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The prioritization of volunteering revival measures of the Qanat

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ABSTRACT

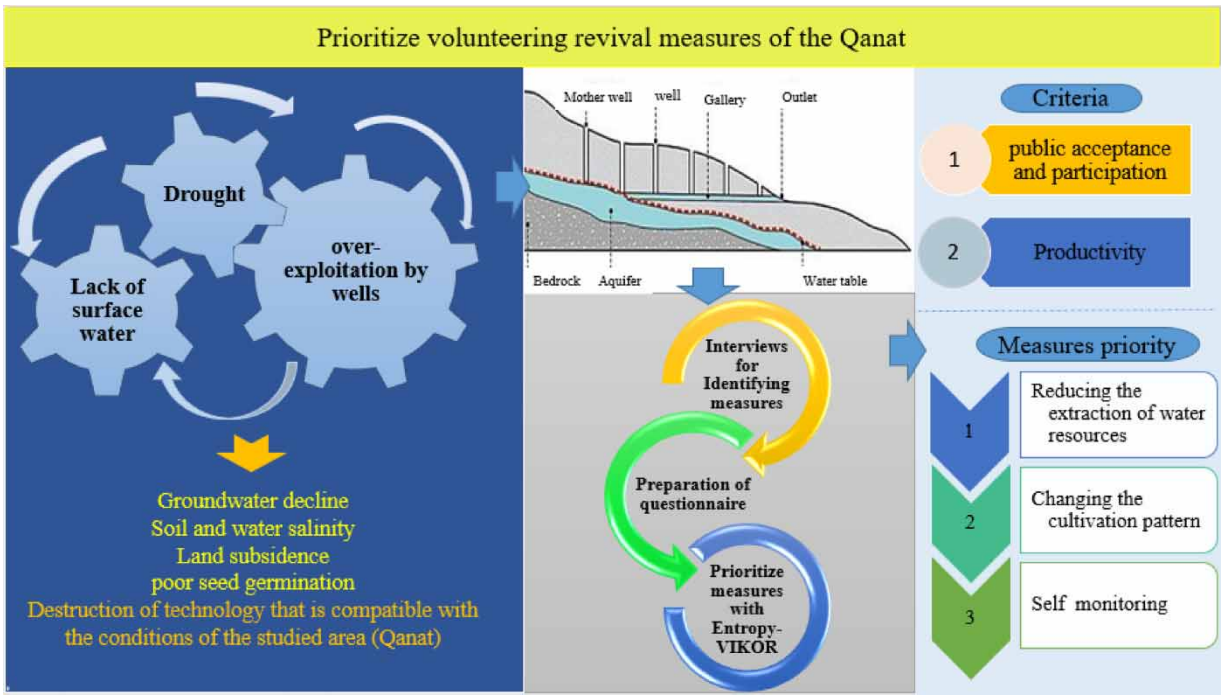
The Fariman-Torbat Jam Plain has been under high pressure due to the imbalance of groundwater caused by excessive water extraction. Current conditions necessitate the preservation of appropriate extraction methods. Although the revival of the Qanat is known to be a highly compatible method, its high cost poses a challenge. Identifying and prioritizing measures to revive the Qanat can be a critical factor in managing this challenge. This study identified and prioritized the measures of the revival of the Qanat by using questionnaires, interviews with experts, and the entropy–VIKOR method. The results showed that among the 10 measures identified, reducing the extraction of water and changing the cultivation pattern were the top two priorities, and other measures were placed next. By implementing these measures, it is possible to partially respond to the demands of the natives while preventing further deterioration of the consequences that endanger the plain. Furthermore, considering the fact that the implementation of any measure can be beneficial, they should be determined based on region characteristics and then implemented in order of priority to obtain more favorable results.

Key words: entropy–VIKOR, groundwater, MCDM, participation, productivity

HIGHLIGHTS

- The revival of the Qanat is an effective and compatible solution for dry and semi-dry regions.
- The knowledge of voluntary measures related to the revival of the Qanat can help policymakers to achieve easier and faster results for the implementation of projects.

