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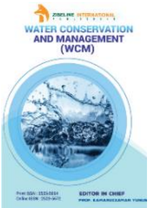

RESEARCH ARTICLE

PRIORITY-BASED DECISION MODEL FOR REHABILITATION OF WATER NETWORKS USING FAHP

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ABSTRACT

Determining the priority of large-scale water network rehabilitation projects is a decision-maker challenge. This study aims to provide decision-makers with a robust, cost-effective, and adaptable model that prioritizes water distribution network rehabilitation projects using a multi-criteria decision-making method. The study explored the main factors that influence setting the priority of large-scale rehabilitating the water network. Accordingly, five main factor categories were determined: physical, operational, socioeconomic, environmental, and quality of service. Each of these categories was evaluated and weighed by experts and stakeholders. The results showed that the physical factors weigh the highest in the decision process. Conversely, socioeconomic and environmental factors weigh the least in the decision process. The attained factors were used in developing a comprehensive priority-based decision model using a fuzzy analytical hierarchy process to facilitate the decision-making process. The weights of contributing factors and the comparative strength of these factors were judged by experts and stakeholders. A sensitivity analysis of the model revealed that the operational factors were more influential on the decision although the physical factors had more weight. The study tested the model on five water distribution networks in Amman, Jordan. The test results showed that the model was successful in providing a sound priority list of network rehabilitation projects to the decision-maker.

KEYWORDS

FAHP, fuzzification, water supply networks, prioritization, network rehabilitation

1. INTRODUCTION

1.1 Background

Water Distribution Networks (WDNs) play an expensive and essential role in the infrastructures of any community. Network construction or rehabilitation projects consume a significant amount of the water supply fund allocation. The WDNs' expenditure rises to reach about 80% of the water supply total expenditure (Kleiner, 2001). Unfortunately, pipe leakage, damage, and deterioration in these networks are unavoidable and cause significant loss of drinking water. The deterioration of network pipes can be classified into two types: pipe structural failure that involves the construction method and inner surface corrosion that is triggered by a drop in water quality (Kleiner, 2001). Furthermore, network failure can be caused by inadequate installation and operation. Therefore, leakage repair and maintenance works are continuously performed, and maintenance costs may vary based on the installation environment.

Minimizing water losses in WDNs is still a crucial step for saving resources and optimizing WDNs' performance in developing countries (Morais and Almeida, 2010). Often, the rehabilitation of WDN is foreseen as a prominent step in improving the network performance and upholding their hydraulic capacity by replacing or strengthening segments of pipes that have high breaking frequencies (Giustolisi et al., 2006). Nonetheless, expanding WDNs over different terrains and weaving networks with different materials over time added another layer of confusion over which network or section of the network must be rehabilitated first. Moreover, the extraordinary expenses of network rehabilitation add another challenge to decision-makers. Therefore, a comprehensive water network assessment is necessary for well-chosen decisions. Hence, the assessment of WDNs includes several factors based on understanding the static and the dynamic factors, such as pipe deterioration mechanism, operational factors, and advanced field inspection techniques (Sægrov et al., 1999).

The integration of decision-making models in the management of WDNs has been increasing recently. Early rehabilitation studies tackled leak detection and forecasting techniques to cut down water losses caused by pipe breaks (Giustolisi et al., 2006). Later, models evolved to determine pipe rehabilitation types based on different considerations. Computer-Aided Rehabilitation for Water Networks (CARE-W), presented by was one of the early models utilized in the rehabilitation of networks (Sægrov et al., 2003). It outlines rehabilitation annual programs and determines the level of rehabilitation based on leakage, pipe failures, hydraulic insufficiency, and cost-effectiveness. Later, integrated a leak management strategy with a decision-making tool to enhance the reliability of WDNs (Christodoulou et al., 2008). Some researchers utilized a decision support model to differentiate between main pipes rehabilitation methods and rank them based on the most suitable solution (Ammar et al., 2012). The model incorporated the functional and structural characteristics of main pipes as significant factors in the network performance within multiple rehabilitation scenarios. Tabesh and Saber ranked pipe rehabilitation scenarios using GIS, hydraulic analysis, breakage, and physical characteristics (Tabesh and Saber, 2012).

Kessili and Benmamar built an AHP-PROMETHEE II model for the prioritization of rehabilitation projects for sewer networks in Algeria

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(Kessili and Benmamar, 2016). The model considered several aspects including financial, environmental, structural, hydraulic, social, and technical attributes of the sewer networks. A group researchers introduced a multi-criteria decision-making model to organize the pipes rehabilitation (Salehi et al., 2018). The model focused on the rehabilitation of pipes within a network based on the pipes' attributes. These attributes were divided into thirty technical and twelve non-technical characteristics. Although a group researchers addressed the rehabilitation of pipes within a network, the application of this model can be insufficient for setting the priority of large-scale rehabilitation projects (Salehi et al., 2018). Moreover, the required information for each pipe was significantly large, which necessitated an over-detailed data collection process. Besides, some of the requested information might not be considered vital to the decision-maker. Gül and Firat developed a multi-criteria model to determine the priority of regions for WDN rehabilitating using the Entropy method combined with the ELCETRE I and PROMETHEE II methods (Gül and First, 2020). The goal of the model was to reduce capital investment costs, water losses, and operating costs. Consequently, the model considered 28 factors related to physical characteristics, hydraulic parts, water demand, and operation of the networks. The model's focus on reducing capital investment cost rendered capital investment as the primary theme in the decision process.

