Scientia Iranica A (2015) 22(2), 319–330

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
www.scientiairanica.com

An integrated decision support system for dam site selection

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Received 5 February 2013; received in revised form 20 September 2013; accepted 28 July 2014

KEYWORDS
Dam site selection;
Fuzzy AHP;
Multi-Criteria Decision-Making (MCDM);
VIKOR;
Water resources management.

Abstract. Selection of suitable site for dam is one of the problems associated with water resources management, and it is dependent on a set of qualitative and quantitative criteria. Such problems can be resolved using Multi-Criteria Decision-Making (MCDM) approaches. This study aims to develop a MCDM method integrated with fuzzy logic and group decision-making, specifically focused on dam site selection. A fuzzy AHP method was extended to group decision making, and then the resulting group fuzzy AHP was combined with the VIKOR method. In the integrated method, fuzzy concepts were used to account for decision-makers' subjective judgments when considering the uncertainties of the site selection process. Group fuzzy AHP was used to determine the weights of different criteria and VIKOR was used to rank alternatives. The integrated method was applied to selection of the optimal site for an earth dam in Harsin city, Iran. The results show that the proposed method is an effective and reliable method in selecting the optimal dam site.

1. Introduction

Selection of the best site for a dam is among the decisions that are of particular importance in water supply management, as an optimal selection can improve the security of the water supply of a region and groundwater regeneration. However, dam construction is very expensive and has long-term environmental impacts. Therefore, the selection of optimal location for dam could lead to significant cost saving. In order to locate the optimal dam site, various studies are necessary. Decision-making and planning on issues of such significance cannot be conducted only through the traditional viewpoint of cost-benefit analysis. Decisions on these issues are related to different criteria, and the criteria related to water resource management themselves have many different characteristics accompanied by uncertainties. This makes decision-making and planning a very complex task. The most important characteristics of water resource management are as follows:

1. The attributes are in conflict with each other in some cases;
2. Some attributes are not measurable;
3. Various organizations and individuals are interested in water resources;
4. Each attribute contains a lot of information and a lot of research is needed;
5. Evaluation of some qualitative attributes is complex and they can be judged only by verbal variables;
6. Qualitative attributes are associated with uncertainty, so the opinions of different people must be used to assess them.

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Multi-Criteria Decision Making (MCDM) methods are very suitable in addressing these problems. In MCDM, among all possible alternatives, the best one is selected based on evaluation criteria. MCDM methods have been usually introduced based on classical mathematics. Often MCDM problems are dependent on different and in some cases, conflicting criteria. It is also possible that complying with the nature of decision making problems, the expert opinions could be different, or there could exist no exact information about them. In such conditions, utilizing traditional MCDM methods does not render the capacity to handle uncertainties and may in some cases lead to wrong decision making results. To address this problem, researchers have expanded the MCDM methods based on fuzzy sets (fuzzy MCDM methods).

Analytic Hierarchy Process (AHP) which was first introduced by Saaty [1], is one of the most powerful and simplest MCDM methods. Many researchers have extended the AHP based on fuzzy sets (fuzzy AHP methods). Fuzzy AHP methods are systematic approaches to the determination of the criteria weights and justification problem by using the concepts of fuzzy set theory and hierarchical structure analysis. The most important and earliest fuzzy AHP methods include the following: Van Laarhoven and Pedrcyz [2] presented the first study on the application of fuzzy logic principle to AHP; Buckley [3] initiated trapezoidal fuzzy numbers to express the decision maker's evaluation on alternatives with respect to each criterion while Van Laarhoven and Pedrcyz [2] used triangular fuzzy numbers; Chang [4] introduced a new approach for handling fuzzy AHP with the use of triangular fuzzy numbers for pair-wise comparison scale of fuzzy AHP, and the use of the extent analysis method for the synthetic extent values of the pair-wise comparisons; Cheng [5] proposed a new algorithm for evaluating naval tactical missile systems by the fuzzy AHP based on grade value of membership function; Deng [6] presented a fuzzy approach for tackling qualitative multi-criteria analysis problems in a simple and straightforward manner.

The VIKOR which is an abbreviation of the Serbian expression of "VlseKriterijumslca Optimizacija I Kompromisno Resenje", meaning "multi-criteria optimization and compromise solution" [7], was first introduced by Opricovic [8] as an MCDM method. The VIKOR is used to solve discrete multi criteria problems with non-commensurable and conflicting criteria. It focuses on ranking and selecting from a set of alternatives, and determines compromise solutions for a problem with conflicting criteria. It is one of the most widely used MCDM methods in rating problems.

To date, MCDM and fuzzy MCDM methods have been used in the various fields of water engineering by many researches. These include urban water supply of Zahedan city, Iran [9], watershed management [10], San Francisco river basin management [11], urban water supply of Zahedan, Iran [12], prioritization of water management for sustainability [13], urban water supply, Melbourne city, Australia [14], ranking the reservoirs systems [15], environmental assessment of water programmers [16], water resources planning [17], assessment model of water supply system [18], application of recycled water for household laundry in Sydney, Australia [19], mapping urban water demands [20], evaluating water transfer projects [21], and flood risk assessment [22].

The main objectives of the present study are firstly to determine effective criteria in dam site selection, secondly to present a fuzzy MCDM method to determine the criteria weights based on opinions of a decision making group and rating proposed sites, and thirdly to select the optimal site for the Harsin dam as a case study.

A fuzzy AHP approach was extended to group decision-making. The resulting group fuzzy AHP was then combined with VIKOR. Group fuzzy AHP was used to determine the weights of criteria, and VIKOR was used to rank alternatives. The integrated method was applied to the selection of the optimal site for an earth dam in Harsin city, Iran.

2. Method

The method used in this study is based on the integration of fuzzy AHP and VIKOR methods. The weights that are obtained from group fuzzy AHP calculations are considered and used in VIKOR calculations. Decision making in this integrated method involves several essential steps.

2.1. Forming a team of decision makers

This team involves dam construction experts and decision makers.

2.2. Determining effective criteria and potential alternatives

In this step, effective criteria in locating the dam site are determined by using comprehensive review of literature and expert opinions. The potential alternatives are then proposed based on determined criteria.

2.3. Developing the hierarchical structure

The hierarchy diagram is a graphic representation of a complex problem in which objectives, criteria, and alternatives are at the highest, intermediate and lowest levels, respectively.

2.4. Defining the fuzzy scale

In order to express the importance of criteria and formation of the pair-wise comparison matrix, a fuzzy scale is defined by decision makers. Table 1 shows a fuzzy scale that was used in this study. The graphical form of this scale is shown in Figure 1.

