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Presentation of a new decision-making plan for prioritizing the rehabilitation of sustainable groundwater resources (case study: 9 aflaj of Oman)

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ABSTRACT

This research for the first time, presents a plan for the rehabilitation of aflaj systems in Oman from a technical point of view. Using the analytical hierarchy process (AHP) in Expert Choice software. Nine famous aflaj systems in Oman were prioritized based on indicators including length, population, precipitation, discharge, quality, distance from the river network, cultivated area, and soil permeability. A snowball method for selecting participants was used, and a 28-item questionnaire was engaged to assess the relative importance of nine criteria when choosing the prior falaj. A scientific method is applied in a new case in this study to prioritize the aflaj for rehabilitation, and the method applied in this research enables to prioritize them to achieve the desired goal. The AHP method prioritizes the falaj Daris as the first ranking, based on the technical perspectives, with a relative value of 0.222. Findings show that in an equal condition, among these nine aflaj, it would be better that water decision-makers assign the budget to falaj Daris for rehabilitation aims.

Key words: aflaj systems, AHP, Oman, rehabilitation, sustainable groundwater resource

HIGHLIGHTS

- In this decision making plan, each effective parameter with each number of falaj can be considered.
- This plan can speed the process of choosing the prior falaj for rehabilitation decision.

1. INTRODUCTION

Archaeological hydraulic irrigation systems have been developed and used by various civilizations throughout history indicating their advanced understanding of water management (Esenarro *et al.* 2023). These ancient civilizations recognized the importance of water resources for agricultural purposes, allowing them to overcome the challenges of arid and semi-arid environments. From the aflaj of Oman to the terraced fields of the Inca Empire, these systems demonstrate the remarkable engineering technology achieved by these societies. They constructed these canals, aqueducts, and underground tunnels to transport water from rivers, springs, or underground sources to irrigate their fields.

The traditional irrigation systems of Oman, known as aflaj (singular: falaj), have been in use for centuries and are based on open channels that convey water from sources like springs or groundwater (Al-Ghafri 2004). Throughout rural Oman, these systems have been used to manage land and water sustainably (Al-Marshudi 2007). The aflaj irrigation systems of Oman have a long history, dating back to at least 1,000 B.C. according to Al-Tikriti (2002). They are commonly found in the northern mountainous regions where rainfall is adequate to support ephemeral wadi flow and groundwater recharge. These systems distribute water to cultivate various crops, with the date palm being the most significant (Al-Ghafri 2005). Additionally, they serve various other purposes, such as providing domestic water and previously, drinking water (Majidi *et al.* 2022).

Due to the limited amount of rainfall that most crop-producing regions in Oman receive, agriculture in the country is heavily reliant on irrigation for production (Norman *et al.* 1998; Al-Ghafri *et al.* 2003). As noted by Norman *et al.* (1998), the annual rainfall in these areas usually ranges from 100 to 200 mm (Al-Ghafri 2018). To support agriculture, Oman uses these aflaj as a sustainable groundwater resource for producing water (Al-Ghafri 2004). These aflaj systems generate approximately 680×10^6 m^3 of water annually, of which 410×10^6 m^3 is utilized for irrigation purposes (Al-Ghafri 2018).

Nowadays, there are several challenges that the aflaj irrigation system is facing in modern times. One of the main challenges is the decline in water availability due to factors such as over-extraction, climate change, and drought. This has led

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to a reduction in the flow of water in some of the channels, which has affected the productivity of the agricultural land that depends on the aflaj system.

Another challenge is the deterioration of the physical infrastructure of the aflaj system. Some factors such as sedimentation and siltation, land use and urbanization, human activities, climate change and environmental factors and, ageing and neglecting proper maintenance cause problems for the aflaj structure. This change makes the falaj dry up.

For instance, due to the heavy precipitation and flooding or the high permeability coefficient of the soil around the falaj, sediment and silt move with the water and enter in to aflaj through the shafts and can accumulate inside the aflaj over time and change the structure and make the aflaj dry. Urban development near aflaj regardless of its border (harim) can create challenges to the aflaj's structure. Aflaj also require regular maintenance due to ageing to ensure their proper functioning. The underground channels, tunnels, and shafts can be prone to erosion, collapse, or blockages over time.

Addressing this challenge requires significant investments in repairing and maintaining the aflaj infrastructure and structure while preserving its cultural and historical significance. However, determining the optimal allocation of resources for the rehabilitation of deteriorated aflaj systems is a critical concern, particularly when faced with budgetary constraints. It becomes necessary to prioritize aflaj networks that are in dire need of restoration and make strategic decisions based on various factors, such as the historical and cultural significance, water demand, and potential socio-economic benefits associated with each falaj.

To address these challenges, there have been various efforts to rehabilitate and modernize the aflaj system, such as through the use of new technologies for water management and conservation, as well as through educational and cultural programs aimed at preserving traditional practices and knowledge. For the maintenance of aflaj, MRMEWR has designated a special department. Research and surveys were conducted by this department in order to develop and maintain aflaj systems. A big budget is allocated for aflaj maintenance (MRMEWR 2001). However, there is a big concern about which aflaj are the priority for rehabilitation and needs this budget. There are many parameters belonging to aflaj's condition, which affect this matter. They might be different from the expert's opinion. Two approaches can be considered for this aim, technician and management approaches. In this paper, according to the available data for aflaj, the technician approach will be discussed and investigated by the usage of the famous analytical hierarchy process (AHP) for the determination of the prior aflaj.

AHP is a structured decision-making method that helps in evaluating and prioritizing different alternatives based on multiple criteria (Saaty 1979). It is based on the idea that complex decisions can be broken down into a hierarchy of smaller, more manageable decision problems (Jabal *et al.* 2022; Liqiang *et al.* 2022). The AHP allows decision-makers to systematically compare and weigh the importance of different criteria and alternatives, leading to more informed and consistent decision-making (Nasri *et al.* 2021; Chomba *et al.* 2022; Nyakundi *et al.* 2022).

Some research was carried out in the protection of aflaj across the world regarding social, ecological, and touristic purposes for making the aflaj to be lived. Nourikia & Zivdar (2020) illustrated that qanats (the equivalent of aflaj in Iran) had an important role in water abstraction in the past. Due to urban development, these groundwater resources are at risk. Therefore, to keep these sustainable resources, despite physical maintenance, the social and ecological aspects of qanats are also required to be emphasized. Mousazadeh *et al.* (2023) used content and thematic analysis to present a model for sustainable protection of 10 UNESCO qanats in Iran. Their protection model is similar to the guidelines for reshaping the behaviors of the tourists, natives, and officials.

However, there is no research on prioritizing the aflaj system with respect to their technical specification regarding the aim of rehabilitation. Many researchers used AHP in their work for water resources management but not aflaj systems. Gheorghe & Toma (2019) emphasized the application of the analytic hierarchy process (AHP) for evaluating the impacts of water management policies in Romania. They explained that Romania faces significant challenges related to water resources management, including water scarcity, pollution, and inefficient water use. The results of the study demonstrated the effectiveness of the AHP in evaluating the impacts of water management policies in Romania, with the highest priority given to policies that prioritize water conservation and reuse. Deepa & Kumar (2020) provided a comprehensive overview of the application of AHP in water resources management. They stated that the AHP is a structured decision-making method that can be used to evaluate and prioritize different alternatives based on multiple criteria. At last, the authors discussed the strengths and limitations of the AHP, as well as potential areas for future research and improvement.