1.2 WDNs Rehabilitation in Jordan

Water scarcity in Jordan, a developing country, has reached an alarming level. The available water resources whether it is surface or groundwater are no longer meeting the natural growth demand. Therefore, these resources are continuously decreasing. Unfortunately, refugee waves from neighboring war-worn countries have increased the gravity of the problem. Current renewable water resources in Jordan are falling behind sharply. The water per capita share dropped intensely from 1975 through 2010 from 500 m^3 to 140 m^3 (IWMI, 2016). It is projected that the per capita share of water will fall to 90 m^3 per capita in 2025, assuming that the current water resources remain unchanged. Such value means that the water shortage status will move to extreme water poverty. Moreover, the declining rate of surface water resources caused high reliance on hard-to-replenish groundwater resources.

Consequently, the groundwater level is dropping at a rate of 2 m/year in main aquifers. The drop in water level in some areas has reached 5 - 20 m/year (MWI, 2017). Recently, the water demand in Amman witnessed an increase from 120 MCM to 209 MCM over the period 2006 to 2020 (Miyahuna, 2020). Furthermore, the water demand in the northern governorates that hosed the Syrian refugee waves increased by 40 %. This increase dramatically affected the non-revenue water (NRW) quantities in the north of Jordan (Breulmann et al., 2021). The severity of the water status forced the authorities to maximize water-harvesting projects and minimize water losses. Therefore, it became crucial and highly necessary to improve the WDNs' efficiency through rehabilitation and reduce the high Non-Revenue Water rates (NRW).

The rehabilitation process of WDNs in Jordan faces several challenges that necessitate the use of a prioritization system. The water distribution networks were constructed of several distribution subnetworks at different times and with different materials. The deterioration of these network materials is dissimilar. Over the last decades, authorities in Jordan switched the type of water supply from continuous to intermittent supply. Water is supplied to residents for one or two days and sometimes a few hours per week. Moreover, the sudden increase in population and variation in housing concentration created significant pressure on certain areas. Hence, water leakage, insufficient water delivery, and water pressure failure became more frequent and network maintenance costs increased considerably and required an overall network rehabilitation project. As several networks need urgent rehabilitation and the cost of rehabilitating WDNs is enormous, a prioritization criterion became essential for cost-effective management. The priority of WDN rehabilitation projects in Jordan has been often chosen for areas or regions by a very limited number of people in the Ministry of Water and Irrigation and funding agencies supporting these projects such as the German Development Agency Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), Japan International Cooperation Agency (JICA), and the United States Agency for International Development (USAID).

Although literature described several models to prioritize water network rehabilitation, the majority of these models are based on many technical properties of the WDN such as physical properties and hydraulic analysis of the networks. Conversely, several non-technical properties of the WDN such as compliance with specification and installation quality are considered essential elements in the decision process have not been considered previously in the literature. Therefore, there is a need for a tool that prioritizes WDN rehabilitation projects that is based on an optimized number of technical and non-technical properties of the WDN and is based on serviceability, reducing water leakage, and meeting water demands. Hence, this study aims to employ a multi-criteria decision tool to prioritize WDN rehabilitation projects and provide decision-makers with a robust and adaptable prioritization model. The study objectives are identifying the influencing factors that control the priority decision of water network rehabilitation, developing an adaptable and reliable model for prioritizing WDN rehabilitation projects, and employing this model on actual WDNs in Jordan. Eventually, this study presents a decision model for prioritizing WDN rehabilitation projects that combines rigorous decision-making criteria with future-change flexibility and is based on achieving optimum serviceability, meeting water demand, and reducing water losses.

2. METHODOLOGY

To achieve the study objectives, it is necessary to have a systematic methodology that is flexible for future changes, cost-effective, and addresses the focal points regardless of their complexity for the stakeholders and decision-makers to rehabilitate WDNs. A powerful tool for achieving the study objectives is the analytical hierarchy process (AHP). The AHP was introduced by Saaty in 1980 as a multi-criteria decision approach based on understanding the complicated relationships between goals and related attributes to help the decision-maker differentiate the importance of the different elements in any problem. The AHP approach was used in several models and frequently integrated with ranking methods. Al-Barqawi and Zayed evaluated municipal water main pipes performance utilizing AHP concepts in infrastructure management (Al-Barqawi and Zayed, 2008). Some researchers ranked several trenchless methods to rehabilitate WDNs in Romania using AHP (Aşchilean et al., 2018).

A group researcher recently used AHP to evaluate risk in water and wastewater projects (Kheradmand et al., 2021). Although AHP has been applied to different multi-criteria decision-making problems, the involvement of human judgment and preferences in the decision process creates a state of vagueness and uncertainty that AHP may not manage properly (Afolayan et al., 2020). The merge of AHP and the fuzzy method has shown a dynamic system in which a multi-component hierarchal approach is combined with a flexible system that is capable of handling uncertainties and credibly represents human judgment (Ahmed and Kilic, 2019; Afolayan et al., 2020). Therefore, this study employed the fuzzy analytical hierarchal process (FAHP) in developing a priority model. Accordingly, the study consisted of two steps: first, exploring the main categories and corresponding factors for assessing existing water distribution networks. Second, developing an adaptable analytical tool for prioritizing WDNs' urgencies for rehabilitation works using FAHP.