Table 1. Fuzzy scale used in this study.

Linguistic variables	Fuzzy numbers
Very Low (VL)	(0.1, 0.1, 0.3)
Low (L)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
High (H)	(0.5, 0.7, 0.9)
Very High (VH)	(0.7, 0.9, 0.9)

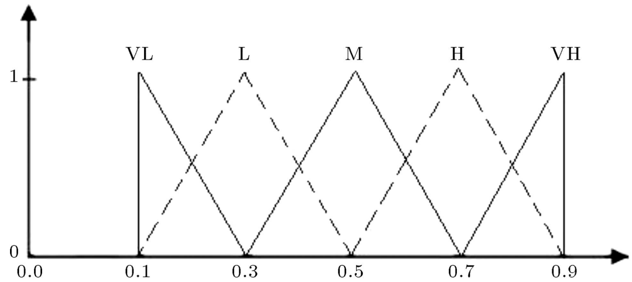

Figure 1. Graphical form of fuzzy scale used in this study.

2.5. Pooling the decision maker's opinions

The expert's opinions, expressing the importance of the criteria are pooled using a questionnaire.

2.6. Obtaining the aggregated fuzzy weight of criteria

The decision maker's opinions about the importance of the different criteria are aggregated. The aggregated fuzzy weight of criterion $j(\tilde{W}_j)$ is obtained as:

$$\tilde{W}_j = (a_j, b_j, c_j), \tag{1}$$

where:

$$a_j = \underset{k}{\text{Min}}\{a_{jk}\},$$

$$b_j = \frac{\sum_{k=1}^{k} b_{jk}}{K},$$

$$c_j = \underset{k}{\text{Max}}\{c_{jk}\}, \quad k = 1, 2, ..., K, \tag{2}$$

with K being the number of decision groups.

2.7. Forming the fuzzy pair-wise comparison matrix of criteria

Each criterion in the hierarchical structure is compared with other criteria in a fuzzy pair-wise comparison matrix. The fuzzy pair-wise comparison matrix is defined as:

$$\tilde{A} = \begin{bmatrix} (1,1,1) & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & (1,1,1) & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \dots & (1,1,1) \end{bmatrix}, \tag{3}$$

$$\tilde{x}_{ij} = (1,1,1), \ (i,j = 1,2,3,...,n; \ i = j), \tag{4}$$

$$\tilde{x}_{ij} = \frac{\tilde{W}_i}{\tilde{W}_j}, \ (i,j = 1,2,3,...,n; \ i \neq j), \tag{5}$$

where $\tilde{A}$ is a fuzzy pair-wise comparison matrix, $\tilde{x}_{ij}$ is a triangular fuzzy number that expresses the relative importance of criterion i with respect to criterion j. $\tilde{W}_i$ and $\tilde{W}_j$ are the aggregated fuzzy weights of criteria i and j, respectively.

2.8. Applying Chang's extent analysis

Chang's extent analysis is used to determine the relative weights of the criteria. The method of Chang's extent analysis [4] is briefly described below.

Let $X = \{x_1, x_2, x_3, ..., x_n\}$ be an object set, and $G = \{g_1, g_1, g_3, ..., g_m\}$ be a goal set. Each object is taken and extent analysis is performed for each goal. Therefore, m extent analysis values for each object can be obtained as:

$$M_{gi}^1, M_{gi}^2, ..., M_{gi}^m, \quad i = 1, 2, 3, ..., n, \tag{6}$$

where $M_{gi}^j (j = 1, 2, 3, ..., m)$ all are triangular fuzzy numbers. The steps of Chang's extent analysis are as follows.

The values of fuzzy synthetic extent with respect to the ith object (S_i) are defined as:

$$S_i = \sum_{j=1}^{m} M_{gi}^j \bigotimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1}. \tag{7}$$

To obtain $\sum_{j=1}^{m} M_{gi}^j$, the fuzzy addition operation of m extent analysis values is performed for a particular matrix such that:

$$\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right). \tag{8}$$

To obtain $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1}$, the fuzzy addition operation of $M_{gi}^j (j = 1, 2, 3, ..., m)$ values is performed such that:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right). \tag{9}$$

The inverse of the vector in Eq. (9) is then computed according to:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right). \tag{10}$$

As $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two triangular fuzzy numbers, the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as:

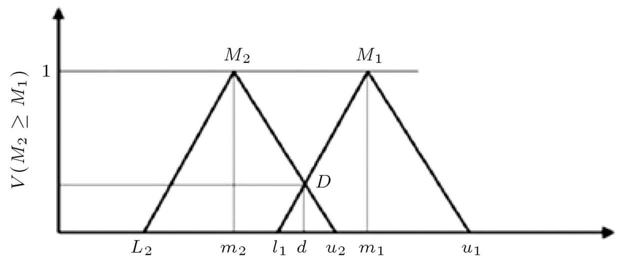

Figure 2. The intersection between M_1 and M_2 [4].

$$V(M_2 \geq M_1) = \sup_{y \geq x} \lfloor \min(\mu_{M_1}(x), \mu_{M_2}(y)) \rfloor. \tag{11}$$

And it can be expressed as:

$$V(M_2 \geq M_1) = hgt(M_1 \bigcap M_2) = \mu_{M_2}(d)$$

$$= \begin{cases} 1 & \text{if } \ m_2 \geq m_1 \\ 0 & \text{if } \ l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \tag{12}$$

Figure 2 is a graphical representation of Eq. (12) where d is the ordinate of the highest intersection point D between μ_{M_1} and μ_{M_2}. To compare M_1 and M_2 we need both values of $V(M_1 \geq M_2)$ & $V(M_1 \geq M_2)$.

If the degree of possibility for a convex fuzzy number is greater than k, then convex fuzzy $M_i(i = 1, 2 \cdots k)$ numbers can be defined as follows:

$$V(M \geq M_1, M_2, ..., M_k) = V[(M \geq M_1)$$

$$\text{and } (M \geq M_2) \text{ and ... and } (M \geq M_k)]$$

$$= \min V(M \geq M_i), \quad i = 1, 2, 3, ..., k. \tag{13}$$

Assuming that:

$$d'(A_i) = \min V(S_i \geq S_k) \quad \text{for} \quad k = 1, 2, ..., n; \quad k \neq i, \tag{14}$$

the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), ..., d'(A_n))^T, \tag{15}$$

where $A_i(i = 1, 2...n)$ are n elements. The normalized weight vectors are obtained as:

$$W = (d(A_1), d(A_2), ..., d(A_n))^T, \tag{16}$$

where W is a non-fuzzy number.

