AQUA
Water Infrastructure, Ecosystems and Society

 AQUA – Water Infrastructure, Ecosystems and Society Vol 71 No 5, 642 doi: 10.2166/aqua.2022.031

Development of a new comprehensive framework for the evaluation of leak management components and practices

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ABSTRACT

Leaks cause significant operational problems in water distribution systems (WDSs). The methods for managing leaks are time-consuming and costly. Therefore, the suitability and applicability of water loss management (WLM) methods should be analyzed. In this study, a new comprehensive framework was proposed using the scoring table to evaluate and highlight the reliability of data and to analyze the current application level of leakage management practices in WDSs. The developed framework consists of 60 sub-components determined to cover the WLM practices. A scoring structure was created to analyze these sub-components in measurable criteria. The developed framework was applied to three pilot administrations, and the results were discussed. The data quality (quite good, good, doubtful, poor, and quite poor) is classified according to the application level of the leakage management practices. The data quality of leakage management components and the application levels of practices are at good level in Administrations I and II and at moderate level in Administration III. The weaknesses and strengths in administrations were defined in the scope of leakage management, and the components that need improvement are determined dynamically. This framework will provide more accurate data for sustainable leakage management in the administration and make field applications more systematic.

Key words: current status analysis, data quality assessment, leakage, leakage management practices, scoring structure

HIGHLIGHTS

- The current application level of leakage management practices was evaluated.
- A new model was developed for evaluation.
- The developed model consists of 60 leakage management practices.
- A scoring structure was created to analyze these sub-components.
- The model was tested using field data.

INTRODUCTION

Failures and leaks occur in mains and service connections in water distribution systems (WDSs) due to various factors. Non-revenue water (NRW) is defined as water delivered to WDSs but not charged (Lambert *et al.* 1999). The NRW volume includes the components of the real losses, apparent losses, and unbilled authorized consumptions (Pearson 2019). Globally, annual leakage rates in WDSs are in the range of 25–30% (European Commission 2014), while the NRW rate is around 30% (Liemberger & Wyatt 2019; Berardi & Giustolisi 2021). A significant part of water resources is lost in the network due to leakages. While the leakage rate is more than 50% in developing countries around the world, this rate is between 3 and 7% in well-maintained networks in developed countries (Puust *et al.* 2010; Gupta & Kulat 2018; Duan *et al.* 2020; Moslehi *et al.* 2021). Moreover, according to the World Bank, nearly 48 billion m^3 of water gets lost annually from WDSs, costing US $14 billion to water utilities (Mutikanga *et al.* 2013; Gupta & Kulat 2018). In the report published by the Turkish Water Institute (SUEN), according to the data from 25 administrations, the average NRW rate is 42%, with the lowest and highest values being 22 and 67%, respectively (SUEN 2020). In addition, the total annual economic loss due to NRW in the administrations exceeded 7 billion Turkish Liras in the year 2017 (SUEN 2017).

Trends in climate change and global warming negatively affect surface and groundwater resources in terms of quantity and quality (IPCC 2015). In systems with high leakages, more water is supplied to the systems to meet the demand, existing resources are insufficient, and as a result, new resources are sought, and access to clean water becomes increasingly difficult with excessive water consumption. Therefore, these negative effects of NRW or leakages should be minimized (Bakhtiari *et al.* 2020). Reducing all water loss components to zero is neither technically possible nor economically viable. The water loss components should be accurately assessed and prioritized for minimizing loss (Al-Washali *et al.* 2020).

In the literature, basic methods, including pressure management (PM) (Kanakoudis & Gonelas 2016; Creaco & Walski 2017; Muhammetoglu *et al.* 2018), district metered area (DMA) planning (Ferrari & Savic 2015; Campbell *et al.* 2016), active leakage control (ALC) (Berardi *et al.* 2015; Candelieri *et al.* 2015; Cabral *et al.* 2019; Lipiwattanakarn *et al.* 2019), leakage modeling (Guo *et al.* 2021), failure repair, and maintenance and pipe material management (Deidda *et al.* 2014; Marchionni *et al.* 2016; Agathokleous & Christodoulou 2017), have been applied for the reduction, prevention, and management of leakages. However, before applying these methods, it is important to analyze the current state of the system and the current application levels of leakage management practices, in terms of reducing the initial investment and operation–maintenance costs (Yilmaz *et al.* 2021a).

A detailed analysis of the current state of the network, operating conditions, and system components is the first and critical step in developing a water loss management (WLM) strategy (Liemberger & Farley 2004; Farley & Limberger 2005). In WDS data, equipment and technical capacity should be sufficient for ALC, and failure repair and maintenance and PM strategies should be applied for ensuring a sustainable WLM. The network characteristics and operating conditions should be monitored regularly in order to define the prevailing situation correctly (Vicente *et al.* 2016; Monsef *et al.* 2018; Moslehi *et al.* 2021). The standard water balance table, minimum night flow (MNF), and component analysis (with failure records) methods have been applied for the estimation of leaks in WDSs. The failure rates, network conditions, and field data used in these methods are highly effective in estimating leaks (Amoatey *et al.* 2018). Unreported leaks, which constitute a significant part of the leaks in WDSs, occur mostly at the service connections. The ALC in DMAs should be applied in order to determine and reduce these leaks in the WDSs (Boztaş *et al.* 2019).

Water utilities work hard to reduce water losses, but this results in high costs. To control water loss, first, the relative contribution to the loss of the various components should be identified. Next, how much would have to be spent for loss reduction in a particular component should be considered. Based on this, what kind of investment has the greatest impact in terms of the least cost should be determined (Moslehi *et al.* 2021; Serafeim *et al.* 2022). In leakage management, the most appropriate level at which leaks can be reduced should be defined to ensure water, energy, and financial efficiency. Therefore, the current state of the systems should be analyzed, the application levels of the methods should be determined, and the requirements should be defined (Yılmaz *et al.* 2021b). A new algorithm was proposed by Firat *et al.* (2021) in order to define the economic leakage level (ELL) in WDSs. In this algorithm, parameters that include the consideration of the current state of the administration (current leakage rate, personnel, and equipment) and the current application levels of methods (DMA, PM, and ALC practices) are considered as the fundamental component (Firat *et al.* 2021). Wu *et al.* (2022) proposed a comprehensive solution framework for anomaly detection and localization by integrating data-driven analytics with hydraulic model calibration. The proposed approach has been proved to be effective at analyzing the monitoring data for flow and pressure to detect anomaly.

Leaks cause water resource inefficiency, an increase in operating costs, a decrease in service quality, and an increase in customer complaints. In the literature, studies were carried out within the scope of determining and analyzing leaks according to various methods in general. However, the methods applied to manage leaks are generally time-consuming and costly. Therefore, the current state of the administration, personnel, technical, and financial capacity should be examined, and the applicability of methods and the application levels of the currently applied methods should be analyzed on the basis of measurable, appropriate, and objective criteria. Therefore, in this study, a new comprehensive framework is proposed using the scoring table to evaluate and highlight the reliability of data and to analyze the current application levels of leakage management practices in WDSs. The developed framework consists of 60 sub-components determined to cover the WLM practices. The purpose of this study is not to calculate the level of leakage or the ELL. Rather, the quality of the data used in leakage management and analysis and the application levels of the applied methods are questioned. Thus, the data quality (quite good, good, doubtful, poor, and quite poor) is classified according to the application levels of the leakage management practices. The class of the component is determined according to the examination and evaluation made in the administration. This classification is not made by the personnel in the administration. Accordingly, it will be possible to provide more accurate data for sustainable leakage management in the administration and make field applications more systematic.

Comprehensive evaluation framework for leakage management practices

Leaks are one of the most fundamental problems in transmission lines and distribution systems. Some of the leaks that occur in WDSs are openly exposed (reported leaks). However, a significant part of the failures are unreported failures (Lambert *et al.* 1999; Pearson 2019). *Passive leak control* is applied to manage reported failures, while *active leak control* is applied to reduce unreported leaks. The most basic methods applied to reduce leaks are PM (García-Ávila *et al.* 2019; Özdemir *et al.* 2021), DMA planning and MNF analysis (Negharchi & Shafaghat 2020; Marzola *et al.* 2021), failure management (Arai *et al.* 2010; Kahn *et al.* 2020), and leak detection with regional or local acoustic equipment (Giaquinto *et al.* 2018; Shukla & Piratla 2020). However, these methods require team, equipment, institutional and personnel experience, and financial capacity. Therefore, the prevailing situation in the administration, its technical and institutional experience, applicability, and the necessity of methods should be evaluated in detail. Moreover, the current levels of the application of the WLM methods applied in the administration should be analyzed. The methods/processes that can be applied for the effective and sustainable management of the WLM components in the administration should be determined on the basis of this analysis.

