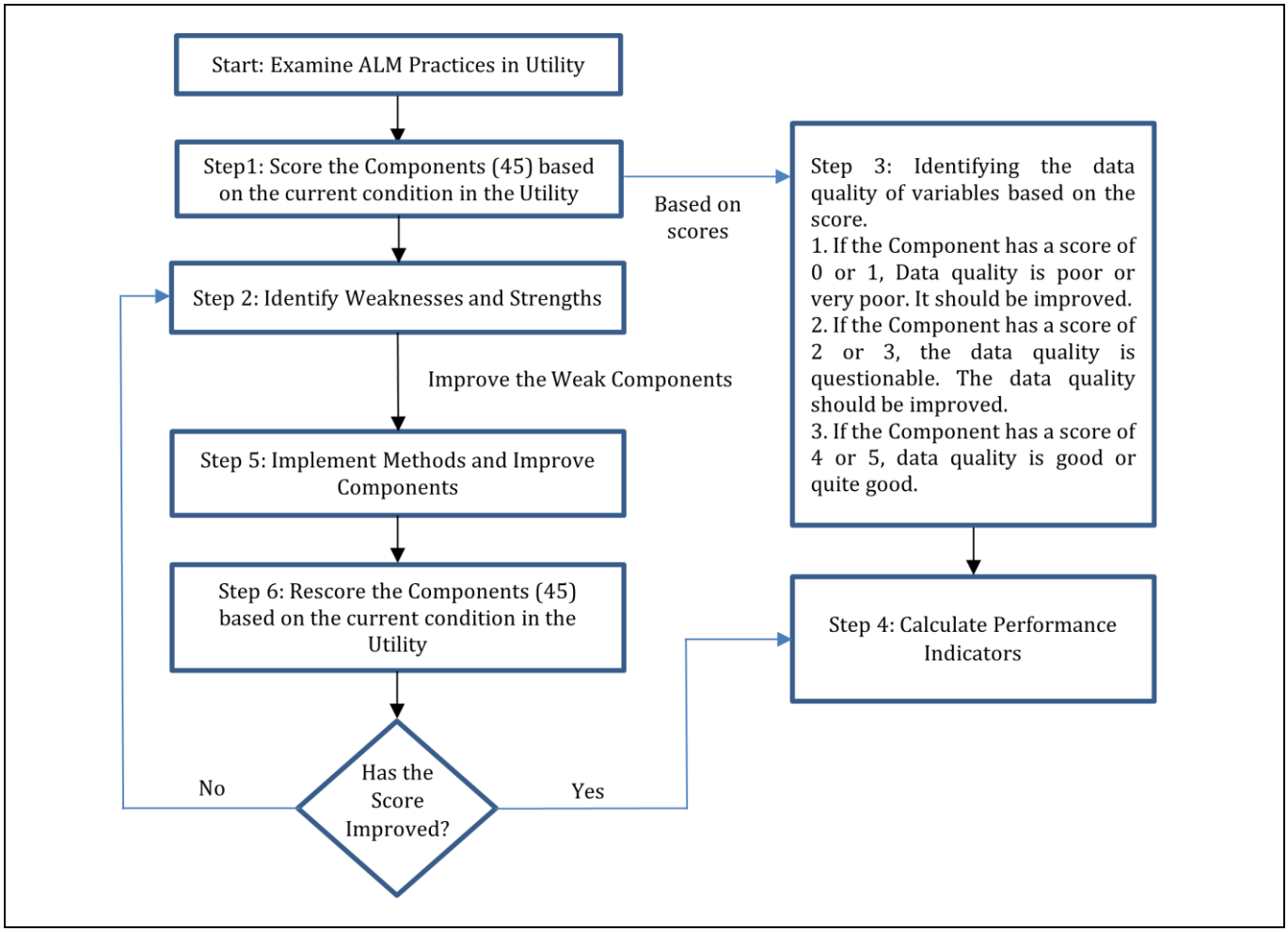


Figure 1. The Flow chart for implementation of assessment system.

The current status assessment matrix covers the ALM practices which are the practices of identifying, reducing, preventing, monitoring the AL, analyzing their economic effects and performance monitoring. The data matrix covers the data used in performance assessment in ALM. The components in data matrix and current status assessment matrix are integrated with each other. Thus, data quality of components in the data matrix is defined based on the scoring process in the current status assessment matrix. In this model, the gap analysis matrix includes the weaknesses in ALM practices based on the scoring process.

In this system, the current status assessment matrix consists of a total of 45 ALM practices defined based on the IWA water balance table, literature and field experience. The IWA water balance table is used to calculate the rate and volumes of the real losses, AL and NRW components with standard terminologies. As it is known, the data of the variables should be accurately obtained and monitored in order to analyze the water budget table. Moreover, the planning information systems, customers and billing systems, continuous updating of data and regular reporting are required to carry out these analyses. In addition, it is quite important to develop the performance evaluation system and to define appropriate and applicable indicators. Conducting regular performance analysis and defining the cost analysis structure for apparent loss reduction practices provide to manage the AL efficiently. The ALM components cover the identification, reduction, prevention, and monitoring, sustainable management and performance analysis under three main headings: (i) technical, (ii) operation and maintenance, (iii) commercial and economic (Tables 1, 2, 3).

Technical main heading covers the number of customers, planning and management of information systems, customer management system, billed authorized consumptions, data related to customer's water meters, losses due to illegal connections, data related to inspection for illegal connections etc. Operation and maintenance main heading include the components of apparent loss reduction, analysis of factors and customer water management. Moreover, this heading includes the integration of information systems, remote reading and monitoring of customer meters etc. Commercial and economic main heading covers the components of the performance analysis of the AL, monitoring the meter reading efficiency and revenue water, cost analysis of the ALM practices. The ALM practices was divided into three group, "Basic ", "Moderate ", "Advanced " based on the applicability and difficulty of the practices (Tables 1, 2, 3). Basic practices that refer to the most basic level components, should be implemented or provided as a priority in the utility.

Table 1. The scoring structure for basic level components of apparent losses.