GRAPHICAL ABSTRACT



INTRODUCTION

Water resources play a significant role in providing all living organisms with an adequate food supply and a stable environment. Worldwide, freshwater availability is only 2.5%, with two-thirds frozen in polar ice caps and glaciers. Pressure on water resources is increasing as a result of rapid urbanization, and many of the world's major aquifers are depleting (Cacal & Taboada 2022). The water crisis is becoming more complex every day in countries located in the desert belt area of the world, like Iran (Madani *et al.* 2016).

The ancient Persians invented a good way of accessing groundwater and overcoming the water crisis based on the principle of environmental respect and adaptation to nature in the central plateau (Veicy 2021). This invention that made life possible in this region is known as a Qanat (Aghazadeh 2013). Qanat technology is a gently sloping tunnel that drains the groundwater from the aquifer and leads it to the surface using gravity flow conditions (Figure 1). In other words, Qanat benefits from the differences between the earth's surface elevations to convey water from the upstream aquifer to the earth's surface downslope (Semsar Yazdi 2011). Although it is an Iranian invention and has been in use in Iran for thousands of years (Sanaan Bensi 2020), it has been introduced to people in other regions of the world including Jordan, Afghanistan, UAE, Pakistan, Turkey, China, Syria, Iraq, Saudi Arabia, Oman, India, Yamane, Aljazeera, Tunis, Libya, Marrakesh, Egypt, Germany, Russia, England, Spain, Czech, Slovakia, Cyprus, France, Peru and Chile, and Mexico (Mahan *et al.* 2019; Saatsaz & Rezaei 2023).

Recently, non-native technologies like wells have been replaced by Qanat for water extraction. Wells have significantly harmed aquifers and lowered groundwater levels (Taghvi-Jeloudar *et al.* 2013; Maghrebi *et al.* 2022). Furthermore, soil and water salinization, land subsidence, increased pumping costs, and reduction of water quality are some of the most visible consequences of using wells (Sanaan Bensi 2020). In comparison with wells, the Qanat has several advantages, including that this system does not use any kind of fuel, the water speed in a Qanat is always controlled, its mechanisms are consistent with indigenous knowledge and local expertise, and the Qanats are supported by a socio-economic system that ensures their sustainability (Semsar Yazdi & Labbaf Khaneiki 2017; Mahan *et al.* 2019). As previously said, the water crisis in Iran has reached a critical point owing to the recent drought and climate change, causing significant repercussions on the economy, water resources, agriculture, and natural ecosystems. This problem is especially acute in the central plateau and exacerbated by a population increase.

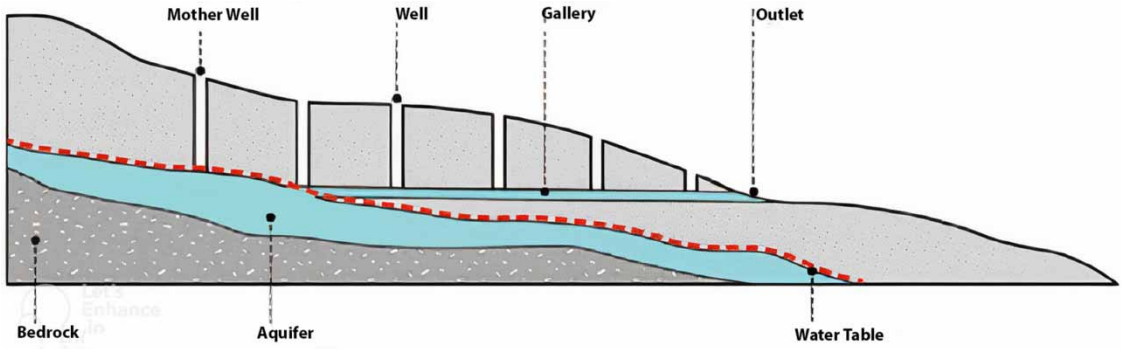


Figure 1 | Schematic section of a typical Qanat (Karimian *et al.* 2021).

