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Annals of Environmental Science and Toxicology OPEN ACCESS JOURNAL

ISSN: 2641-2969 DOI: https://dx.doi.org/10.17352/aest

Research Article

Presenting a conceptual model of leakage management system in urban water supply network from two preventive and operational perspectives (Case study of Tokyo and Tehran metropolises)

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Received: 22 April, 2021
Accepted: 07 June, 2021
Published: 08 June, 2021

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Keywords: Comparative comparison; Leakage; Water distribution network; Tehran; Tokyo

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Abstract

The existence of leakage in the urban water supply network can be considered one of the main challenges in the country's water industry. The purpose of this study is a comparative comparison of water leakage management patterns in Tokyo and Tehran. In this study, the existing documents in the field of water leakage management in both cities were collected, classified, and evaluated. A comparison at the level of preventive measures showed that the city of Tokyo has a conceptual model (with an effective water ratio of more than 98%) with «corrective» subdivisions including old network management and providing solutions for maintenance and repair of the current network and also subdivisions including «technology development» and «education.» However, in Tehran, due to financial constraints, the preventive approach (PM[1]) is entirely passive, and emergency maintenance (EM[2]) units usually enter into operation after the incident. Operational comparisons showed that the Tokyo Water Leakage Control System consists of two main parts: "continuous monitoring" and "measures commensurate with the type of challenge" and is based on strategic policies. In Tehran, the movement towards using new technologies to control leakage in urban water supply networks has been significant; However, these measures are not based on a plan and have created unbalanced growth in this regard.

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[1]Prevention Maintenance

[2]Emergency Maintenance

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Introduction

Depreciation, obsolescence, and inefficiency of water transmission and distribution facilities are considered one of the main challenges in the water industry. Depreciation of facilities and urban water supply network leads to leakage and waste of large amounts of extracted and treated water [1]. Simultaneously, having a clear, codified, and purposeful plan can prevent the loss of Non-Revenue Water. The existence of strategic, technical, and operational plans will also lead to improving the level of system performance [2]. It should be noted that leakage in urban water supply networks is considered an event. Therefore, different prevention programs can be used to reduce the effects of this type of event. The experience of management science shows that before the occurrence of repetitive events, time-consuming and costly investments should be made to control the factors that trigger the accident [3,4]. In other words, the famous phrase «prevention is better than cure» also applies to water leakage. Various studies on leakage management and control methods have been performed [5-16], which will be evaluated later. Cutler and Golter (1985) analyzed water leakage in North American cities in their study. In the mentioned study, the effects of material, diameter, and age of pipes on the phenomenon of water leakage were investigated. The conclusions were expressed in both general and local forms (case study) [11]. Englehart, et al. (2000) conducted research on strategies to increase the resilience of the urban water network management system. In this study, the prospects of the United Kingdom were considered by considering economic, hydraulic, qualitative, and confidence-building criteria [12]. In another study, Morais and Almerida (2007) prioritized leakage management strategies in the water network of cities in the Brazilian province of Pernambuco using group decision-making methods. In this research, the maintenance of water supply networks has been selected as the most critical aspect of leakage management, and its various dimensions have been analyzed [13]. Poost, et al. (2010), as well as Motikanga, et al. (2012) in separate review studies, examined leak management methods in the urban water network.

The mentioned research was carried out to compare all operational methods in three levels of evaluation, identification, and control [14,15]. In another study, Jang, et al. (2019) managed leakage management in an urban water network using a combination of artificial neural network (ANN) and Principal Component Analysis (PCA) methods. Using a combination of statistical methods and machine learning, the researchers carried out leak detection and incident prediction operations (in operational conditions) at a much faster rate than usual [16]. Many studies have been conducted in the field of prediction, management, and control of leakage in urban water supply networks. However, most studies in the technical field include leak detection and leakage control, and not much research has been done to investigate leakage management patterns in water networks. Most research is about strategic evaluations and rankings, and less attention has been paid to preventive and operational aspects. This study aims to extract, evaluate, and compare comparative water leakage management patterns in Tokyo and Tehran (at both preventive and operational levels).