The main problems encountered in WLM can be given as follows: (i) the lack of a roadmap for data collection, monitoring, and analysis, (ii) the lack of a methodology that evaluates the application levels of leakage components in detail, (iii) the absence of a method that identifies the weaknesses/strengths and the risks based on the current situation analysis, and (iv) the lack of setting appropriate targets based on the current situation analysis. Therefore, it is important to develop a current status evaluation framework for devising an effective, sustainable (which is applicable), and a long-term WLM strategy in administration.

A sustainable strategic WLM model, which includes a current condition evaluation matrix, a data matrix, a performance evaluation system, and a method recommendation matrix, has been proposed and outlined by Bozkurt *et al.* (2022). In this study, a new comprehensive framework for leakage management practices was developed on the basis of the WLM model proposed by Bozkurt *et al.* (2022). This assessment model is directly associated with the data used in leak analysis. Thus, it is planned to define the components that lack data or methods, to make gap analysis, to define the components that need improvement, and to identify the weaknesses and strengths of the system. In this model, a total of 60 components, which are grouped as 'Basic-Level Practices', 'Moderate-Level Practices', and 'Advanced-Level Practices', were defined to cover leakage management (Tables 1–3). The applicability, requirements (financial, data, technological capacity, and experience), and difficulty levels of the components in the field are considered in this grouping. While the scoring results in the administration are evaluated separately for these levels, a general evaluation is made for the whole matrix at the same time. The aim here is to reveal the current state of the administration at each implementation level. Thus, information that will form a reference in determining the priority sub-components in improvement will be produced.

The leakage components are scored between 0 and 5 (0 point (quite poor), 1 point (poor), 2 points (insufficient), 3 points (moderate), 4 points (good), and 5 points (quite good)) in the developed framework. Components with 0 and 1 points constitute weakness in leakage management (if data quality is poor, the components should be improved). The priority target for these components is determined as 3 points (moderate level), then 4 points (good level), and finally 5 points (quite good level). Similarly, components with 2 and 3 points constitute weakness in leakage management (if data quality is questionable, it needs improvement); however, they could be used in analysis. For these components, the priority target is 4 points (good level) and then 5 points (quite good level). On the other hand, if a component has a score of 4 (good data quality) or 5 (if data quality is very good, the current status should be kept), this component constitutes the strength of the administration. The final target for components with a current score of 4 were defined as 5 (quite good level) based on technical and economic criteria. Components with a current score of 5 are evaluated as 'existing conditions should be kept'.

ANALYSIS AND DISCUSSION

The framework proposed in this study was tested with real field data in pilot administrations. For this, the Bursa Water Administration (Administration 1), the Kayseri Water Administration (Administration 2), and the Denizli Water Administration (Administration 3) in Turkey were chosen as study areas (Figure 1). Administration 1, located in the west of Turkey, has a surface area of 10,820 km^2. This administration has a network main line length of approximately 7,100 km. The water requirement of the administration is met from surface and underground water resources. Administration 2, located in the west of Turkey, has a surface area of 12,321 km^2. This administration has a network main line length of approximately

Table 1 | The scoring structure for basic-level components

Basic-level components	Quite poor 0	Poor 1	Insufficient 2	Moderate 3	Good 4	Quite good 5
Main length	No digital network plan, main length unknown	Main length unknown, only some of the available lines exist in paper/CAD, and no updates or field calibrations.	Main length is approximate, some (25–50%) have a GIS database, and some are in CAD/ paper, no scheduled updates.	A certain part of the network length (50–75%) has a GIS database, and there is no systematic update program.	A certain part of the network length (75–90%) has a GIS database, and updates are regularly within a certain plan.	More than 90% of the network length has a GIS database, updates are regularly within a certain plan, and the unknown data rate is below 10%.
Number of service connection	No digital network plan, the number of connections unknown	No correct data for service connections, part of network plan on paper, part on CAD/GIS (0–25%), and no field updates.	Except for renewed areas, some of the old regions (25–50%) have a GIS database, and no planned updates.	Except for renewed areas, some of the regions (50–75%) have a GIS database, and update is available within the schedule (1–2 years).	Except for renewed areas, there is a GIS database of 75–90% of the old regions, and updates are made regularly within a certain plan.	Except for renewed areas, more than 90% of the old regions have a GIS database, and updates are made regularly within a certain plan.
Number of valves	No digital network plan and the number of valves unknown	No correct data, a part of the network plan on paper, a part on GIS (0–25%), and no field calibration.	Except for renewed areas, some regions (25–50%) have a GIS database, and no planned updates.	Except for renewed areas, some regions (50–75%) have a GIS database, and there is an update (1–2 years).	Except for renewed areas, some regions (75–90%) have a GIS database, and updates are regular.	Except for renewed areas, some regions (more than 90%) have a GIS database, and updates are made within a plan.
Planning of Information Management System (IMS)	No work to develop the IMS	The basic systems (CIS, CAD) are available, and data are kept on a unit basis.	Some units have information systems, keeping and verifying data on a unit basis.	There are some IMSs, in other units, they are at planning stage, and integration is being planned.	Units have IMS, data are kept, some systems have integration with one another, and integration of all systems is planned.	There are integrated information systems, data are kept regularly, and systems are integrated.
Water Resources, System Input Flow Management System (SCADA)	No work for this component	No data for monitoring, planning for main resource is in progress.	There is SCADA for monitoring of main resource and input flow.	A certain part (more than 50%) of the sources feeding the system is monitored by SCADA.	The sources that feed the system are monitored with SCADA (more than 90%).	The resources are monitored with the SCADA (more than 90%), and there is integration with other systems.
WLM Database (SCADA Distribution)	No work to monitor data with SCADA	No SCADA monitoring system for system input flow and planning for main reservoirs.	There is SCADA for monitoring of main resource and reservoir, and no monitoring in the system.	Input flows/reservoirs (more than 90%) are monitored by SCADA, and flow/ pressure are monitored in pilot DMA.	Input flow in system/ DMAs (more than 90%) are monitored with SCADA, and there is integration with some databases.	Input flow in system/ DMAs are monitored by SCADA (more than 90%), and there is data sharing with other systems.
Distribution System GIS Database	No work for the GIS-based distribution system	Network/fittings unknown, some of the available lines exist in paper/CAD, and no updates.	A part of the system (25–50%) has a GIS database, the other part is in CAD, and no scheduled updates.	A part of the system (50–75%) has a GIS database and map, and updates are made periodically.	A part of the system (75–90%) has a GIS database and a digital map, and updates are made periodically.	More than 90% of the system has a GIS database and a digital map, and there is a systematic update program.
CRM	No work for CRM	Calls are kept in Excel, there is no detailed analysis reporting, and a CRM is being planned.	Calls are received with CRM, analysis is not made, and feedback is provided for customers.	Calls are received by CRM, no instant team monitoring, and analysis is made with annually.	Calls are managed with CRM, teams are directed and monitored, and analyses are available.	Calls are managed with CRM, teams are directed and monitored, and detailed analyses are available with GIS integration.