The Fariman-Torbat Jam Plain, which covers an area of 6,312.91 km^2, is one of the most important plains of the central plateau (Figure 2). This plain is located in the east of Khorasan Razavi Province (Parsapour *et al.* 2016) and is bounded on the north by Farhadgerd and Tous, on the east by the Harirud River (border of Iran and Turkmenistan), on the west by the Binalood and Bakharz plains, and on the south by the Plain of Taybad and the border of Iran and Afghanistan (Zohouriyan & Rahmat Zadeh 2022). Groundwater resources are the primary water source in this region, which is available through wells, Qanats, and springs. The number of wells (deep and semi-deep), Qanats, and springs is 1,127, 305, and 529, respectively (Agricultural Jihad Organization of Khorasan Razavi Province 2021; Khorasan Regional Water Company 2021).

This Plain frequently experiences droughts of varying duration and severity, leading to reduced water supply, crop damage, ecological loss, and socio-economic hardship (Faye 2022). On the other hand, indiscriminate extracting for profit has exacerbated these consequences. In general, due to natural and human factors, the aquifer has been experiencing a yearly drop of 1.5 m. This issue is expected to worsen in the future (Parsapour *et al.* 2016). Therefore, it is necessary to focus on water management and sustainability issues to prevent further aggravation of the previously mentioned consequences in this region (Mianabadi & Pourreza-Bilondi 2023).

No one can deny that sometimes the only option to exploit groundwater is to drill wells. However, this should not be used as a pretext to replace the active Qanat with wells. Where traditional knowledge can provide sustainable solutions to new demands, more expensive and modern solutions are not always needed (Manuel *et al.* 2018; Mahan *et al.* 2019). It should be noted that the Qanat is more than just a way of extracting groundwater. It represents a unique and integrative system of indigenous knowledge and wisdom in the sustainable management of land, water, and agricultural biodiversity. Additionally, it fosters collaboration in farming communities. Based on information from the regional Water Company, the

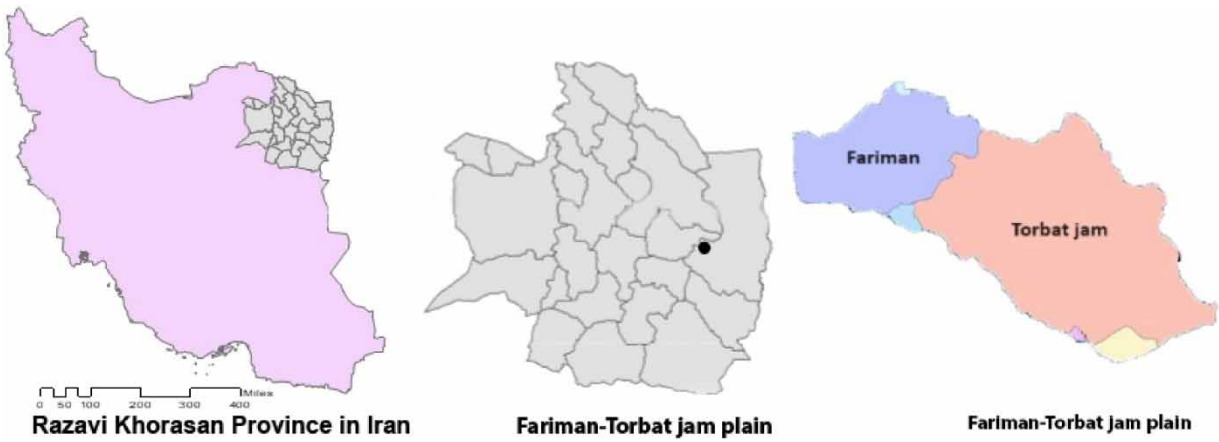


Figure 2 | Fariman-Torbat Jam Plain.