Awadallah & Al-Zboon (2021) focused on the application of the AHP for the prioritization of water resources development projects in Jordan. They first explained the importance of water in Jordan to prioritize the development of water resources projects. The AHP is proposed as a useful tool for this purpose. The results of the study demonstrated the effectiveness of the AHP in prioritizing water resources development projects in Jordan.

Liqiang *et al.* (2022) attended the application of the AHP-fuzzy comprehensive evaluation method for predicting the water-blocking capability of water seepage-resistance strata. They explained that water seepage is a significant problem in underground mining. They have used AHP to predict the water-blocking capability of water seepage-resistance strata in a case study. The authors identified a set of evaluation criteria, such as rock strength, water conductivity, and porosity, and used the AHP to calculate priority weights for each criterion. The findings of the study demonstrate the effectiveness of the AHP-fuzzy comprehensive evaluation method in predicting the water-blocking capability of water seepage-resistance strata.

As can be seen, no research was carried out in this field and subject. In this paper, for the first time, a decision-making framework for finding the prior falaj of Oman with the aim of rehabilitation is presented. In situations where limited budgetary resources are available for maintaining and rehabilitating aflaj structures, it becomes imperative to develop a systematic decision-making plan to prioritize which aflaj systems should receive rehabilitation efforts. In this way, by considering some of the technical parameters to aflaj, experts' opinions and using the AHP method, this analysis is carried out.

The paper comprises several sections that detail the study's methodology, results, and implications. Section 2, titled the 'Materials,' outlines the case study, 'Methods' section presents the conceptual framework and the use of AHP in mapping and considering technical factors for prioritizing the rehabilitation of sustainable water resources. Afterwards, the relative weight of indicators against each other and against aflaj systems is presented in Section 3, then a broad look is carried out at the findings. Finally, Section 4 summarizes the results.

2. MATERIALS AND METHODS

Assorted types of aflaj can be found in Oman, based on their sources of water. These types include Ghaili, Iddi (Dawoodi), and Aini (Al-Ghafri 2004). Despite this, the methods of administration and management are very similar. In this study, a survey was carried out on only Iddi aflaj. Figure 1 shows the cross-section of Iddi aflaj.

2.1. Case study

On the Arab Peninsula, Oman lies between the latitudes 16° 84′ 00″ and 26° 82′ 00″ north and the longitudes 51° 85′ 00″ and 59° 84′ 00″ east (Al-Balushi *et al.* 2016). Oman shares borders with the United Arab Emirates, Saudi Arabia, and the Republic of Yemen. Approximately 309,500 km^2 of the country is covered by plains, rivers, and mountains with varying topography. It covers approximately 3% of the entire area and overlooks the Gulf of Oman and the Arabian Sea. The amount of mountain ranges in the region is approximately 15%, with the Al-Hajr mountains accounting for the majority (Gastli & Charabi 2010).

Oman with almost 4112 aflaj is one of the countries which has the largest number of aflaj. The aflaj of this country provide about seven billion cubic meters of underground water annually for different consumers including agricultural, industrial, and domestic parts (MRMEWR 2001). The falaj has always been known as one of the most important achievements of mankind to

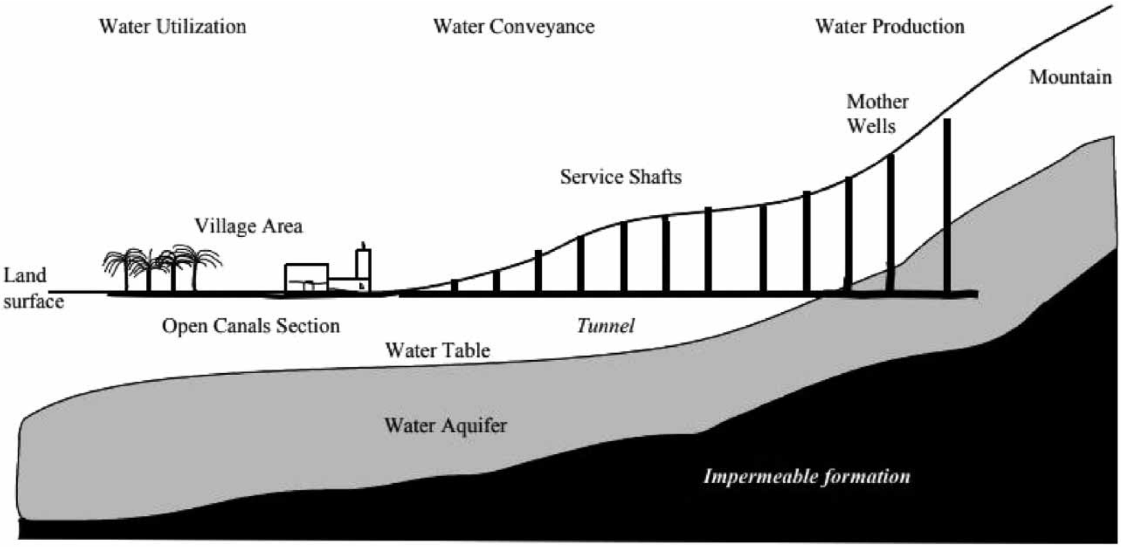

Figure 1 | Cross-section of aflaj (Iddi type) (Al-Ghafri 2004).

extract water in desert areas, so its preservation and maintenance have always been of concern to man throughout history, and many tools have been used to dig and protect it. The falaj technique is one of the most brilliant techniques, and a very thoughtful Omani invention that collects high areas of earth or wadies (dried rivers) with the help of gravity and without the use of traction force and any type of electrical or thermal energy with natural flow.

Nine aflaj systems were selected for this study. Daris, Al-Wakil, Al-Malki, Al-Muyasar, Al-Khatmain, Al-Wasit, Al-Hamra, Al-Ayn, and As-Seeb are these aflaj systems (See Figure 2). Three of were listed as UNESCO heritage areas, including Al-Khatmain, Daris, and Al-Malki. Figure 3 presents a picture of these aflaj systems.

2.2. AHP method

AHP is a decision-making framework developed by Thomas L. Saaty in the 1970s (Jayakumar & Mahajan 2021). It is a structured approach to decision-making that is widely used in business, engineering, and other fields where complex decisions need to be made. AHP allows decision-makers to break down a problem into its constituent parts, analyze the relative importance of each part, and make informed decisions based on the results of the analysis (Veisi *et al.* 2022). AHP is based on the idea that decision-making involves comparing and prioritizing a set of criteria or alternatives. This involves making judgments about the relative importance of each criterion or alternative, and AHP provides a structured way of doing this (Liu *et al.* 2022).