(*Continued.*)

Table 1 | Continued

Basic-level components	Quite poor 0	Poor 1	Insufficient 2	Moderate 3	Good 4	Quite good 5
Analysis of factors affecting real losses	No work available for this analysis	There are not enough data for analysis, and improvement is being planned.	There are enough data, some components are analyzed, and MNF is analyzed in a DMA.	The factors in reservoirs are analyzed, and MNF and flow-pressure analysis are made in pilot DMA.	Leaks are analyzed in connections, mains are analyzed separately, and flow-pressure analysis is made.	Failures in connections and mains are analyzed separately, and flow-pressure analysis is performed with GIS integration.
Strategy development for detection of leakages	No work for real loss reduction and management strategy	There are no data for monitoring the system, and field data are not enough for analysis and strategy.	There is no strategic plan, randomly selected areas are audited, and improvement is being planned.	There is a PM with flow-pressure analysis in a DMA, and short-term strategy is being planned.	There are PM, ALC, MNF, and speed of repair quality, mid-term prevention-monitoring strategic plans.	There are PM, speed and quality of repairs, ALC, material management, long-term strategic plans are available.
Active Leak Control (ALC) Program, Plan and Strategy	No ALC operation	There is no ALC strategy, only in case of complaints, detection is made, data are insufficient.	DMA planning, MNF analysis and detection are made in the region where leakages are high.	ALC strategy is planned in a DMA, leak detection is made, and plan is made to extend the system overall.	There is an ALC strategy and roadmap for methods, and there is a leak detection team C&B analysis standard.	There is an ALC strategy and roadmap for methods, there is a C&B analysis standard, and GIS integration is available.
DMA planning	No DMA planning	There is no DMA plan, data are not enough, and improvement is being made.	There is a pilot DMA in renewed areas or regions with high failure, and data are monitored in this DMA.	There are DMAs in a part of the systems (50–75%), and MNF analysis and leak detection are made.	There are DMAs in a part of the systems (75–90%), MNF analysis is made, and there is a C&B standard.	There are DMAs in a certain part of the system (75–90%), MNF and C&B analysis are made, and GIS integration is available.
MNF analysis	No MNF analysis work	There is no ALC–DMA strategy, data are not enough, and improvement is being planned.	MNF analysis and monitoring is made in the pilot DMA.	MNF analysis is made in a certain part of the system (50–75%), and leak detection is made.	MNF analysis is made in a certain part of the system (75–90%), leak detection is made, and there is a C&B standard.	MNF analysis is made in a certain part of the system (75–90%), leak detection is made, and C&B is monitored by GIS.
Failure repair speed and time analysis and improvement	No failure repair speed and time improvement work	Reported failures are saved on paper, teams are managed by phone, and no detailed reporting.	Failures are saved in Excel, teams are managed by phone, improvement is made for CRM, and repair duration is estimated.	Calls are managed with CRM, teams are not monitored instantly, and improvement is being planned.	Calls are managed with CRM, teams are managed instantly, and graphical analysis is available.	Calls are managed with CRM, teams are managed instantly, and graphical analysis and GIS integration are available.
Systematic measurement and monitoring of real loss components for water balance calculations	There are no works to measure the real loss components in the field.	The technical data are not sufficient to monitor the reservoirs and WDS. Planning is being made for improvement..	Controls are made randomly in reservoirs, MNF analysis is planned in DMA, and technical background is improved.	A certain part of the reservoirs are inspected, and leaks are determined with MNF analysis in a limited number of pilot DMAs.	Reservoirs and DMAs are monitored regularly, and leaks are determined and monitored on site with MNF in DMAs.	Reservoirs and DMAs are monitored regularly, leaks are determined on site by MNF analysis in DMAs, and GIS integration is available.
Performance Monitoring System (PMS) and Integration of Systems	No work for PMS and integration	There is no PMS, and the data are not enough for detailed analysis.	Performance analysis is made in Excel with the data received by the user, and integration is not enough.	Performance analysis is made in Excel, and integration of systems is being planned.	There is a PMS, some systems have integration, and integration of all systems is being planned.	Performance analysis in DMAs is done through the PMS, and GIS integration is available.

(*Continued.*)

Table 1 | Continued

Basic-level components	Quite poor 0	Poor 1	Insufficient 2	Moderate 3	Good 4	Quite good 5
Monitoring of GIS data update and verification practices	No monitoring of GIS data update-verification practices	Experience is not enough for monitoring of GIS data update, and improvement is being planned.	There is a GIS unit, the departments control the data entry and update, there is no report, and the monitoring is insufficient.	There is a GIS unit, data entry-update are controlled by this unit, and data updates are made at least 1–6 months.	There is a GIS unit, data entry and updating are controlled by this unit, a report on data updating is prepared at least monthly.	There is a GIS unit, data entry and updating are controlled, a report is prepared at least weekly, unit leaders responsible for data entry are informed.
Performance analysis and monitoring for DMAs	No performance analysis in DMAs	In DMAs, the NRW rate indicator is monitored annually, and there are not enough data for other indicators.	In DMAs, basic-level indicators (based on water balance) are monitored, and work is done for process indicators.	In DMAs, technical–economic process indicators are monitored by PMS, and works are made for C&B analysis.	In DMAs, technical–economic ILI and UARL are analyzed and monitored, the target is defined, and C&B analysis is made.	In DMAs, technical–economic ILI, UARL, and ELL are monitored, the target is defined, C&B analysis is made, and GIS integration is available.
Analysis and monitoring of network failure maintenance–repair cost	No work to calculate maintenance–repair cost	There are not enough data experience for repair cost calculation, detailed field data are not kept, and costs are estimated.	Failure repair cost is calculated, some components are predicted, and planning is made to improve analysis.	The repair cost in mains and connections is analyzed (every 1–2 years), and all components are considered.	The repair cost in mains and connections is analyzed by the model and updated annually, and all components are considered in the analysis.	The repair cost in mains and connections is analyzed by the model and updated annually, and unit costs per connection and main are known.
Analysis and monitoring of network operating efficiency	No work to analyze this component	Operating efficiency approximately is estimated, and improvement is being planned.	Annual report is prepared for efficiency, and income and expenses are presented to the manager.	A report is prepared every 6 months for efficiency, and income and expenses are presented to the manager.	Operational efficiency is regularly analyzed and monitored annually, and revenues and costs are monitored regularly.	Operational efficiency is regularly analyzed and monitored annually, revenues and costs are monitored, and GIS integration is available.

3,000 km. The water requirement of the administration is met from surface and underground water resources. Administration 3, located in central Anatolia in Turkey, has a surface area of 17,000 km^2. This administration has a network main line length of approximately 8,000 km. The water requirement of the administration is met from underground water resources.

An on-site examination and scoring was made on the basis of the scoring tables for each variable in accordance with the situation prevailing in the administration. These components are not scored by the administration's technical staff or decision makers. In order to define the current state of the administration, each administration was visited separately by the authors (expert team in this article) at different times in 2021. In this context, all practices in the administration were evaluated in units, namely, the Drinking Water Management Department, the SCADA Department, the GIS Department, and the Information Technology Department. The activities and reports of the departments were examined to evaluate the quality of the practices for the determination of leakage components in the field. In addition, the quality of the system's basic data was evaluated by the queries made in the SCADA, GIS, and Information Technology Departments.

Evaluation for basic-level practices

The score results and targets for basic-level practices in administrations are evaluated separately (Table 4). Gradual targets were defined by considering the current scores of the components in the basic-level practices (Table 4). If the current scores of the variable are 0 and 1, the primary target for these components is defined as a moderate-level target (Target I). Then, the targets defined for this variable are a good-level target (Target II) and a very good-level target (Target III), respectively. If the current scores of the variable are 2 and 3, the primary target for these components is defined as a good-level target (Target II). Then, the target defined for this variable is quite a good-level target (Target III). If the current score of the variable

Table 2 | The scoring structure for moderate-level components

Moderate-level components	Quite poor 0	Poor 1	Insufficient 2	Moderate 3	Good 4	Quite good 5
Operating pressure	No pressure measurement	Measurements are made in case of complaints, data are not kept, and there is no systematic measurement.	Measurements are made at randomly determined points, and in case of need, there is no systematic and measurement plan.	Measurements are made and monitored at the entrances of the pilot DMA, where the topography changes a lot. Failures are high. Calibration is done very rarely.	There is a planned and regular PM strategy in DMAs, it is regularly monitored by SCADA, and the average calibration period of the devices is 1–2 years.	There is a planned and regular PM strategy in DMAs, and it is regularly monitored by SCADA. Calibration is made regularly (average 1 year).
Roadmap for managing WLM components	No work for any roadmap for managing water loss components	There is not enough experience about WL practices, and there is only a flow chart for the measurement systems.	It is planned to prepare a roadmap for the basic methods in WLM and to determine the path for field works, and the flow charts are insufficient.	There is a program and road map for the management of main and basic components, there is no C&B analysis standard, and flow charts are insufficient.	There is a strategic plan for the WLM, a roadmap is ready for the methods and field works, the C&B standard was defined, and flow charts were created.	There is a strategic plan for the WLM, a roadmap is ready for the methods and field works, the C&B standard and flowcharts were defined, and reports are available.
GIS-based valve failure database, maintenance–repair and control program	No work for this component	GIS valve failure database is not available, maintenance is done in case of failure, and data are kept in paper.	There is a GIS-based valve failure database, maintenance is done in case of failure and kept in Excel, and there is no planned maintenance program.	There is a GIS-based valve failure database, valve maintenance is done annually in selected regions, and the GIS database is updated in case of failure maintenance.	There is a GIS-based valve failure database, a systematic program is created annually for valve maintenance, and the GIS database is regularly updated.	There is a GIS-based valve failure database, a systematic maintenance is created based on the failure density, and the GIS database is regularly updated.
Failure Management System (integrated with GIS)	No work for this component	Data are kept in Excel, detailed analysis is not made, and improvement is being planned.	Failures are received through the CRM, analysis inquiry is not made, and feedbacks for customers are made.	Faults are managed with CRM, there is no team monitoring, analysis is made annually, and feedbacks for customers are made.	There is a regular failure system, calls are managed with CRM, teams are managed instantly, and graphical analysis is available.	There is a regular failure system, calls are managed with CRM, teams are managed instantly, and analysis is made with GIS.
SCADA Reservoir Monitoring System and Database	No work for this component	Levels are measured, data are kept in Excel, and flow rates are not monitored by SCADA.	Levels/flows in main reservoirs are monitored with the SCADA system.	Levels/flows in a part of the reservoirs (more than 90%) are monitored by SCADA, and no integration with other systems.	Levels/flows (more than 90%) are regularly monitored by the SCADA, and there is integration with some databases.	Levels/flows are regularly monitored by the SCADA system, and integration is available (GIS-based water balance analysis).
Network Maintenance and Repair Management (MRM) System (with GIS)	No work for this component	There is no network MRM plan, data are kept in paper form, and no details for analysis.	Data for network MRM is kept on Excel, and planning is made for system design.	Network MRM practices are made through the system, there is no systematic planning, and analysis is done over total data.	Only in DMAs, network MRM data are entered into the GIS regularly, and detailed analyses are made with GIS integration.	There is a GIS-based network MRM system. Analysis is made with GIS integration based on the density of failures.