2.1 Model formulation

2.1.1 Influential factors determination

The study considered determining the main categories and influential factors in the available literature, experts' judgments, and stakeholders' feedback. Firstly, influencing factors were collected and grouped into categories as presented in the literature (Sægrov et al., 1999; Kleiner, 2001; FCM and NRC, 2003; Rajani & Kleiner, 2004; Giustolisi et al., 2006; Christodoulou et al., 2008; Ammar et al., 2012; Haider et al., 2015; Salehi et al., 2018; Al-Sheriadeh & Amayreh 2020; Kheradmand et al., 2021). Then, multiple individually set open-discussion interviews were conducted with seven stakeholders from water authorities in Jordan, engineering consultants, and funding agencies. The collected factors and categories were presented to the stakeholders to explore these factors' importance and pursue other potential principal factors in the priority of network rehabilitation. The meeting with stakeholders resulted in adding several new factors, removing insignificant factors, and merging similar ones. Eventually, a questionnaire was established to estimate the significance of every factor and define its role in setting the priority decision for WDN rehabilitation.

The study identified using the literature survey and the stakeholder interviews five main categories: environmental, operational, physical, socioeconomic, and quality of service. These five categories played the role of controlling indices of the priority decision process. Although not present frequently in the literature, the stakeholders' interviews added the quality of service and socioeconomic categories to the environmental, operational, and physical categories that are mentioned in the literature. The stakeholder justified the addition by their relation to the level of service and power exerted by these factors on the decision-making process. Figure 1 shows the categories and their assigned factors. Each category contains 3 to 5 factors that are either qualitative or quantitative. Each factor contains several attributes that are influential in the decision-making process.

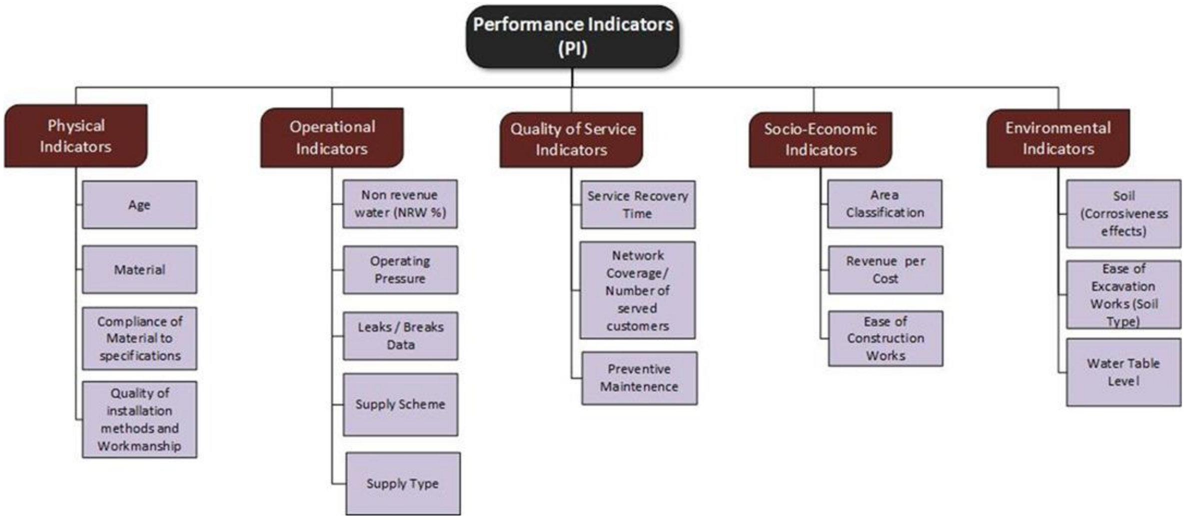

Figure 1: Decision-making factors

The Physical factors category comprises the WDN physical properties and design and installation aspects that are essential to the decision maker. Commonly, these factors address the functionality of the network as hydraulic elements. These factors include the pipes' age and material, compliance of material to specifications, and installation quality. The pipe age and material are often the measured basis for the durability of the pipes for long-term use. Therefore, the pipe deterioration can be a function of the pipe's material and age. Nevertheless, pipe replacement is not always caused by pipe corrosion or deterioration. In many cases, the failure in hydraulic capacity is related to inadequate design consideration or installation. The compliance of the installation procedures and activities to the technical specifications and good engineering design plays a significant role in the performance of the network. Poorly installed projects, defectively designed projects, or weak approaches like inappropriate trench support or non-durable filling material are responsible in many cases for an early failure of the network. Hence, the physical factors can render each project a unique case.

The operational factors category encompasses the key operating elements and operative concerns. This category is comprised of the operating pressure, supply type and scheme, leakage incidents, and NRW values. Incidents of WDNs' leakage, breaks, and losses have been commonly associated with the use of inexperienced labor during pipe installation, the short intermittent supply, high hydraulic pressure that is caused by improper design or operating practices to satisfy the high demand during the short supply duration, inadequate maintenance, and illegal water abstraction (Al-Sheriadeh and Amayreh, 2020). Water leakage plays a substantial part in the WDN rehabilitation decision. Operational Studies revealed that the leakage from small-diameter pipes such as house connections is the greatest, and leakage from main pipe joints and fitting was noted as comparatively higher than from other network components (Abu-Shams and Rabadi, 2003; Farley and Trow, 2015).