The AHP process involves several steps. First, the decision-maker identifies the problem and divides it into a set of criteria or alternatives. The decision-maker then creates a pairwise comparison matrix, which is a table that shows how each criterion or alternative compares to every other criterion or alternative in terms of importance. The decision-maker assigns numerical values to each comparison based on their relative importance. Next, the decision-maker calculates the weighted scores for

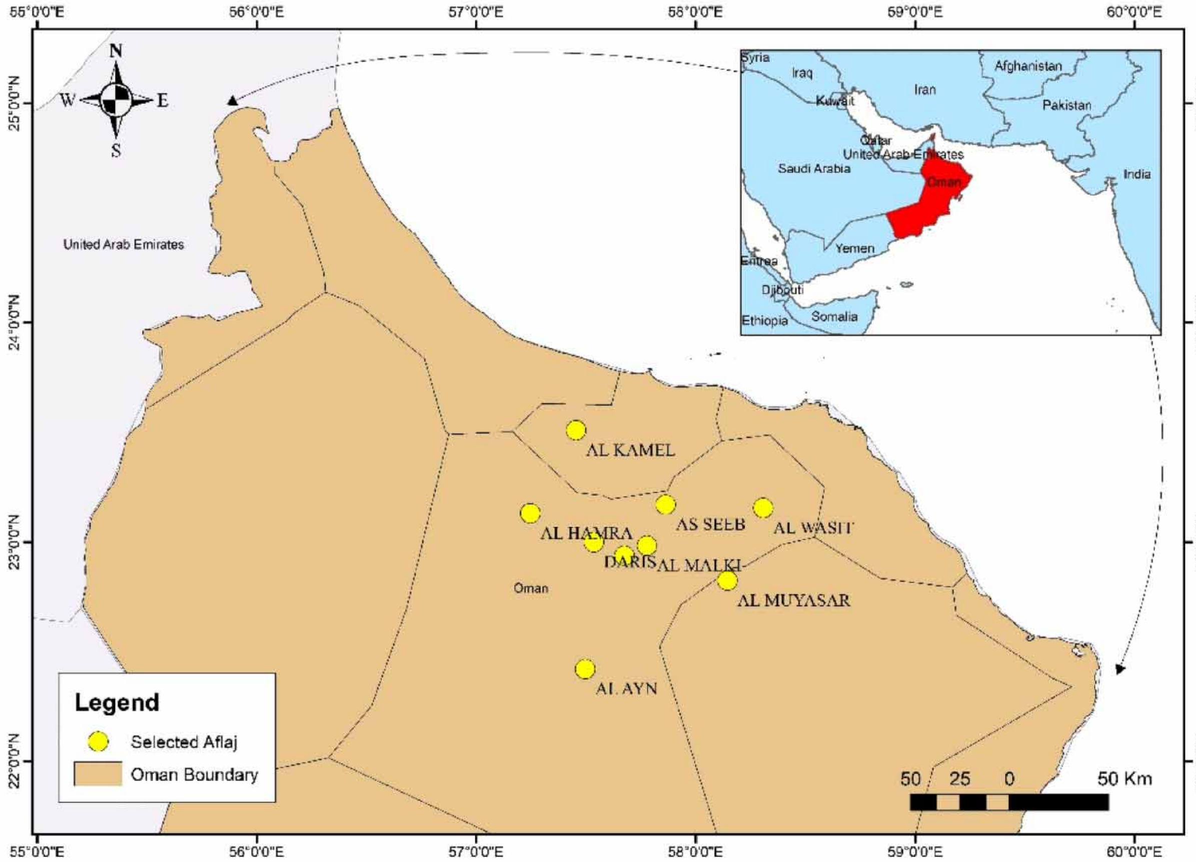

Figure 2 | Geographical location of the Sultanate of Oman.

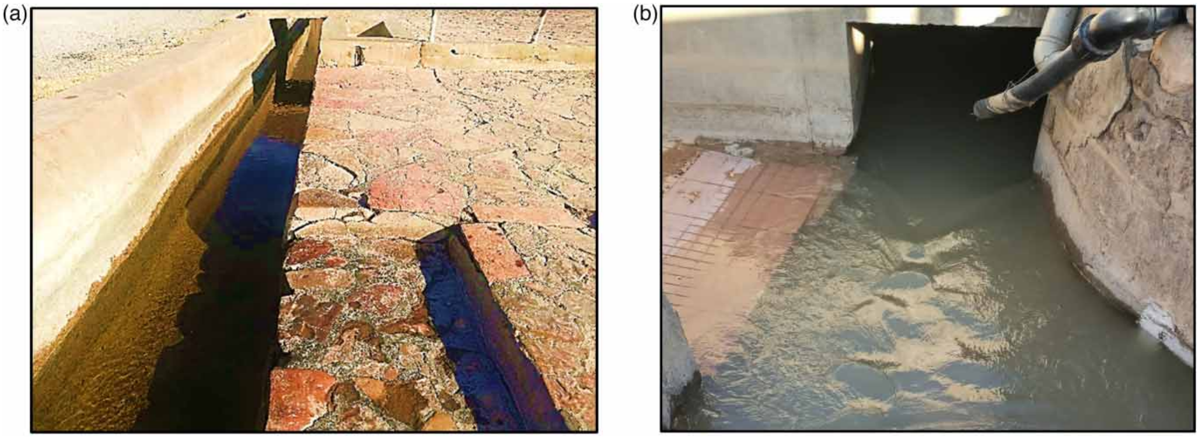

Figure 3 | Selected aflaj in Oman. Falaj Al-Khatmain (Photographer: Ali Mohtashami), (b) Falaj Al-Hamra (Photographer: Zahra Al-Abri).

each criterion or alternative, based on the pairwise comparison matrix. The weights represent the relative importance of each criterion or alternative in achieving the overall objective (See figure 4).

Once the weights have been calculated, the decision-maker can use them to evaluate the alternatives and make a decision. This involves multiplying the weight of each criterion by the score of each alternative for that criterion and summing the results to obtain a total score for each alternative. The alternative with the highest score is then selected as the best option. In brief, hierarchical analysis processes can be used when decision-making is faced with several competing options

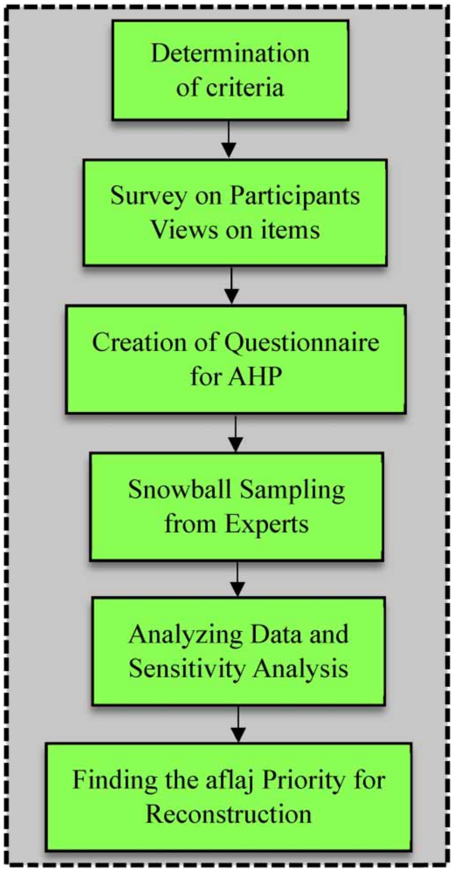

Figure 4 | Flowchart of this study.

and decision-making criteria. The proposed criteria can be quantitative or qualitative. This decision-making method relies on pairwise comparisons. In order to begin this process, the decision-maker creates a hierarchical decision tree. A hierarchical decision tree shows compared factors and options in the decision process. Then pairwise comparisons are made. These comparisons show the weight of each factor in line with the options evaluated in the decision process. Finally, the logic of the hierarchical analysis process creates the matrices obtained from pairwise comparisons in such a way that the optimal decision is obtained.