Leaks in the distribution system (mains and service connections)	There are no studies for this component.	There is no ALC/DMA, inspection is made in the region with high complaints, and leaks are estimated.	Unplanned inspection is made in regions with complaints or is randomly determined, MNF is analyzed in pilot DMA, and leaks are estimated.	Leakages are determined on the site on the basis of MNF in a part of the system (50–75%), and loss volume is calculated in the other regions.	Leakages are determined on the site according to MNF analysis in 75–90% of the system, and improvement is planned for the other regions.	Leaks are determined in the field by MNF analysis in more than 90% of the system.
Leaks in reservoirs	No work for this component	Data are not enough for analysis, there is no inspection program, and leaks are not analyzed.	Main reservoirs are monitored, there is no systematic inspection, and reservoirs are randomly controlled.	A part (more than 50%) of the reservoirs is randomly selected and inspected, and the leakage volume is estimated for all reservoirs.	Reservoirs (between 75 and 90%) are inspected and controlled annually, and the leakage volume is calculated.	Reservoirs (more than 90%) are inspected and controlled annually, and the leakage volume is calculated.
Leak detection and repair technical capacity (team, device)	No work for this component	There is only ground microphone, personnel is insufficient, there is no leak detection team.	There is a ground microphone and detection team, detection quality in the mains is average, and leaks in connections are detected with low accuracy.	Technical capacity and personnel experience is average, there is a ground microphone and at least one team, leak detection is done with average (50–75%) accuracy.	Technical capacity/personnel experience is good, there is a regional recorder and ground microphone, and detection accuracy is high (more than 75%).	Technical capacity/personnel experience is good, there is a regional recorder and ground microphone, and detection accuracy is high (more than 90%).
Analysis of factors affecting the failure	No work for this component	No failure management system, data are kept on paper, and no detailed analysis and evaluation	Data are kept on Excel, and records and analysis are not detailed but only graphically based on some pipe properties.	Data are recorded, spatial and temporal analyses are made due to the network characteristic, and planning is made with hydraulic/environmental factors.	Data in mains/connections are saved, spatial/temporal analyses are made based on physical and environmental factors, and GIS integration is being planned.	Data in mains/connections is kept, GIS integration is available, and spatial/temporal analysis is made due to physical, environmental, and hydraulic factors.
Pressure-flow leakage failure analysis	No work for this component	Data are not enough for pressure-flow analysis, and improvement is being planned.	The relationship between pressure and flow is analyzed in a DMA and compared with field and improvement is being planned.	The relationship between pressure and flow is regularly monitored by SCADA in pilot DMAs, pressure-failure leakage is monitored, and analysis is done.	The relationship between pressure and flow is monitored by SCADA in DMAs, pressure-flow fault analysis is done, and regions that need PM are known.	Flow-pressure leaks are monitored by SCADA in DMAs, regions requiring PM are known, and C&B is analyzed.
Leak management and prevention in reservoirs	No work for this component	Data are not sufficient to monitor the reservoir, and there is no control and maintenance program.	Unplanned inspections are made in reservoirs, and maintenance and control program are being planned.	Maintenance is made every 1–2 years in main reservoirs, and regular maintenance program in other reservoirs is being planned.	Annual maintenance is made regularly in main reservoirs, and leakage inspection is made every 1–2 years in other reservoirs.	Annual maintenance-inspection is carried out regularly in the main and distribution reservoirs.

(*Continued.*)

Table 2 | Continued

Moderate-level components	Quite poor 0	Poor 1	Insufficient 2	Moderate 3	Good 4	Quite good 5
PM strategy	No work for this component	Data are not enough for pressure-flow analysis, and improvement is being planned.	The relationship between pressure and flow is analyzed in pilot DMA and compared with field improvement is being planned.	PM is applied and monitored with PRV on the basis of flow-pressure analysis in DMAs, and there is no standard for C&B/ gains.	Based on flow-pressure analysis, the regions where PM is required are known, different types of PRV are used, and there is a C&B standard.	Based on flow-pressure analysis, the regions where PM is required are known, flow-sensitive or time-adjusted PRV is used, and there is a C&B standard.
Service connection failure/leak prevention strategy	No work for this component	There are not enough data about failures in connections, and data are not suitable for strategy.	Awareness of the necessity of a strategic plan for failure prevention, planning for material management in a DMA.	There is pipe material management in some DMAs, there is a PM strategy based on the flow-pressure analysis, and a short-term strategic plan is made.	Factors are analyzed in DMAs, basic prevention strategic plans are in place and constantly updated, and planning for temporal and spatial inquiry is made with GIS.	Factors are analyzed in DMAs, basic prevention and mitigation strategic plans are in place and constantly updated, and temporal and spatial inquiry is made with GIS.
Monitoring of real loss performance indicators	There are no studies for this component.	There are not enough data, real loss rate is analyzed, and basic indicators are being planned.	There is an analysis template in Excel for basic indicators, and advanced indicators are not analyzed.	There is an analysis template in Excel for process indicators, the advanced indicators are being planned, and an annual report is being prepared.	The ILI, ELL, and process indicators for real losses are systematically calculated, changes are monitored and reported.	The ILI, ELL, and process indicators are systematically calculated and reported, and GIS integration is available.
Monitoring PM practices	No work for this component	Flow-pressure leakage is monitored in areas where PM is applied, and work is planned for process indicators.	Flow-pressure failure is monitored in PM areas, basic indicators are calculated, and advanced indicators are not analyzed.	Flow-pressure failures and process indicators are monitored in areas where PM is applied, and works are made for the analysis of advanced indicators.	Flow-pressure failures and process indicators are monitored, ILI andUARL are monitored, and C&B analysis is being planned.	Flow-pressure failures and ILI and UARL are monitored, and C&B analysis is made and monitored.
Monitoring the MNF practice	No work for this component	MNF and pressure flow in DMAs are monitored, and planning is made for the basic and advanced indicators.	MNF and flow rates saved in DMAs are calculated, and works are made for other indicators and economic components.	MNF and gains/benefits are calculated and monitored in DMAs, and costs/economic components are monitored.	MNF in DMAs is monitored by the developed system, benefits and costs/ economic components are monitored, planning is made for GIS integration.	MNF in DMAs is monitored by the developed system, benefits, costs, and economic components are monitored, and GIS integration is available.