Basic Level Components	Quite Poor (0)	Poor (1)	Insufficient (2)	Moderate (3)	Good (4)	Quite Good (5)
Technical Components						
Number of Customers (ID1)	Estimated	A part of customers (<25%) is up-to-date	A part of customers (25-50%) is up-to-date.	A part of customers (50-75%) is up-to-date.	A part of customers (75-90 %) is up-to-date.	A part of customers (more than 90 %) is up-to-date.
Planning of Information Management System (IMS) (ID2)	No work	The basic systems are available.	Some units have IMS	There is some IMS.	Some systems are integrated with each other.	There are integrated information systems.
Customer Management and Billing System (CMBS) (ID3)	CMBS is not regular	The readings period is more than 3 months.	The readings period is 3 months.	The readings period is 2 months.	The readings period is 1 months.	The readings period is 1 months. GIS integration is available.
Billed Authorized Consumptions (ID4)	Reading efficiency is less than 25%	Reading efficiency is between 25-50%	Reading efficiency is between 50-75%	Reading efficiency is between 75-90%	Reading efficiency is more than 90%	Reading efficiency is more than 90%. GIS integration is available.
Determination and Monitoring of Meter Inaccuracies (ID5)	No work	It is determined in pilot DMA (>2 years)	It is determined in pilot DMA (2 years)	It is determined for system (2 years)	It is determined for system (average 1 years)	It is determined for system annually. GIS integration is available
Operation and Maintenance Components						
Systematic Measurement and Monitoring of Apparent Loss Components for Water Balance Calculations (ID6)	No work	Inaccuracies are determined in a DMA (more than 2 years),	Inaccuracies are determined in a DMA (average 2 years).	Inaccuracies (every 1-2 years) are determined in the system.	Inaccuracies (annually) are determined in the system.	Inaccuracies (annually) are determined in the system. GIS integration is available.
Analysis of Factors Affecting Apparent Losses (ID7)	No work	Effective factors are only estimated.	Inaccuracies are monitored in a DMA.	Inaccuracies are monitored with field data.	Apparent losses are regularly analyzed with field data.	Apparent losses are regularly analyzed. GIS integration is available
Apparent Loss Reduction and Management Strategy (ID8)	No work	There is awareness for necessity of the strategy.	Monitoring strategy is planned in a DMA.	Strategy is planned in a pilot DMA.	Management strategy is constantly updated.	Strategy is constantly updated. GIS integration is available.
Monitoring, Cut off Strategy and Roadmap for Unpaid Customers (ID9)	No work	Debts up to 24 invoices are monitored.	Debts up to 18 invoices are monitored.	Debts up to 12 invoices are monitored.	Debts up to 6 invoices are monitored.	Debts up to 3 invoices are monitored.
Analysis and Monitoring of Total Operating Revenues (ID10)	No work	Total revenue is reported (2 years).	Total revenue is reported annually.	Total revenue is reported every 6 months.	Total revenue is reported monthly.	Total revenue is reported monthly. GIS integration is available
Commercial and Economic Components						
Updating the Customer Information Management System (CIMS) (ID11)	No work	CIMS is available, there is no up-to-date.	CIMS is updated in pilot DMAs.	CIMS is updated in DMAs.	CIMS is updated regularly.	CIMS is updated regularly. GIS integration is available.
Monitoring Customer Meter Reading Efficiency (ID12)	Efficiency is less than 25%	Efficiency is between 25-50%	Efficiency is between 50-75%	Efficiency is between 75-90%	Efficiency is more than 90%	Efficiency is more than 90%. GIS integration is available.
Integration of Performance Monitoring and Information Systems (PMIS) (ID13)	No work	Performance is analyzed in Excel (1-2 years)	Performance is analyzed in Excel annually.	Performance is analyzed in Excel monthly.	Performance is analyzed with the system regularly.	Performance is analyzed with the GIS-based system.
Billing and Collecting Accuracy/Efficiency Analysis (ID14)	No work	Billing and collecting efficiency are reported every 12 months.	Billing and collecting efficiency are reported every 6 months.	Billing and collecting efficiency are reported every 3 months.	Billing and collecting efficiency are reported monthly.	Billing and collecting efficiency are reported monthly. GIS integration is available
Monitoring and Analysis of Collected Customers and Volumes (ID15)	No work	Customers and consumptions are analyzed every 12 months.	Customers and consumptions are analyzed every 6 months.	Customers and consumptions are analyzed every 3 months.	Customers and consumptions are analyzed monthly.	Customers and consumptions are analyzed monthly. GIS integration is available

Table 2. The scoring structure for moderate level components of water balance in the developed model.

Moderate Level Components	Quite Poor (0)	Poor (1)	Insufficient (2)	Moderate (3)	Good (4)	Quite Good (5)
Technical Components						
Customer Water Meter Age (ID16)	No work	A part of the meters (<25%) is known.	A part of the meters (25-50%) is known.	A part of the meters (50-75%) is known.	A part of the meters (75-90%) is known.	A part of the meters (>90%) is known.
Meter Management Database (Integrated with GIS) (ID17)	No work	A part of database (<25%) is up to date	A part of database (25-50%) is up to date	A part of database (50-75%) is up to date	A part of database (75-90%) is up to date	A part of database (>90%) is up to date
Losses due to Customer Meter Inaccuracies (ID18)	No work	It is estimated for water balance.	It is determined in pilot DMAs (2 years).	It is determined in pilot DMAs annually.	It is determined in the system annually.	It is determined in the system annually. GIS integration is available
Calibration of Customer Meters and Existence of Test Laboratory (ID19)	No work	New meters are tested in other laboratories.	Meters are tested in other laboratories.	There is a test laboratory, meters are tested.	Meters are tested and old meters are rarely tested in laboratory.	There is a laboratory, all meters are tested.
Public Awareness for Illegal Uses (ID20)	No work	Activities are planned at certain periods (>12 months).	Activities are planned at certain periods (6-12 months).	Activities are planned at certain periods (3-6 months).	Activities are planned at certain periods (1-3 months).	Activities are planned at certain periods (monthly).
Operation and Maintenance Components						
Management and Analysis of Customer Complaints (ID21)	No work	Data are analyzed with Excel at certain periods (6-12 months).	Data are analyzed with Excel at certain periods (3-6 months).	Data are analyzed with CRM at certain periods (average 3 months).	Data are analyzed with CRM at certain periods (monthly).	Data are analyzed with CRM at certain periods (monthly). GIS integration is available
Installing and Monitoring Control Meters for Sites (ID22)	No work	There is awareness of the need for improvement.	Control meter is applied for pilot sites.	Control meter is applied in a DMA, Consumptions are monitored.	Control meter is applied in DMAs. Consumptions are monitored.	Control meter is applied in DMAs. Consumptions are used in MNF analysis.
Target Definition for NRW and Key Components (ID23)	No work	There is no reliable and regular data.	The target is defined with system input volume.	The target is defined in DMAs for water balance.	The target for water balance and ILI is defined.	The target for water balance, ILI and ELL is defined.
Existence of Written Technical Specification and Guide for Customer Meter Preference and usage (ID24)	No work	There is no restriction for meter preference in new subscriptions.	There is a technical specification and guide for meter selection and replacements.	There is a technical specification and guide for meter selection.	There is a technical specification and guide. Meters are provided by companies.	There is a technical specification and guide. Meters are provided by the institution or authorized companies.
Roadmap for Managing WLM Components (ID25)	No work	There is only a flow chart for the measurement systems	There is a program and road map for management of main components.	There is a road map for management of main and basic components.	There is a strategic plan and roadmap for methods and works, the C&B standard is defined.	There is a strategic plan and roadmap for methods and works. The C&B standard and flowcharts were defined.
Commercial and Economic Components						
Monitoring of Apparent Loss Performance Indicators (ID26)	No work	Indicators are analyzed in Excel (>2 years).	Indicators are analyzed in Excel every 1-2 years.	Indicators are analyzed in Excel annually.	Indicators are analyzed by system regularly.	Indicators are analyzed regularly. Information systems are integrated.
Meter Renewal Strategy Based on Economic Analysis (ID27)	No work	Only faulty meters are replaced.	Only meters over 10 years old are replaced.	Meter renewal strategy based on C&B analysis is made in a DMA.	Meter renewal strategy and cost-benefit analysis is made.	Meter renewal strategy and cost-benefit analysis is made. GIS integration is available
Analysis and Monitoring of Apparent Loss Cost Due to Meter Inaccuracies (ID28)	No work	Costs are analyzed (>2-3 years).	Costs are analyzed (2 years).	Costs are analyzed (1-2 years).	Costs are analyzed monthly.	Costs are analyzed monthly. GIS integration is available.
Analysis and Monitoring of Apparent Loss Cost (ID29)	No work	Costs are analyzed (>2-3 years).	Costs are analyzed (2 years).	Costs are analyzed (1-2 years).	Costs are analyzed monthly.	Costs are analyzed monthly. GIS integration is available.
Analysis and Monitoring of NRW Cost (ID30)	No work	Costs are analyzed (>2-3 years).	Costs are analyzed (2 years).	Costs are analyzed (1-2 years).	Costs are analyzed monthly.	Costs are analyzed monthly. GIS integration is available.

