A Holistic Approach to Strengthening Stability, Adaptability, and Environmental Stewardship in Water Supply Systems Management

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The process of extracting, treatment, and distributing drinking water is subject to contamination risks and the continuity of its delivery to consumers. Therefore, this research focuses on risk assessment through an applied study on the supply systems of drinking water produced by a station in Qaliobia Governorate: Benha. The scope of the research encompassed three consecutive phases. The first phase involved identifying the risks affecting the water supply system during the source, treatment, and distribution stages and their impact on reliability, resilience, and sustainability. The second phase included the evaluation and analysis of these risks using the Analytic Hierarchy Process (AHP) and Generic Risk Matrix (GRM). The final phase involved proposing risk response alternative strategies and evaluating them using the Relative Importance Index (RII) to reduce the impact of these risks. The results indicate the need to prioritize resources and efforts to enhance the treatment phase of the water supply system, as its importance represents 65% of the total water supply system phases, to mitigate risks and improve water quality. The results also indicate that automatic dosing regimens have an RII = 0.94, emphasizing their critical role in enhancing the reliability, resilience, and sustainability of the water supply system.

1. Introduction

Ensuring a safe and reliable water supply is a critical challenge worldwide, requiring a comprehensive risk management strategy. The World Health Organization (WHO) emphasizes the necessity of integrating such strategies within water supply systems (WSS) to mitigate risks and enhance service efficiency. A typical WSS consists of three primary components: the water source (intake), water treatment plants (WTP), and distribution networks, which include subcomponents like tanks, pumps, and valves. However, these systems face significant operational challenges, leading to inefficiencies and service disruptions. For example, approximately 25% of total water production is lost, 30% of the water network exceeds 30 years in age, some zones experience low pressure, and many WTPs operate inefficiently due to inadequate disinfection and filtration stages [1].

Despite the critical need for risk assessment, existing studies lack a systematic framework for evaluating risks across all WSS levels. This research aims to bridge this gap by developing a comprehensive

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risk assessment framework that addresses vulnerabilities at each hierarchical level of the WSS. To achieve this, the study employs the Analytic Hierarchy Process (AHP), a compensatory decision-making approach suited for multi-criteria evaluation. Dos Santos [2] identified AHP as an effective method for assessing risks with a moderate number of criteria, making it a suitable choice for this study.

2. Literature Review

2.1. Water Supply Systems (WSS) in Egypt

The water supply system consists of three main components: intake sources, treatment facilities, and a distribution network. Water is collected from natural sources, purified in treatment plants, and then distributed through an extensive network to consumers [3].

2.2. Risks in Water Supply Systems

Source of water, quality of water, design period of the project, design population and design flow, are the required studies for water supply systems. Hamed [4] reviewed six main challenges that water management in Egypt faced: The most important challenge is the rising water demand due to the growing population, The second challenge is the Nile flow reduction due to the construction of Ethiopian Dams, The third challenge is the quality of the water in the water networks due to the interaction with the human activities, The fourth challenge is climate change which affects the Nile flows and the different demands of the water sector, The fifth one is the sea level rise which threatens the Delta of the Nile and the sixth challenge is the institutional setting of water management.

While in treatment stage, Reda& Mobasher [5] collected the most risks affected the WTPs as: Unsatisfied treatment, Maneuvers outside operation requirements, Unadjusted chemical doses, Incorrect operation and Power failure. While in distribution stage, collected the most risks affected the WTPs as: Pipe mains breaks, Unsatisfied quality, Discontinuity of the service, Network leakage, Unsuitable pipe materials, Un-cleaned pipes, Pipe corrosion, Low and high pressure and Power failure.

2.3. Multi Criteria Analysis (MCA)

An approach for making decisions with several attributes is the Analytic Hierarchy Process (AHP). It was created by Saaty [6], who came up with a method for improving judgments based on hierarchy and reducing the consistency of expert judgments, pair-wise comparisons, judgment scales, the distribution of criteria weights, and the choice of the best option from a small set of options by computing their utility functions. The AHP provides a perfect proposal for multifaceted decision-making problems. The AHP processes the subjective and individual preferences of a person or group in decision-making using objective mathematics [7]. The AHP is based on the idea that arranging difficult situations into a clear and understandable hierarchical structure might help with decision-making [8], [9].

The Relative Importance Index (RII) is a method used to analyze ordinal data collected through a Likert scale and rank variables based on their importance or significance. It was initially proposed by Shash [10] and has been subsequently adopted and used by other researchers in various studies. When conducting research or surveys using a Likert scale questionnaire, respondents are typically asked to rate their level of agreement, preference, or importance on a set of statements or variables. The Likert scale usually consists of several response options, such as "strongly agree," "agree," "neutral," "disagree," and "strongly disagree" [11].

3. Material and method

3.1. Case Study Description

Qaliobia Governorate is one of Egypt's governorates, with Benha as its capital. It is located in the eastern Nile region at the head of the delta and is the third governorate within the "Greater Cairo" region. To meet the drinking water demands of its residents, Qaliobia Governorate has seven large water filtration plants that draw from various sources, including the Tawfikia Wind, Ismailia Canal, and the Nile River (Damietta Branch), with an average actual capacity of 472,930 cubic meters per day. Additionally, there are 30 small filtration plants in varying operational statuses (operational, non-operational, or decommissioned), with a combined actual capacity of 63,736 cubic meters per day (Qaliobia Drinking Water Company).