Monitoring of leak detection (team and inspection) practices	No work for this component	There are not enough data for monitoring, an work is being done for improvement.	Leak detection activities/inspections/detected leaks in DMAs are kept in Excel, and reporting is done annually.	Leak detection activities/inspections/detected leaks are kept in Excel, and system development is done.	Leak detection activities/leaks are monitored by the system, C&B analysis is monitored, and GIS integration is being planned.	Leak detection activities/leaks are monitored by the system, C&B analysis is monitored and GIS integration is available.
Analysis and monitoring of the cost of real losses	No work for this component	There are not enough data for analysis, and improvement is being planned.	Cost analysis is made in the pilot region and planning is made for the overall system.	In the system, loss costs are analyzed (1–2 years), and regional changes are not analyzed.	In the system, loss costs are analyzed regularly (annual), and GIS integration is being planned.	In DMAs, costs are calculated regularly and integrated with GIS, and regional variations are analyzed.
Analysis and monitoring of leak detection equipment-monitoring cost	No work for this component	There are not enough data for the cost analysis, and work is being done for improvement.	The cost of this component is analyzed in the pilot region and planning is made for the overall system.	In the system, the costs of this component are analyzed (1–2 years), and regional variations are not analyzed.	In the system, the cost of this component is analyzed regularly (annual), and GIS integration is being planned for regional analysis.	In DMAs, costs are calculated regularly and integrated with GIS, and regional variations are analyzed.

Table 3 | The scoring structure for advanced-level components

Advanced-level components	Quite poor 0	Poor 1	Insufficient 2	Moderate 3	Good 4	Quite good 5
Total service connection length (on private property)	Service connection length unknown	No accurate data for service connection length, a part of the network plan on paper, a part on CAD/GIS (0–25%), no field calibration.	Except for renewed regions, some of the old regions (25–50%) have a GIS database, no planned updates.	Except for renewed regions, a certain part of the old regions (50–75%) has a GIS database, and there are updates within certain planned (1–2 years).	Except for renewed regions, there is a GIS database of 75–90% of the old regions, and updates are made regularly within a certain plan.	Except for renewed regions, more than 90% of the old regions have a GIS database, and updates are made regularly within a certain plan.
Establishment of a WLM strategic plan	No WLM strategic plan study	There is no WLM strategic plan and enough data, improvement is being planned, and the process is managed by using a short-term plan.	In order to create a WLM strategic plan, current situation assessment works are made and a model is established.	The current situation/ budget and target/ personnel/technical capacity are analyzed, and WLM plan is made for the short term (5 years).	The current situation and budget/target/personnel are analyzed, there is a 5–10-year WLM plan, and there is coordination between units.	The current situation, budget, targets/personnel and capacity are analyzed, there is a long-term WLM plan, and there is coordination between the units.
Number of unreported (network/service connection) leaks (failure)	No data on the number of unreported failures	No regular leak inspection and detection policy, work is done in case of complaints, no record.	There is no planned/ systematic leak detection policy, a random audit is done annually, and the total data are kept in excel.	There is leakage control within a certain program throughout the system, there is a separation of main and connection, and data are kept.	There is a DMA-based leak detection plan, the detected leaks and their details are kept in CRM, and analysis and inquiries are made.	There is a DMA-based leak detection plan, the leaks are kept in CRM, and temporal and spatial analysis is performed with GIS integration.
Leak controlling on private property service connections	No work for inspection of this leak component	No regular leak inspection and detection policy, work is done in case of complaints, no record.	There is no planned/ systematic leak detection policy, a random policy is implemented, and data are kept.	There is leakage control within a certain program throughout the system, and records are kept.	There is a DMA-based leak detection plan, the leaks are kept in CRM, and graphical/temporal analysis is made.	There is a DMA-based leak detection plan, the leaks are kept in CRM, and temporal/spatial inquiry is made with GIS.
Integration of databases with one another (GIS–SCADA–CIS–CRM)	There are no works for this component.	Capacity is not sufficient for improvement/ integration, and there is an awareness for improvement.	There are some information systems (CIS/GIS), and the work is being planned for improvement and integration.	There are some systems (CIS/GIS/SCADA/CRM) and integration with one another is being planned.	There are information systems (CIS/GIS/ SCADA/CRM), some systems have integration, and integration of all systems is being planned.	There are information systems (CIS/GIS/ SCADA/CRM), all systems are integrated, and data sharing is available.
Hydraulic model	There is no work for this component.	There are not enough basic data to create a hydraulic model, and data are being collected.	For a part of the system (less than 50%) or some DMAs, there is a hydraulic model but no calibration.	There is a calibrated hydraulic model in a part of the system (50–75%) or some DMAs, and GIS integration is available.	There is a calibrated hydraulic model (75–90%) in DMAs, and GIS integration is available.	There is a calibrated hydraulic model (more than 90%) in DMAs, and GIS integration is available.
Real-time monitoring of the system	No work for real-time monitoring system	There is no data/ technical capacity for monitoring, and work is being done for improvement.	Flow pressure is monitored in a pilot area with sufficient data, and improvement is being planned.	In some DMAs with high leakage, real-time monitoring is implemented, and leakage pressure is monitored.	There is a real-time monitoring system in some DMAs, and leakage flow pressure is monitored.	There is a DMA-based real-time monitoring system, and leakage flow pressure is monitored instantly.

Hydraulic model–based leak detection – monitoring	There is no work on the hydraulic model in the system.	There is no area monitored with the hydraulic model, and planning is being made for monitoring in the pilot area.	Monitoring is made in a DMA with the calibrated model, and improvement is being planned for other regions.	Monitoring is done in some regions (more than 50%) with the calibrated hydraulic model, and GIS integration is available.	Monitoring is done in some regions (more than 75%) with the calibrated model, and GIS integration is available.	Monitoring is done in some regions (more than 90%) with the calibrated hydraulic model, and GIS integration is available.
Leak monitoring with a pressure sensor, noise logger, and correlator	There is no work for this component.	No zone monitored by a pressure sensor, improving network and field data in pilot DMA.	Work is being done to meet the technical requirements, and planning is being done in the pilot region.	There is one monitoring system, and leak monitoring is made in the pilot region with a pressure sensor/recorder/correlator.	Leaks are monitored in some DMAs with pressure sensors/recorders/correlators, and the sensors do not stay permanently.	Equipment/knowledge is sufficient, and leaks are monitored continuously with a pressure sensor, noise recorder, and correlator with a specific plan.
Analysis and monitoring of ILI and UARL indicators	There is no work for this component.	Data are unreliable and insufficient to calculate these components, and work is being done for improvement.	Regular data are available only in renewed regions for analysis, and improvement is being made for other regions.	Regular data are available only in renewed regions and pilot DMAs, and UARL and ILI can be calculated and monitored.	UARL and ILI in systems and DMAs are regularly analyzed, monitored in Excel, and targets are set.	UARL and ILI in systems and DMAs are regularly analyzed, and regional changes are monitored by GIS.
Determination of the most appropriate loss rate level for real losses	There is no work for this component.	Data for analysis are available but not up-to-date, data are unreliable/insufficient, and work is made to improve data quality.	Only one DMA has regular data, some indicators are calculated, and work is being planned to calculate the most appropriate rate.	Indicators are calculated/monitored with regular data in DMAs, and the most appropriate rate is calculated in Excel.	The most appropriate rate analysis in the system/DMAs is made with the developed model, and it is updated annually.	The most appropriate rate in the system/DMAs is analyzed by the developed model and updated annually. GIS-based analysis is made.
Failure rate change monitoring and useful life analysis	There is no work for this component.	Failure records are kept in paper form, there is no detailed analysis and evaluation, and planning is made for improvement.	Analysis and inquiries for total records are not detailed, and they are made graphically according to some pipe properties.	Failure rates are analyzed in mains/connections with physical factors, there is GIS integration, and economic life analysis is being planned.	Spatial/temporal analysis is made in mains/connections with physical–environmental data by GIS, and economic life is analyzed in a DMA.	Spatial/temporal analyses are made in mains/connections due to physical and environmental factors, there is GIS integration, and economic life analysis is made.
Estimation of leakage components with failure and leakage records	There is no work for this component.	There are no data or information on the number and details of failures and leaks, and the technical background is not sufficient.	Reported failures exist, unreported leaks are missing, data are inconsistent, and leaks are estimated.	Reported failures are available, the unreported leaks in pilot DMAs are saved, leakage time and rate is estimated with the fault type, and leaks are analyzed.	Reported faults are available, unreported leaks in DMAs are saved, details of fault type, duration, unit leakage rate are kept, and leaks are analyzed.	Reported and unreported faults are available in DMAs, details of fault type, duration, and unit leakage rate are kept, and GIS integration is available.