Saaty (1979) stated three principles of the AHP. These principles are the following (Saaty 1979):

1. Invertible condition:

   If the preference of element A over element B is equal to n, the preference of element B over element A is $\frac{1}{n}$.
2. Homogeneity principle
3. Dependency principle

Using this method, four steps must be followed:

1. Modeling
2. Pairwise comparison
3. Computation of relative weights
4. Combination of relative weights

Decision elements are grouped according to their relationship to the problem in the Modeling step. There are two types of decision elements: decision criteria and decision alternatives. In AHP, problems with several criteria are categorized based on a hierarchy of levels. It represents the main goal of decision-making at the highest level. The second level shows the major criteria. It is possible to break into sub-indexes. The last level is the exhibition of decision options.

In the pairwise comparison stage, the experts make comparisons between the criteria and sub-criteria of decision-making parameters and determine their rankings relative to each other. These comparisons are made based on nine quantitative parameters (Sepehri *et al.* 2020).

The preference of an option or factor compared to itself is equal to one, so the principle of inverseness of one factor compared to another and the preference of one for a factor or option compared to itself are the two main properties of the two-by-two comparison method in the AHP process. These two properties are used to compare the n options of the decision-maker only to answer $n(n-1)/2$ the question.

In relative weight computation**,** the first level of the hierarchy states the main criteria. The first questionnaire aimed to find the pairwise ranking of between each the two criteria. Aczél & Saaty (1983) expressed that the average geometric mean is the best way for pairwise comparison combination. Therefore, the geometric mean must be computed for each row of the matrix. As these values are not normal, a normalization technique must be carried out on them. For this aim, the geometric mean achieved for each row must be divided into the summation of the geometric mean column. The new column shows the eigenvalues. Eigenvalues present the last weight matrix. The researchers used rating scores to compare the importance of each criterion, creating a pairwise matrix that had eight rows and eight columns, with diagonal elements equal to 1. The principal eigenvalue, represented by $\lambda_{\max}$, is determined for a square matrix of judgement with n rows or columns (Saaty & Vargas 1979).

Based on reciprocal matrices, a consistency ratio is calculated to ensure consistency. Saaty (1991) demonstrated that the largest eigenvalue, denoted as $\lambda_{\max}$, of a reciprocal matrix is always equal to or greater than the number of rows or columns (n). When there are no inconsistencies in pairwise comparisons, $\lambda_{\max}$ is equal to n. The closer the $\lambda_{\max}$ values are to n, the more consistent the comparisons are. The degree of inconsistency within the $n \times n$ matrix is measured by the quantity $\lambda_{\max} - n$. The weights assigned are checked for consistency using this method (Mishra *et al.* 2022).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{1}$$

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} \tag{2}$$

In this case, CR, CI, and RI indicate the consistency index, consistency ratio, and random index, respectively. As per the following, RIs are established for variables with more than 10 variables (Saaty & Tran 2007). A matrix is considered consistent if the consistency ratio (CR) is equal to or less than 0.1 (Saaty & Vargas 1979). If the CR exceeds this value, the assessments must be revised to mitigate inconsistencies. In order to accomplish this, the pairwise comparison matrix needs to be reformulated. RI is the random index, which can be obtained from Table 1 (Yilmaz 2022).

The flowchart of this study is summarized as follows

1. Define the problem and identify the criteria or alternatives to be evaluated.
2. Check the items in the eyes of experts who know the principal goal.
3. Create a questionnaire according to previous step experts.
4. Use the snowball technique and distribute them among the responders.
5. Create a pairwise comparison matrix that shows how each criterion or alternative compares to every other criterion or alternative in terms of importance. Assign numerical values to each comparison based on their relative importance. Calculate the weighted scores for each criterion or alternative, based on the pairwise comparison matrix. The weights represent the relative importance of each criterion or alternative in achieving the overall objective. Evaluate the alternatives by multiplying the weight of each criterion by the score of each alternative for that criterion and summing the results to obtain a total score for each alternative.
6. Select the alternative with the highest score as the best option.

2.3. Technical approach

From a technical point of view, only the technical characteristics of the falaj are considered to prioritize their rehabilitation. As aflaj are safe and sustainable water sources, they are prioritized for rehabilitation based on this view. This involves examining the engineering and technical aspects of these ancient underground water systems. It focuses on understanding the construction, operation, and maintenance of aflaj from a technical standpoint. Therefore, related parameters in this point of view are listed as follows (See figure 5):

Table 1 | Random index values

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

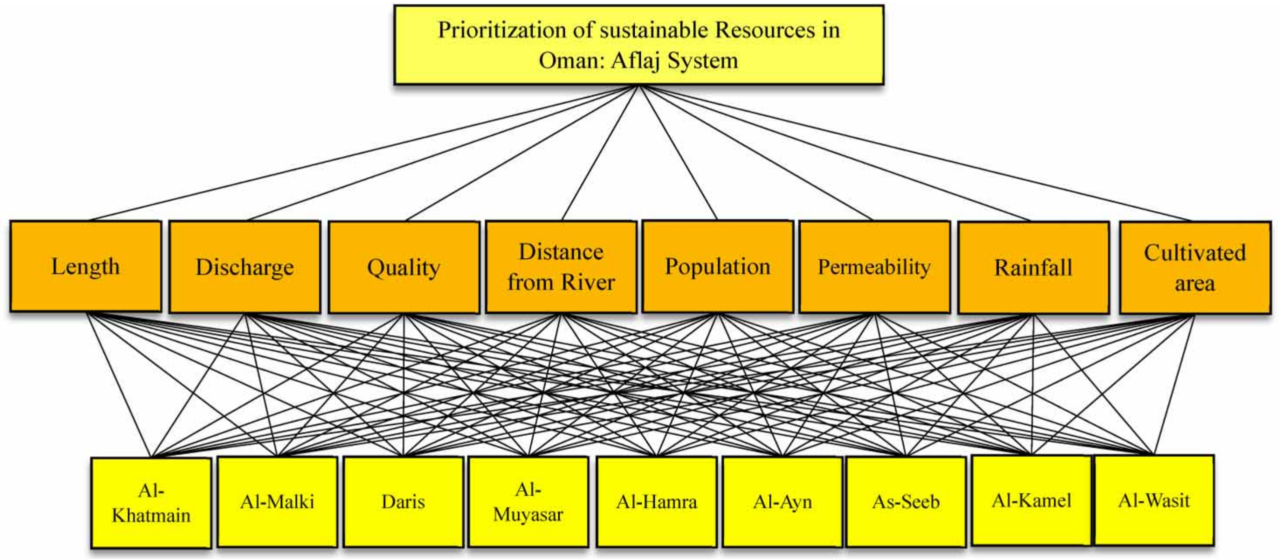

Figure 5 | Hierarchical decision-making structure for prioritizing the selected aflaj systems.