2.9. Applying the VIKOR method to rank alternatives

Assume an MCDM problem has m alternatives $(A_1, A_2, ..., A_m)$ and n decision criteria $(C_1, C_2, ..., C_n)$. The following steps are involved in the VIKOR method [23,24].

The decision matrix can be obtained as:

$$X = (x_{ij})_{m \times n}, \tag{17}$$

where x_{ij} is the performance of alternative A_i with respect to criterion j. The normalized decision matrix can be obtained as:

$$F = (f_{ij})_{m \times n}, \tag{18}$$

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \ i = 1, 2, 3, ..., m; \ j = 1, 2, 3, ..., n. \tag{19}$$

The best values (f_j^+) and the worst values (f_j^-) of all criterion functions for $j = 1, 2, ..., n$ are determined as:

$$f_j^* = \max_i f_{ij}, f_j^- = \min_i f_{ij}, \text{if } j \in B, \tag{20}$$

$$f_j^* = \min_i f_{ij}, f_j^- = \max_i f_{ij}, \text{if } j \in C, \tag{21}$$

in which f_j^* and f_j^- represent the positive ideal solution and the negative ideal solution for the criterion j, respectively; B is the set of benefit criteria (+) and C is the set of cost criteria (-).

The values of S_i and R_i for $i = 1, 2, 3, ..., m$ are computed as:

$$S_i = \sum_{j=1}^{n} \frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)}, \tag{22}$$

$$R_i = \max_j \left[\sum_{j=1}^{n} \frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right], \tag{23}$$

where w_j $(\sum_{j=1}^{n} w_j = 1, w_j \in [0, 1], \ j = 1, 2, ..., n)$ are the relative importance weights of the criterion j.

The Q_i values for $j = 1, 2, 3, ..., n$ are computed as:

$$Q_i = v \left[\frac{S_i - S^*}{S^- - S^*} \right] + (1 - v) \left[\frac{R_i - R^*}{R^- - R^*} \right], \tag{24}$$

$$S^* = \min_i S_i, \tag{25}$$

$$S^- = \max_i S_i, \tag{26}$$

$$R^* = \min_i R_i, \tag{27}$$

$$R^- = \max_i R_i, \tag{28}$$

with v introduced as a weight for the strategy of maximum group utility, whereas $1 - v$ is the weight of the individual regret.

Ranking the alternatives (sorting by the values S_i, R_i and Q_i in decreasing order), the results will be three ranking lists. Proposed as a compromise solution, the alternative A_1 which is the best rank by the measure

Q_i (minimum) will be reached if the following two conditions (Condition 1 and Condition 2) are satisfied:

Condition 1. Acceptable advantage:

$$Q_{A_2} - Q_{A_1} \geq \frac{1}{n-1}, \tag{29}$$

where A_2 is the alternative with second position in the ranking list by Q_i, and n is the number of alternatives.

Condition 2. Acceptable stability in decision making:

The alternative A_1 must also be the best rank by S_i or/and R_i. This compromise solution is stable within a decision making process, which could be the strategy of maximum group utility (when $v > 0.5$ is needed), or "by consensus" $v \approx 0.5$, or "with veto" ($v < 0.5$).

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives $A_1, A_2, ..., A_M$ if Condition 1 is not satisfied; A_M is determined by the relation $Q_{A_M} - Q_{A_1} \geq (1/(n-1))$ for maximum M (the positions of these alternatives are "in closeness"), or:
- Alternatives A_1 and A_2 if only Condition 2 is not satisfied.

3. Case study

The case study focuses on selection of a suitable site for an earth dam in Harsin City. The aims of this dam are developments in agriculture and industry, drinking water supply, power generation, fisheries, etc. in Harsin City, Iran. The city is located 16 km east of Kermanshah (the capital of Kermanshah Province, Iran). Its longitude and latitude are $34°16'$ and $45°35'$ respectively.

In the first step, to determine effective factors in selecting an appropriate earth dam site for the Harsin dam, a comprehensive literature review was conducted and the most important criteria were selected. A brief explanation of the selected criteria is presented below.

Health of dam site (C_1): In this criterion, geotechnical and geological parameters were considered.

Overall cost (C_2): The overall cost includes the costs of construction of dam body and reservoir, water diversion during construction, water transfer to consumption location, energy supply, site preparation, land use, and other costs associated with the dam project.

Annual yield (C_3): It is the annual volume of the water that passes through the cross section of the river at the dam site. Annual yield plays an important role in locating the dam site.

Topographic conditions (C_4): The existence of a secondary valley or rock abutments with suitable topography around the main river is important for constructing dam spillway. In general, the best site for an earth dam is where a wide valley with high walls leads to a narrow canyon with tenacious walls.

Access to materials and facilities (C_5): Access to materials (borrow sources, cement, etc.) and facilities (power transmission lines, oil and gas distribution pipelines, road, etc.) is also important in deciding the best location for a dam.

Economic development (C_6): The effects of dam construction on agricultural and industrial development, power generation, fishery, job creation, etc. (which are related to economic development) are regarded as important attributes for selecting the dam site.

Water quality (C_7): Quality of water stored in reservoirs used for drinking and agricultural purposes is important.

Damage of dam body and reservoir (C_8): Environmental damages (wildlife, vegetation, cutting trees, etc.), and socio-economic damages (destroying mines, historical monuments, agricultural lands, displacement of peoples, displacement of roads, railway and power lines, changing the route of oil and gas pipelines, telecommunication facilities, etc.) caused by the construction of the dam body should be considered.

Volume of reservoir (C_9): When the reservoir that is created after dam construction has a large volume, the surface area of the reservoir water is increased and it has more impact on the local climate. Furthermore, evaporation and potential for water pollution will increase with increasing the surface area. Therefore, the dam should be constructed where the reservoir capacity is optimal.

River flow regime (C_{10}): Seasonal rivers have more sediment transport and hence lower water quality. In addition, the management of water resources is more difficult due to the lack of accurate information on the discharge of water entering the reservoir. Therefore, a permanent flow regime would be more favorable.