(*Continued.*)

Table 3 | Continued

Advanced-level components	Quite poor 0	Poor 1	Insufficient 2	Moderate 3	Good 4	Quite good 5
Estimation of leakage and establishment of water balance based on MNF	There is no work for this component.	No ALC and DMA plan, data–technical capacity is insufficient, and improvement is being planned.	Leaks in mains/ connections are determined by MNF analysis in pilot DMAs separately, and leakage volume is calculated.	The leaks are determined by MNF in 50–75% of the system, there are data on mains and connections, and leaks are analyzed.	The leaks in mains/ connections are determined by MNF analysis in the system (75–90%), and leaks are analyzed.	The leaks in mains/ connections are determined by MNF analysis in the system (more than 90%), and GIS integration is available.
GIS-based integrated WLM model	There is no work for this component.	There are some databases, but their up-to-date status is doubtful, and the capacity is not sufficient for improvement and integration.	Basic databases are working correctly and up-to-date, and the capacity is being improved for integration of IMSs.	There are information systems, work is being planned for integration, and flow pressure and WBA are managed in the GIS-based WLM model.	Some systems are integrated, planning is made for integration of all systems, some analyses are made with GIS, and planning is made for all.	There are integrated information systems, all systems are integrated (GIS integration is available), and flow pressure and MNF indicators are made by this model.
Definition of the ELL	There is no work for this component.	There are not enough information and data, there is awareness, and planning is being made for ELL.	The C&B components in WDS are analyzed by the Excel template, and the ELL structure is being planned.	The C&B and ELL analysis in WDS or DMA is made by using an Excel template, and the ELL analysis system is planned.	The C&B and ELL analysis in WDS or DMA is made by using the model, and the target is defined accordingly.	The C&B and ELL are analyzed in WDS or DMAs by using the model, the target is defined, and GIS integration is available.
Network renewal C&B analysis and monitoring	There is no work for this component.	Initial investment costs of renewal are known, there are not enough data and experience to analyze.	There is no C&B standard, the renewal costs are known, the benefits are estimated, and improvement is planned.	C&B standard is planned, renewal costs are known, and benefits are calculated in pilot DMAs with failure/leaks data.	C&B analysis is made, and renewal and operating costs and gains are calculated and monitored in detail.	C&B analysis is done, renewal and operating costs/gains are calculated and monitored, and GIS integration is available.
Analysis and monitoring of ALC cost	There is no work for this component.	There are not enough data/information for analysis, and improvement is being planned.	Cost is analyzed in the pilot region, and planning is done for the overall system.	In the system, the costs are analyzed (1–2 years), and regional variations are not analyzed.	The costs are analyzed regularly (annual), and planning is made for integration with GIS.	In DMAs, costs are calculated regularly and integrated with GIS, and regional variations are analyzed.
Analysis and monitoring of C&B of DMA	There is no work for this component.	There are not enough data/information for analysis, and improvement is being planned.	Cost is analyzed in the pilot region, and planning is done for the overall system.	In the system, the costs are analyzed (1–2 years), and regional variations are not analyzed.	The costs are analyzed regularly (annual), and planning is made for integration with GIS.	In DMAs, costs are calculated regularly and integrated with GIS, and regional variations are analyzed.
Analysis and monitoring of PM C&B	There is no work for this component.	There are not enough data/information for analysis, and improvement is being planned.	Cost is analyzed in the pilot region, and planning is done for the overall system.	In the system, the costs are analyzed (1–2 years), and regional variations are not analyzed.	The costs are analyzed regularly (annual), and planning is made for integration with GIS.	In DMAs, costs are calculated regularly and integrated with GIS, and regional variations are analyzed.

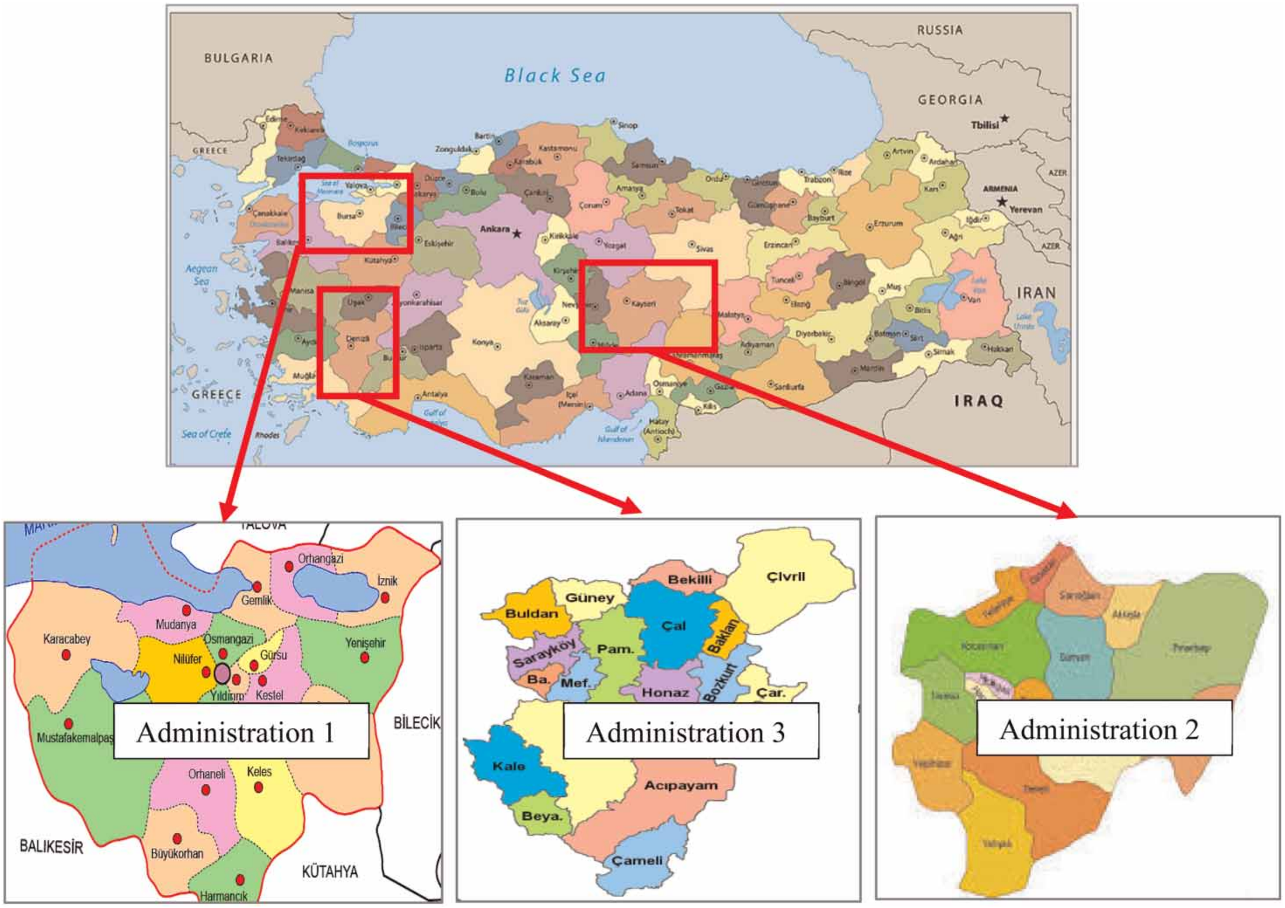

Figure 1 | Pilot administrations selected in the study.

is 4, the primary target for these components is defined as quite a good-level target (Target III). If the current score of the variable is 5 (quite good level), it would be appropriate to keep the current situation as such. Thus, appropriate and realistic targets were determined in the administration according to the current conditions.

Network length and the number of service connections are the most basic data used in leakage management. Therefore, these data should be collected systematically. These components should be at least four points (good level) for ensuring an accurate and reliable leakage analysis. In pilot administrations, these components are generally at good or quite good level (ID2 is at the average level in Administration 2). The quality of the most basic data is at good level. Valves play quite an important role in shutting off the water in case of failure in the WDS, creating the network operation plan and applying DMAs on site. While the valve component is at a good level in Administrations 1 and 3, it is moderate in Administration 2, where this component should be improved and updated systematically.

SCADA and other information systems are important in monitoring hydraulic data in WDSs. In particular, hydraulic parameters should be monitored regularly for monitoring the water produced and supplied to the system, establishing the water budget, the analysis of MNF, the flow-pressure analysis, and WLM indicators. Information systems planning is at a good level in Administrations 1 and 2 and at an insufficient level in Administration 3. The water production SCADA component is at quite good level in all three administrations, and all resources are monitored regularly. The component of monitoring hydraulic data with SCADA in DMAs is at quite good level in Administration 2 and at moderate level in Administrations 1 and 3.