- Length
- Discharge rate
- Quality (electronic conductivity or EC)
- Distance from river network
- Population
- Permeability of soil
- Precipitation
- Cultivated area

Longer aflaj generally present greater challenges in terms of maintenance and inspection. The length of the falaj increases the distance that needs to be covered for routine inspections and repairs. This can make them more time-consuming and resource-intensive to identify and address any structural issues. The discharge rate of a falaj affects the velocity of water within the tunnel. Higher flow rates can lead to increased erosion of the falaj structure, especially in sections with softer or less stable materials. High EC values indicate higher salt concentrations, which can affect water usability including domestic purposes and agricultural aims. Considering EC helps prioritize aflaj with lower EC values, indicating better water quality for various purposes. The distance between the mother well and the river network can influence the quality of water supplied to the falaj. Longer distances may increase the likelihood of sedimentation and the accumulation of impurities in the water during conveyance. Sedimentation can affect the water quality and contribute to blockages or reduced flow within the falaj. As the population increases, the demand for water for various purposes also rises. This demand must be supplied by the falaj of that region. Therefore, with the increment in population, it is more critical to provide the required water for them. The permeability of the soil can affect the water loss from the falaj. If the soil surrounding the falaj is highly permeable, it may allow water to seep out of the falaj channel and infiltrate into the surrounding soil. This can result in reduced water flow within the falaj and may necessitate rehabilitation efforts to address the water loss. Also, the permeability of the soil can influence erosion around the falaj structure. In areas with high soil permeability, water seepage can lead to erosion of the soil adjacent to the falaj, potentially compromising its structural stability. Precipitation can contribute to erosion and sedimentation around and inside the falaj's structure. Heavy rainfall events can cause soil erosion and sediment transport, which may lead to sedimentation within the falaj channel, reducing its capacity and obstructing water flow. The other reason is increasing the flooding risks. Excessive precipitation can increase the risk of flooding in the areas surrounding the falaj. Flooding can damage the falaj's structure, disrupt water flow, and introduce debris or contaminants into the system. The cultivation area irrigated from the water of a falaj is also important in the rehabilitation of the falaj system. When a larger cultivated area relies on the falaj for irrigation, it emphasizes the importance of rehabilitating and maintaining that falaj to sustain agricultural productivity. Therefore, the larger the cultivated area, the more crucial it becomes to invest in its rehabilitation to ensure the sustainable water supply necessary for agriculture.

To achieve this goal, nine aflaj systems (Iddi type) have been selected for prioritization for rehabilitation. Table 2 explains the specifications of these aflaj. Some of the information including length, discharge, quality, and cultivated area was derived from the Ministry of Agriculture, Water Resources and Fisheries report in 2001 (MRMEWR 2001). Twenty experts in related fields provided ratings for suggested parameters, which were then averaged to determine the main score. This score was entered into a matrix, and statistical formulas were used to calculate the criteria based on this score. In order to determine the accuracy of the calculations, both the inconsistency index and the random index were calculated. It is important to note that the inconsistency index value should be less than 0.1.

2.4. Structure of questionnaire

The questionnaire designed for the determination of priority purpose can show the pairwise comparison between two related parameters. The pairwise comparison is used to assess the relative importance or priority of different factors and parameters. Experts according to Table 3 choose the prior parameter by ticking the check box. Figure 6 illustrates a part of this questionnaire.

The questionnaire is structured as a pairwise comparison matrix. The matrix lists all possible combinations of parameters, and experts are asked to compare each pair. After the questionnaire is completed by the experts, the data are analyzed using AHP to derive overall rankings or weights for the parameters. These rankings can then inform decision-making processes and guide the prioritization of rehabilitation efforts based on the perceived importance of each parameter.

Table 2 | Specification of nine aflaj systems

Number	Name	Wilayat Name	Length (m)	Discharge (m^3/s)	Quality (EC) ($\mu s/cm$)	Distance from River Network (m)	Population	Permeability of Soil (m/s)	Precipitation (mm)	Cultivated area (m^2)
1	Al-Khatmain	Nizwa	2,481	0.2277	922	1	10,450	8×10^{-3}	178.08	703,148
2	Al-Malki	Izki	14,878	0.2264	760	231	25,178	7.5×10^{-3}	169.12	392,202
3	Daris	Nizwa	7,990	0.6321	540	315	70,232	2.1×10^{-5}	165.2	1,715,502
4	Al-Muyasar	Al Mudhaibi	4,862	0.0682	400	1429	1,457	7×10^{-3}	101.36	184,964
5	Al-Hamra	Al Hamra	5,265	0.5749	600	245	15,428	7×10^{-5}	88.48	815,522
6	Al-Ayn	Adam	6,361	0.0851	1,810	18,145	18,845	1×10^{-6}	120.4	1,115,124
7	As-Seeb	Samail	596	0.0249	750	35	883	2.5×10^{-3}	117.04	207,932
8	Al-Kamel	Ar Rustaq	3,466	0.0351	1,293	13	2,058	1×10^{-2}	79.52	63,522
9	Al-Wasit	Bidbid	443	0.091	400	10	679	1×10^{-2}	87.92	19,497

Table 3 | Saaty's fundamental scale for comparative judgments (Saaty 1979)

Numerical values	Comparative judgements	Description
1	Equally preferred	Equal preference or importance or desirability
3	Moderately preferred	A little more important or a little more important or a little more desirable
5	Strongly preferred	A preference with strong importance or desirability
7	Very strongly preferred	Preference with very strong importance or desirability
9	Extremely preferred	Completely important or completely more important or completely appropriate
2, 4, 6, 8	Values intermediate	Intermediate preferences when there is an intermediate state.

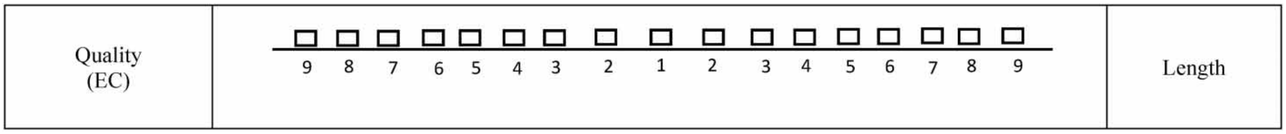

Figure 6 | A part of questionnaire distributed among the experts.

3. RESULTS AND DISCUSSION

Aflaj systems are an ancient and intricate system of water channels that have been used in the Middle East, particularly in Oman, for over 1,500 years. These systems are important because they provide a sustainable and reliable source of water for agriculture and domestic use in an arid region with limited water resources. Therefore, the preservation of these resources is important for the country.

According to MRMEWR, there are around 4112 aflaj in Oman which indicates a large amount of it. To this end, there is always a question, of which falaj has the highest priority for rehabilitation or, what is the list of prior falaj for rehabilitation (MRMEWR 2001).