These kinds of leakage are often caused by improper installation or installation by inexperienced labor. Another operating factor that can be crucial is the system's water pressure. The relationship between system pressure and leakage is intricate. Although increasing the system pressure satisfies the customers' needs, the network leakage increases with pressure proportionally (Abu-Shams and Rabadi, 2003). In addition, intermittent water supply has been practiced by water authorities to optimize water supply serviceability to all customers under water shortage. Intermittent water supply can reduce water leakage in defective network areas. Nevertheless, intermittent supply adversely affects the networks' durability due to the cyclic pattern of supply joined with variations in water pressure, supply duration, and quantities (Al-Sheriadeh and Amayreh, 2020). NRW value has gained more interest recently and has become an influential factor. It consists of physical leak losses, commercial losses (customer billing errors and illegal water drawing), and any authorized unbilled volume. High NRW levels are unfavorable to any system of water supply. It threatens the financial and technical viability of any utility. The supply type is concerned with the method of water supply (i.e. by gravity or by pumping), which is shaped primarily by the service area's topography, while the supply scheme is mostly related to the water management to meet the serviceability goals and regularity needs of the service area.

The Quality-of-Service factors address the problems related to the supplied water quality and quantity, construction conformity with regulations and standards, and responding to subscribers' complaints. It includes service recovery time, number of served customers, and preventive maintenance. Service recovery time is often used as a service quality measure. It indicates the time spent responding to the complaints from the time of reporting to the time of fixing the problem. The size of network coverage exerts a significant weight in deciding which rehabilitation project to initiate. Large and densely populated areas create a challenge for operators and put the network under continuous stress. An ideal water management system schedules an optimized preservation program to extend the durability of the network elements and improve the network performance. Nevertheless, having such plans is not always achievable, especially in difficult topography, environment, and restricted resources.

The Socioeconomic factors address the financial burdens and social structure of served areas. It includes area classification, revenue per cost, and ease of construction. Typically, the service area classification is based on the subscriber's concentration per served area. In addition, social factors such as lifestyle that are often related to educational and cultural customs or type of service area (i.e. recreational or commercial) may influence the maintenance of water supply services. The Revenue-per-cost indicator measures the billing revenue to the total cost for the available network. Ease of construction is concerned with the difficulty level in construction activities in the available area, which is often related to the highway width and distances between customers. The Environmental factors are concerned with the nature of the place in which the pipes are laid. It includes soil type in terms of corrosivity to pipes, excavation ease, and water table level. These factors generally influence the construction work and durability of the network. For example, soil type and water table level have a substantial impact on the used excavation machinery, pipe material, and the expenses associated with rehabilitation works.

As the aforementioned factors have different weights on the decision process, it was necessary to state the importance level for each factor to be applied in the FAHP calculations. Accordingly, a questionnaire was established to estimate the importance level of these factors by stakeholders. The questionnaire comprised primarily of three parts; the first part collected participant's information, in which participants answered questions about their current experience, affiliation, and experience length. In the second part, the participant gives weight to each factor and attribute as a score between one and ten (one means very low impact and ten means very strong impact). In the third part, the participant compares categories and factors in a pairwise comparison. In this part, tables were arranged for participants to compare all categories and factors by choosing a level of strength between two factors according to the Saaty scale (Saaty, 1990). The pairwise comparison was explained to the expert to give preference for one factor over another. After formulating the questionnaire, 5 evaluators reviewed the statements and the questionnaire's adequacy as a tool to evaluate the influencing factors. Consequently, the questionnaire was modified according to the reviewers' remarks to make it understandable to the readers.

Upon completion of the formulation of the questionnaire stage, stakeholders and experts in WDN construction and rehabilitation were contacted. The experts and stakeholders were asked to answer the questionnaire and specify the importance level. Close contact was maintained with the respondents to clarify misunderstandings and answer their questions. The contacted stakeholders and experts were engineers with a long history of experience (over 20 years) and worked in the WDNs rehabilitation projects. The respondents were experts and stakeholders from the water authorities in Jordan such as the Ministry of Water and Irrigation, the private engineering companies that have worked in water and NRW reduction projects, and the funding agencies that support water rehabilitation projects in Jordan. Eventually, twenty-three responses were attained; the questionnaire was checked later to ensure attaining clear response and no missing information.

2.1.2 Building FAHP model

Although the fuzzy algorithm was introduced in the 1960s by Zadeh, it continues to gain more interest from researchers (Zadeh, 1965). Zadeh transformed a range of points into a fuzzy set that is defined by a membership function related to a real number in a particular numerical interval (Zadeh, 1965). The idea of the membership function was introduced to represent how fuzzy sets or points belong between 0 and 1 compared to a Boolean system where it is only 0 or 1. In the membership, there is a point or set of points of full membership that is represented by 1 and a point or set of points of no membership represented by 0. The remaining points will take values that vary between zero and one that represent a portion of the membership. In this study, the triangular membership function was selected. The triangular membership function is described by three parameters: lower and upper limits, (a) and (b), respectively, that are bounding a middle value (m). The triangular membership function is presented as follows:

$$A(x,a,m,b) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{m-a}, & x \in [a,m] \\ \frac{b-x}{b-m}, & x \in [m,b] \\ 0, & x \geq b \end{cases} \tag{1}$$

The scores obtained from the experts were transformed into six matrices: five matrices representing the five categories and an overall performance matrix. Each matrix size is set to a number of factors under the assigned category. Following the AHP method and the basics of matrix formation, if the number of factors is defined by n, the number of rows i, the number of columns j, and the importance weights obtained from experts are reflected as w_{ij} as w_{11}, w_{12}, w_{13}, ……,w_{nn} for each matrix M.