The GIS database (ID7) should be up-to-date in order to effectively manage all assets and to implement leak prevention and control strategies efficiently. Moreover, the regular Customer Relationship Management (CRM) component (ID8) in the administration should be at good level in order to systematically and quickly manage and repair the reported faults and to manage calls more systematically. These components are at quite good level in all three administrations in terms of effective management of faults and calls and the efficient implementation of leak prevention and control methods.

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
ID1	Main Length	5				4				4			
ID2	Number of Service Connection	5				4				3			
ID3	Number of Valves	5				3				4			
ID4	Planning of Information Management System (IMS)	4				4				2			
ID5	Water Resources, System Input Flow Management System (SCADA)	5				5				5			
ID6	WLM Database (SCADA Distribution)	3				5				3			
ID7	Distribution System GIS Database	5				4				4			
ID8	Customer Relationship Management (CRM)	4				5				4			
ID9	Analysis of Factors Affecting Real Losses	5				4				2			
ID10	Strategy Development for Detection of Leakages	4				5				4			
ID11	Active Leak Control (ALC) Program, Plan and Strategy	5				4				3			
ID12	DMA Planning	5				3				4			
ID13	MNF Analysis	5				3				4			
ID14	Failure Repair Speed and Time Analysis and Improvement	4				5				4			
ID15	Systematic Measurement and Monitoring of Real Loss Components for Water Balance Calculations	4				5				3			
ID16	Performance Monitoring System (PMS) and Integration of Systems	4				5				3			
ID17	Monitoring of GIS Data Update and Verification Practices	5				5				3			
ID18	Performance Analysis and Monitoring for DMAs	2				2				2			
ID19	Analysis and Monitoring of Network Failure Maintenance-Repair Cost	1				3				2			
ID20	Analysis and Monitoring of Network Operating Efficiency	1				2				3			
	Average Scores	***4.05***				***4.00***				***3.30***			

Gray shading indicates the gradual targets defined for components.

Leakage volume decreases in WDSs depending on the level of application of the leakage reduction and prevention method. Therefore, such methods should be applied correctly and systematically. The current application levels of components, ID11 (ALC), ID12 (DMA planning), ID13 (MNF analysis), ID14 (fault repair speed and time), and ID15 (water balance analysis), are questioned for systematic measurement and monitoring of leakages. These components are at good and/or quite good level in Administration 1, at good level in Administration 2 (ID12 and ID13 components are at moderate level), and at good level in Administration 3 (ID11 and D15 components are at moderate level). Accordingly, it is understood that an awareness for leak management practices in administrations is formed, and field applications for basic methods are at good level.

Leakage management methods are generally time-consuming and costly. Therefore, it is necessary to monitor the benefits from the methods and analyze the performances, the costs, and system operating efficiency. In the developed system, the components of ID16 (performance monitoring system), ID17 (monitoring of GIS update activities), ID18 (performance analysis and monitoring in DMAs), ID19 (fault repair costs), and ID20 (network operating efficiency monitoring) were defined and evaluated.

The components ID15, ID16, and ID17 are at good level in Administrations 1 and 2 and at moderate level in Administration 3. However, ID18, ID19, and ID20 components are generally at insufficient level in three administrations. Accordingly, these components should be applied more effectively in order to analyze and improve system operating efficiency in administrations.

In basic-level practices, the average scores of the components were calculated as 4.05 in Administration 1, 4.00 in Administration 2, and 3.30 in Administration 3. Accordingly, Administrations 1 and 2 are generally at good level in basic-level practices, while Administration 3 is at moderate level. In Administration 1, the components of ID6, ID18, ID19, and ID20 (performance monitoring and cost analysis) constitute the weakness of the administration and need improvement. In Administration 2, components ID3, ID13, ID18, ID19, and ID20 (performance monitoring and cost analysis) constitute the weakness of the administration and need improvement. In Administration 3, components ID2, ID4, ID6, ID9, ID11, ID15, ID16, ID17, ID18, ID19, and ID20 (data monitoring, performance evaluation, and cost analysis) should be improved.

The quality of basic data based on the measurement frequency, monitoring and database was evaluated within the scope of leakage management in the administrations. According to the scoring results, it was determined that the basic data measurement, monitoring, and storage components are at good level in three administrations and that the capacity and experience of the administrations are sufficient in this context. These basic data form the basis for the correct implementation of leakage prevention and reduction practices. Accordingly, it can be interpreted that the data situation required for detailed analysis and evaluation within the scope of leakage management in administrations is at good level. Similarly, the most basic leak management practices are generally at good level depending on good data quality in administrations. It is thought that the institutional and personnel experience are sufficient for the most basic practices in administrations. On the other hand, it was determined that the performance evaluation and monitoring components for the leakage components in the administrations are at moderate and/or insufficient level. These components create weaknesses in leak management and, therefore, they need to be improved as a priority.

Evaluation for moderate-level practices

The score results and targets for moderate-level practices in administrations are evaluated separately (Table 5).

The operating pressure (ID21) is the most basic operating data considered in leak management. Pressure should be measured regularly in order to monitor the changes in failures/leaks due to the pressure, to decide PM, and to define the most appropriate pressure level. This component is at good level in Administrations 1 and 2 and at insufficient level in Administration 3. A roadmap for WLM (ID22) is quite important for effective planning and implementation of WLM processes according to a specific flow in the field. This component is at good level in Administration 1 and at moderate level in Administrations 2 and 3.

Regular monitoring and systematic maintenance of the network are required in order to reduce operating costs. In this context, ID23 and ID26 components question maintenance and repair practices in the administration. Field works for these components in three administrations are at insufficient or poor level. A fault management system integrated with GIS (ID24) makes a significant contribution to more effective management of faults and the determination of factors. Moreover, the SCADA reservoir monitoring system (ID25) is useful for technical personnel in network operation and monitoring demand flow. These components are at good level in general.

Leaks in the WDSs and reservoirs should be identified and monitored on the basis of site inspections for ensuring an accurate leak analysis. In this context, the ID27 and ID28 components question the inspection of leaks in the distribution system and reservoirs. Moreover, the application levels of ID31, ID32, and ID33 components are highly effective in reducing leaks. The application of these components are at average level in the three administrations. The ID35 component (leakage performance monitoring) and the ID36 component (PM monitoring) are at good level in Administration 2 and at moderate level in Administrations 1 and 3. The components of ID38 and ID39 (the performance monitoring of MNF and leak detection practices) are at moderate level in Administrations 1 and 3 and at good level in Administration 2. Accordingly, performance analysis and monitoring practices are generally at good level in Administration 2.

Operation and production costs vary depending on the volume of leakage. Moreover, failure repairs cause significant annual costs. Therefore, these cost components should be analyzed with field data in order to analyze the system efficiency.

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
ID21	Operating Pressure	5				4				2			
ID22	Roadmap for Managing WLM Components	4				3				3			
ID23	GIS Based Valve Failure Database, Maintenance-Repair and Control Program	1				2				1			
ID24	Failure Management System (Integrated with GIS)	2				5				4			
ID25	SCADA Reservoir Monitoring System and Database	4				4				4			
ID26	Network Maintenance and Repair Management (MRM) System (with GIS)	1				0				3			
ID27	Leaks in the Distribution System (Mains and Service Connections)	4				3				2			
ID28	Leaks in Reservoirs	2				3				4			
ID29	Leak Detection and Repair Technical Capacity (Team, Device)	4				4				4			
ID30	Analysis of Factors Affecting the Failure	4				4				3			
ID31	Pressure-Flow-Leakage-Failure Analysis	5				5				3			
ID32	Leak Management and Prevention in Reservoirs	3				2				5			
ID33	Pressure Management (PM) Strategy	3				4				5			
ID34	Service Connection Failure/Leak Prevention Strategy	3				3				3			
ID35	Monitoring of Real Loss Performance Indicators	3				4				3			
ID36	Monitoring PM Practices	3				4				3			
ID37	Monitoring the Minimum Night Flow Practice	4				5				3			
ID38	Monitoring of Leak Detection (Team and Inspection) Practices	3				5				3			
ID39	Analysis and Monitoring of the Cost of Real Losses	4				4				2			
ID40	Analysis and Monitoring of Leak Detection Equipment-Monitoring Cost	3				3				3			
	Average Scores	***3.25***				***3.55***				***3.15***			

Gray shading indicates the gradual targets defined for components.

The ID39 and ID40 components are at good and moderate levels in Administrations 1 and 2. The application level of these components in Administration 3 is at insufficient level.