The rehabilitation of aflaj systems is important for several reasons. Firstly, these systems are an important part of the cultural heritage of the region and represent a unique engineering achievement of ancient times. Therefore, preserving and restoring these systems is essential to maintain the cultural identity and historical legacy of the region. Secondly, aflaj systems are a critical source of water for agriculture, which is the livelihood of many people in the region. The reconstruction of these systems is essential to ensure that farmers have access to water for irrigation, which is necessary for cultivating crops and sustaining their livelihoods. Thirdly, the rehabilitation of aflaj systems can help to mitigate the impacts of climate change, which is expected to exacerbate water scarcity in the region. By restoring these systems and improving their efficiency, more water can be conserved and used efficiently, reducing the demand forr other sources of water.

3.1. Main findings

In order to prioritize these aflaj systems, some steps are carried out. This study was conducted in Oman to collect data using multiple steps. Initially, a survey was performed to identify effective indicators of the parameters affecting rehabilitation. Since no literature was available on this subject, the indicators were listed based on the opinions of 10 experts.

Next, a questionnaire consisting of 28 items was used to measure attitudes towards the impacts of the priority of reconstruction, using a nine-point scale that ranged from ‘equally preferred’ to ‘extremely preferred’. Twenty extension experts in water, agriculture, and aflaj systems were selected through snowball sampling, a non-probability sampling method. The questionnaire was evaluated for content and face validity by state supervisors in sustainable development. The reliability of the instrument was found to be acceptable at 0.85. For clarity and internal consistency, the questionnaire was slightly modified to ensure participant comprehension of the sustainability goal. Finally, nine factors (indicators of the priority of rehabilitation) were identified.

As part of the AHP process, a hierarchical network is created, starting at the top with the main objective (goal), followed by the criteria and options. The objective of this study is to determine the priority of the aflaj system in Oman for rehabilitation (selected aflaj are Daris, Al-Hamra, Al-Khatmain, Al-Wasit, Al-Muyasar, Al-Malki, Al-Ayn, As-Seeb, Al-Kamel) of these sustainable water resource. An overview of the analytical hierarchy is shown in Figure 6.

The next step is to identify the key criteria for evaluating the objective. The first stage identified eight key criteria, including length, quality, distance from the river network, population, permeability of soil, discharge rate, cultivated area, and precipitation. Each row’s value was compared to each column’s value, resulting in a rating score for each indicator (as shown in Table 4). The score matrix was then normalized to assign weights to each parameter. The researchers calculated the weight of each parameter (as shown in Table 5) by averaging the values in each row of the normalized matrix.

During this step, nine aflaj systems participated in pairwise comparisons of the eight criteria. Another purpose of this research was to compare and determine the relative importance of factors that affect the prioritization, with the general goal of rehabilitation of sustainable groundwater resources, aflaj systems in Oman. Table 6 and Figure 7 show the final result of AHP. Regarding them, falaj Daris which is listed as one of the UNESCO heritages, ranked first due to its high relative weight. This value is calculated based on the all relative weights of pairwise comparison. After that, falaj Al-Hamra was placed in the Hamra village ranked second as its relative weight is 0.137.

Table 4 | Pairwise comparison and relative weight of indicators

	Length	**Quality**	**Distance from river network**	**Precipitation**	**Cultivated area**	**Discharge**	**Permeability of soil**	**Population**
Length	1	[a]6	[a]4	[a]3	[a]7	[a]6	[a]4	[a]5
Quality		1	5	3	2	1	6	2
Distance from River Network			1	[a]3	[a]5	[a]6	[a]2	[a]3
Precipitation				1	1	[a]4	2	3
Cultivated Area					1	[a]4	4	3
Discharge						1	5	5
Permeability of Soil							1	[a]3
Population								1
CR	0.05							

[a] Means the higher weight value of column indicator.

Table 5 | Relative and normalized weight values

Ranking	Parameters	Relative weight	Normalized weight
1	Discharge	0.306	1
2	Quality	0.230	0.753
3	Cultivated area	0.149	0.487
4	Precipitation	0.112	0.365
5	Population	0.086	0.282
6	Permeability coefficient	0.052	0.170
7	Distance from river network	0.041	0.134
8	Length	0.024	0.080
CR		0.07	

Table 6 | Priority ranking of aflaj according to relative weight

Ranking	Name of falaj	Relative weight
1	Daris	0.222
2	Al-Hamra	0.137
3	Al-Khatmain	0.130
4	Al-Wasit	0.118
5	Al-Muyasar	0.101
6	Al-Malki	0.098
7	Al-Ayn	0.085
8	As-Seeb	0.063
9	Al-Kamel	0.047
CR	0.05	

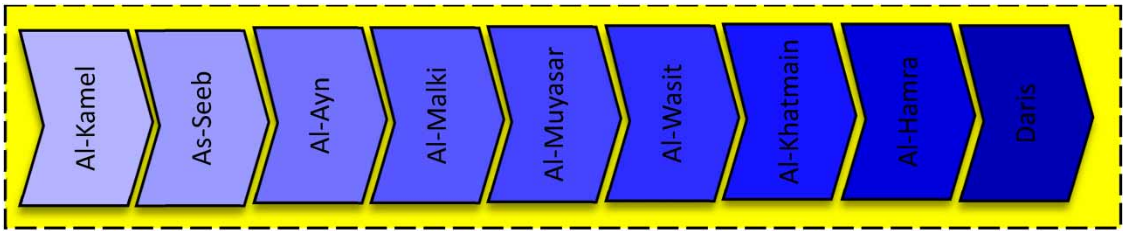

Figure 7 | Priority list of aflaj achieved by AHP for rehabilitation.

The relative weight values between Al-Hamra and Al-Khatmain are close to each other. This means that they can be considered the same weight. Al-Muyasser and Al-Malki, and Al-Ayn and As-Seeb have this situation. Their weights are almost the same. However, Al-Kamel has the least relative weight value in comparison to others.

A radar chart, also known as a spider chart or web chart, can be used to visualize the performance scores of the alternatives across multiple criteria. In a radar chart, each criterion is represented by a spoke, and the performance score for each alternative is plotted as a point on each spoke. The resulting shape of the chart can provide a quick visual representation of how each alternative performs across different criteria. The radar chart for the alternatives with respect to the relative weights of indicators is depicted in Figure 8 (Based on Table 7).