Table 3. The scoring structure for advanced level components of water balance in the developed model.

Advanced Level Components	Quite Poor (0)	Poor (1)	Insufficient (2)	Moderate (3)	Good (4)	Quite Good (5)
Technical Components						
Number of Customers with High and Specific Consumption (ID31)	No work	A part of customers, <25% are up to date.	A part of customers (25-50%) is up to date.	A part of customers (50-75%) are up to date.	A part of customers, 75-90% up to date.	A part of customers (>90%) are up to date.
Losses Due to Illegal Use (ID32)	No work	This component is estimated for water balance.	The areas with complaints are controlled.	The inspection policy is randomly implemented.	An inspection policy is implemented.	An inspection policy is implemented. GIS integration is available.
The Number and Rate of Inspection for Illegal Connections (ID33)	No work	There is not enough or regular data.	Data is kept in Excel. Users are registered in CIMS annually.	Data is kept in Excel. Users are registered in CIMS.	Data is kept in system. Users are registered.	Data is kept in system. GIS integration is available.
Inspection Policy for Management of Illegal Connection and Uses (ID34)	No work	There is no regular inspection policy.	The inspection is planned in regions with complaints.	The inspection is planned in regions with complaints or randomly selected.	A systematic audit strategy is implemented.	A systematic strategy is implemented. GIS integration is available.
Monitoring Water Consumption and Resource Efficiency (ID35)	No work	Consumptions are monitored with annual data.	Efficiency is analyzed in a certain period (1-2 years).	Efficiency is analyzed in DMAs.	Efficiency is analyzed.	Efficiency is analyzed. GIS integration is available.
Operation and Maintenance Components						
Integration of Databases with Each Other (GIS-SCADA-CIS-CRM) (ID36)	No work	The capacity of databases is insufficient	The capacity of information systems is improved.	Integration of databases is being planned.	Some systems are integrated.	All systems are integrated.
Remote Reading and Monitoring of Authorized Unbilled Customers (ID37)	No work	The system is being planned for pilot DMA.	The reading system is implemented in a pilot DMA.	The reading system is implemented in DMAs.	The system is implemented (75-90%)	The reading system is implemented for customers (>90%)
Remote Reading and Monitoring of High and Specific Consumption Customers (ID38)	No work	The reading system is being planned in a DMA.	The reading system is implemented in a pilot DMA.	The reading system is implemented in DMAs.	The reading system is implemented (75-90%)	The remote reading system is implemented (>90%)
Remote Reading and Monitoring of Authorized Billed Customers (ID39)	No work	The system is being planned for High customers.	The reading system is applied only for High customers.	The reading system is implemented in a DMA.	The system is implemented in DMAs.	The system is implemented. GIS integration is available.
Regulations and Specifications for Water Loss Components (ID40)	No work	A roadmap is being prepared for illegal uses.	Roadmaps for illegal uses, unpaid customers are available.	Roadmaps and manuals are available.	Roadmaps, manuals and calibration docs are available.	Roadmaps, flowcharts, checklists, manuals and calibration docs are available.
Commercial and Economic Components						
Defining the Optimum Level for Apparent Losses (ID41)	No work	Data is not reliable for calculation.	The optimum level is defined in WDSs or DMAs (>2 years).	The optimum level is defined in WDS/ DMAs (1-2 years).	The optimum level is defined annually.	The optimum level is defined annually. GIS integration is available.
Efficiency and Economical Analysis and Monitoring of WLM Practices (ID42)	No work	Efficiency is monitored (>2 years).	Efficiency is monitored (1-2 years).	Efficiency is monitored (6-12 months).	Efficiency is monitored (3-6 months).	Efficiency is monitored (1-3 months).
Analysis and Monitoring of Performance Evaluation Indicators (ID43)	No work	Indicators are analyzed in Excel (>2 years).	Indicators are analyzed in Excel every 1-2 years.	Indicators are analyzed in Excel annually.	Indicators are analyzed regularly.	Indicators are compared by integration of systems
Analysis of the Cost of Illegal Use (ID44)	No work	Cost is analyzed (>2 years).	Costs are analyzed (2 years).	Cost is analyzed (1-2 years).	Cost is analyzed monthly.	Cost is analyzed monthly. GIS integration is available.
Analysis and Monitoring of Meter Replacement Cost (ID45)	No work	Costs are analyzed, there is not enough data for C&B analysis.	Investment costs are analyzed, C&B analysis is made in the pilot DMA.	Meter replacement strategy is applied based on C&B in the DMAs.	Replacement strategy is applied based on C&B.	Meter replacement strategy is applied based on C&B. GIS integration is available.