Methods and materials

Urban, demographic, and water network characteristics of Tokyo and Tehran are summarized in Table 1. According to the table, it can be seen that the parameters of population, urban area, and per capita water consumption in Tokyo are 4.5, 3, and 1.3 times more than in Tehran, respectively. In contrast, the amount of leakage rate in Tehran is estimated to be about 11 times more than the leakage rate in Tokyo. In the following study, the reasons for this difference in leakage rates between Tokyo and Tehran will be examined. In the following study, the reasons for this difference in leakage rates between Tokyo and Tehran will be examined.

At the beginning of this study, reports, and information related to the urban water supply network, methods, and strategic, technical, and operational management systems of both Tokyo and Tehran (in the field of water supply network leakage management) were extracted.

In the next step, the data were validated and classified according to two approaches of preventive and operational measures. Data were extracted from Tokyo city from analysis and review of Tokyo Water Company reports [19-24]. To extract data related to the leakage management method in the Tehran water supply network, three face-to-face interviews were conducted in the non-revenue water unit of Tehran Water and Sewerage Company (at the level of managers, experts, and contractors).

Then, after studying the classified documents and information, conceptual models were drawn to structure and configure the preventive and operational approaches of the water leakage management system in Tokyo and Tehran. Using a concept map can also be very effective in organizing strategies, problem-solving, and decision-making. There is no such approach to drawing conceptual models of leakage management in urban water networks. Concept maps lead to the systematization of activities in an organization and prevent the emergence of taste actions by human resources. Using this view, with the help of a top-down view, the scattered or purposeful behaviors of a management system can be graphically modeled, and its strengths, weaknesses, opportunities, and threats can be analyzed. In the final part, after determining the conceptual models of leakage management in the urban water supply network, the model of Tokyo and Tehran cities were compared

Table1: Urban, demographic, and water network characteristics of Tokyo and Tehran.

Parameter	Tehran	Tokyo
Population (million people)	8.5	38
Urban area (square kilometers)	730	2188
Per capita water consumption	250	320
Network material	Ductile iron, polyethylene, cement asbestos, PVC	Lead, ductile iron, stainless steel, polyethylene, PVC
Percentage of losses in 2018	22.90%	Less than 2%
Reference	[18]	[17]

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from two perspectives of preventive and operational measures. In the final part, after determining the conceptual models of leakage management in the urban water supply network, the model of Tokyo and Tehran cities were compared from two perspectives of preventive and operational measures. This comparative comparison was made from two aspects of leak management history analysis and processes (preventive and operational). The general algorithm of steps and steps of this research is shown in Figure 1.

Results and discussion

Analysis of leakage management history in tokyo and tehran

Changes in the leakage rate of the Tokyo Water Supply Network between 1913 and 2007 (about a century) are shown in Figure 2. As shown in the figure above; the time history of Tokyo leakage rate changes can be divided into four stages, which will be described further below.

The first phase involved measures to control leakage in the Tokyo metropolitan water network (since 1913), which began with two general measures: "Flow Meter" and "Acoustic - Rod."

Between 1913 and 1945, two major events included; The Kanto earthquake and World War II led to a sharp increase in leakage rates in Tokyo's water network. However, after the Kanto earthquake, the leakage rate increased from 12.6% to 20%, and after World War II reached 80% [19, 20]. After World War II, the second phase of leakage management began with the implementation of ductile iron pipes in the Tokyo Municipal Water Network (instead of lead pipes). The use of Ductile Cast Iron Pipes increased between 1955 and 1960 due to self-sufficiency in production, improvement of technical knowledge in creating high resistances, and positive experience in the use of Seismic Coupling Pipes [21].