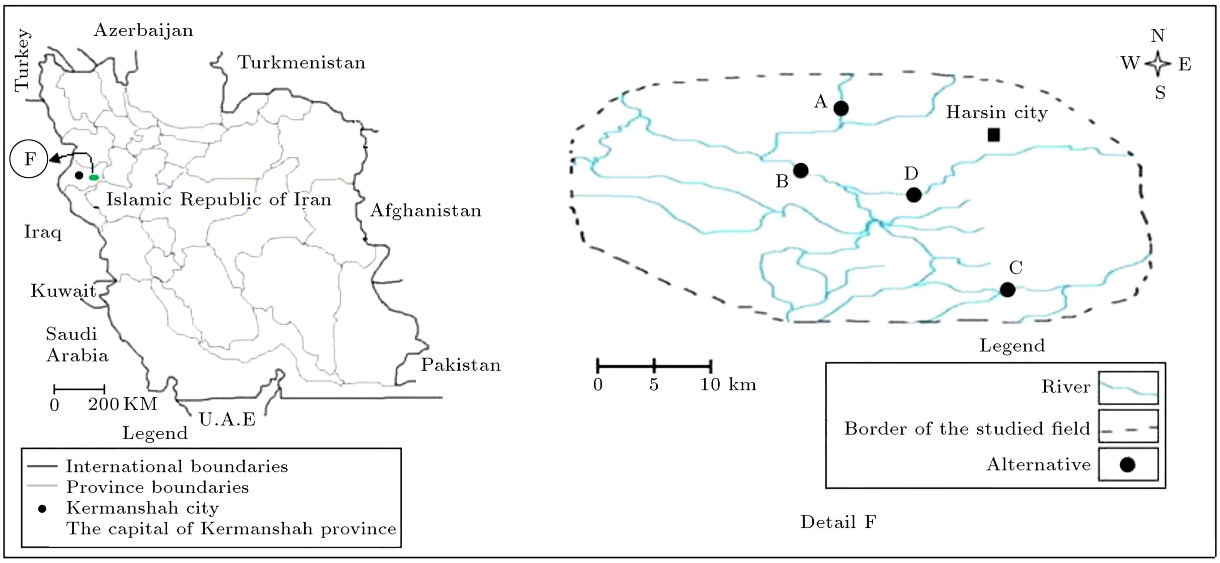

Figure 3. Alternatives for the Harsin earth dam site.

Water diversion and transfer (C_{11}): The dam site should be located where the costs of water diversion during construction and water transfer to consumption location are minimum.

Annual volume of sediment (C_{12}): If the annual volume of sediment entering the reservoir is kept to minimum, the volume of the reservoir during its useful life, water quality and the efficiency of dam would be higher.

Probability of dam break (C_{13}): The dam should be constructed in a place that minimizes the socio-economic risks posed by a possible dam break.

Probable maximum flood (C_{14}): The maximum volume of water caused by thawing snow and ice or other atmospheric precipitation occurring within a specified return period in rivers is called probable maximum flood.

Average annual evaporation (C_{15}): Due to the annual average temperature differences in different regions in Iran, evaporation from the dam reservoirs varies regionally. This variability has effects on the retention time of water in the reservoir (in terms of volume) and consequently on the efficiency of the dam.

Environmental impacts (C_{16}): Changing weather conditions, vegetation, and wild life are other attributes that play significant roles in locating the dam site.

Social impacts (C_{17}): The social impacts of relocation of population centers and the integration of different ethnic cultures due to the appropriation of residential lands for dam construction, reservoir dewatering and also utilizing the dam water in downstream should be considered.

Political impacts (C_{18}): The dam construction goals for reducing political tensions including water supply of a city, preventing grievances and immigration of residents of a border city, etc. are among the attributes that should also be considered.

After collecting and evaluating the required information based on the selected criteria (mentioned above), four feasible alternatives were proposed for the Harsin earth dam site. The locations of the proposed alternatives are shown in Figure 3 and identified by 'A', 'B', 'C' and 'D' letters.

After selecting the criteria for locating the earth dam site and considering alternatives (see Figure 3), the integrated fuzzy AHP and VIKOR method was applied to select the best site. Figure 4 shows the problem of Harsin earth dam site selection using a hierarchical structure. The structure has three levels: objective (locating the Harsin earth dam site), criteria (C_1 to C_{18}) and alternatives (A, B, C, and D).

To assess the relevance of the criteria incorporated in the fuzzy AHP group method, a questionnaire was developed, and 4 experts (E_1, E_2, E_3 and E_4) involved in Harsin earth dam project were asked to express the importance of each criterion using linguistic variables which were inserted in the questionnaire. Table 2 summarizes the expert opinions about the importance of the different criteria.

The aggregated fuzzy weights of the criteria were obtained by integrating expert opinions using Eqs. (1) and (2). Then, a fuzzy pair-wise comparison matrix for determining the weights of criteria was formed according to Table 3 (see Eqs. (3) to (5)).

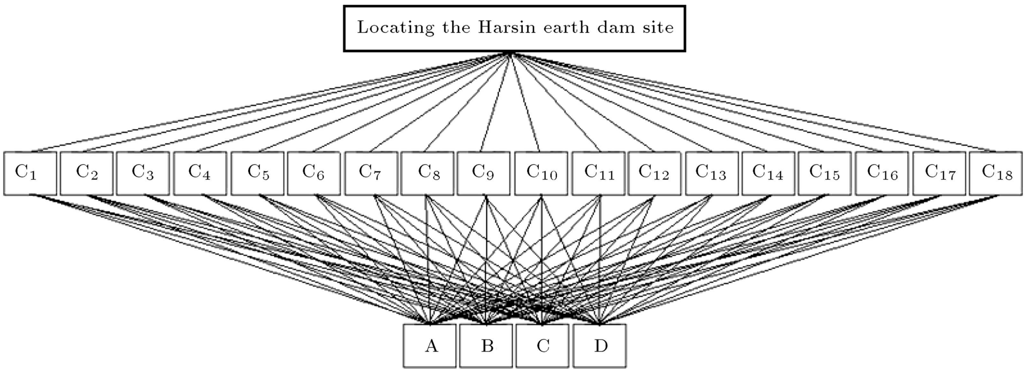

Figure 4. Problem of the Harsin earth dam site selection using a Hierarchical structure.

Table 2. Expert opinions about the importance of the different criteria.