Agricultural Jihad Organization, and interviews with locals, it is unnecessary to construct a new Qanat in the plains since the existing Qanats can be reused with proper measures.

The lack of skilled labor in the region, the high cost of repairing the Qanat, the lack of a suitable place for their discussion, the ignoring of indigenous water knowledge, and locals' participation in decisions are obstacles to the Qanat's revival. These obstacles can be reduced with the cooperation and participation of local communities and organizations (Labbaf Khaneiki 2019, Valizadeh *et al.* 2022, Kokabi 2021). In other words, maintaining and reviving such a system require cooperation from all the shareholders (organizations and people). On the other hand, the cost of Qanat revival is high, and the budget for such projects is limited. So, identifying Qanat revival measures and prioritizing them can be one of the most crucial policy points to solve the water problem and adapt to water scarcity in the study area. Prioritized measures lead to proper and effective budget management, human resources, and equipment. Researchers focused on introducing the Qanat (Sala *et al.* 2010; Semsar Yazdi & Labbaf Khaneiki 2017; Sanaan Bensi 2020), technical dimensions (Abbasi *et al.* 2014; Remini *et al.* 2014), historical dimensions (Avni 2019), quantity and quality of water resources (Zolfagharan *et al.* 2019), factors affecting the sustainability of groundwater resources and Qanat (Bazii 2012; Himat & Dogan 2019), the impact of this indigenous technic on sustainable development (Fadakar Davarani & Sam Aram 2010; Falahtabar & Bohairaei 2011; Faraji Sabokbar *et al.* 2012; Mahan *et al.* 2019), and Qanat and urban architecture (Estaji & Raith 2016; Kokabi 2021). However, few studies focused on identifying voluntary measures for the revival of the Qanat and its prioritization. This study uses questionnaires and interviews with experts and the multiple criteria decision-making (MCDM) model to fill these gaps.

METHODS

According to previous studies, field observations, review of the rules and regulations, upstream documents, and interviews with locals, Agricultural Jihad Organization experts, and Regional Water Company experts, the most significant measures for reviving the Qanat were identified (Table 1). Then measures were prioritized by using the MCDM model.

MCDM is recognized as a complex decision-making tool that encompasses both quantitative and qualitative factors. Recently, various MCDM methods and approaches have been recommended for determining the optimal feasible alternatives (Mardani *et al.* 2015). Opricovic introduced the VIKOR (Vlse Kriterijumsk Optimizacija Kompromisno Resenje) method as a well-known MCDM model that emphasizes the selection and ranking of alternative sets of conflicting criteria (Opricovic 1998; Huang *et al.* 2009; Shen *et al.* 2014; Ganjil & Pradhan 2018). Moreover, VIKOR is an effective tool in multi-criteria decision-making, particularly in a situation where the decision maker is not able or does not know to express his/her preference at the beginning of system design. This technique, in addition to offering two reference points as ideal negative and positive points, considers the relative significance of the interval between them. In this model, there are no paired comparisons between criteria and items, but each option is evaluated independently based on each criterion (Poorahmad & Khaliji 2014; Bani Habib & Chitsaz 2016; Golfam *et al.* 2019; Haider *et al.* 2020).

The VIKOR method uses linear normalization, in which the normalized value is not dependent on its measurement unit (Omidi *et al.* 2022). It should be noted that the criteria are not weighted in this method, and other methods should be used to

Table 1 | Revival measures of the Qanat in the Fariman-Torbat Jam Plain

Number	Measures
1	Reducing the exploitation of water resources
2	Changing the cultivation pattern
3	Changing irrigation methods
4	Land integration
5	Watershed in upstream
6	Self-monitoring
7	Gabion-Bandi
8	Provide human resources
9	Aquifer output aggregation plan
10	The formation of cooperatives

weigh them (Opricovic & Tzeng 2004). The compromise-ranking algorithm of the traditional VIKOR has the following steps (Wang *et al.* 2018).