The research focuses on a key water treatment facility in Qaliobia Governorate: the Benha Water Treatment Plant (WTP). This facility produces 55,706 cubic meters of potable water per day and serves as a primary drinking water source for many communities in the northern and eastern regions of the governorate (Qaliobia Drinking Water Company). Fig. 1 shows the geographic locations of Qaliobia WTPs.
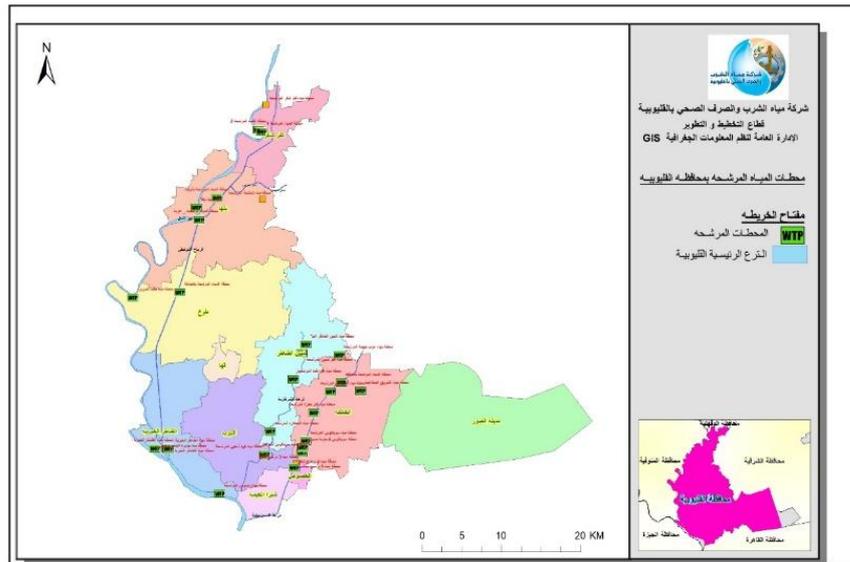

Fig. 1 The geographic location of the study area WTP.

3.2. Analysis Steps

The research methodology consists of four main steps designed to identify, assess, and develop risk response strategies for the water supply system:

Risk Identification: This step involves identifying and analyzing risks that affect the reliability, sustainability, and hydraulic resilience of the water supply system.

Risk Assessment: The identified risks are assessed both quantitatively and qualitatively using Analytical Hierarchy Process (AHP) and Grey Relational Method (GRM) analysis to determine their impact and probability.

Risk Response Development: Based on the assessed risks, appropriate response strategies are formulated to mitigate their effects.

Risk Response Prioritization: The proposed strategies are evaluated and ranked using the Relative Importance Index (RII) analysis to determine their effectiveness and prioritization.

By following these structured steps, the research aims to comprehensively address potential risks in the water supply system and provide recommendations for enhancing its reliability, sustainability, and hydraulic resilience. Fig. 2 outlines the workflow of the methodology.
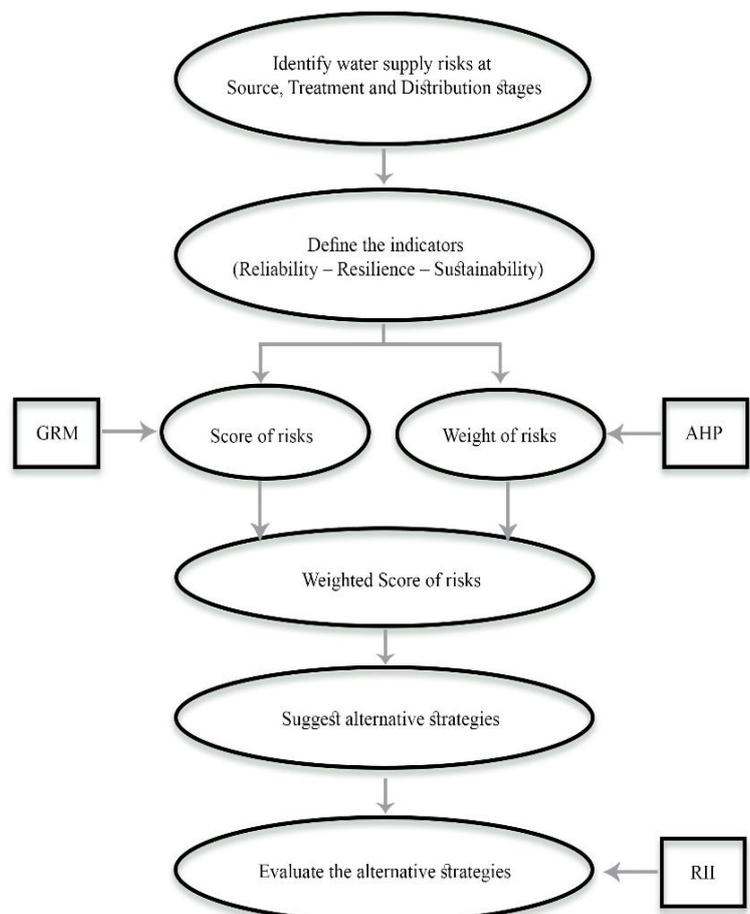

Fig. 2 Research process flowchart.