Criteria	Expert			
	E1	**E2**	**E3**	**E4**
C_1	VH	VH	VH	VH
C_2	M	L	H	H
C_3	VH	H	VH	H
C_4	H	VH	H	M
C_5	VH	VH	VH	VH
C_6	VH	VH	VH	H
C_7	H	H	VH	VH
C_8	H	H	M	H
C_9	L	H	H	M
C_{10}	H	M	L	L
C_{11}	VH	H	VH	VH
C_{12}	M	M	H	H
C_{13}	M	H	M	L
C_{14}	H	H	L	M
C_{15}	M	H	L	H
C_{16}	M	M	H	L
C_{17}	M	M	L	L
C_{18}	L	L	L	L

The weights of the criteria were calculated using the fuzzy HAP process where the values of fuzzy synthetic extent with respect to the ith object ($i = 1, 2, ..., 18$) were obtained using Eq. (7); the results are given in Table 4. Table 5 lists the degrees of possibility $S_i \geq S_k$ ($i, k = 1, ..., 18; i \neq k$) calculated using Eq. (12), while Table 6 enumerates the minimum degrees of possibility $S_j \geq S_i$ obtained using Eq. (14).

These values (Table 6) yield the following weight vector according to Eq. (15):

$$W' = (1.000, 0.960, 0.989, 0.978, 1.000, 0.995, 0.989, 0.973, 0.960, 0.949, 0.995, 0.968, 0.955, 0.960, 0.960, 0.955, 0.929, 0.887)^T.$$

After normalization, the normalized weights of the criteria were calculated using Eq. (16) as:

$$W = (0.0575, 0.0552, 0.0568, 0.0562, 0.0575, 0.0572, 0.0568, 0.0559, 0.0552, 0.0546, 0.0572, 0.0556, 0.0549, 0.0552, 0.0552, 0.0549, 0.0534, 0.0509)^T.$$

The VIKOR method was then applied to rank the alternatives. The normalized decision matrix was obtained using Eqs. (18) and (19), and the resulting matrix is given in Table 7. Table 8 presents the values of f_j^* and f_j^- with respect to each criterion using Eqs. (20) and (21).

Using Eqs. (22) and (23), the values S_i and R_i for alternative i were obtained as:

$$S_A = 0.5424, \quad R_A = 0.0575,$$

$$S_B = 0.3452, \quad R_B = 0.0572,$$

$$S_C = 0.6012, \quad R_C = 0.0575,$$

$$S_D = 0.4996, \quad R_D = 0.0572.$$

The values of S^*, S^-, R^* and R^- were obtained according to Eqs. (25)-(28) as:

$$S^* = 0.3452, \quad S^- = 0.6012,$$

$$R^* = 0.0572, \quad R^- = 0.0575.$$

Then, using Eq. (24) the VIKOR values (Q_i) for each alternative were obtained as:

Table 3. Fuzzy pair-wise comparison matrix of criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	(1.00,1.00,1.00)	(0.78,1.64,9.00)	(0.78,1.13,1.80)	(0.78,1.29,3.00)	(0.78,1.00,1.29)	(0.78,1.06,1.80)	(0.78,1.13,1.80)	(0.78,1.38,3.00)	(0.78,1.64,9.22)
C_2	(0.11,0.61,1.29)	(1.00,1.00,1.00)	(0.11,0.69,1.80)	(0.11,0.79,3.00)	(0.11,0.61,1.29)	(0.11,0.65,1.80)	(0.11,0.69,1.80)	(0.11,0.85,3.00)	(0.11,1.00,9.00)
C_3	(0.56,0.89,1.29)	(0.56,1.45,9.00)	(1.00,1.00,1.00)	(0.56,1.14,3.00)	(0.56,0.89,1.29)	(0.56,0.94,1.80)	(0.56,1.00,1.80)	(0.56,1.23,3.00)	(0.56,1.45,9.00)
C_4	(0.33,0.78,1.29)	(0.33,1.27,9.00)	(0.33,0.88,1.80)	(1.00,1.00,1.00)	(0.33,0.78,1.29)	(0.33,0.82,1.80)	(0.33,0.88,1.80)	(0.33,1.08,3.00)	(0.33,1.27,9.00)
C_5	(0.78,1.00,1.29)	(0.78,1.64,9.00)	(0.78,1.13,1.80)	(0.78,1.29,3.00)	(1.00,1.00,1.00)	(0.78,1.06,1.80)	(0.78,1.13,1.80)	(0.78,1.38,3.00)	(0.78,1.64,9.00)
C_6	(0.56,0.94,1.29)	(0.56,1.55,9.00)	(0.56,1.06,1.80)	(0.56,1.21,3.00)	(0.56,0.94,1.29)	(1.00,1.00,1.00)	(0.56,1.06,1.80)	(0.56,1.31,3.00)	(0.56,1.55,9.00)
C_7	(0.56,0.89,1.29)	(0.56,1.45,9.00)	(0.56,1.00,1.80)	(0.56,1.14,3.00)	(0.56,0.89,1.29)	(0.56,0.94,1.80)	(1.00,1.00,1.00)	(0.56,1.23,3.00)	(0.56,1.45,9.00)
C_8	(0.33,0.72,1.29)	(0.33,1.18,9.00)	(0.33,0.81,1.80)	(0.33,0.93,3.00)	(0.33,0.72,1.29)	(0.33,0.76,1.80)	(0.33,0.81,1.80)	(1.00,1.00,1.00)	(0.33,1.18,9.00)
C_9	(0.11,0.61,1.29)	(0.11,1.00,9.00)	(0.11,0.69,1.80)	(0.11,0.79,3.00)	(0.11,0.61,1.29)	(0.11,0.65,1.80)	(0.11,0.69,1.80)	(0.11,0.85,3.00)	(1.00,1.00,1.00)
C_{10}	(0.11,0.50,1.29)	(0.11,0.82,9.00)	(0.11,0.56,1.80)	(0.11,0.64,3.00)	(0.11,0.50,1.29)	(0.11,0.53,1.80)	(0.11,0.56,1.80)	(0.11,0.69,3.00)	(0.11,0.82,9.00)
C_{11}	(0.56,0.94,1.29)	(0.56,1.55,9.00)	(0.56,1.06,1.80)	(0.56,1.21,3.00)	(0.56,0.94,1.29)	(0.56,1.00,1.80)	(0.56,1.06,1.80)	(0.56,1.31,3.00)	(0.56,1.55,9.00)
C_{12}	(0.33,0.67,1.29)	(0.33,1.09,9.00)	(0.33,0.75,1.80)	(0.33,0.86,3.00)	(0.33,0.67,1.29)	(0.33,0.71,1.80)	(0.33,0.75,1.80)	(0.33,0.92,3.00)	(0.33,1.09,9.00)
C_{13}	(0.11,0.56,1.29)	(0.11,0.91,9.00)	(0.11,0.63,1.80)	(0.11,0.71,3.00)	(0.11,0.56,1.29)	(0.11,0.59,1.80)	(0.11,0.63,1.80)	(0.11,0.77,3.00)	(0.11,0.91,9.00)
C_{14}	(0.11,0.61,1.29)	(0.11,1.00,9.00)	(0.11,0.69,1.80)	(0.11,0.79,3.00)	(0.11,0.61,1.29)	(0.11,0.65,1.80)	(0.11,0.69,1.80)	(0.11,0.85,3.00)	(0.11,1.00,9.00)
C_{15}	(0.11,0.61,1.29)	(0.11,1.00,9.00)	(0.11,0.69,1.80)	(0.11,0.79,3.00)	(0.11,0.61,1.29)	(0.11,0.65,1.80)	(0.11,0.69,1.80)	(0.11,0.85,3.00)	(0.11,1.00,9.00)
C_{16}	(0.11,0.56,1.29)	(0.11,0.91,9.00)	(0.11,0.63,1.80)	(0.11,0.71,3.00)	(0.11,0.56,1.29)	(0.11,0.59,1.80)	(0.11,0.63,1.80)	(0.11,0.77,3.00)	(0.11,0.91,9.00)
C_{17}	(0.11,0.44,1.00)	(0.11,0.73,7.00)	(0.11,0.50,1.40)	(0.11,0.57,2.33)	(0.11,0.44,1.00)	(0.11,0.47,1.40)	(0.11,0.50,1.40)	(0.11,0.62,2.33)	(0.11,0.73,7.00)
C_{18}	(0.11,0.33,0.71)	(0.11,0.55,5.00)	(0.11,0.38,1.00)	(0.11,0.43,1.67)	(0.11,0.33,0.71)	(0.11,0.35,1.00)	(0.11,0.38,1.00)	(0.11,0.46,1.67)	(0.11,0.55,5.00)