Step 1: *Structure of the decision matrix*: In this matrix, m represents the considered criteria (which includes productivity and participation, and public acceptance), and n represents the voluntary measures related to the revival of the Qanat.

Step 2: *Normalize the original rating matrix*: The original rating matrix is transformed into a normalized weight-rating matrix with the following equation:

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \tag{1}$$

The weight of the criteria expresses decision-maker's preference regarding the relative importance of the criteria (Dang & Dang 2019; Golfam *et al.* 2019). There are numerous different methods to determine the criteria weight. The entropy is one of them. This method is now widely used in MCDM problems to measure the weights of attributes. The advantage of entropy is that it calculates the weight to avoid the influence of subjective factors based on objective data. According to the above, the entropy method has been used to calculate the weights of the criteria in this study (Shemshadi *et al.* 2011; Ronaghi *et al.* 2019). The entropy values of the criteria follow the following function.

$$E_j = -K\sum_{i=1}^{m} P_{ij}\ln(P_{ij}) = -\frac{1}{\ln m} \tag{2}$$

After calculating E_j, Equation (3) was used to calculate the uncertainty or degree of deviation of each criterion (d_j) from the information obtained for the jth criterion.

$$d_j = (1 - E_j) \tag{3}$$

Finally, we used Equation (4) to determine the standard weight of j:

$$W_j = \frac{d_j}{\sum_{i=1}^{n} d_i} \tag{4}$$

According to the calculated weights, the importance of each index was obtained (Ahangari *et al.* 2016). Then, the normalized matrix was multiplied by a weight and the standard weight matrix was obtained.

Step 3: *Determine fi* and fi*$^-$: After calculating the standard weight matrix, the best fi* and the worst fi- values of all criterion functions were determined, $i = 1, 2 \ldots n$ (Bani Habib & Chitsaz 2016; Mousavi *et al.* 2021).

$$f_i^+ = \max f_{ij},\ f_i^- = \min f_{ij} \tag{5}$$

Step 4: *Compute the values* S_j *and* R: $j = 1, 2 \ldots J$, as shown in the following equations (Golfam *et al.* 2019):

$$S_j = \sum_{i=1}^{n} W_i . \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \tag{6}$$

$$R_i = \max\left[w_i . \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-}\right] \tag{7}$$

Step 5: *Compute the index values* Q_i: $j = 1, 2 \ldots m$, where v is the weight for the strategy of maximum group utility and $1 - v$ is the weight of the individual regret. V is usually assumed to be 0.5:

$$Q_i = V\left[\frac{S_i - S^*}{S^- - S^*}\right] + (1 - V)\left[\frac{R_i - R^*}{R^- - R^*}\right] \tag{8}$$

Step 6: *Ranking the alternatives*: The options were arranged in descending order based on the values of Q, R, and S in three groups. The best option is to have the smallest Q if the following two conditions are satisfied (Opricovic 2011):

The first condition states that if the A_1 and A_2 options have the first and second positions among the m options, the relation (9) is maintained.

$$Q(A_m) - Q(A_1) \geq 1/m - 1 \tag{9}$$

The second condition states that the A_1 option should be the top one among one of the R and S groups at least. If the first condition is not satisfied, both of the options are the best ones. If the second condition is not satisfied, both A_1 and A_2 options are the top options (Zolghadri & Vahdani 2015).

RESULTS AND DISCUSSION

According to the research literature and experts' opinions, the weight of two criteria was computed using the entropy method. As can be seen in Table 2, the productivity coefficient with the highest weight was chosen as the most crucial criterion among the identified factors.

The geometric mean opinions provided by the experts were calculated for each of the criteria. As shown in Table 3, the obtained numbers are listed as members of the decision matrix.