Since pairwise comparison delivers an advanced differentiation between factors of equal weight, it helps solve the complex relationship between factors. Therefore, using the pairwise comparison between every two factors in the weight matrix with the use of the preferred weight as w_{ij}, the un-preferred factor weight will be $1/w_{ij}$ as follows:

$$M = \begin{array}{cccc} 1 & w_{12} & w_{13} & w_{14} \\ 1/w_{12} & 1 & w_{23} & w_{24} \\ 1/w_{13} & 1/w_{23} & 1 & w_{34} \\ 1/w_{14} & 1/w_{24} & 1/w_{34} & 1 \end{array} \tag{2}$$

The process of building a fuzzy pairwise comparison matrix is based on implementing the following steps: Normalization of Fuzzy Weights, Calculation of Fuzzy Weights, Fuzzy Weights Aggregation and defuzzification, Consistency Calculations, Combined Matrix Calculation, Global Score Calculation, and Sensitivity Analysis.
In the normalization step, the values of column cells are divided by the summation of the cells in the column as follows:

$$w_i = \frac{r_i}{\sum_{i=1}^{n} r_i} \tag{3}$$

Where w_i is the normalized weight calculated for each row.

This procedure was repeated in all columns. The number of rows in the matrix should equal the number of factors involved.

The calculations of the fuzzy weights for each matrix are performed using the Row Geometric Mean Method (RGMM) as follows:

$$\left[exp\frac{1}{n}\sum_{j=1}^{n} ln(a_{ij})\right] = \left(\prod_{i=1}^{n} a_{ij}\right)^{\frac{1}{n}} \tag{4}$$

Where r is the row geometric mean, i is the row number, and j is the column number in the matrix.

The aggregation and de-fuzzification are performed using the weighted average mean, as recommended for environmental problems by (Pedrycz et al., 2011):

$$value = average(Fuzzy\ values) = \frac{w_{11} + w_{12} + \cdots\cdots w_{1n}}{n} \tag{5}$$

Where w is the elements in the fuzzified matrix

The consistency calculation is performed to verify that the judgments by the participants are consistent. It minimizes the inaccurate results caused by inconsistencies. The consistency calculation is performed using the consistency index formula (CI):

$$CI = \frac{(\lambda max - n)}{n-1} \tag{6}$$

Where n is the number of factors and λ_{max} is the maximum eigenvalue of the comparison matrix.

A squared matrix's eigenvector is a scalar multiple of that vector. So, for an (n x n) square matrix named A, v is a non-zero vector, the product of matrix A and vector v is defined as the multiplication of a scalar quantity λ and the given vector, such that:

$$Av = \lambda max \times v \tag{7}$$

Saaty suggested using the Random Index (RI), derived from a randomly generated matrix, and comparing it to the CI (Saaty, 1987). The values for RI were chosen following Saaty and the values for RI for the number of criteria N less than three is zero (Saaty, 1987).

The consistency ratio was calculated using the consistency ratio formula by (Alonso and Lamata, 2006):

$$CR = \frac{\lambda_{max} - N}{2.7699N - 4.3513 - N} \tag{8}$$

Where λ_{max} is the eigenvalue, and n is the number of factors.

The geometric mean method was used for calculating the combined weights for all respondents. Consequently, the weight for each category is calculated based on the included factors.

The global score for the network was calculated through the hierarchy levels based on the provided data for the tested network. Each factor's weight calculated from FAHP is incorporated as part of the category weight. When comparing several networks, the global scores for the networks are calculated and then sorted to represent a priority list to facilitate rehabilitation decision-making.

2.2 Case study application

The developed FAHP model was tested using five water distribution networks that belong to five different distribution zones (DZ) in Amman Governorate that are under consideration for rehabilitation. These zones are DZ-13-Khilda, DZ-04-Al Taj, DZ-28-Tabarbour, DZ-05-Al Joufih, and DZ-27-Tariq. The purpose of this test is to elucidate the work of the FAHP model and verify the ability of the model to prioritize WDN rehabilitation projects. The data collection for this test was conducted during the summer and fall of 2021. It is worth noting that until the time of publishing this study, no rehabilitation has been implemented in these distribution zones.

2.3 Sensitivity Analysis

A sensitivity analysis test was implemented to check the certainty level within the model output. The analysis was applied to the category's factors with increments of 5% from the calculated weights in the model. Subsequently, the variation in the global score was monitored following the change in the local parameters. The sensitivity impacted is calculated using the equation:

$$S = ((|V/N - V'/n|) / V) * 100 \tag{9}$$

Where S is the sensitivity expressed as the variation index, V is the unperturbed vulnerability index, V' is the vulnerability index after variation, N is the number of parameters used in the determination of V, and n is the number of parameters used in determining V'.

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3. RESULTS AND DISCUSSION

3.1 Model Formulation

The data from the experts' responses were collected and used to estimate the weight for each factor and category. Results of the five main categories according to each respondent are presented in Table 1. The results in Table 1 show variation among experts on the importance of each category. The variation between experts' opinions was noted among the experts even within the same affiliation. The results show agreement among most of the experts on the importance of physical and operational attributes on the network. Alternatively, some experts considered the environmental and socio-economic attributes as the critical factors in the decision of network rehabilitation priority.