Moderate practices refer to the components that are implemented in the second stage according to the ec8onomic, technical and technological capacity of the utility. Advanced practices refer to components implemented in a utility based on the implementation level of basic and moderate components. Technical, technological, economic and financial capacity must be sufficient in the utility to implement these components. If these basic level components are insufficient in a utility, it is not possible to talk about intermediate and advanced level components. The model recommends that utilities lacking sufficient capacity and budget should first improve basic-level components. Later, they can focus on moderate and advanced components. This provides the applicability of this model across utilities. The flow chart for implementation of this model is given in Figure 1. It is possible to apply the system proposed in this study to any utility. Data and activity reports in each department of utility should be recorded and saved regularly. It is also possible to identify critical practices (low-scoring), prioritize these components, and monitor the improvement processes over time by applying

this system annually. In this system, scoring tables were created (Figure 1, step 1) in order to define the current status of ALM practices in utilities. The scoring results are evaluated in the gap analysis (matrix) (Figure 1, step 2 and step 3) as;

The scoring system basically includes 6 graded points (0, 1, 2, 3, 4, and 5). The points of 0 and 1 indicate that the current status of practices is quite poor and poor. The targets for these practices are gradually defined as 3 (moderate, Target I), then 4 (good: Target II) and finally 5 (quite good: Target III). The points of 2 and 3 demonstrate that the data quality of ALM practices is questionable/insufficient and moderate quality. The targets for these practices are gradually defined as 4 (good: Target II) and finally 5 (quite good: Target III). The point of 4 shows that the data quality of ALM practices is at good level. The target is defined as 5 (Target III) by considering economic conditions. The point of 5 indicates that the data quality of ALM practices is at quite good level and the current condition of these components should be kept. This scoring system should be applied by experts from outside the utilities to assess the practices more accurately. The current status of ALM practices is determined based on the scoring system applied in utilities (Figure 1, step 3). Moreover, the performance indicators are calculated based on the data quality (data matrix) (Figure 1, step 4). Then, the weaknesses in ALM defined based on the scoring system are improved by applying the ALM methods and tools (Figure 1, step 5). This assessment system should be applied periodically. Thus, the improvement level of practices that were defined as the weaknesses in ALM with initial scoring, could be monitored. For his aim, all components are re-scored in the utility (Figure 1, step 6). It is not economical or possible to reduce the water loss components to zero. The current status of components is quite important in order to define appropriate and feasible targets for improvement of ALC. It is not technically and economically possible in many cases to improve the components with poor status to a quite good level. For this reason, a gradual and appropriate target is defined by considering the current status of data quality.

3 Analysis and results

The assessment and scoring model were tested in three utilities (Malatya: Utility I, Bursa: Utility II and Denizli: Utility III) Türkiye (Figure 2). Utility I, Utility II and Utility III has the main line length of approximately 3000 km, 7100 km and 8000 km, respectively. In these utilities, water supply is done in different ways. Utility I and III has generally underground water resources and Utility II has surface and underground water resources. The total population served in utility 1 is 700 000, the total number of customers is 350 000. There are a total of 1064 drinking water tanks in this utility. The average rate of the water losses in 2022 year is the 35 %. The total population served in utility 2 is 3.19 million, the total number of customers is 1.4 million. There are a total of 916 drinking water tanks and 41 drinking water treatment facilities in this utility. The average rate of the water losses in 2022 year is the 25 %. The total population served in utility 3 is 1000 000, the total number of customers is 600 000. There are a total of 617 drinking water tanks in this utility. The average rate of the water losses in 2022 year is the 28 %. These components are scored by the external experts at different time in 2022 year. In this context, the units of the Customer Information Management, the SCADA, the GIS and the Information Technology were visited and the activity reports were reviewed. The current implementation levels of apparent loss practices in utility have been scored by experts who are the manuscript's authors) from outside the utility in order to make a more accurate assessment. For objective scoring, data, reports and activity documents recorded in the utility are considered as evidence.

3.1 Basic practices

The scoring model is applied in utilities separately for basic level (Table 4). The components of basic data and databases which should first be at good level for sustainable ALM. Therefore, the data quality and implementation level of these components were tested. It is seen that utility II has the best performance in this group. The current status of ID1 and ID2 components in utility II is good. These components are generally at average level in utilities I and III. The ID3 and ID4 are quite good in utility II and moderate in utilities I and III. These should be good in order to increase the revenue rate and to ensure the efficiency of the utility. Therefore, planning should be made for the improvement of these components in utilities I and III and implemented in the field.

The components under the operation and management heading are important in terms of correctly analyzing the AL components and the factors affecting the AL, developing the reduction strategy and ensuring operational efficiency. It will be possible to conduct other advanced analyzes depending on the data quality and current status of components. According to the scoring results, the performance of utility 2 is generally better than other utilities.

The current status of ID7, ID9, and ID10 is good or quite good in Utility 2, poor/insufficient in utility I, and moderate in utility III. The ID7 component queries the analysis of influencing factors based on field data for the reduction of AL. This component should be at good level for reduction of the current losses and to prevent new losses. The components of ID9 and ID10 are important in terms of generating revenue from authorized billed consumptions and monitoring the operating income. The status of ID6 and ID8 is average in utilities II and III, and quite poor in utility I. The ID6 component should be at good level for identification of AL accurately, evaluation of the influencing factors correctly, and develop a prevention strategy.

The under commercial and economic components are important in terms of monitoring ALC, monitoring meter reading and billing efficiency, and consumptions. The current status of ID12, ID14, and ID15 is good in utility I, quite good in utility II, and insufficient in utility III. The ID12 component queries the meter reading efficiency. The components of ID14 and ID15 query the accuracy of system invoicing, efficiency and monitoring of collected consumptions. The implementation level of these components should be at least good for the revenue and the collection rates. The status of ID11 and ID13 is quite good in utility II, quite poor in utility I and insufficient in utility III. These components query the integration and systematic updating of the performance monitoring system and other information systems. Information systems should be regular and up-to-date for accurate performance assessment.