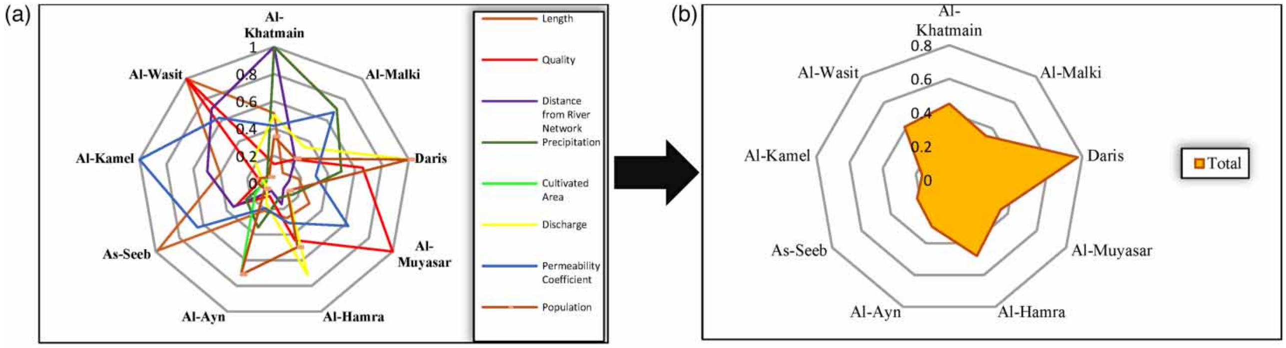

Figure 8 | Radar chart of aflaj systems rehabilitation plan. (a) Separate indicators, (b) overall.

Table 7 | Weight value of aflaj system regarding to the all criteria

Alternative	Total	Length	Quality	Distance from river network	Precipitation	Cultivated area	Discharge	Permeability coefficient of soil	Population
Al-Khatmain	0.453	0.514	0.14	1	1	0.344	0.498	0.421	0.344
Al-Malki	0.341	0.098	0.229	0.237	0.712	0.237	0.344	0.68	0.237
Daris	0.773	0.182	0.657	0.112	0.498	1	1	0.309	1
Al-Muyasar	0.352	0.296	1	0.079	0.162	0.112	0.112	0.625	0.112
Al-Hamra	0.479	0.271	0.444	0.162	0.112	0.498	0.712	0.309	0.498
Al-Ayn	0.296	0.213	0.1	0.059	0.344	0.712	0.162	0.194	0.712
As-Seeb	0.22	0.985	0.317	0.344	0.237	0.162	0.059	0.647	0.079
Al-Kamel	0.163	0.402	0.106	0.498	0.059	0.079	0.079	1	0.162
Al-Wasit	0.411	1	1	0.712	0.079	0.059	0.237	0.625	0.059

Figure 8(a) shows the radar chart for all the indicators separately. According to this figure, the red line shows the quality criteria and Al-Muyasar has the most weight value which shows the best quality among other aflaj. The precipitation factor presented by the dark green line has the highest weight value toward falaj Al-Khatmain. The discharge element which is ranked as the first factor, in this study, is approached to falaj Daris. Falaj Daris, the prior falaj for rehabilitation has the most weight values due to discharge, length, and cultivated area indicators. Figure 8(b) shows the overall weight value with respect to all indicators. Falaj Daris ranked first and then Al-Hamra ranked second.

Figure 9 is achieved from Expert Choice software and shows the performance sensitivity. Based on the various objectives, as well as the overall objective, the alternatives were prioritized in relation to each other.

In decision-making, performance sensitivity is an important aspect to consider because it helps decision-makers understand how changes in the performance of the alternatives can affect the final ranking or selection of the best option.

The results of the pairwise comparisons of criteria and alternatives and the overall comparison were visualized using a performance sensitivity graph. The graph displays the results for each alternative (falaj) using different colors (as shown in Figure 9). The x-axis represents the eight criteria that were used in the model, and the y-axis shows how each criterion contributed to each system's total score (alternative), as well as the gradient sensitivity analysis.

This graph shows the prior falaj, Daris, with a green color. The right y-axis presents the relative weight values of aflaj against each other. Daris has the highest relative weight value around 0.222. after that, the difference between each sequential aflaj weight value is lower than 0.02.

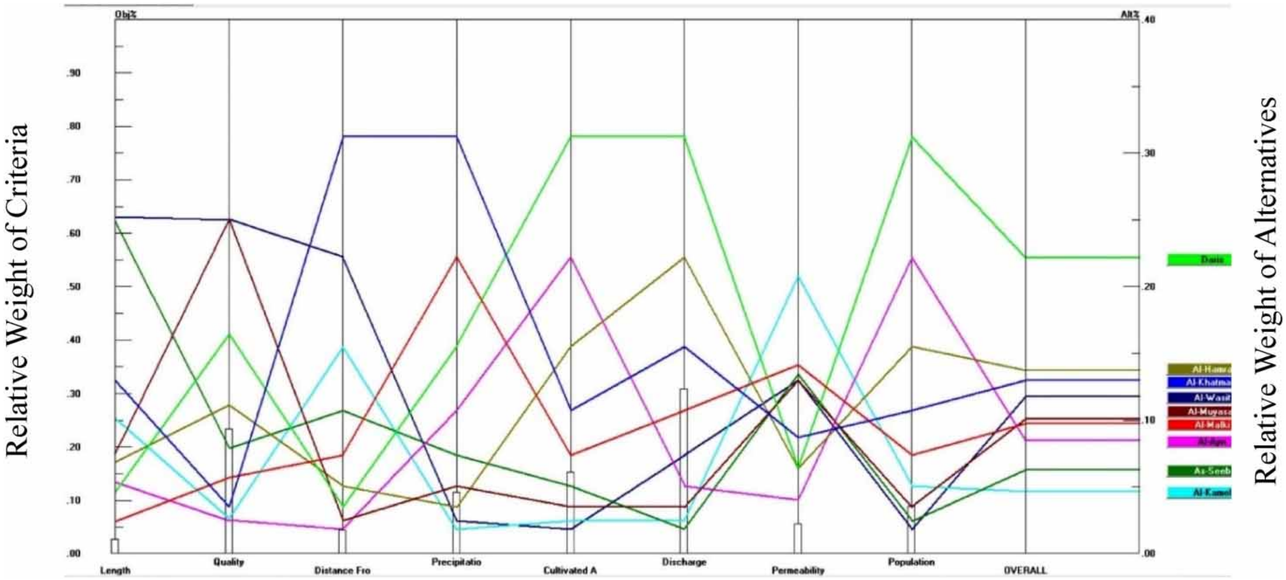

Figure 9 | Sensitivity analysis on one parameter of the model.

3.2. Sensitivity analysis

Sensitivity analysis in AHP is a technique used to measure the stability of the rankings obtained through the AHP method. AHP is a decision-making method that involves breaking down a complex decision problem into a hierarchy of criteria and sub-criteria, and then pairwise comparing them to determine their relative importance. Sensitivity analysis in AHP involves evaluating how sensitive the final rankings are to changes in the priorities assigned to the criteria and sub-criteria. This is done by systematically varying the priority weights assigned to the criteria and sub-criteria and observing how the final ranking changes. Expert Choice is a software tool that can be used to perform AHP and sensitivity analysis. In Expert Choice, sensitivity analysis involves changing the weights of the criteria and sub-criteria and observing how the overall ranking of the alternatives changes. This helps decision-makers understand the impact of different priorities on the final decision and helps to identify any potential biases or errors in the decision-making process.

The study examines how changes in the values of indicators affect the achieved values of relative weight. The investigation looks at 5, 10, and 15% changes in the values of indicators and determines whether the list of priorities is affected.

To illustrate, if the relative weight value of the discharge indicator is 0.302, adding 10% of this value to itself would result in a new relative value of 0.3322. The process is repeated for all indicators, and changes are observed in the performance sensitivity graph. The study found that there was no difference in the priority list when a 5 or 10% change was made. However, a 15% change did result in a change to the priority list, occurring in the middle of the list, as shown in Figure 10.