	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}
C_1	(0.78,2.00,9.00)	(0.78,1.06,1.80)	(0.78,1.50,3.00)	(0.78,1.80,9.00)	(0.78,1.64,9.00)	(0.78,1.64,9.00)	(0.78,1.80,9.00)	(1.00,2.25,9.00)	(1.40,3.00,9.00)
C_2	(0.11,1.22,9.00)	(0.11,0.65,1.80)	(0.11,0.92,3.00)	(0.11,1.10,9.00)	(0.11,1.00,9.00)	(0.11,1.00,9.00)	(0.11,1.10,9.00)	(0.14,1.38,9.00)	(0.20,1.83,9.00)
C_3	(0.56,1.78,9.00)	(0.56,0.94,1.80)	(0.56,1.33,3.00)	(0.56,1.60,9.00)	(0.56,1.45,9.00)	(0.56,1.45,9.00)	(0.56,1.60,9.00)	(0.71,2.00,9.00)	(1.00,2.67,9.00)
C_4	(0.33,1.56,9.00)	(0.33,0.82,1.80)	(0.33,1.17,3.00)	(0.33,1.40,9.00)	(0.33,1.27,9.00)	(0.33,1.27,9.00)	(0.33,1.40,9.00)	(0.43,1.75,9.00)	(0.60,2.33,9.00)
C_5	(0.78,2.00,9.00)	(0.78,1.06,1.80)	(0.78,1.50,3.00)	(0.78,1.80,9.00)	(0.78,1.64,9.00)	(0.78,1.64,9.00)	(0.78,1.80,9.00)	(1.00,2.25,9.00)	(1.40,3.00,9.00)
C_6	(0.56,1.89,9.00)	(0.56,1.00,1.80)	(0.56,1.42,3.00)	(0.56,1.70,9.00)	(0.56,1.55,9.00)	(0.56,1.55,9.00)	(0.56,1.70,9.00)	(0.71,2.13,9.00)	(1.00,2.83,9.00)
C_7	(0.56,1.78,9.00)	(0.56,0.94,1.80)	(0.56,1.33,3.00)	(0.56,1.60,9.00)	(0.56,1.45,9.00)	(0.56,1.45,9.00)	(0.56,1.60,9.00)	(0.71,2.00,9.00)	(1.00,2.67,9.00)
C_8	(0.33,1.44,9.00)	(0.33,0.76,1.80)	(0.33,1.08,3.00)	(0.33,1.30,9.00)	(0.33,1.18,9.00)	(0.33,1.18,9.00)	(0.33,1.30,9.00)	(0.43,1.63,9.00)	(0.60,2.17,9.00)
C_9	(0.11,1.22,9.00)	(0.11,0.65,1.80)	(0.11,0.92,3.00)	(0.11,1.10,9.00)	(0.11,1.10,9.00)	(0.11,1.00,9.00)	(0.11,1.10,9.00)	(0.14,1.38,9.00)	(0.20,1.83,9.00)
C_{10}	(1.00,1.00,1.00)	(0.11,0.53,1.80)	(0.11,0.75,3.00)	(0.11,0.90,9.00)	(0.11,0.82,9.00)	(0.11,0.82,9.00)	(0.11,0.90,9.00)	(0.14,1.13,9.00)	(0.20,1.50,9.00)
C_{11}	(0.56,1.89,9.00)	(1.00,1.00,1.00)	(0.56,1.42,3.00)	(0.56,1.70,9.00)	(0.56,1.55,9.00)	(0.56,1.55,9.00)	(0.56,1.70,9.00)	(0.71,2.13,9.00)	(1.00,2.83,9.00)
C_{12}	(0.33,1.33,9.00)	(0.33,0.71,1.80)	(1.00,1.00,1.00)	(0.33,1.20,9.00)	(0.33,1.09,9.00)	(0.33,1.09,9.00)	(0.33,1.20,9.00)	(0.43,1.50,9.00)	(0.60,2.00,9.00)
C_{13}	(0.11,1.11,9.00)	(0.11,0.59,1.80)	(0.11,0.83,3.00)	(1.00,1.00,1.00)	(0.11,0.91,9.00)	(0.11,0.91,9.00)	(0.11,1.00,9.00)	(0.14,1.25,9.00)	(0.20,1.67,9.00)
C_{14}	(0.11,1.22,9.00)	(0.11,0.65,1.80)	(0.11,0.92,3.00)	(0.11,1.10,9.00)	(1.00,1.00,1.00)	(0.11,1.00,9.00)	(0.11,1.10,9.00)	(0.14,1.38,9.00)	(0.20,1.83,9.00)
C_{15}	(0.11,1.22,9.00)	(0.11,0.65,1.80)	(0.11,0.92,3.00)	(0.11,1.10,9.00)	(0.11,1.00,9.00)	(1.00,1.00,1.00)	(0.11,1.10,9.00)	(0.14,1.38,9.00)	(0.20,1.83,9.00)
C_{16}	(0.11,1.11,9.00)	(0.11,0.59,1.80)	(0.11,0.83,3.00)	(0.11,1.00,9.00)	(0.11,0.91,9.00)	(0.11,0.91,9.00)	(1.00,1.00,100)	(0.14,1.25,9.00)	(0.20,1.67,9.00)
C_{17}	(0.11,0.89,7.00)	(0.11,0.47,1.40)	(0.11,0.67,2.33)	(0.11,0.80,7.00)	(0.11,0.73,7.00)	(0.11,0.73,7.00)	(0.11,0.80,7.00)	(1.00,1.00,1.00)	(0.20,1.33,7.00)
C_{18}	(0.11,0.67,5.00)	(0.11,0.35,1.00)	(0.11,0.50,1.67)	(0.11,0.60,5.00)	(0.11,0.55,5.00)	(0.11,0.55,5.00)	(0.11,0.60,5.00)	(0.14,0.75,5.00)	(1.00,1.00,1.00)