The third step in managing Tokyo water leakage was the implementation and replacement of stainless steel pipes. In 1980, statistical analysis showed that more than 90% of the city's water network had been repaired. Therefore, using detailed expert studies, the managers decided to replace the water supply network infrastructure with stainless steel pipes. Statistical and computational evaluations showed that economically, the replacement of network infrastructure is far more justifiable than the repair and modification of the current network. Studies have shown that with increasing the percentage of use of stainless steel pipes, the rate of water leakage has decreased, and in 2005 it reached 4.4% [23]. However, in the fourth stage, the leakage rate gradually decreased and reached a steady state below 2% in the period after 2012 [23]. In 1329, the initial Tehran plumbing project was implemented for a population of 900 people, and two steel pipelines with a diameter of 40 inches and a capacity of 242,000 cubic meters per day were considered to transfer water from Bilqan reservoir to the first treatment plant in Tehran (Jalalieh) [25]. The leakage rate of the Tehran water supply network in 1984 was estimated to be about 29% [26]. However, according to the collected data [18], the percentage of leakage in 1997 reached 22.9%. In other words, according to the activities of the ruling management system, the amount of water leakage has decreased by about 0.47% per year. Tehran>s urban water network has undergone various and extensive changes over time, which, unfortunately, unlike Tokyo Bank, there is no coherent data of the process of these changes.

Comparison of tokyo and tehran leakage management conceptual

The general model of leakage management of the water supply network in Tokyo and Tehran is presented in Figure 3. The Tokyo city management model is based on the percentage of leakage in six phases, and the Tehran city management model consists of five continuous and interconnected stages.

As shown in Figure 3a; The general model of Tokyo leakage management is divided into six separate stages based on the amount of leakage rate, in which a series of measures are taken [19,23]. According to Figure 3a, it can be seen that at leakage rates greater than 25%, the programs are more operational. But when, with the help of operational techniques, part of this leakage was controlled to less than 25%; its operational nature is reduced and added to the set of preventive measures. In Tehran, in recent years, a five-step model for managing consumption, leakage, and other issues related to the urban water network has been presented, which is shown in Figure 3b. Considering the above-mentioned figure, it can be concluded that the Tehran water leakage management system in the first step emphasizes organizing the current situation

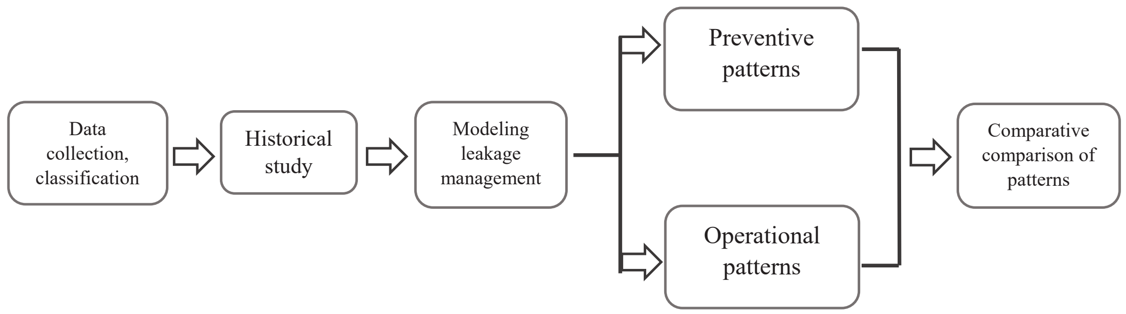

Figure 1: General algorithm and implementation steps to compare leakage management in Tokyo and Tehran.

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and stabilizing the current situation. In the next step to reduce the apparent loss (unauthorized use and costs due to error in measuring equipment) and then the actual loss (leakage from transmission lines and main lines of the distribution network, leakage and overflow from water storage tanks, and leakage from branches to meters Joint) has planned. After reducing the apparent and actual water losses, Refers the principle of transparency includes; data calibration, validation, and complete mastery of network information. Finally, after creating the mentioned infrastructure, it focuses on controlling the management of demand and authorized consumption without income. It should be noted that in the current situation of Tehran, the amounts of apparent wastage, actual wastage, and other unauthorized expenditures are estimated at 11, 9, and 2.9 percent, respectively [25]. One of the main differences between the leakage management system in the Tokyo and Tehran municipal water supply networks is related to the type of problem and the nature of the water wastage issue. Almost all of Tokyo>s water wasted was from a municipal water network (real leakage); But in Tehran, most of the water losses are related to apparent losses. Apparent losses are divided into two general parts: unauthorized costs and costs due to errors in measuring equipment. Part of the apparent loss is related to the cultural issues, and social infrastructure of communities (unauthorized use), and the other part is related to technology issues (consumption due to errors in measuring equipment). In fact, the existence of deficiencies in cultural infrastructure and lack of attention to measurement issues has led to an increase