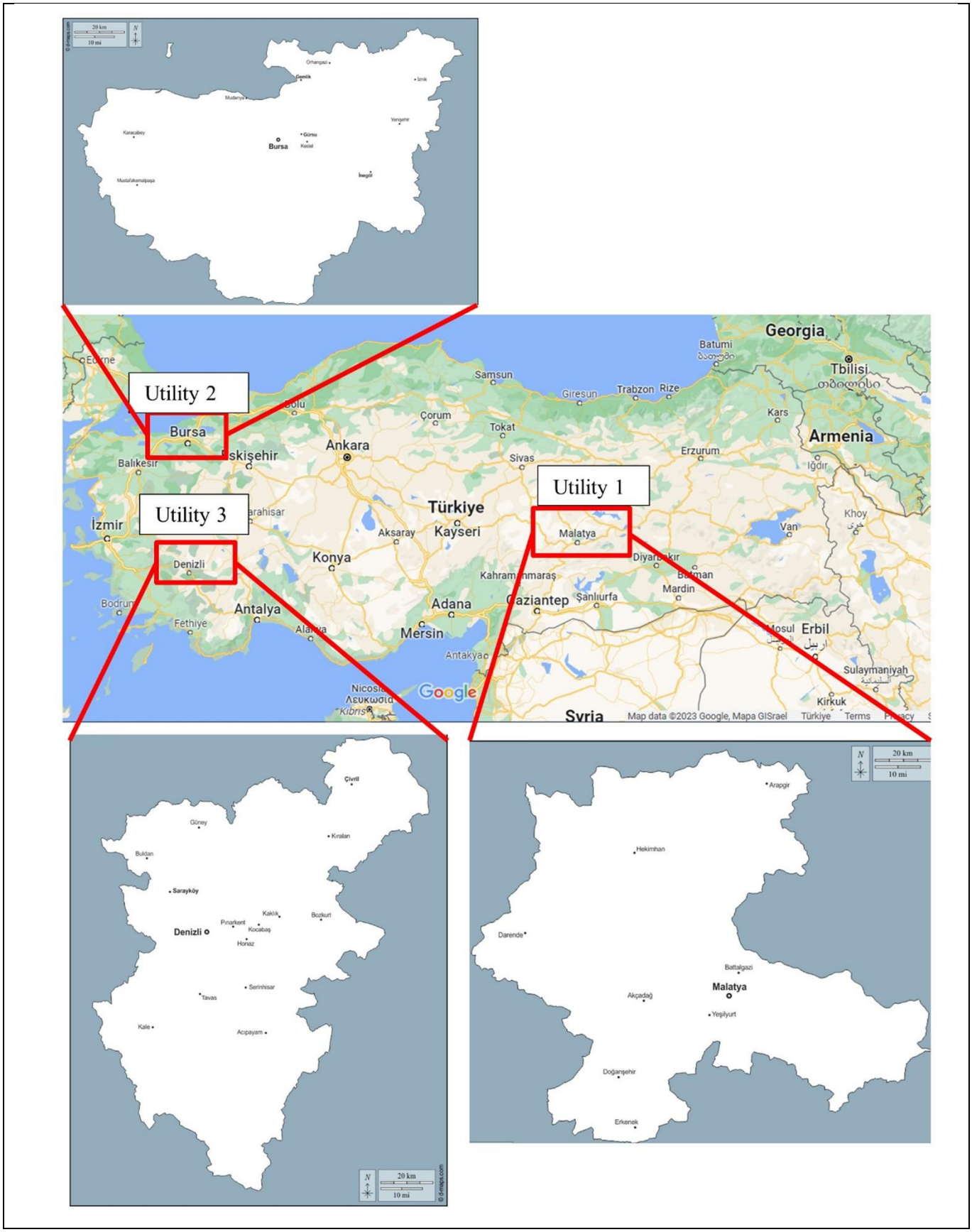


Figure 2. Pilot utilities selected in the study.

Table 4. The scoring results and targets for basic level components in pilot administrations.

ID	Components	Administration I				Administration II				Administration III			
		Score	Targets			Score	Targets			Score	Targets		
			I	II	III		I	II	III		I	II	III
Technical Components													
ID1	Number of Customers	3		✓	✓	4			✓	3		✓	✓
ID2	Planning of Information Management System (IMS)	2		✓	✓	4			✓	2		✓	✓
ID3	Customer Management and Billing System (CMBS)	3		✓	✓	5				3		✓	✓
ID4	Billed Authorized Consumptions	4			✓	5				3		✓	✓
ID5	Determination and Monitoring of Meter Inaccuracies	0	✓	✓	✓	3		✓	✓	2		✓	✓
Operation and Maintenance Components													
ID6	Systematic Measurement and Monitoring of Apparent Loss Components for Water Balance Calculations	1	✓	✓	✓	3		✓	✓	2		✓	✓
ID7	Analysis of Factors Affecting Apparent Losses	0	✓	✓	✓	4			✓	2		✓	✓
ID8	Apparent Loss Reduction and Management Strategy	0	✓	✓	✓	2		✓	✓	3		✓	✓
ID9	Monitoring, Cut off Strategy and Roadmap for Unpaid Customers	2		✓	✓	5				3		✓	✓
ID10	Analysis and Monitoring of Total Operating Revenues	2		✓	✓	4			✓	3		✓	✓
Commercial and Economic Components													
ID11	Updating the Customer Information Management System (CIMS)	0	✓	✓	✓	5				2		✓	✓
ID12	Monitoring Customer Meter Reading Efficiency	4			✓	5				2		✓	✓
ID13	Integration of Performance Monitoring and Information Systems (PMIS)	0	✓	✓	✓	4			✓	3		✓	✓
ID14	Billing and Collecting Accuracy/Efficiency Analysis	4			✓	5				2		✓	✓
ID15	Monitoring and Analysis of Collected Customers and Volumes	4			✓	4			✓	3		✓	✓

It was noticed that the current status of customer management and billing system, the number of customers, authorized consumptions, monitoring of customer reading efficiency, billing and collection efficiency monitoring is good. The current capacity is at sufficient level for monitoring authorized customers, reading consumptions and monitoring billing performance in utilities. These components are fundamental data for making analyzes within the scope of AL, monitoring changes and developing a prevention strategy. Moreover, the components of monitoring total operating income, establishing a performance monitoring system, and cutting strategy for non-paying customers are at average level. The current status of these components needs to be improved in order to reduce and prevent AL.

3.2 Moderate practices

The moderate level components were scored in utilities (Table 5). According to the scoring results, the current status of ID16 and ID17 are quite good in utilities II and III, and at poor/insufficient level in utility I. These components are especially important for monitoring meters, minimizing inaccuracy rates and establishing a meter renewal program. The components of ID18 and ID20 are insufficient or poor in utilities. It is necessary and important to determine the losses due to meter inaccuracies according to field data. Therefore, the implementation level of this component should be at good level.

The main heading of operation and maintenance query the components of target setting for AL, technical specification for water meters, the roadmap for WLM components and control meter practices. The current status of all components under this heading are good in utilities II and III. However, in utility, the component of ID 25 is at good level, and the others are at insufficient/poor level. These components are important for target definition according to basic indicators, roadmap definition for effective management of losses and technical specifications for meters.