3.2.1. Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is a multi-criteria analysis method which is used to manage and analyze complicated judgments referring to mathematics and sensibility. This research uses the AHP analysis to get a weight of various risks in the WSS. The steps for AHP method are as follows [12], [13].

I. Create a hierarchical form divided to three levels, first level is the objective, the second is the criteria (standards), and the third level is the attribute levels.

II: Create the comparison matrix $A_{n \times n}$ (which n represents the number of alternatives) and assign each part a_{ij} with the nine-scale technique from 1 (Equivalent Importance) to 9 (Extreme Importance).

III: Calculate r_i (the significance ranking indicator) as:

$$r_i = \sum_{j=1}^{n} a_{ij} \ (i = 1,2, \ldots \ldots, n)$$

Where r_i is the significance ranking indicator, and a_{ij} is the part of the comparison matrix $A_{n \times n}$.

IV: Analyze the decision matrix $B_{n \times n}$, and assign each matrix part b_{ij} as the following way:

$$b_{ij} = \begin{cases} \dfrac{r_i - r_j}{r_{max} - r_{min}} \times (k_m - 1) + 1 & r_i \geq r_j \\ \left[\dfrac{|r_i - r_j|}{r_{max} - r_{min}} \times (k_m - 1) + 1 \right]^{-1} & r_i < r_j \end{cases} \ (i,j = 1,2, \ldots \ldots, n)$$

Where b_{ij} is the part of the decision matrix $B_{n \times n}$, r_i is the significance ranking indicator of indicator i, r_j is the ranking indicator of indicator j, r_{max} is the maximum amount of the ranking indicator, and r_{min} is the minimum amount of the ranking indicator. K_m is defined as:

$$k_m = \frac{\max (r_i)}{\min (r_i)} \ (i = 1,2, \ldots \ldots, n)$$

V: Create the optimum transferal matrix $C_{n \times n}$, and each matrix part is C_{ij} , as:

$$C_{ij} = \frac{1}{n} \sum_{k=1}^{n} \left(lg \frac{b_{ik}}{b_{jk}} \right) (i,j = 1,2, \ldots \ldots, n)$$

Where C_{ij} is the part of the optimum transferal matrix $C_{n \times n}$, and b_{ij} is the part of the decision matrix $B_{n \times n}$.

VI: Create the quasi-optimum consistent matrix $D_{n \times n}$, which every matrix part is d_{ij} as:

$$d_{ij} = 10^{c_{ij}} (i,j = 1,2, \ldots \ldots, n)$$

Where d_{ij} is the part of the quasi-optimum consistent matrix, and C_{ij} is the part of the optimum transferal matrix $C_{n \times n}$.

VII: Calculate the eigenvector of the maximum eigen value for matrix $D_{n \times n}$. Later, the weight ω_i of a piece factor can be gotten after standardization. The weight vector that is combined of the weight of every factor is as:

$$\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$$

Where ω is the weight vector.

3.2.2. Generic Risk Matrix (GRM)

Generic Risk Matrix (GRM) method is used to evaluate the risks by identifying the possibility of incident, the impact and risk factors. In this study, for the development of GRM, appropriate impact and probability values were selected. At the same time, the risk factor is estimated as the multiplied of probability and impact value. Then the risk category is determined (high, medium and low). Table 1 illustrates the impact, probability scale and risk factor category. This specific scale was chosen because it clearly defines the boundaries for classifying risks. This scale aligns with the research methodology and the evaluation standards used in similar studies, providing a reliable basis for comparison and analysis [14].

Table 1 Impact, probability scales and indicated risk factor.

Probability	Risk Factor				
0.90	0.05	0.09	0.18	0.36	0.72
0.70	0.04	0.07	0.14	0.28	0.56
0.50	0.03	0.05	0.10	0.20	0.40
0.30	0.02	0.03	0.06	0.12	0.24
0.10	0.01	0.01	0.02	0.04	0.08
Impact	0.05	0.10	0.20	0.40	0.80

3.2.3. Relative importance index (RII)

Relative importance index (RII) used to analyze the risks' relative importance in order. The Relative Importance Index (RII) measures each risk's relative importance as determined by experts [15]. The RII for variable k is calculated as shown by the below equation.

$$RII = \frac{\sum S_k}{S \times N}$$

Where S_k is the score of variable k assigned by participants from 1 to 5, S is the highest score which equals 5 and N is the total number of experts. The RII's influence on the dependent variable increases with its value. The evaluation criteria listed in Table 2 are used to assess the RII scores [16].