The maximum and minimum values for each criterion and, subsequently, the values of utility (S), regret (R), and VIKOR indices were calculated (Table 4).

By controlling the two conditions of acceptable advantage and acceptable stability, the measures of reducing the extraction of water resources and changing the cultivation pattern were ranked first and second, respectively. The expansion of wells was initially helpful for farmers of plain, improving their incomes and overall quality of life. However, excessive water extraction caused severe environmental damage, such as decreased aquifer levels of plain, loss of vegetation, and extreme soil erosion. Moreover, the decrease in aquifer levels caused farmers to drill wells with a depth of 300 m in the plain, but, despite

Table 2 | The result of Shannon's entropy

Criteria	Public acceptance and participation	Productivity
E_{ij}	0.9956	0.9919
d_j	0.0044	0.008
W_j	0.3554	0.6446

Table 3 | The decision matrix

	Public acceptance and participation	Productivity
Weight of the criteria	0.3554	0.6446
Reducing the extraction of water resources	7.53	4.73
Changing the cultivation pattern	7.15	4.26
Changing irrigation methods	6.16	5.37
Land integration	6.92	3.79
Watershed in upstream	5.20	4.83
Self-monitoring	6.16	5.54
Gabion-Bandi	5.32	3.37
Provide human resources	2.79	6.1
Aquifer output aggregation plan	3.91	1.9
The formation of cooperatives	4.08	6.71

Table 4 | The values of *S*, *R*, and *Q* for each measure

Measures	1	2	3	4	5	6	7	8	9	10
S	0.151	0.239	0.287	0.305	0.457	0.274	0.553	0.686	0.848	0.465
R	0.151	0.187	0.185	0.223	0.314	0.184	0.299	0.64	0.488	0.465
Q	0	0.0995	0.133	0.184	0.387	0.122	0.439	0.884	0.845	0.547

this, wells were not as efficient as they once were. Therefore, by reducing water withdrawal, it is possible to help reach the aquifer to a relative balance and the revival of Qanat. On the other hand, the cooperation of locals in changing the cultivation pattern or the cultivation of specific products compatible with water resources is an essential measure in water resource management, improving the aquifer, and revival of Qanat. The combination of the two measures, which are top priorities in this study, can play a more significant role in preventing the reduction of the plain aquifer and help to revive the Qanat more effectively. By reviving the Qanat, the conditions for achieving sustainable development in the plain will also be provided.

Jalili & Ashofteh (2023), Salehi Shafa *et al.* (2023), and Moslemi *et al.* (2017) pointed out the role of changing the cultivation pattern in the optimal use of surface and groundwater resources and also maintaining the balance of the aquifer. Furthermore, Emamifar *et al.* (2020) believed in the effect of combining these two measures on preserving the aquifer balance.

According to the Jihad Organization and Regional Water Company Report, the Fariman-Torbat Jam Plain is critical and prohibited. This means that the aquifer level of this plain has drastically reduced due to natural and human factors. According to the rules related to critical and prohibited plains, legal wells must harvest less than what they are permitted to harvest, and drilling illegal wells must be prevented. In this regard, identifying and monitoring illegal wells or, in other words, in the form of a measure mentioned in this study as self-monitoring is essential. Based on the results of Table 4, this variable is ranked third. Keyhomayoon *et al.* (2022) introduced the monitoring of unauthorized wells as one of the essential measures of aquifer revival and balancing projects.

Furthermore, the issue of water shortage in the plain is severe, and evaporation and water wastage in the fields are contributing to the problem. It is necessary to upgrade irrigation methods with new techniques that can reduce water wastage while providing sufficient water for plants. However, since most of the lands are small, using new irrigation methods can be very costly and challenging to implement new irrigation methods. Therefore, it is crucial to adopt new irrigation methods and integrate the land in these areas to enhance irrigation efficiency. These measures are in the fourth and fifth ranks, respectively. The study carried out by Jafari & Bradley (2018) emphasized irrigation technology compatibility and the crucial role of forming cooperatives in dry climates. Einloo *et al.* (2022) also confirmed that changing irrigation methods, integrating land, and changing cultivation patterns are successful strategies to balance the groundwater aquifer, revive Qanat, and provide sustainable development.