Table 1: Experts weight scores for main categories

Expert	Physical	Operational	Quality of Service	Environmental	Socio-Economic	Affiliation*
E1	0.411	0.411	0.059	0.059	0.059	A
E2	0.140	0.391	0.365	0.050	0.054	A
E3	0.139	0.388	0.363	0.036	0.074	A
E4	0.323	0.171	0.125	0.191	0.191	C
E5	0.360	0.360	0.191	0.062	0.028	A
E6	0.368	0.080	0.368	0.102	0.082	A
E7	0.389	0.363	0.140	0.069	0.039	A
E8	0.366	0.366	0.102	0.083	0.083	A
E9	0.610	0.185	0.064	0.071	0.071	A
E10	0.389	0.363	0.140	0.069	0.039	A
E11	0.032	0.060	0.303	0.303	0.303	A
E12	0.070	0.133	0.345	0.345	0.108	A
E13	0.586	0.265	0.050	0.050	0.050	A
E14	0.319	0.047	0.169	0.232	0.232	A
E15	0.358	0.079	0.128	0.218	0.218	F
E16	0.579	0.169	0.169	0.038	0.044	C
E17	0.589	0.161	0.161	0.045	0.045	F
E18	0.538	0.058	0.135	0.135	0.135	C
E19	0.551	0.254	0.117	0.054	0.025	F
E20	0.301	0.520	0.099	0.030	0.049	F
E21	0.586	0.265	0.050	0.050	0.050	F
E22	0.123	0.476	0.305	0.047	0.047	F
E23	0.505	0.072	0.288	0.075	0.061	C

* Experts affiliation index: A: authority, C: engineering consultant, F: funding agency

The weight calculations for each category and factor showed that the physical category had the highest weight at 38% compared to the categories, while the environmental category had the least weight at 9%.

The contribution percentage of each category to the decision process is shown in Figure 2:

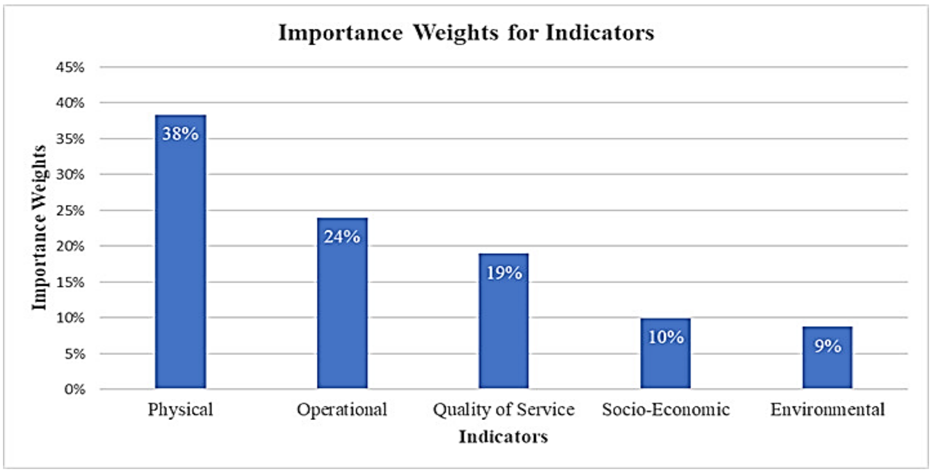

Figure 2: Importance weights for Indicators

The estimated percentage weights for all factors within each category are presented in Figures (3 a-e). The collective results after combining the experts' responses show that the initial placement of the water network is the most crucial element in network rehabilitation decisions. As illustrated by experts' responses, the major factors were proper installation and compliance with the assigned technical specifications by authorities. Furthermore, some experts expressed that utilizing the best available techniques and experienced labor to professionally install WDN components with the proper excavation methods and covering pipes with compacted layers is much more important than the other physical properties. In their opinion, the network, if properly installed, will uphold its best performance for a long period regardless of the network material and age and will not require frequent maintenance. Therefore, these networks will have less rehabilitation priority. Consequently, age was placed third in terms of importance level according to the expert judgment followed by pipe material.

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(a)

(b)

(c)

(d)

(e)

Figure 3: Performance factors weights. a) Physical factors, b) Operational factors, c) Quality of Service factors, d) Socio-economic factors, e) Environmental factors

The durability of the network is maintained by the operational conditions. The questionnaire results show that the operational category was placed second after the physical factors. Under the operational factors category, the number of breaks in the WDN elements and the NRW percentage had the highest weight. Furthermore, when comparing breaks in main pipelines and house connections, priority scores were higher for house connections. Experts noted that the rate of breaks in house connections is generally higher than in main pipelines due to multiple factors such as the smaller diameter of house connections and the inappropriate installation conditions of old galvanized pipes house connections. Consequently, a high rate of pipe breaks will result in a high level of NRW losses. The operating pressure scored an intermediate weight among the operational factors. Among operating pressure, high and excessively high-pressure operating conditions are frequently related to a high deterioration rate in WDNs. Therefore, they attained the highest score while very low to moderate pressure operations had less impact, so they scored less. The scores of supply type and scheme were the lowest. Although experts' estimations were diverse regarding the supply scheme and flow type, they generally agreed to prefer a continuous supply scheme over intermittent supply and gravity flow over pump supply. In the quality of service category, the top weight of the evaluated factors was for the service recovery time. The experts explained that the networks benefit financially and operationally from the shortened complaints response time; hence, the subscribers' satisfaction will be improved. Yet, a shorter recovery service time is hard to attain in all regions due to the complicated conditions of some locations and the lack of skilled maintenance equipment and teams.

The socioeconomic category reflects the financial part and the social condition of the area. Generally, experts believe that subscribers in any served area are entitled to receive water through an efficient network irrespective of the project's cost, the complexity of excavation works, or population density. Nevertheless, experts agree that high population density in urban areas should have a higher priority for rehabilitation over rural areas. Areas of easy excavation work are typically favored due to the cost efficiency. In addition, projects with a high ratio of revenue to cost will be highly prioritized in rehabilitation. The overall experts' scores and estimated weights showed that revenue-per-cost has the highest impact amongst the socioeconomic factors at around 39%, while the area classification had 33% and the ease of construction works had 28%.