Table 2 RII scores and corresponding Importance level.

| RII	Importance Level
0: 0.20	Low = L
0.21: 0.40	Medium low = M-L
0.41: 0.60	Medium = M
0.61: 0.80	Medium high = M-H
0.81: 1.00	High = H

4. Results

After executing the evaluations, the results were carried out. These results were plotted on graphs and comparative graphs also are plotted. At the end of this chapter, a summary of researcher's viewpoint is provided. The risks affecting the water supply system at the source, treatment and distribution stages were grouped as shown in Table 3:

Table 3 risks affecting the water supply system

Source stage	treatment stage	distribution stage
S1: Low quality of water source. **S2:** Population increases. **S3:** Pumping / Valves breakage. **S4:** Power failures. **S5:** Natural hazards. **S6:** Climate changes. **S7:** Queuing time at water source. **S8:** Pollutants resulting from human activities.	**T1:** Unsatisfied treatment. **T2:** Incorrect operation. **T3:** Maneuvers outside operation requirements. **T4:** Unadjusted chemical doses. **T5:** Power failure.	**D1:** Unsuitable pipe materials. **D2:** Network leakages. **D3:** Uncleaned pipes. **D4:** Pipe Corrosion. **D5:** Pipe mains break. **D6:** Unsatisfied Quality. **D7:** Low/high pressure. **D8:** Discontinuity of the service.

A hierarchy model for AHP analysis is as shown in Fig. 3.
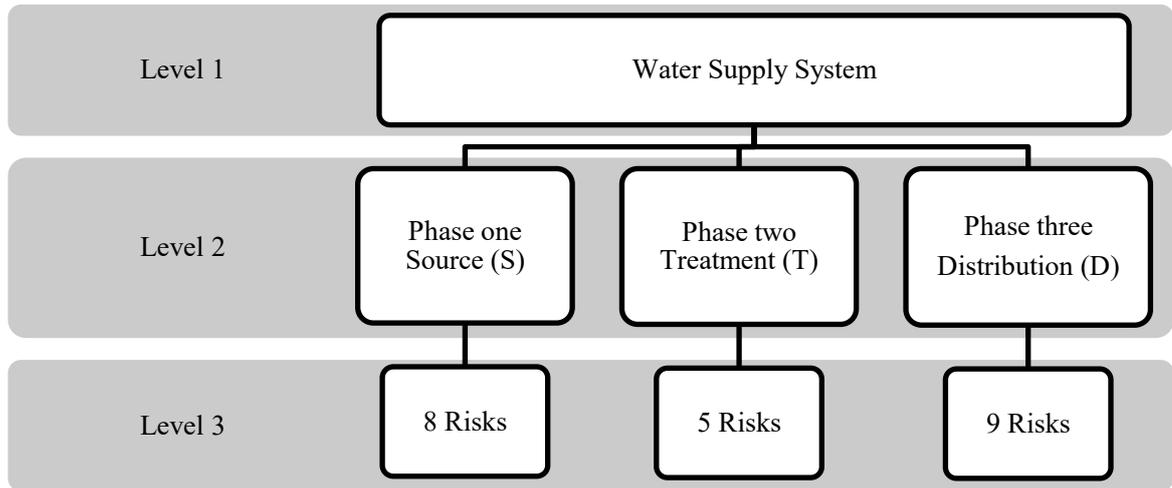
Fig. 3 AHP hierarchy model general scope.

Pairwise comparison was performed to determine the relative importance between two closely related items on a scale of 1 to 9. The matrices were filled by the head of WTP, engineers and technicians in the WTPs, then using SPSS program to remove outliers and finding the arithmetic mean of all matrices to arrive to the final matrix. First, a matrix of Source stage, treatment stage and distribution stage [S, T, D] is done to produce a weight of each stage depending on the importance of each respect to others for Benha, then using SPSS program to remove outliers and finding the arithmetic mean of all matrices to arrive to the final matrix which shown in Table 4.

Table 4 Pair-wise comparison matrix for the stages.

Code	S	T	D
S	1.00	0.24	0.34
T	4.17	1.00	3.70
D	2.94	0.27	1.00

Then AHP calculation was done to calculate the eigen vector (weight) of each stage and the results showed that the treatment stage (T) has the largest weight equal 0.65, then the stage of distribution (D) has a weight of 0.24, otherwise the source stage (S) has the lowest weight which equals 0.11.

In the same context, risk matrices [S1, S2, …., S8], [T1, T2, T3, T4], [D1, D2, …, D8] were created at the source, treatment, and distribution stages to calculate the weight of each risk as shown in Fig. 4 to Fig 6.
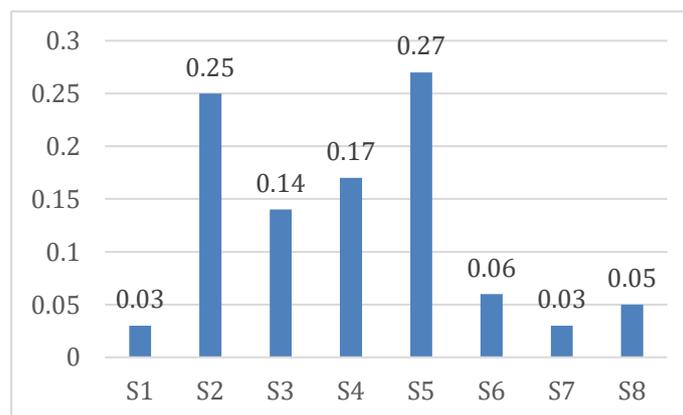
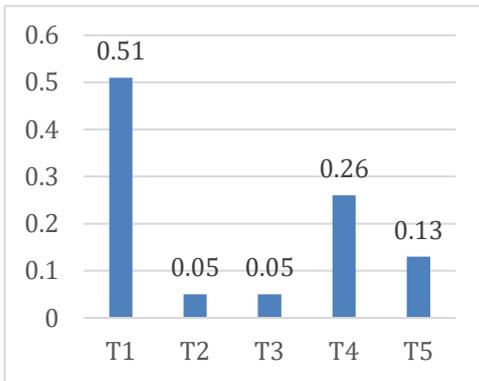**Fig. 4** Eigen Vector for source risks.