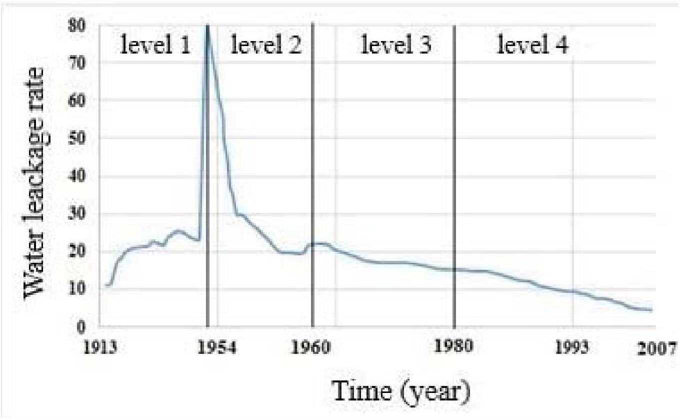

Figure 2: Changes in leakage rates in Tokyo between 1913 and 2007 [19].

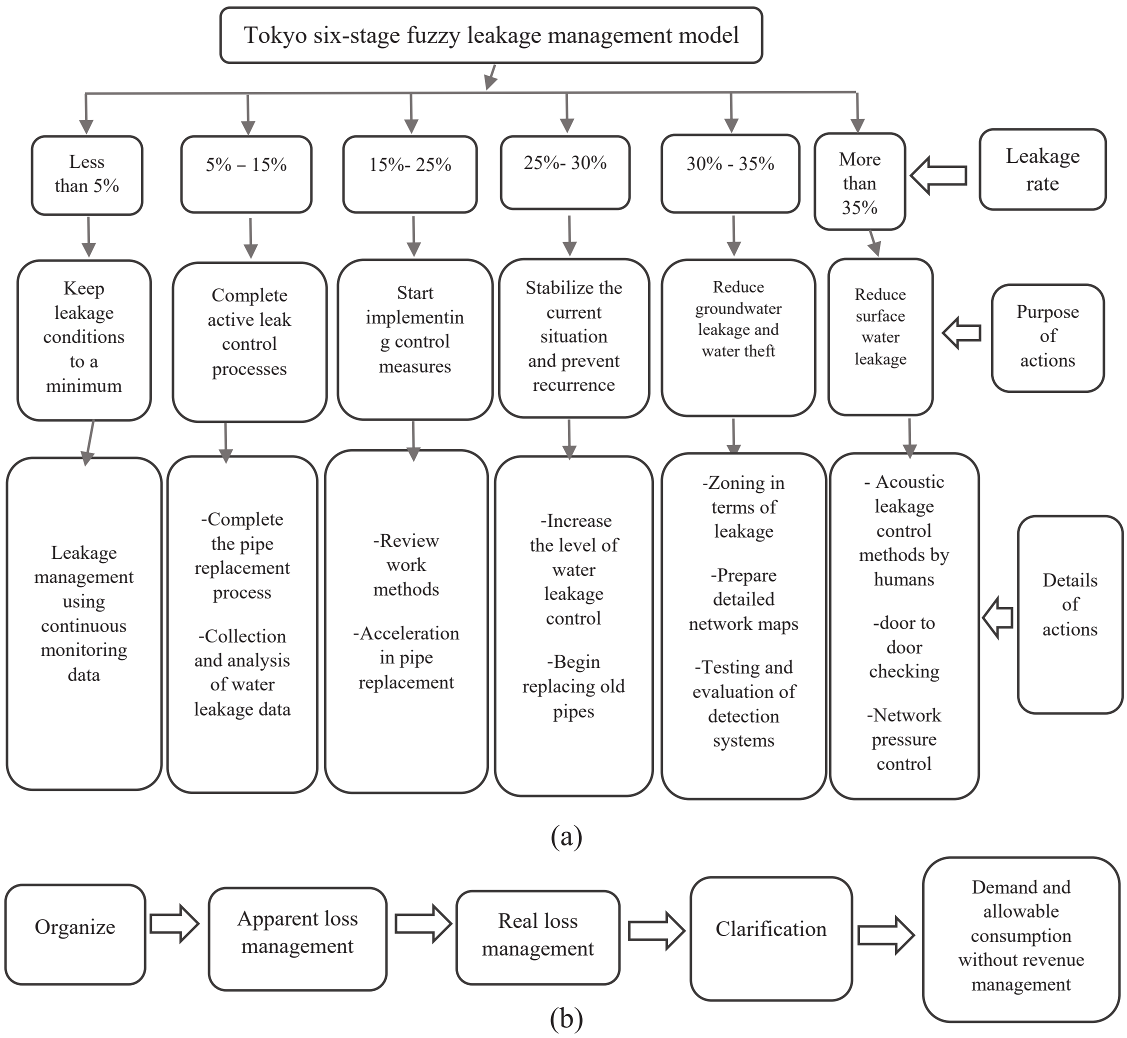

Figure 3: Leakage management model a) Tokyo six-stage fuzzy [23] and b) Tehran five-stage [25].

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in the amount of water loss in the Tehran water supply network. This indicates that rational planning should be done to educate and cultivate the citizens of the areas with illegal uses. Units of measurement should also perform specific monitoring of the accuracy of the data sent by the tools and, after identifying the device problems, take action to fix them. Another major difference between Tokyo and Tehran, water management systems, is in the database and how data is extracted, collected, classified, and validated. Surveys show that statistical data has been collected and archived in Tokyo since the early years of the Water Organization establishment. However, in Tehran, in the current situation, there is no coherent system for documenting information and experiences. Due to these complete and coherent statistical data, general decisions in Tokyo are more fundamental, with higher reliability, and with more financial, time, and manpower costs (in the field of leakage in urban water supply networks) than Tehran has taken place. In the following, the conceptual models of preventive and operational management of water leakage from the water supply network of Tokyo and Tehran will be compared and examined.

Preventive level models

Patterns of preventive leakage management of the water supply network in Tokyo and Tehran are shown in Figure 4. The Tokyo city model includes short-term and long-term time cuts, but the model of Tehran is set as a fixed management agenda.

The main Tokyo Water Leakage Management Program was developed in 1962 (the water leakage rate was 20%) by the Tokyo Water Authority. This program started with the priority of preventing water leakage; followed two goals of minimization were "total loss and leakage" and "reduction of leakage detection costs." Considering Figure 4a, it can be seen that the program consists of three general parts, including corrective measures and long-term prevention, corrective measures and short-term prevention, as well as technology development and education. In this program, the city of Tokyo was divided into three general sections: central areas, middle areas, and peripheral areas, based on hydraulic water transmission, age of the distribution network, land conditions, and the amount of demand. According to the divisions of this program, the time required to implement the goals of the program in the Central Area, Intermediate Area, and Surrounding Area were 4, 5, and 7 years, respectively [20]. As can be seen in Figure 3-a, in these years, the water leakage rate was between 15 and 25 percent, and more emphasis was placed on control and preventive measures that lead to maintaining the situation. It is worth noting that after further studies on the hydraulic behavior of the leakage, methods such as "Minimum Night Flow (MNF)"