Implementing upstream watershed management, as well as the Gabion-Bandi, to manage and control floods, or aquifer management, are other necessary measures that can be very effective in infiltrating water to aquifers and feeding aquifers. As mentioned in the study by Bagherian *et al.* (2021), if implemented properly, watershed management measures will have positive economic and social effects. Otherwise, it will have adverse consequences and add to watershed problems. For example, to revive the Qanat of Samakhun Village in Nasrabad District, watershed measures were taken. This measure was unsuccessful because it was implemented downstream instead of upstream.

According to Rahimi-Feyzabad *et al.* (2021), modifying the cultivation pattern and watershed management operations are significant strategies for the management and revival of groundwater. These two measures are ranked sixth and seventh, respectively. Given the significant cost of reviving the Qanat, the formation of cooperatives can be adequate to cover the costs of reviving. Furthermore, these cooperatives can efficiently strengthen user participation and create positive interactions between relevant institutions and users. This measure is ranked eighth among other measures. The importance of participation, or providing human resources, in enhancing the revival of the aquifer and Qanat was highlighted by Kokabi (2021), Ghasemi *et al.* 2021, and Valizadeh *et al.* (2022). Finally, the aquifer output aggregation plans to minimize water wastage and provide human resources for repairing and maintaining the Qanat ranked ninth and tenth.

It should be noted that the proposed measures in lower ranks do not mean that they are insignificant, but according to the opinions applied to the study area, their ranking order has been formed in this style.

CONCLUSION

Drought, the increase in extraction from deep wells, the increase in temperature, and evaporation have caused a severe water crisis in the Fariman-Torbat Jam Plain. Considering that natural factors are unpredictable, it is essential to seek solutions that decrease human hazards and meet people's water requirements. The revival of the Qanat is one of the most important solutions in this region. In order to obtain positive outcomes and proper budget allocation, it is required to identify and prioritize important and effective measures for the revival of the Qanat in the region. In some places of the plain, measures should be done separately, while in others, a mix of measures should be implemented consecutively. These measures may appear to be simple to implement at first glance, but there will be no satisfactory results unless they are accompanied by local participation. Indeed, the participation of locals makes the implementation process easier and faster due to their experience obtained in this region. It should be mentioned that locals also believe that reviving the Qanat is the best option to save the region from the crisis. However, due to ethnic differences and lack of funds, they are less willing to do it. Therefore, in order to attract more voluntary participation from them, it is necessary to resolve these issues before implementing any measures. In the following, recommendations were made to accelerate the reviving of Qanat, followed by the revival of the plain aquifer:

1. In this study, changing the method of irrigation and reducing the extraction of water are considered vital measures in reviving the Qanat. Thus, to implement irrigation methods with high efficiency in the agricultural sector, it is necessary to provide conditions for obtaining low-interest loans.
2. Considering the significance of the revival of the Qanat, and the lack of income of locals, it is critical to increase the proportion of financial assistance from organizations.
3. Considering that the measure of changing the cultivation pattern is the second priority measure in reviving the Qanat, it is necessary to hold periodic meetings to present a new cultivation pattern compatible with the conditions of the region while using the knowledge of the locals.
4. Projects for reviving the Qanat are currently underway. Nevertheless, they are not implemented purposefully. To be targeted, the next studies should design plans for reviving the Qanat and policymakers should choose the plan with the best results according to the region's conditions.
5. In future studies, it would be better to identify and prioritize the potential economic, social, and environmental impacts of Qanat revival projects.
6. It is recommended to use other MCDM methods in future studies on this plain and compare the results with this study.

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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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