3.3. Discussion (explanation of findings)

In this study, the purpose is to figure out among the selected aflaj system, what is the priority for reconstruction. Aflaj is the masterpiece heritages that remain for us for more than 3,000 years. This sustainable resource due to its age, needs some rehabilitation and maintenance procedures; however, the water decision-makers could not decide which of them has more priority. In this study, after entering the achieved data from the questionnaire into Expert Choice software, the priority list is acquired. The list is sorted by the computed weight value as the following, Daris (0.222), Al-Hamra (0.137), Al-Khatmain (0.130), Al-Wasit (0.118), Al-Muyasar (0.101), Al- Malki (0.098), Al-Ayn (0.085), As-Seeb (0.063), and Al-Kamel (0.047). This means that according to the nine indicators, falaj Daris has the highest weight value among all the aflaj and in equal condition, this falaj must be rehabilitated first.

Nine indicators considered in this research are length, quality, distance from the river network, precipitation, cultivated area, discharge, permeability of soil, and population. Results showed that among these criteria, discharge rate has the highest weight value which represents the importance of this factor in making decisions. After that quality of water has the greatest weight value. The length has the least value which shows its least role in rehabilitation aim from a technical point of view.

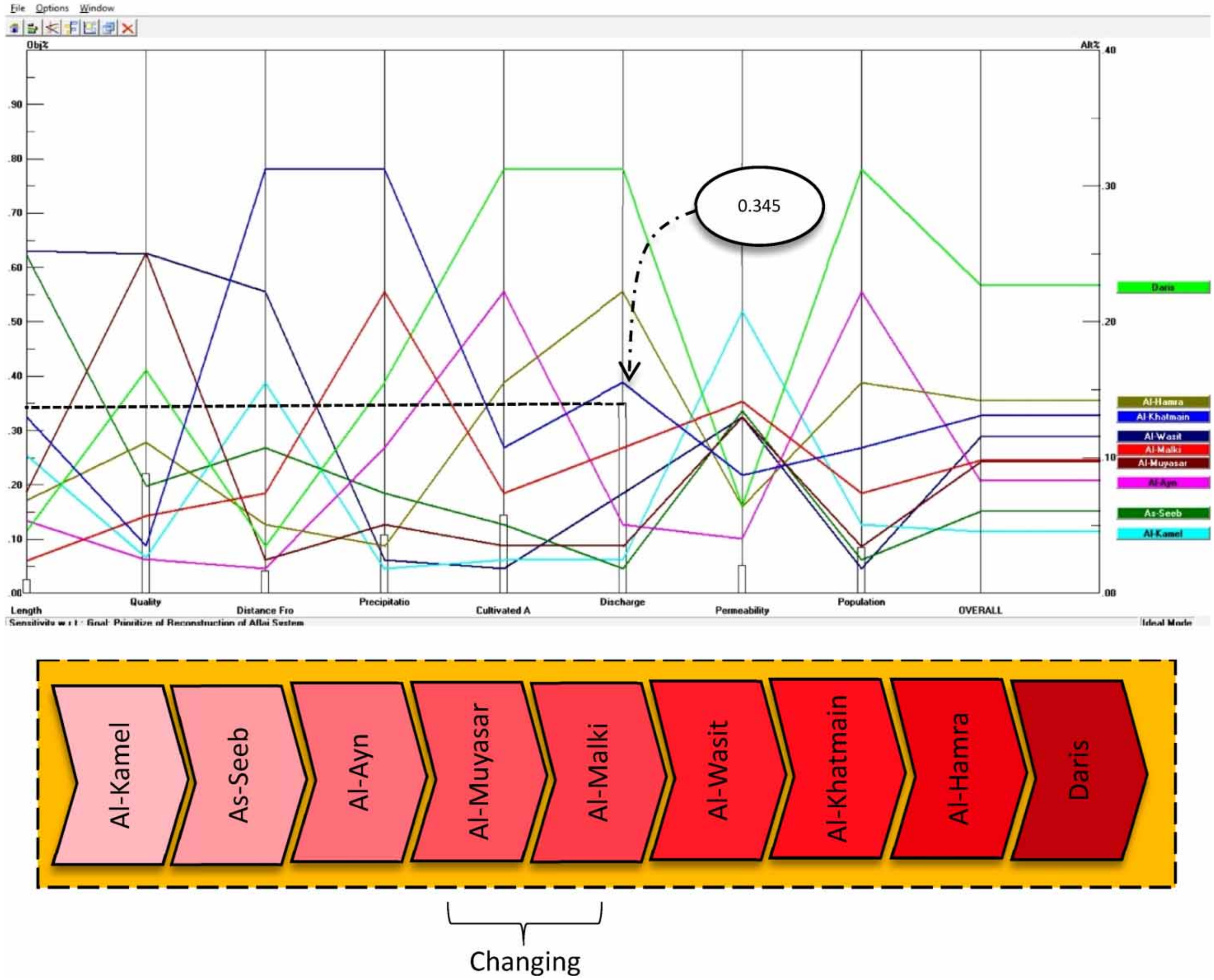

Figure 10 | Effect of 15% increment in discharge indicator on priority list.

3.3.1. Limitation and future work

AHP has several advantages over other decision-making methods. It provides a structured and systematic approach to decision-making, which can help decision-makers avoid biases and make more informed decisions. It can also be used to analyze complex problems with many criteria and alternatives. AHP is also flexible and can be adapted to different decision-making contexts.

However, AHP also has some limitations. It relies on subjective judgments, and the results can be influenced by the decision-maker's biases and preferences. The pairwise comparison matrix can also be time-consuming and difficult to create, particularly when there are many criteria or alternatives.

For future work, the authors recommend considering more data in this model, depth of water, number of beneficiaries of the falaj, and number of shafts.

4. CONCLUSION

Aflaj is the most remarkable sustainable water resources in Oman. Research has shown that the most pressing challenge in the current discussion on aflaj rehabilitation is the wasteful rehabilitation of aflaj that is not actually a priority. It is crucial to establish a sophisticated agenda and framework for decision-making, considering the intricate nature of water and irrigation matters. According to experts, there is currently no scientific and specific solution to prioritize them, and prioritization is based on limited criteria. To address this gap, this research introduces a new scientific method for prioritizing aflaj reconstruction using the AHP. This article also presents a framework as a comprehensive approach that utilizes multi-criteria decision analysis for prioritizing sustainable groundwater resources, and aflaj systems, for reconstruction. To demonstrate its effectiveness, a case study was conducted on the selection of nine aflaj systems in Oman. This approach provides a suitable scientific platform for further work on this issue. Additionally, this research prioritizes aflaj for restoration that achieves desired irrigation with allocated costs. Using the AHP method, the Iddi falaj Daris was prioritized for reconstruction from a technical perspective with 0.222 weight. For future works, the author suggests considering the managerial technical point of view in order to compare these two technical points together. Also, other methods such as analytic network process (ANP), and Fuzzy-AHP can be engaged for this aim.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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