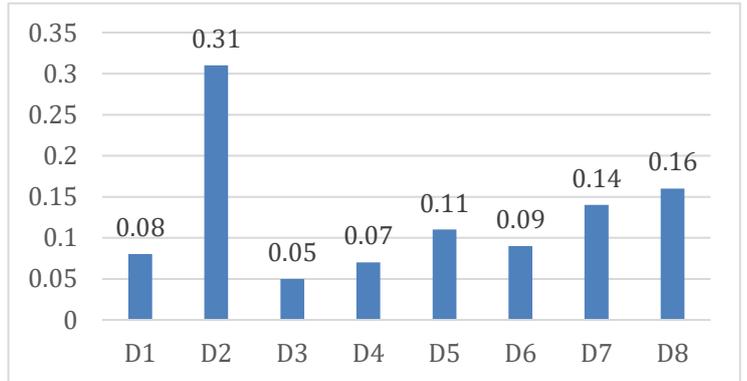**Fig. 5** Eigen Vector for treatment risks.

Fig. 6 Eigen Vector for treatment risks.

After the Eigen Vector (ω), relative weight, is calculated, the global weight is calculated, the global weight is calculated by multiply the relative weight of each risk and the weight of its corresponding stage as shown in Table 5. This process helps determine the overall importance of each risk within the context of the entire system or project.

Table 5 Relative weight, Rank and Global weight calculation.

	Weight	Risk Code	Relative Weight	Global Weight	Global Rank
Source	0.11	S1	0.03	0.003	20
		S2	0.25	0.028	10
		S3	0.14	0.015	16
		S4	0.17	0.019	14
		S5	0.27	0.030	9
		S6	0.06	0.007	18
		S7	0.03	0.003	21
		S8	0.05	0.006	19
Treatment	0.65	T1	0.51	0.332	1
		T2	0.05	0.033	7
		T3	0.05	0.033	7
		T4	0.26	0.169	2
		T5	0.13	0.085	3
Distribution	0.24	D1	0.08	0.019	13
		D2	0.31	0.074	4
		D3	0.05	0.012	17
		D4	0.07	0.017	15
		D5	0.11	0.026	11
		D6	0.09	0.022	12
		D7	0.14	0.034	6
		D8	0.16	0.038	5

Then, GRM analysis involves assigning a score to each risk based on its probability of occurrence and its potential impact. This score is usually determined by evaluating the likelihood of the risk event happening and the severity of its consequences. The risk scores are typically categorized into different levels (e.g., low, medium, high) to indicate the level of concern and prioritize risk management actions.

As shown in Table 6: At the source stage: Out of the eight risks identified, five risks are categorized as high risks (HR). This indicates that these risks have a significant potential impact on the reliability, resilience, and sustainability of the water supply system at the source stage. And two risks are classified as medium risks (MR). The remaining risk is classified as low risks (LR), suggesting a relatively lower level of severity compared to the high-risk category.

Table 6 GRM for Benha WSS source risks.

Code	Risk Probability	Risk impact	Risk Score	Risk Category
S1	0.8	0.6	0.48	HR
S2	0.8	0.7	0.51	HR
S3	0.5	0.3	0.17	HR
S4	0.3	0.7	0.20	HR
S5	0.4	0.7	0.24	HR
S6	0.3	0.2	0.07	MR
S7	0.4	0.1	0.04	LR
S8	0.6	0.2	0.13	MR

As shown in Table 7: At the treatment stage: Four of five risks identified in the treatment stage are categorized as high risks (HR). This implies that these risks pose a substantial threat to the reliability, resilience, and sustainability of the water supply system during the treatment process. The remaining risk is classified as low risks (LR), suggesting a relatively lower level of severity compared to the high-risk category.

Table 7 GRM for Benha WSS treatment risks.

Code	Risk Probability	Risk impact	Risk Score	Risk Category
T1	0.3	0.8	0.24	HR
T2	0.4	0.4	0.16	HR
T3	0.2	0.2	0.04	LR
T4	0.2	0.7	0.16	HR
T5	0.2	0.7	0.16	HR

As shown in Table 8: At the distribution stage: Among the risks identified in the distribution stage, two risks are classified as medium risks (MR). This suggests that the impact of this particular risk on the system's reliability, resilience, and sustainability is relatively medium. The remaining risks in the distribution stage are categorized as high risks (HR), indicating their significant potential to disrupt the water supply system and its desired outcomes.