In the environmental category, the included factors had relatively comparable weights. The environmental factors' calculated weights are 31.17 %, 37%, and 31.47 %, respectively. The overall weights for each factor as calculated by FAHP are illustrated in Table 2. Among all factors, it clearly shows that a very old network, made of galvanized material, has very poor installation conditions and specifications, has high operating pressure ranges, has a high number of breaks, and has low NRW% scores will have the highest priority.

Table 2: Performance indicator weights

Category	Factor	Attribute	Description	Importance score (1-10)
Physical	Age	Very Old	> 50 years	9.39
		Old	(35 – 40) years	7.39
		Medium	(10 -35) years	4.43
		Newly Installed	< 10 years	1.26
	Material	Ductile Iron	-	2.57
		HDPE		2.3
		Steel		5.96
		Galvanized		9.21
	Comply with Technical Specifications	All used material complies with the specifications	-	1.3
		Some of the used materials comply with the specifications		5.13
		Material is not according to specifications		9.21
	Quality of installation methods and workmanship	Excellent	> 90 %	1.78
		Moderate	(60- 90) %	4.35
		Poor	(50 - 60) %	6.69
		Very Poor	< 50 %	9.04
Operational	NRW %	High	> 40 %	9.04
		Medium	(30 – 40) %	6.46
		Low	< 30 %	3.13
	Operating Pressure	Very High	> 7 bars	8.30
		High	(5- 7) bars	5.61
		Moderate	2.5-5 bars	2.48
		Very Low	< 2.5	1.35
	Number of Leaks / Breaks in the pipes of the distribution network	High	> 3 leaks / Km/year	8.71
		Medium	(1 – 3) leaks / Km /year	5.13
		Low	< 1 leak / Km/year	2.3
	Number of Leaks / Breaks for the house connections	High	> 5 leaks /20 h. c /Km/ year	8.65
		Medium	(3 – 5) leaks /20 h. c /Km/ year	5.3
		Low	< 3 leaks /20 h. c /Km/year	2.4
	Supply Scheme	Intermittent	-	6.8
		Continuous		4
	Supply Type	Gravity	-	3.43
		Pumping		7.14
Quality of Service	Service Recovery Time	Long	> 6 hours	7.8
		Medium	(3- 6) hours	5
		Short	< 3 hours	1.78
	Network Coverage	Majority Covered	-	1.87
		Some covered		4.96
		Majority not covered		8.09
	Preventive Maintenance	Scheduled	-	1.87
		Not Scheduled		7
Socio-Economic Indicators	Area Classification	Urban	> 20 h.c / km	7.17
		Rural	< 20 h.c / km	3
	Revenue per cost	Positive	-	6.82
		Negative		2.61
	Ease of Excavation Works	Easy	-	5.65
		Medium		4.83
		Hard		3.87

Table 2: Performance indicator weights

Environmental Indicators	Soil Type/ ease of excavation works	Rocks	-	5.83
		Clay		4.87
		Sand		2.70
	Corrosion effect	Aggressive Effect	-	2.91
		Normal Effect		7.39
	Water Table Level	Deep	> 5 m	1.91
		Moderate	(3 – 5) m	4.10
		Shallow	(1 – 3) m	6.48

3.2 Case study application

The developed FAHP model was tested using five water distribution networks in Amman Governorate that are under consideration for rehabilitation. These zones are DZ-13-Khilda, DZ-04-Al Taj, DZ-28-Tabarbour, DZ-05-Al Joufih, and DZ-27-Tariq. The geographical extent of the WDNs is shown in Figure 4.

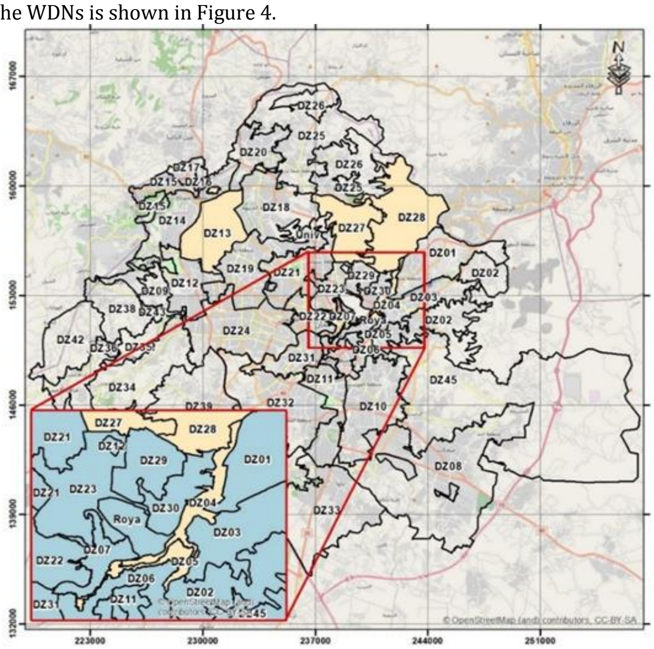

Figure 4: Study Area from Amman Distribution Zones

The required data for each WDN were obtained from different sources in the Jordanian Water Authorities and the current private water service operators in the Amman area (Miyahuna, LLC). The data consists of GIS map layers for the water networks, including the extent of distribution pipes, number of active/inactive subscriber and house connections, pipe material, pipe diameters, year of installation, valves, PRVs, supply sources, distribution tanks' locations, service area map, street base map, and accessibility to pipe maps. Also, the NRW estimation for the last quarter of the year 2021 was obtained for each WDN. The number of house connections for the five WDNs was: 43230 for DZ13 – Khilda, 5000 for DZ04 - Al Taj, 13840 for DZ28 – Tabarbour, 2471 for DZ05 - Al Joufih, and 4682 for DZ27 – Tariq.