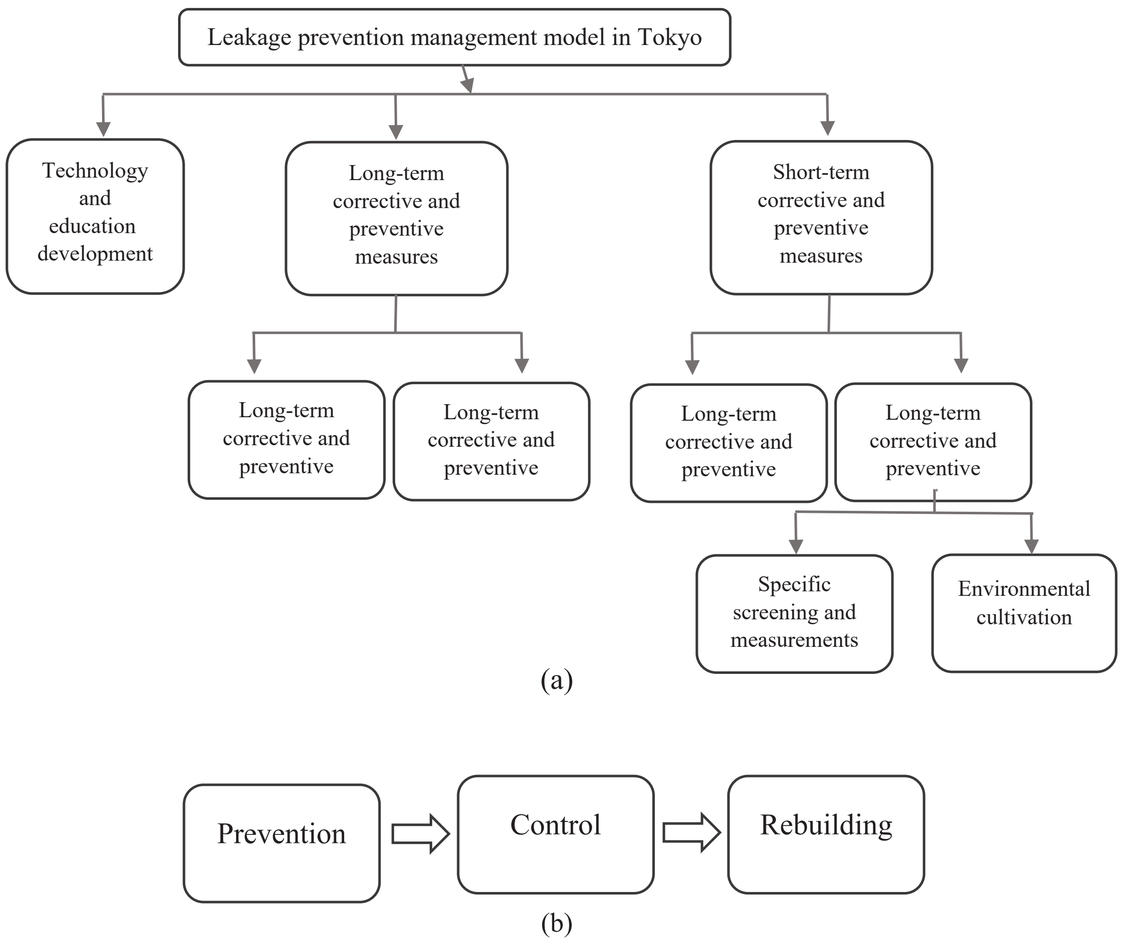

Figure 4: Leakage prevention management model in (a) Tokyo [20] and (b) Tehran [25].

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[27] were used to determine the actual amount of leakage (in environmental patrols).

Field studies of Tehran Water and Sewerage Company showed that the basis of control measures in this complex is based on the minimum night flow. In other words, the operating forces of the water network in the specified time periods collect the data of minimum night flow and predict the occurrence of leakage in the future by analyzing the changes in this factor. Tehran Water and Wastewater Revenue Management System in this preventive method controls the existing conditions by defining Thresholds. The general outline of the preventive management model of leakage in Tehran>s urban water network is shown in Figure 4b.

As shown in the figure; in this management system, three functional phases include; Prevention, control, and reconstruction are considered. In this process, due to budget constraints for the third step (reconstruction), most of the time and financial costs are spent for the prevention and control department using the minimum night flow technique. In terms of comparing leakage management patterns in Tokyo and Tehran, it should be noted that Tokyo city managers, regardless of financial constraints, have chosen the most appropriate method appropriate to the local conditions of their region. After implementing short-term and long-term remedial measures, they have implemented many programs and measures for technology development, research, and development of specialized and general education. But in the city of Tehran or in a larger view in Iran, financial constraints always lead to a decrease in the flexibility of managers and their maneuverability in the implementation of various engineering projects. In the current situation, the model of preventing the occurrence of leakage in Tehran may be the best available method and commensurate with financial resources, but it is a significant distance from international standards.