Table 8 GRM for Benha WSS distribution risks

Code	Risk Probability	Risk impact	Risk Score	Risk Category
D1	0.4	0.3	0.07	MR
D2	0.3	0.7	0.40	HR
D3	0.4	0.5	0.36	HR
D4	0.4	0.5	0.12	MR
D5	0.4	0.7	0.20	HR
D6	0.3	0.3	0.18	HR
D7	0.5	0.3	0.28	HR
D8	0.3	0.5	0.36	HR

To take into consideration the weight of each risk, its probability and impact, the weighted score is calculated for each risk by multiply the weight of the risk and the score as shown in Fig. 7.
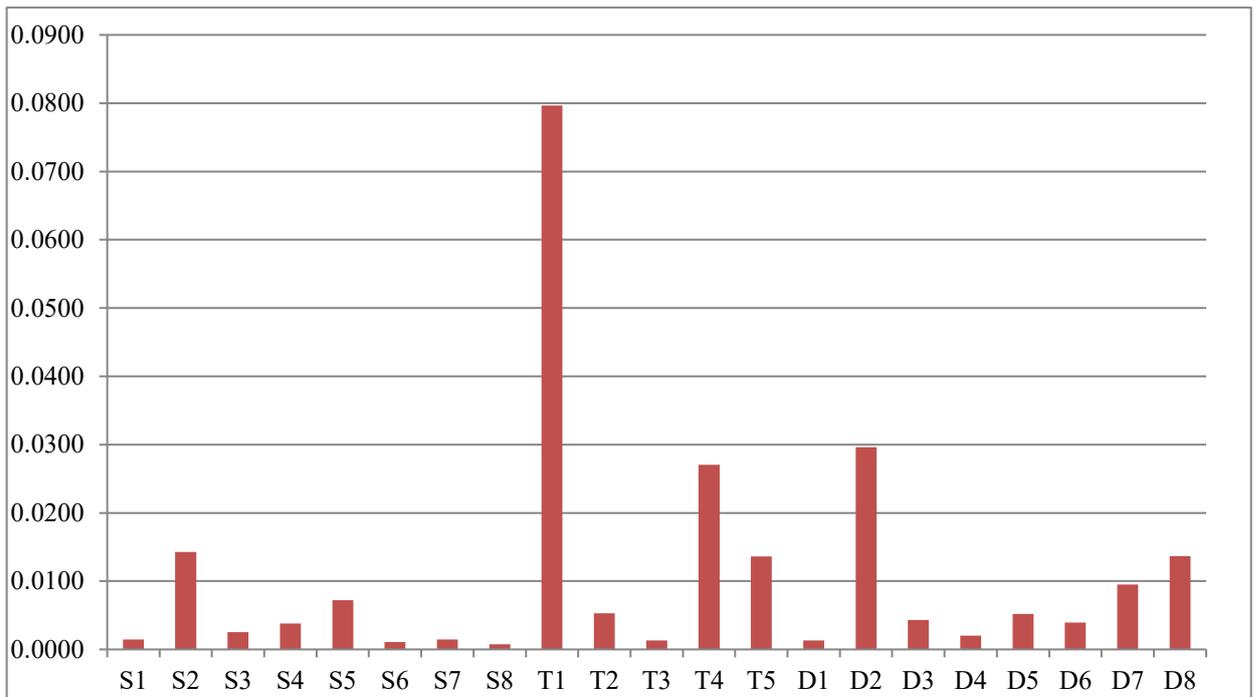
Fig. 7 Weighted score for Benha WSS risks.

To reduce the risks of the WSS at the source, treatment and distribution stages, some alternative strategies are recommended as shown in Fig. 8.

Water Source Risks Response Alternatives Strategies

AS1	•Online measurement of quality of raw water
AS2	•Unusual sources of water
AS3	•Sludge treatment
AS4	•Installation of water meters
AS5	•Automatic water quality and level monitoring

Water Treatment Risks Response Alternatives

AS6	•Emergency operating procedures
AS7	•Automatic dosing regimens
AS8	•Resilience capacity
AS9	•Conduct regular maintenance and inspections of equipment

Water Distribution Risks Response Alternatives Strategies

AS10	•Decrease of Leakage
AS11	•Setting up permanent water flow and pressure monitoring meters
AS12	•Introduction of Network reliability analysis
AS13	•Reducing the frequency of low water flow or pressure situations
AS14	•Using new automatic control types in place of valves
AS15	•Water Quality Sensors and Control
AS16	•Regular Flushing and Maintenance

Fig. 8 Risks Response Alternatives Strategies.

Strategies are suggested to mitigate the impact of risks on the WSS as shown in Fig. 8; to determine the relative importance index (RII) to each strategy the author performed an electronic questionnaire with the correlate multiple 40 experts, each expert evaluates each risk alternative strategy as one of the following rate: (EI) if the strategy is Extremely Important, (I) if the strategy is important, (A) if the strategy is Average