The main heading of commercial and economic query the cost analysis of apparent loss practices and economic analysis for meter replacement. These components are important in terms of efficiency analysis in WLM practices. The current status of all components in this group are poor in utilities. The components of ID26, ID28, and ID29 are at poor level in utilities II and III, and at quite poor level in utility I. These components are important in analyzing the effects of the methods applied in ALM on performance and in determining the costs. The current status of ID27 and ID30 are moderate in utility II, and insufficient in utilities I and III. These components should be improved in order to analyze and monitor efficiency.

It was understood that the components of calibration of meters and existence of laboratory, calibration of customer meters, meter management database, existence of technical specification, target definition for NRW, water meter age are at good level. The capacity is at sufficient level for monitoring water meters, calibration of meters, roadmap for managing WLM and meter installing and management specification in utilities.

Table 5. The scoring results and targets for moderate level components in pilot administrations.

ID	Components	Administration I				Administration II				Administration III			
		Score	Targets			Score	Targets			Score	Targets		
			I	II	III		I	II	III		I	II	III
Technical Components													
ID16	Customer Water Meter Age	1	✓	✓	✓	4			✓	4			✓
ID17	Meter Management Database (Integrated with GIS)	2		✓	✓	5				4			✓
ID18	Losses due to Customer Meter Inaccuracies	0	✓	✓	✓	1	✓	✓	✓	2		✓	✓
ID19	Calibration of Customer Meters and Existence of Test Laboratory	4			✓	3		✓	✓	3		✓	✓
ID20	Public Awareness for Illegal Uses	2		✓	✓	0	✓	✓	✓	1	✓	✓	✓
Operation and Maintenance Components													
ID21	Management and Analysis of Customer Complaints	3		✓	✓	5				4			✓
ID22	Installing and Monitoring Control Meters for Sites	0	✓	✓	✓	4			✓	4			✓
ID23	Target Definition for NRW and Key Components	0	✓	✓	✓	4			✓	3		✓	✓
ID24	Existence of Written Technical Specification and Guide for Customer Meter Preference and usage	4			✓	5				4			✓
ID25	Roadmap for Managing WLM Components	2		✓	✓	4			✓	3		✓	✓
Commercial and Economic Components													
ID26	Monitoring of Apparent Loss Performance Indicators	0	✓	✓	✓	1	✓	✓	✓	2		✓	✓
ID27	Meter Renewal Strategy Based on Economic Analysis	3		✓	✓	3		✓	✓	1	✓	✓	✓
ID28	Analysis and Monitoring of Apparent Loss Cost Due to Meter Inaccuracies	0	✓	✓	✓	2		✓	✓	2		✓	✓
ID29	Analysis and Monitoring of Apparent Loss Cost	0	✓	✓	✓	2		✓	✓	2		✓	✓
ID30	Analysis and Monitoring of NRW Cost	0	✓	✓	✓	4			✓	3		✓	✓

However, it was seen that the components of the losses due to meter inaccuracies, performance monitoring and economic analysis, cost analysis of AL and customer meter renewal are at insufficient level. These components are the fundamental practices in terms of analyzing performance changes in ALM, analyzing and monitoring system operating efficiency, and cost analysis of reduction methods. Therefore, these components need to be improved for a sustainable and efficient operation of the system.

3.3 Advanced practices

The advanced level components were scored in utilities (Table 6). These components are important for accurate analysis of the water budget, effective management of illegal uses and ensuring water resource efficiency. The component of ID31 is at good level in utilities I and III, and at average level in utility 3. This component is important in terms of identifying and monitoring customers with high consumption. The components of D32, ID33, and ID34 were at average in utilities II and III, and at insufficient in utility I. Moreover, the level of ID35 is good in utilities II and III and at quite poor in utility I.

The technical main heading query the components of integration of information systems, remote readings the customers and legislation for WLM components. The current status of ID36 is good in utility II and moderate in utilities I and III. This component should be at good level, for regular monitoring, sharing and analysis of data. However, the components of ID37, ID38 and ID39 are at poor level in utilities. These components query the remote reading of high consumption customers, authorized unbilled and residential billed customers. This component should be improved for ensuring the reading efficiency. The main heading of analysis and management of AL query the components of identifying the most appropriate level for AL, efficiency and economic analysis, benchmarking analysis, cost analysis for illegal connections and meter replacement practices. In this main heading, current status of all components is quite poor in utility I, at insufficient in utilities II and III. These components are important for performance analysis and target definition for advanced indicators, cost analysis for illegal usage and meter replacement.

The components of the number of customers with high consumption, integration of databases, regulations and specifications for WLM, monitoring of water consumption are at good level. The capacity is at sufficient level for monitoring customers, information system and database management and regulations and specifications for ALM in utilities. However, it was seen that the components of the remote reading of customers, inspection policy for illegal connections, commercial and economic, and cost analysis of ALC and economic analysis are at insufficient level. These components are the fundamental practices in terms of analyzing performance changes in ALM, analyzing and monitoring system operating efficiency, and cost analysis of reduction methods. Therefore, these components need to be improved for a sustainable and efficient operation of the system.

Table 6. The scoring results and targets for advanced level components in pilot administrations.

ID	Components	Administration I				Administration II				Administration III			
		Score	Targets			Score	Targets			Score	Targets		
			I	II	III		I	II	III		I	II	III
Technical Components													
ID31	Number of Customers with High and Specific Consumption	4			✓	4			✓	3		✓	✓
ID32	Losses Due to Illegal Use	2		✓	✓	2		✓	✓	2		✓	✓
ID33	The Number and Rate of Inspection for Illegal Connections and Uses	2		✓	✓	3		✓	✓	3		✓	✓
ID34	Inspection Policy for Management of Illegal Connection and Uses	2		✓	✓	3		✓	✓	3		✓	✓
ID35	Monitoring Water Consumption and Resource Efficiency	0	✓	✓	✓	4			✓	4			✓
Operation and Maintenance Components													
ID36	Integration of Databases with Each Other (GIS-SCADA-CIS-CRM)	3		✓	✓	4			✓	3		✓	✓
ID37	Remote Reading, Monitoring and Reduction of Authorized Unbilled Customers	0	✓	✓	✓	1	✓	✓	✓	1	✓	✓	✓
ID38	Remote Reading and Monitoring of High and Specific Consumption Customers	0	✓	✓	✓	1	✓	✓	✓	1	✓	✓	✓
ID39	Remote Reading and Monitoring of Authorized Billed Customers	0	✓	✓	✓	2		✓	✓	1	✓	✓	✓
ID40	Regulations and Specifications for Water Loss Components	4			✓	5				3		✓	✓
Commercial and Economic Components													
ID41	Defining the Optimum Level for Apparent Losses	0	✓	✓	✓	4			✓	2		✓	✓
ID42	Efficiency and Economical Analysis and Monitoring of Water Loss Prevention-Control-Monitoring-Analysis Activities	0	✓	✓	✓	2		✓	✓	2		✓	✓
ID43	Analysis and Monitoring of Performance Evaluation (Benchmarking) Indicators	0	✓	✓	✓	3		✓	✓	3		✓	✓
ID44	Analysis and Monitoring of the Cost of Illegal Use	0	✓	✓	✓	1	✓	✓	✓	3		✓	✓
ID45	Analysis and Monitoring of Meter Replacement Cost	0	✓	✓	✓	3		✓	✓	3		✓	✓