The collected datasets were reviewed to confirm the completeness and suitability of the data. The WDN age data were estimated from the date of WDN construction. The collected data show that the distribution network in some zones within Khilda is constructed of galvanized pipes and steel pipes. Galvanized and steel pipes were the default choice for pipe material decades ago, therefore, the network in these zones is considered old. For the specifications compliance data, the private water service provider confirmed that the WDNs in the selected five areas complied with the technical specifications at the time of construction. Operating pressure data were attained from design and maintenance reports for the distribution zone networks. The water supply type, which is usually pump supply or by gravity, was also identified from the hydraulic study and supply maps for selected areas.

The water authorities have applied an intermitted-supply scheme in Amman to confront the water shortage and maintain sufficient water supply for basic needs. Therefore, intermittent supply was chosen for almost all WDNs in the model. Since Amman is a metropolitan area, the area classification is considered urban for all selected areas. The revenue per cost was estimated based on the area classification, the number of customers, and the ease of construction work. For the network coverage, data from the annually published reports by water authorities showed that unsubscribed consumers are less than 2% of the total number of customers in these areas. The time of response for customers' problems is estimated by Miyahuna as medium for all WDNs. Amman is characterized by being a mountainous area with a deep water table; therefore, the water table level was considered deep for all selected areas. The corrosiveness impact is considered normal for all soil types within these areas.

The developed FAHP utilized data collected for the five selected WDNs. The calculated priority scores for the five compared areas are shown in Table 3:

Table 3: Final Calculated Scores for zones

Priority	Distribution Zone Name	Global score (%)
1	DZ13 – Khilda	53.69
2	DZ04 - Al Taj	53.03
3	DZ28 – Tabarbour	51.69
4	DZ05 - Al Joufih	43.62
5	DZ27 – Tariq	42.81

According to the model results, the Khilda and Al-Taj WDNs scores were higher than the other areas while the Khilda area scored slightly higher than Al-Taj. The proximity of these two areas' scores is believed to be caused by the higher number of customers in Khlida and the severely deteriorated pipes in Al-Taj.

The model results were shared and discussed with stakeholders from water authorities to have their feedback and opinions regarding the priority list. The stakeholders approved that the resulting priority list would be the most suitable priority for rehabilitation works based on the service area, topography, and network conditions. Therefore, it can be concluded that the priority model was successful in setting a priority list for WDNs in Amman.

3.3 Sensitivity Analysis

A sensitivity analysis study was implemented to identify the effect of each category on the global score. The data for the Khilda area were used as a representative. The sensitivity analysis results are shown in Table 4. Remarkably, the analysis shows that although the physical factors category has the highest weight in the model, the global score was more sensitive to the operational factors category. Conversely, similar to the categories' weights, the environmental and socioeconomic categories had the lowest impact on the WDN global score.

Table 4: Percent change in global score due to a percentage change in an indicator

	Change percentage in indicator					
Indicator	5%	10%	15%	20%	25%	30%
Physical	1.265	2.530	3.795	5.060	6.325	7.589
Operational	2.892	5.784	8.676	11.569	14.461	17.353
Quality of Service	0.834	1.669	2.503	3.338	4.172	5.007
Socio-Economic	0.005	0.010	0.015	0.020	0.026	0.031
Environmental	0.003	0.007	0.010	0.013	0.017	0.020

4. Conclusions

The study explored creating a decision model that prioritizes water network rehabilitation projects. The available models in the literature focused primarily on technical factors in prioritizing rehabilitation projects. The study explored the main technical and non-technical factors that stakeholders consider in their decisions. Based on stakeholders' evaluation, the study classified these influential factors into five main categories that are dominant in the decision-making process: physical, environmental, operational, socioeconomic, and quality of service. The weight of these categories and factors was judged by 23 experts. An FAHP model was developed based on the studied categories and their weights. The study showed that among the five main categories, the physical factors attained the highest weight of around 38%, followed by the operational factors at 24%. The quality-of-service factors were placed third with 19% of the total weight, with the service recovery time being the key attribute. Socioeconomic and environmental factors were less weighted with 10% and 9%, respectively. The study found that compliance with technical specifications and quality of installation exert significant weight among the physical factors. Among the operational factors, the number of breaks and the NRW had the highest weight percentages. The study noticed that the factors in the quality-of-service, socioeconomic, and environmental categories were relatively comparable. These comparable factors signal comparable competition in the decision-making process. According to the model and experts' evaluation, it was found that a very old network, made of galvanized material, has very poor installation conditions and specifications, has high operating pressure ranges, has a high number of breaks, and has low NRW% scores will have the highest priority for rehabilitation. The model was tested on five WDNs that need rehabilitation in Amman, Jordan. The test results showed that the model was successful in providing a sound priority list of network rehabilitation projects to the decision-maker. The revision of the technical factors and the inclusion of several non-technical factors helped provide the decision-makers with a refined priority list that addresses the WDN's most pertinent needs. A sensitivity analysis of the model revealed that the operational factors were more influential on the decision although the physical factors had higher weight.

Declaration and Statements

- The authors declare no competing interests in publishing this work.
- All data that support the findings of this study are available from the corresponding author upon reasonable request

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