Important, (NI) if the strategy isn't Important and finally (ENI) if the strategy isn't extremely important. The results of the questionnaire as illustrated in Fig. 9 to Fig. 11.
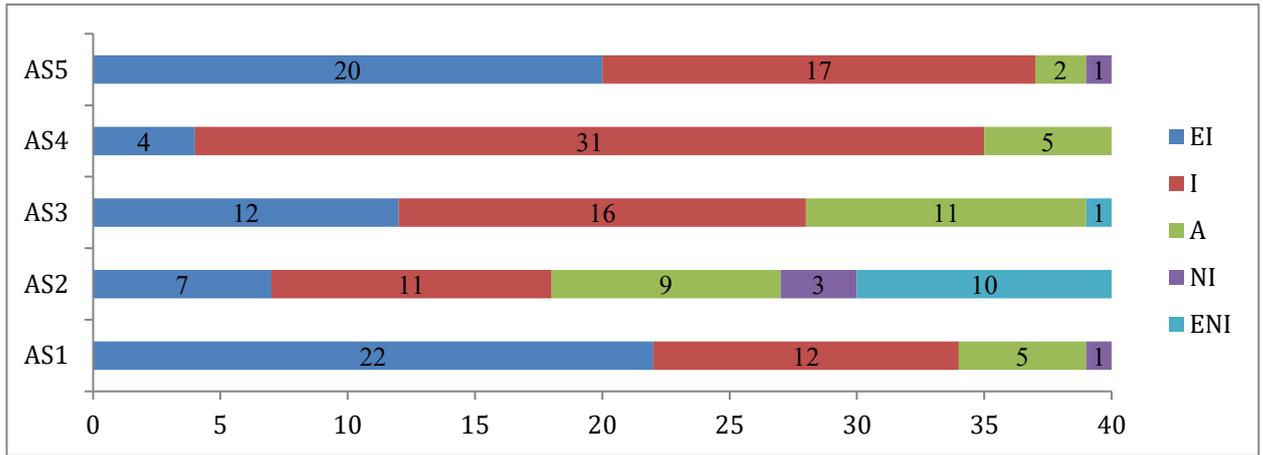

Fig. 9 Water Source Risks Response Strategies evaluation questionnaire results.
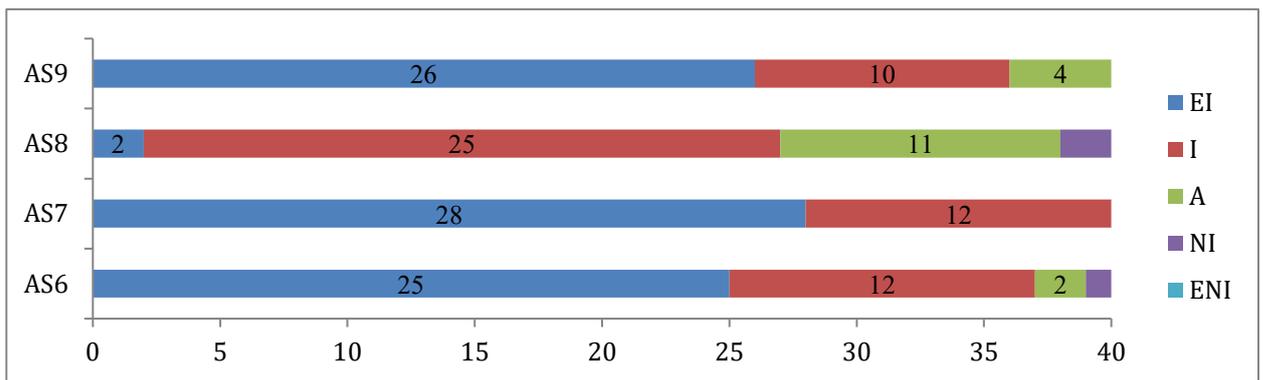

Fig. 10 Water Treatment Risks Response Strategies evaluation questionnaire results.
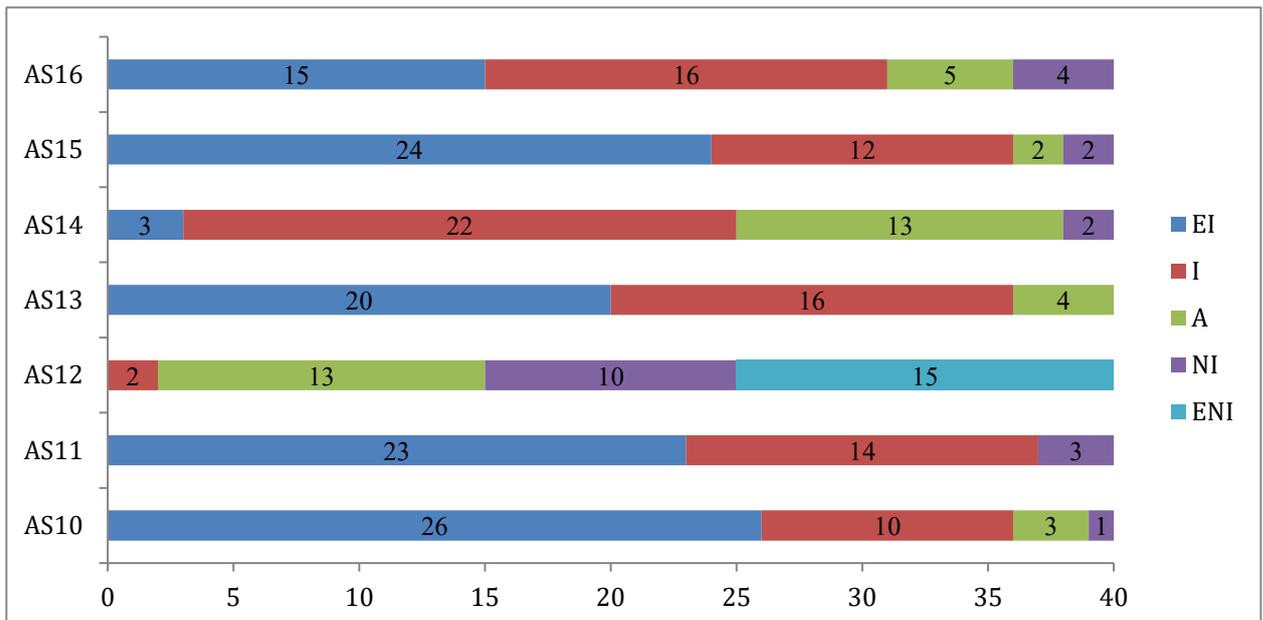

Fig. 11 Water Distribution Risks Response Strategies evaluation questionnaire results.