The gains from the implementation of assessment and scoring model are;

(i) The current implementation level of ALM practices is gradually assessed according to the dynamic condition of utility,

(ii) The components that need improvement are identified within scope of ALM,

(iii) Achievable and appropriate goals are defined based on the current status,

(iv) The roadmaps for improvement of ALM practices are defined.

According to the test results, the basic components have the highest scores in all utilities. This is essentially an expected result. In the developed model, it is expected that basic components should be applicable in apparent loss management in general. In the administrations where these components are weak or insufficient, it is necessary to improve the technical, technological and personnel capacity. In this model, these infrastructure conditions and the potential of the administration in apparent loss management are questioned in basic level practices. It was been determined that the scores for the intermediate and advanced components are generally insufficient in the administrations where the basic level components are insufficient.

The components in the proposed model are scored according to the examinations and inspections. The data, databases, reports and documents currently used in the relevant units of the administration are considered. However, the activities carried out in the administration should be reported regularly, the data should be saved and the databases should be up-to-date.

Since the basic level components are the easiest components to implement in many administrations in general, they are also easy to score. The current status of basic components should be at sufficient level in administration for the implementation of intermediate and advanced level components. For this reason, it is not possible to obtain reports of especially advanced components and scoring becomes difficult. In addition, the lack of awareness of decision maker or technical personnel in administrations about some of the components in this group is also a challenge. It is difficult to understand such detailed information and processes, especially in administrations where water loss management is perceived as just filling the water balance table. For this reason, before applying this model in such administrations, the processes and components applied in apparent loss management are explained in detail.

In this study, the current status assessment system was tested in three utilities and weaknesses and strengths were identified. Apparent loss management plans should be created in utilities by focusing on improving weaknesses based on this current situation analysis. Apparent loss management has a dynamic

process depending on the change in the number of customers and network conditions. The current implementation level of ALM components is different in each utility. It also changes over time within a utility. This system should be implemented systematically in the utilities (generally in 6-month or 12-month periods) to evaluate the effects of the work to be done to improve the weaknesses. The critical components (especially components with low scores in the base-level components) may improve at each implementation stage. Components with low scores, especially at the basic level, compared to the current scores in pilot utilities, are critical components. It is possible to identify critical components and monitor recovery processes over time with the systematic and regular application of this system. The most important difference of this study from other studies is that the current situation in the utility is evaluated in a wide scope. In addition, it is the monitoring of recovery processes on an annual basis depending on the dynamic structure of ALM components. Currently, only the current situation in the pilot utilities has been analyzed. Studies need to be completed to analyze the progress or impact of efforts to improve weaknesses in these utilities. Upon completion of the studies, this model can be applied again to evaluate the improvements over time and the effects of the work done in the field.

In this study, an evaluation system consisting of a total of 45 components has been developed for a sustainable apparent loss management. In future studies, the number of components can be increased or decreased by taking this study as a reference. In addition, in future studies, the most appropriate targets can be determined with the optimization algorithm according to the dynamic structure of the utility, based on the existing scores. Thus, it can be ensured that resources are used more efficiently in administrations and that water loss management studies are carried out more planned and systematically.

4 Conclusions

In this study, a current status assessment system was developed for analyzing the quality of data and monitoring the current status of apparent loss management practices. This assessment system was implemented in pilot utilities. This system provides the opportunity to question in detail the quality, measurement frequency and accuracy of the data used in the apparent loss management in utilities. Various methods and tools have been applied for the detection, prevention, reduction and sustainable management of AL. This assessment system contributes to the evaluation of the current implementation level of these methods and tools. The level of improvement in the quality of data and the implementation of methods and tools within the scope of apparent loss management in utilities is also monitored by implementing this system on an annual basis. On the other hand, in the literature, studies are generally carried out to determine water meter inaccuracies or to analyze the factors that cause meter inaccuracies in pilot regions. Therefore, the scope of the studies conducted in pilot areas is generally limited. However, the assessment system proposed in this study can be applied to any administration. The apparent loss management processes of the administrations can be evaluated in a holistic and comprehensive manner. Apparent loss management has a dynamic process depending on the change in the number of customers and network conditions. Therefore, the assessment system should be applied annually. It is possible to identify critical components and monitor recovery processes over time with the systematic and regular application of this system. In addition, it is the monitoring of recovery processes on an annual basis depending on the dynamic structure of apparent loss management components. In future studies, the scope and number of ALM practices could be increased or decreased by taking this study as a reference. In addition, the components that need improvement can be identified by applying multi-criteria methods.

The main problem experienced in the implementation of this study is the lack of sufficient information and data on the units in scoring the components. Incomplete or inadequate recording of reports in units, especially for apparent loss prevention, reduction and detection methods, makes scoring difficult. In addition, decision makers or technical personnel in the unit are generally concerned about having high scores. Therefore, experts from outside the utility should score the components. As a result, this assessment model will provide reference information for the decision maker and technical staff in utilities, to create a roadmap for sustainable ALM.

5 Acknowledgment

This study was produced from the PhD thesis conducted by Cansu Bozkurt. The authors thank Inonu University, Scientific Research Project Funding for their financial support (FBA-2021/2457). This research was supported by TUBITAK (Turkish National Science Foundation) under the Project Number 220M091.

6 Author contribution statement

In this study, Mahmut Fırat contributed to improve the idea behind the study. When Cansu Bozkurt contributed to the establishment of the current status evaluation system and the evaluation of the application levels, and to the writing of the article. Mahmut Fırat controlled the writing, editing, and evaluation of the results.

7 Ethics committee approval and conflict of interest statement

"There is no need to obtain an ethics committee approval in the article prepared". "There is no conflict of interest with any person/institution in the article prepared".