Operational level models

The conceptual model of the operational management system of water leakage in Tokyo and Tehran can be seen in Figure 5. Looking at Figure 5a, it can be seen that one of the main emphases of the Tokyo Leak Management Operational Model is its reliance on statistical data analysis and the use of intelligent control systems (soft sensors) when an event occurs (determining the exact point of the leakage). It should also be

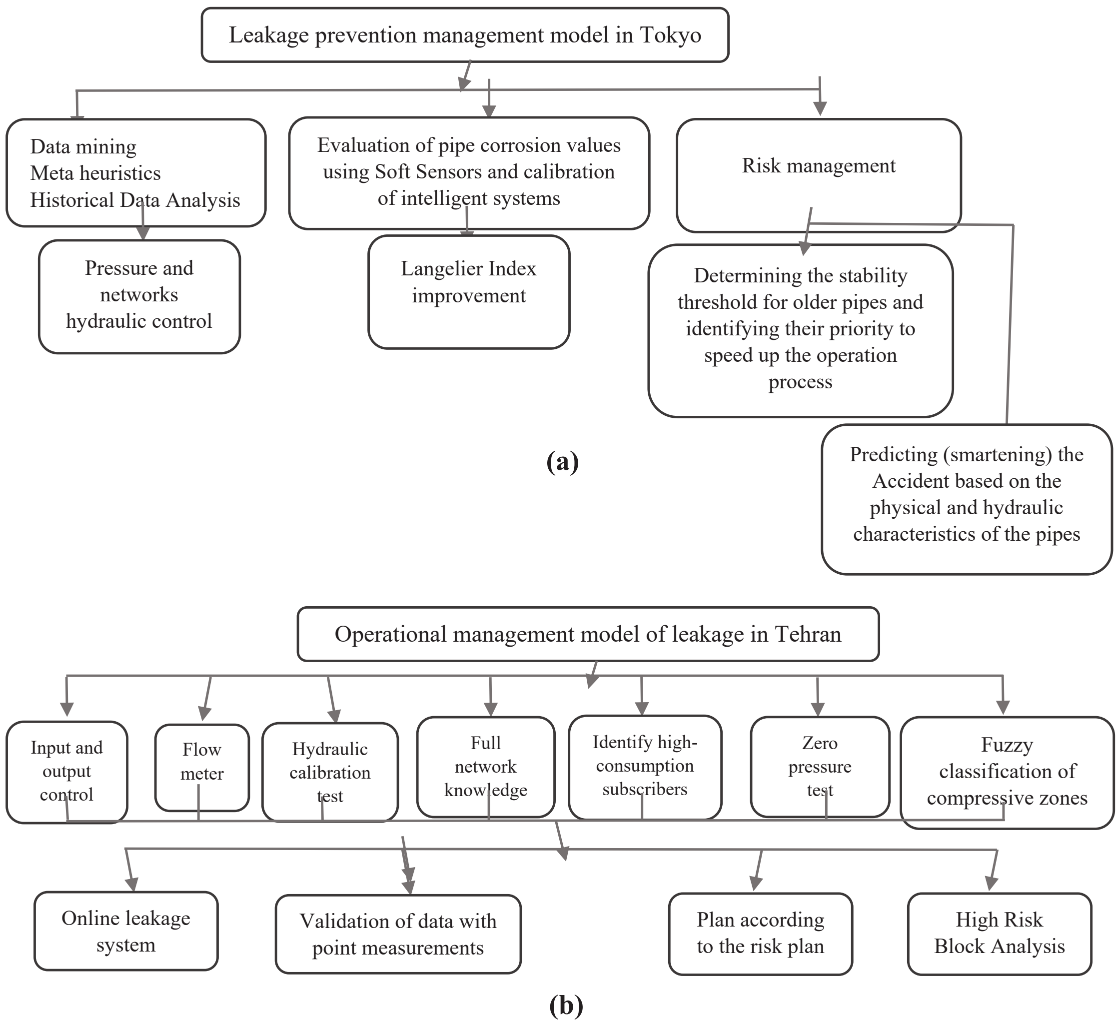

Figure 5: Operational model of leakage management in (a) Tokyo [19] and (b) Tehran [25].