Based on the results of this questionnaire, a static analysis is done to calculate the mean value (μ), and Standard Deviation (α) by using (Likert) scale, then, the Relative Important Index (RII) [17]. The outcome of this survey as shown in Table 9.

Table 9 coefficient of variance (CV) calculation and RII calculation.

		μ	α	cv	RII	
	Source Risks Response Alternatives Strategies					
AS1	Online measurement of quality of raw water	4.375	0.807	18.437	0.875	High
AS2	Unusual sources of water	3.050	1.449	47.513	0.370	Medium Low
AS3	Sludge treatment.	3.950	0.904	22.896	0.790	Medium High
AS4	Installation of water meters	3.975	0.480	12.068	0.795	Medium High
AS5	Automatic water quality and level monitoring	4.400	0.709	16.112	0.880	High
	Treatment Risks Response Alternatives Strategies					
AS6	Emergency operating procedures	4.525	0.716	15.816	0.905	High
AS7	Automatic dosing regimens	4.700	0.464	9.874	0.940	High
AS8	Resilience capacity	3.675	0.656	17.846	0.735	Medium High
AS9	Conduct regular maintenance and inspections of equipment	4.550	0.677	14.890	0.910	High
	Distribution Risks Response Alternatives Strategies					
AS10	Decrease of Leakage	4.525	0.751	16.589	0.905	High
AS11	Setting up permanent water flow and pressure monitoring meters demand of water	4.425	0.844	19.071	0.885	High
AS12	Introducing network reliability analysis	2.050	0.959	46.802	0.410	Medium
AS13	Reducing the frequency of low water flow or pressure situations	4.400	0.672	15.268	0.880	High
AS14	Using new automatic control types in place of valves	3.650	0.700	19.173	0.730	Medium High
AS15	Water Quality Sensors and Control	4.450	0.815	18.313	0.890	High
AS16	Regular Flushing and Maintenance	4.050	0.959	23.690	0.810	High

As shown in Table 8, at the source stage, according to the assessment, AS5 (Automatic water quality and level monitoring) has the highest importance index, indicating its significance in the overall functioning of the system. On the other hand, AS2 (Unusual sources of water) has the lowest importance index,

indicating that it may have a relatively lower impact on the overall performance of the system. It is stated that at the treatment stage, two alternative strategies, AS7 (Automatic dosing regimens) has the highest importance index. This indicates that this strategy is considered a priority in terms of their implementation in the water supply system (WSS) at the treatment stage. Given that the treatment stage has been identified as having the highest rank in the risk evaluation, it suggests that strategy related to automatic dosing regimens is crucial in mitigating and managing the risks associated with water treatment. While at the distribution stage as shown in Fig. 5-38, the strategy AS10 (Decrease of Leakage) has the highest importance index among the seven risk alternative strategies. This indicates that addressing and mitigating the risk of low water flow or pressure situations is considered the most important strategy in the distribution stage of the water supply system (WSS). This suggests that reducing water leakage is also a significant concern in ensuring the efficient and reliable distribution of water.

5. Discussions

This study developed a comprehensive risk assessment framework for evaluating vulnerabilities within water supply systems (WSS) at all hierarchical levels. The results highlight key risk factors affecting system efficiency. Then by applying the Analytic Hierarchy Process (AHP), we identified the most critical risks and ranked them based on their impact on system performance. Despite its effectiveness, the AHP method has certain limitations. One limitation is its reliance on expert judgment, which introduces subjectivity in risk prioritization.

Our findings align with previous studies that emphasize the importance of risk assessment in WSS. Similar to the work of Dos Santos [2], which demonstrated the effectiveness of AHP in multi-criteria decision-making, our study confirms that AHP provides a structured and quantifiable approach to risk evaluation. However, unlike previous research that primarily focused on specific components of WSS, our framework integrates risk assessment across the entire system.

6. Conclusions

- In this study, a risk management methodology was employed to identify and evaluate the risk events associated with the water supply systems (WSS) under investigation. The study focused on three main phases of the water supply process: water source, water treatment plants, and water distribution networks. For each phase, the potential risk events that could affect the reliability, resilience, and sustainability of the WSSs have been identified and analyzed.
- In order to assess the impact of risk events on the reliability, resilience, and sustainability of the water supply system, the study utilized the Analytic Hierarchy Process (AHP) method, which is a multi-attribute decision-making technique. The application of the Analytic Hierarchy Process (AHP) method in this study has demonstrated its effectiveness in obtaining the weights of the criteria and assessing the importance of different phases in the water supply system. This finding highlights the significance of effective water treatment processes in providing safe and high-quality water to consumers.
- The study concludes by proposing alternative strategies to address the identified risks in the water supply system. These strategies were developed based on expert opinions and insights gained from previous experiences in the field.

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