8 References

[1] Ncube M, Taigbenu AE. "Assessment of apparent losses due to meter inaccuracy using an alternative, validated methodology". *Water Supply*, 19(4), 1212–1220, 2019.

[2] Pearson D. *Standard Definitions for Water Losses: A Compendium of Terms and Acronyms and Their Associated Definition in Common Use in the Field of Water Loss Management*. 1st ed. London, UK, IWA Publishing, 2019.

[3] Şişman E, Kızıöz B. "Trend-risk model for predicting non-revenue water: An application in Turkey". *Utility Policy*, 67, 101137, 2020.

[4] Yilmaz S, Firat M, Ateş A. "Analysis of network useful life and cost-benefits for sustainable water management". *Sigma Journal of Engineering and Natural Sciences*, 42(1), 130–140, 2024.

[5] Mutikanga HE, Sharma SK, Vairavamoorthy K. "Assessment of apparent losses in urban water systems". *Water Environment Journal*, 25(3), 327-335, 2011.

[6] Mutikanga HE, Sharma SK, Vairavamoorthy K. "Methods and tools for managing losses in water distribution systems". *Journal of Water Resources Planning and Management,* 139(2), 166-174, 2013.

[7] Fontanazza CM, Notaro V, Puleo V, Freni G. "The apparent losses due to metering errors: a proactive approach to predict losses and schedule maintenance". *Urban Water Journal*, 12(3), 229–239, 2015.

[8] See KF, Ma Z. "Does non-revenue water affect Malaysia's water services industry productivity?". *Utility Policy*, 54, 125–131, 2018.

[9] Moahloli A. "Domestic water meter optimal replacement period to minimize water revenue loss". *Water SA*, 45(2), 165–173, 2019.

[10] Horbatuck KH, Beruvides MG. "Water Infrastructure System Leakage Analysis: Evaluation of Factors Impacting System Performance and Opportunity Cost". *Water*, 16(8), 1080, 2024.

[11] Seago CJ, Mckenzie RS, Liemberger R. "International benchmarking of leakage from water reticulation systems". *IWA Leakage 2005 Conference, Halifax,* Canada, 15-19 June 2005.

[12] Liemberger R, Wyatt A. "Quantifying the global non-revenue water problem". *Water Supply*, 19(3), 831–837, 2019.

[13] Albaina I, Bidaguren I, Izquierdo U, Esteban GA. "Impact of valves on reading errors in domestic ultrasonic water meters". *Engineering Research Express,* 7(1), 0155, 2025.

[14] Criminisi A, Fontanazza CM, Freni G, La Loggia G. "Evaluation of the apparent losses caused by water meter under-registration in intermittent water supply". *Water Science Technology*, 60(9), 2373-2382, 2009.

[15] Arregui F, Cabrera E, Cobacho R, García-Serra J. "Reducing apparent losses caused by meters ınaccuracies". *Water Practice and Technology,* 1(4), wpt2006093, 2006.

[16] Mesquita AM, Ruiz RM. "A financial economic model for urban water pricing in Brazil". *Urban Water Journal,* 10(2), 85-96, 2013.

[17] Alvisi S, Luciani C, Franchini M. "Using water consumption smart metering for water loss assessment in a DMA: a case study a case study". *Urban Water Journal*, 16(1), 77–83, 2019.

[18] Firat M, Yılmaz S, Ateş A, Özdemir Ö. "Determination of economic leakage level with optimization algorithm in water distribution systems". *Water Economics and Policy*, 7(3), 2150014, 2021.

[19] Akdeniz T. "A case study on integrated management of water losses in Antalya, Turkey". *Water Practice and Technology,* 17(10), 2023–2030, 2023.

[20] Negese AS, Kebede HH. "Performance evaluation of water supply distribution system: a case study of Muke Turi town, Oromia region, Ethiopia". *Water Practice and Technology*, 18(10), 2211–2222, 2023.

[21] Karadirek İE. "How does ageing of customer water meters effect the accuracy?". *Sigma Journal of Engineering and Natural Sciences*, 41(2), 408–414, 2023.

[22] Fontanazza CM, Notaro V, Puleo V, Freni G. "Effects of network pressure on water meter under-registration: an experimental analysis". *Drinking Water Engineering and Science*, 6, 119-149, 2013.

[23] Arregui FJ, Gavara FJ, Soriano J, Pastor-Jabaloyes L. "Performance analysis of ageing single-jet water meters for measuring residential water consumption". *Water (Switzerland)*, 10(5), 1-18, 2018.

[24] Lai CH, Tan DT, Roy R, Chan NW, and Zakaria NA. "Systems thinking approach for analysing non-revenue water management reform in Malaysia". *Water Policy*, 22(2), 237-251, 2020.

[25] AL-Washali T, Sharma S, Lupoja R, AL-Nozaily N, Haidera M, Kennedy M. "Assessment of water losses in distribution networks: Methods, applications, uncertainties, and implications in intermittent supply". *Resources, Conservation and Recycling*, 152, 104515, 2020.

[26] Mendoza AA, Benavides-Muñoz H. "Evaluation of domestic water measurement error: a case study". *AQUA-Water Infrastructure, Ecosystems and Society,* 70(2), 217–225, 2021.

[27] Cordeiro C, Borges A, Ramos MR. "Case study a strategy to assess water meter performance". *Journal of Water Resources Planning and Management,* 148(1), 1-11, 2022.

[28] Chandaeng S, Sawangjang B, Kazama S. "Analysis of the factors influencing the fluctuation of non-revenue water in Luangprabang and Satoshi Takizawa". *AQUA-Water Infrastructure, Ecosystems and Society,* 73(3), 453-463, 2024.

[29] Li K, Gao J, Wu W, Qi S, Cao H, Qiu W, Zhu X. "Metering error assessment model considering multiple factors". *Engineering Proceedings*, 69(1), 47, 2024.

[30] Bozkurt C, Firat M, Ateş A. "Development of a new comprehensive framework for the evaluation of leak management components and practices". *AQUA-Water Infrastructure, Ecosystems and Society,* 71(5), 642-663, 2022.

[31] Firat M, Bozkurt C, Ateş A, Yılmaz S, Özdemir Ö. "Development and implementation of a novel assessment system for water utilities in strategic water loss management". *Journal of Pipeline Systems Engineering and Practice*, 14(1), 04022065, 2022.

[32] Bozkurt C, Fırat M, Ateş A. "Su kayıp yönetiminde kullanılan temel verilerin mevcut uygulama düzeyinin değerlendirilmesi için model geliştirilmesi," *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi*, 29(4), 377-383, 2023.