Table 4. The value of fuzzy synthetic extent with respect to the ith object.

S_i	Value
S_1	(0.009,0.079,0.813)
S_2	(0.002,0.048,0.750)
S_3	(0.007,0.070,0.809)
S_4	(0.004,0.061,0.799)
S_5	(0.009,0.079,0.813)
S_6	(0.007,0.075,0.809)
S_7	(0.007,0.070,0.809)
S_8	(0.004,0.057,0.799)
S_9	(0.002,0.048,0.750)
S_{10}	(0.002,0.039,0.750)
S_{11}	(0.007,0.075,0.809)
S_{12}	(0.004,0.053,0.799)
S_{13}	(0.002,0.044,0.750)
S_{14}	(0.002,0.048,0.750)
S_{15}	(0.002,0.048,0.750)
S_{16}	(0.002,0.044,0.750)
S_{17}	(0.002,0.035,0.585)
S_{18}	(0.002,0.026,0.420)

$$Q_A = 0.8850, \qquad Q_B = 0.0000,$$

$$Q_C = 1.0000, \qquad Q_D = 0.3016.$$

In the final step, the alternatives were ranked based on S_i, R_i, Q_i as individuals and the results are presented in Table 9. Based on Q_i, B and D are the alternatives with the first and second positions, respectively. For these two alternatives, Condition 1:

$$(Q_D - Q_B = 0.3016) < \left(\frac{1}{n-1} = 0.33\right), \tag{30}$$

is not satisfied based on Eq. (29), but Condition 2 is satisfied. Therefore, with respect to these results (Table 9), B and D are proposed as the best alternatives for the Harsin earth dam site. Figure 5 shows the front view of these alternatives.

4. Sensitivity analysis

To evaluate the performance of the proposed method, a comprehensive sensitivity analysis was carried out based on the importance of the criteria. In one of the tests, the effect of each criterion was examined by reducing the weight of each criterion separately by

Table 5. Degrees of possibility $S_i \geq S_k$.

i	***k***																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.0 00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.960		0.971	0.983	0.960	0.966	0.971	0.988	1.000	1.000	0.9 66	0.994	1.000	1.000	1.000	1.000	1.000	1.000
3	0.989	1.000	1.000	0.989	0.995	1.000	1.000	1.000	1.000	0.9 95	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
4	0.978	1.000	0.989		0.978	0.984	0.989	1.000	1.000	1.000	0.9 84	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	1.000	1.000	1.000	1.000		1.000	1.000	1.000	1.000	1.000	1.0 00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6	0.995	1.000	1.000	1.000	0.995		1.000	1.000	1.000 1	.000	1.0 00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7	0.989	1.000	1.000	1.000	0.989	0.995		1.000	1.000	1.000	0.9 95	1.000	1.000	1.000	1.000	1.000	1.000	1.000
8	0.973	1.000	0.984	0.995	0.973	0.978	0.984		1.000	1.000	0.9 78	1.000	1.000	1.000	1.000	1.000	1.000	1.000
9	0.960	1.000	0.971	0.983	0.960	0.966	0.971	0.988		1.000	0.9 66	0.994	1.000	1.000	1.000	1.000	1.000	1.000
10	0.949	0.988	0.960	0.971	0.949	0.955	0.960	0.977	0.988		0.955	0.983	0.994	0.988	0.988	0.994	1.000	1.000
11	0.995	1.000	1.000	1.000	0.995	1.000	1.000	1.000	1.000	1.0 00		1.000	1.000	1.000	1.000	1.000	1.000	1.000
12	0.968	1.000	0.978	0.989	0.968	0.973	0.978	0.995	1.000	1.000	0.973		1.000	1.000	1.000	1.000	1.000	1.000
13	0.955	0.994	0.966	0.977	0.955	0.960	0.966	0.983	0.994	1.0 00	0.960	0.988		0.994	0.994	1.000	1.000	1.000
14	0.960	1.000	0.971	0.983	0.960	0.966	0.971	0.988	1.000	1.0 00	0.966	0.994	1.000		1.000	1.000	1.000	1.000
15	0.960	1.000	0.971	0.983	0.960	0.966	0.971	0.988	1.000	1.0 00	0.966	0.994	1.000	1.000		1.000	1.000	1.000
16	0.955	0.994	0.966	0.977	0.955	0.960	0.966	0.983	0.994	1.0 00	0.960	0.988	1.000	0.994	0.994		1.000	1.000
17	0.929	0.978	0.943	0.957	0.929	0.936	0.943	0.964	0.978	0.9 93	0.936	0.971	0.985	0.978	0.978	0.985		1.000
18	0.887	0.950	0.904	0.922	0.887	0.896	0.904	0.931	0.950	0.9 70	0.896	0.941	0.960	0.950	0.950	0.960	0.979	

Table 6. Minimum degrees of possibility $S_i \geq S_k$.