In moderate-level practices, the average scores of the components were calculated as 3.25 in Administration 1, 3.55 in Administration 2, and 3.15 in Administration 3. Accordingly, while Administrations 1 and 3 are at moderate level, Administration 2 is at upper-moderate level. In this group, the components of maintenance and repair, cost analysis, and leak control are at moderate level in administrations and need to be improved.

The data, experience, equipment, and financial requirements of components in moderate-level applications are higher than in basic-level methods. Therefore, the application levels of the components in this group were obtained at lower level. In particular, it was determined that the scores of the failure maintenance, repair, and monitoring programs applications vary in general. On the other hand, it is seen that the practices to reduce and prevent leaks are at average level. It is thought that these methods have the potential to be applied more effectively and systematically in administrations by considering the

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
ID41	Total Service Connection Length (on private property)	5				4				3			
ID42	Establishment of WLM Strategic Plan	3				3				3			
ID43	Number of Unreported (Network/Service Connection) Leaks (Failure)	4				5				4			
ID44	Leak Controlling on Private Property Service Connections	1				5				1			
ID45	Integration of Databases with Each Other (GIS, SCADA, CIS, CRM)	4				4				3			
ID46	Hydraulic Model	4				2				2			
ID47	Real-Time Monitoring of the System	5				0				4			
ID48	Hydraulic Model Based Leak Detection - Monitoring	2				1				2			
ID49	Leak Monitoring with Pressure Sensor, Noise Logger and Correlator	2				2				5			
ID50	Analysis and Monitoring of ILI and UARL Indicators	3				4				2			
ID51	Determination of the Most Appropriate Loss Rate Level for Real Losses	3				4				4			
ID52	Failure Rate Change Monitoring and Useful Life Analysis	2				4				3			
ID53	Estimation of Leakage Components with Failure and Leakage Records	4				4				3			
ID54	Estimation of Leakage and Establishment of Water Balance Based on MNF	4				3				3			
ID55	GIS-based Integrated WLM Model	3				4				1			
ID56	Definition of Economic Leakage Level (ELL)	0				3				1			
ID57	Network Renewal C&B Analysis and Monitoring	1				4				3			
ID58	Analysis and Monitoring of ALC Cost	2				4				3			
ID59	Analysis and Monitoring of C&B of DMA	1				4				3			
ID60	Analysis and Monitoring of PM C&B	1				3				3			
	Average Scores	***2.70***				***3.35***				***2.80***			

Gray shading indicates the gradual targets defined for components.

requirements of these practices. Moreover, it was determined that the components of monitoring the performance of the most basic leak management practices are generally close to the average and/or good levels. Since the application level of the most basic methods is at good level in administrations, it is understood that the capacity and experience related to the performance monitoring is formed. The gradual target was defined by considering the current scores of the components (Table 5).

Evaluation for advanced-level practices

The score results and targets for advanced-level practices in administrations are evaluated separately (Table 6).

The ID41 (total service connection length on private property) component is particularly important for identifying and monitoring illegal uses or leaks on private property. This component is at good level in Administrations 1 and 2 and at moderate level in Administration 3. Leak inspection (ID44) in service connections on private property is at poor level in Administrations 1 and 3 and at quite good level in Administration 2.

The reported failures data (ID43) are required for water balance with component analysis and operating cost and leakage density analysis. A systematic analysis and monitoring of leak components requires the integration of data monitoring and management systems (ID45). Therefore, these components were considered and tested. These components are at good level in all administrations.

Leak detection equipment such as ground microphones, regional recorders, and correlators are applied to detect unreported leaks. The components of the hydraulic model (ID46), real-time system monitoring (ID47), hydraulic model–based leak detection (ID48), and leak detection with a local correlator/logger (ID49) are evaluated. The ID46 component is at good level in Administration 1 and at insufficient level in other administrations.

Leakage volume could be calculated with the bottom-up (MNF analysis) method (ID53) and component analysis (ID54) on the basis of field data, as well as top-down water balance. In administrations, the ID53 and ID54 components are generally at good level. Finally, the costs of field practices in WLM should be determined in order to check efficiency. Therefore, the cost components of ID57, ID58, ID59, and ID60 were evaluated in the three administrations. These components are generally at insufficient level in Administration 1, at good level in Administration 2, and at moderate level in Administration 3.

The average scores of the components in advanced-level practices were calculated as 2.70 in Administration 1, 3.35 in Administration 2, and 2.80 in Administration 3. Accordingly, Administrations 1 and 3 are generally at below moderate or insufficient level, and Administration 2 is above moderate or close to good level.

Field implementation and monitoring of components in advanced applications requires more data, equipment, and experience. Therefore, the scores of the components in this group are generally lower than the basic- and moderate-level practices. In this group, it was determined that especially the regional monitoring and detection of leaks had low scores. The equipment and economic capacity of the administrations need to be improved for the implementation of these components. On the other hand, since the most basic leak detection and prevention methods are applied at good level in administrations, leak estimation methods are also applied effectively according to the data obtained from these applications. However, more work should be done to make more effective cost–benefit analyses of the methods applied, especially for leakage prevention methods.

As a result, the general achievements obtained in this study can be given as follows: (i) the current application levels of leak management components in administrations are scored according to the dynamic structure of the administration, (ii) the weaknesses and strengths are defined in the scope of leakage management, and the components that need improvement are determined dynamically, (iii) realistic and appropriate targets are defined gradually (such as moderate, good, and quite good targets) on the basis of current scores on a component basis, and (iv) this model creates a roadmap in leak management, especially for decision makers and technical personnel, and serves as a reference in terms of ensuring efficiency.

CONCLUSIONS

In this study, a new framework has been developed to analyze and evaluate the current application levels of leakage management components in WDSs. The developed framework was tested in pilot administrations according to real field data. In basic-level practices, the average scores were calculated for Administration 1 (4.05), Administration 2 (4.00), and Administration 3 (3.30). Accordingly, Administrations 1 and 2 are generally at good level, while Administration 3 is at moderate level. It was determined that the basic data measurement, monitoring, and storage components are at good level in three administrations and that the capacity and experience of the administrations are sufficient in this context. It can be interpreted that the data situation required for detailed analysis and evaluation within the scope of leakage management in administrations is at good level. Similarly, basic leak management practices are generally at good level depending on good data quality in administrations. It is thought that the institutional and personnel experience is sufficient for the most basic practices in administrations. On the other hand, it was determined that the performance evaluation and monitoring components for the leakage components in the administrations are at moderate and/or insufficient level.

The average scores of the components in moderate practices were calculated as (3.25) for Administration 1, (3.55) for Administration 2, and (3.15) for Administration 3. Accordingly, Administrations 1 and 3 are generally at moderate level, while Administration 2 is close to good level. The data, experience, equipment, and financial requirements of components in moderate-level applications are higher than in basic-level methods. Therefore, the application levels of the components in this group were obtained at lower level. In particular, the leakage reduction and prevention practices are at average level. It is thought that these methods have the potential to be applied more effectively and systematically in administrations by considering the requirements of these practices. Moreover, since the application level of the most basic methods was at good level in the administrations, it was understood that the capacity and experience related to the performance monitoring is formed.

The average scores of the components in advanced practices were calculated as (2.70) for Administration 1, (3.35) for Administration 2, and (2.80) for Administration 3. Accordingly, Administrations 1 and 3 are generally at insufficient level and Administration 2 is close to good level. Field implementation and monitoring of components in advanced applications requires more data, equipment, and experience. Therefore, the scores of the components in this group are generally lower than the basic- and moderate-level practices. In this group, especially the regional monitoring and the detection of leaks had low scores. On the other hand, since the most basic leak detection and prevention methods are applied at good level in the administrations, leak estimation methods are also applied effectively according to the data obtained from these applications. However, more work should be done to make more effective cost–benefit analyses of the methods applied, especially for leakage prevention methods.

As a result, based on the scoring and evaluations, the proposed framework reveals the current situation according to the dynamic structure of the administration. Achievable targets and road maps are defined for each component by considering the available scores depending on this dynamic structure. It is thought that the framework developed will be a reference for the decision-making and technical personnel in the administrations, especially for defining the current situation in WLM and creating a roadmap.

ACKNOWLEDGEMENTS

This study was produced from the PhD thesis conducted by C.B.. The authors thank Inonu University, Scientific Research Project Funding for their financial support (FDK-2020/2262). This research was supported by TUBITAK (the Turkish National Science Foundation) under Project Number 220M091.

DATA AVAILABILITY STATEMENT

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

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First received 7 March 2022; accepted in revised form 16 April 2022. Available online 27 April 2022