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noted that one of the most important methods to reduce the occurrence of leakage is the use of pressure control systems and hydraulic parameters in the urban water distribution network. Therefore, in Tokyo, leakage in the municipal water network has been controlled by using intelligent dashboards and implementing data mining methods, continuous statistical analysis (data received from sensors), and utilizing meta-innovative optimization algorithms. The pattern of operational leakage management in the city of Tokyo began after the devastation caused by World War II to the city>s infrastructure. Global experience shows that operational processes are of the rapid response type and may have destructive effects on infrastructure in the long run. After World War II (after 1945), most of Tokyo>s water supply network was covered with lead pipes and on the ground based on the available facilities. At that time, with the help of this quick operation, the leakage rate decreased from 80% to 50%. But later, due to technical, environmental, and managerial problems of lead pipes, the network underwent infrastructural changes, which imposed high costs on the ruling system. As mentioned in Figure 3; After reducing the water leakage rate, the volume of preventive processes in Tokyo dominated the operational processes, and the water distribution network became more stable (leakage below 2%).

By observing the operational management model of Tehran (Figure 5b), it can be seen that before the problem of leakage, information, calibration, monitoring system, data validation system, and information related to the demand of the network's subscribers have fundamental and infrastructural problems. Therefore, before entering into solving the leakage control problem, fundamental infrastructure and tools for leakage management should be prepared and completed. Also, despite the high volume of remedial operations, due to the passivity of operational processes, there is no significant improvement in leakage control. In this system, the operators wait for the accident to happen and make instant decisions in case of an emergency. Thus, these challenges have led to significant differences in the model of operational leakage management between the cities of Tokyo and Tehran. According to the present study, Tokyo Water Management System (based on sustainable and appropriate water leakage control conditions) emphasizes the policies of maintaining the existing conditions. Hence as shown in Figure 6; the volume of preventive programs is high (about 80%), and the volume of operational programs is relatively small (about 20%). However, in Tehran, the situation is quite the opposite, and due to the high volume of incidents and a high percentage of leakage, operators are fully involved in operational processes (about 80%) and do not have many opportunities for preventive programs (about 20%).

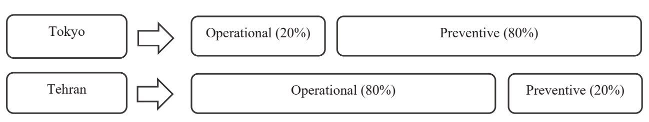

Figure 6: Volume of preventive and operational programs for water leakage management in Tokyo and Tehran in the current situation.

Conclusion

In this study, first, all data related to the water supply network, history, and patterns of leakage management in Tokyo and Tehran were extracted, validated, and prioritized. Then, the collected data were classified in terms of history and two perspectives of preventive and operational models. After drawing a conceptual model, evaluation and comparison between leakage management models of Tokyo and Tehran were performed. The results of historical comparisons of this study showed that the water leakage management system in Tokyo has complete, coherent, and integrated data, which significantly reduces decision errors. In other words, in the Tokyo water leakage management system, all preventive and operational models are in line with the developed strategies, and there is no imbalance between the approved programs and the system performance. But in the Tehran water leakage management system, a proper database has not been compiled and prepared. All decisions and planning are based on incorrect knowledge of the network and its infrastructure. This has caused an imbalance between the needs, programs, and preventive and operational performance models in Tehran>s water leakage management system.

It should be noted that the nature of wasted water or water without income in the cities of Tokyo and Tehran has many differences. Non-revenue water in Tokyo is leaky, and in Tehran is often caused by two phenomena of unauthorized harvesting and measurement error. The section on illegal withdrawals has cultural roots, and perhaps not all of its causes can be attributed to water management systems and organizations. But measurement error is considered a fundamental problem in the urban water network. In terms of preventive and operational management models, it should be noted that in Tokyo, most of the managers> emphasis is on preventive processes (about 80% of the volume of activities). A small part of it (rapid response operations section) includes operational sections (About 20% of the volume of activities). But in the case of Tehran, it should be noted that it is quite the opposite of Tokyo, and due to the existing infrastructure problems (related to the network), most activities include the operational part (about 20% preventive and 80% operational).

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