Min $V(s_i \geq S_k)$	**value**
min $V(S_1 \geq S_k)$	1.000
min $V(S_2 \geq S_k)$	0.960
min $V(S_3 \geq S_k)$	0.989
min $V(S_4 \geq S_k)$	0.978
min $V(S_5 \geq S_k)$	1.000
min $V(S_6 \geq S_k)$	0.995
min $V(S_7 \geq S_k)$	0.989
min $V(S_8 \geq S_k)$	0.973
min $V(S_9 \geq S_k)$	0.960
min $V(S_{10} \geq S_k)$	0.949
min $V(S_{11} \geq S_k)$	0.995
min $V(S_{12} \geq S_k)$	0.968
min $V(S_{13} \geq S_k)$	0.955
min $V(S_{14} \geq S_k)$	0.960
min $V(S_{15} \geq S_k)$	0.960
min $V(S_{16} \geq S_k)$	0.955
min $V(S_{17} \geq S_k)$	0.929
min $V(S_{18} \geq S_k)$	0.887

two levels (i.e., from VH to M). If the importance of C_2, C_3, C_4, C_5, C_7, C_8, C_9, C_{10}, C_{11}, C_{12}, C_{13}, C_{14}, C_{15}, C_{16}, C_{17} and C_{18} is reduced by two levels, the optimal alternatives remain unchanged (alternatives B and D).

Table 7. Normalized fuzzy decision matrix.

Criterion	**Alternative**			
	A	**B**	**C**	**D**
C_1 (+)	0.000210	0.000210	0.000030	0.000270
C_2 (-)	0.008606	0.008216	0.008006	0.007196
C_3 (+)	0.017091	0.016612	0.005397	0.003598
C_4 (+)	0.000150	0.000210	0.000270	0.000270
C_5 (+)	0.000090	0.000150	0.000210	0.000270
C_6 (+)	0.000150	0.000150	0.000210	0.000210
C_7 (+)	0.000270	0.000210	0.000150	0.000150
C_8 (-)	0.000150	0.000150	0.000210	0.000210
C_9 (+)	0.000150	0.000150	0.000090	0.000090
C_{10} (+)	0.005397	0.004888	0.006957	0.006597
C_{11} (-)	0.000150	0.000090	0.000150	0.000270
C_{12} (-)	0.000660	0.000690	0.000750	0.000810
C_{13} (-)	0.000150	0.000030	0.000270	0.000090
C_{14} (-)	0.709743	0.639278	0.226686	0.151124
C_{15} (-)	0.047976	0.053973	0.062339	0.056971
C_{16} (+)	0.000150	0.000270	0.000150	0.000270
C_{17} (+)	0.000090	0.000150	0.000150	0.000090
C_{18} (+)	0.000150	0.000210	0.000150	0.000150

Table 8. Best and worst values with respect to each criterion.

Criterion	f_j^*	f_j^-
C_1 (+)	0.000270	0.000030
C_2 (-)	0.007196	0.008606
C_3 (+)	0.017091	0.003598
C_4 (+)	0.000270	0.000150
C_5 (+)	0.000270	0.000090
C_6 (+)	0.000210	0.000150
C_7 (+)	0.000270	0.000150
C_8 (-)	0.000150	0.000210
C_9 (+)	0.000150	0.000090
C_{10} (+)	0.006957	0.004888
C_{11} (-)	0.000090	0.000270
C_{12} (-)	0.000660	0.000810
C_{13} (-)	0.000030	0.000270
C_{14} (-)	0.151124	0.709743
C_{15} (-)	0.047976	0.062339
C_{16} (+)	0.000270	0.000150
C_{17} (+)	0.000150	0.000090
C_{18} (+)	0.000210	0.000150

If the importance of C_1 is reduced by two levels, the set of alternatives If the importance of C_1 is reduced by two levels, the set of alternatives B, C and D are selected as the optimal alternatives. If the importance of C_4 is reduced by two levels, the alternative B climbs to first position in overall ranking.

Considering the results of the sensitivity analysis and local surveys, the experts involved in design of the dam confirmed the soundness of the research methodology and findings.

5. Conclusions

This paper has two main contributions. First, it presents the influential criteria and their corresponding weights to locate optimal site for a dam. Second, it presents a combined group fuzzy AHP and VIKOR method to locate the dam site. The proposed method has a number of advantages. For instance, it engages different qualitative and quantitative variables in selecting the final choice. The determination of the weights of the criteria is of great importance as they have qualitative nature and are associated with uncertainties. To deal with this feature, the fuzzy AHP approach performed well.

Once the weights of the criteria are determined and all other information from potential dam sites are collected, a decision-making system is needed to prioritize different alternatives. In this study, the VIKOR method was used for prioritization. The method presented in this paper was applied to locate the optimal site for the Harsin dam, Iran. Among the potential alternative locations, sites 'B' and 'D' were found to be the best alternatives. Finally, by considering the results of this integrated method and consulting experts, the alternative 'D' was selected as the optimal location for the Harsin earth dam site. The proposed method is considered an effective and reliable method in selecting the optimal dam site.

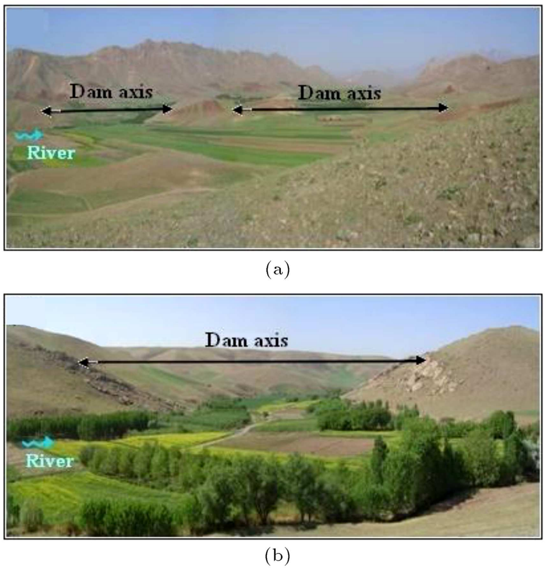

Figure 5. Front view of the proposed alternatives for the Harsin earth dam site: (a) Alternative B; and (b) alternative D.

Acknowledgment

The authors would like to appreciate Kermanshah Regional Water Company and Pandam Consulting

Table 9. Ranking the alternatives.

Alternative	Based on S_i		Based on R_i		Based on Q_i		Proposed alternative(s)		
	Value	Rank	Value	Rank	Value	Rank	Based on Condition 1	Based on Condition 2	Generally
A	0.5424	3	0.0575	2	0.8850	3	B and D	B	B and D
B	0.3452	1	0.0572	1	0.0000	1			
C	0.6012	4	0.0575	2	1.0000	4			
D	0.4996	2	0.0572	1	0.3016	2			

Engineers Company for providing the required information and data.

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