Site selection for managed aquifer recharge using fuzzy rules: integrating geographical information system (GIS) tools and multi-criteria decision making

Bahram Malekmohammadi · Majid Ramezani Mehrian · Hamid Reza Jafari

Abstract One of the most important water-resources management strategies for arid lands is managed aquifer recharge (MAR). In establishing a MAR scheme, site selection is the prime prerequisite that can be assisted by geographic information system (GIS) tools. One of the most important uncertainties in the site-selection process using GIS is finite ranges or intervals resulting from data classification. In order to reduce these uncertainties, a novel method has been developed involving the integration of multi-criteria decision making (MCDM), GIS, and a fuzzy inference system (FIS). The Shemil-Ashkara plain in the Hormozgan Province of Iran was selected as the case study; slope, geology, groundwater depth, potential for runoff, land use, and groundwater electrical conductivity have been considered as site-selection factors. By defining fuzzy membership functions for the input layers and the output layer, and by constructing fuzzy rules, a FIS has been developed. Comparison of the results produced by the proposed method and the traditional simple additive weighted (SAW) method shows that the proposed method yields more precise results. In conclusion, fuzzy-set theory can be an effective method to overcome associated uncertainties in classification of geographic information data.

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Keywords Managed aquifer recharge · Fuzzy inference system · Geographic information systems · Multi-criteria decision making · Iran

Introduction

With population increase, demand for reliable water supplies has increased. The situation is critical in places where groundwater is the only accessible water resource and groundwater use is more than the rate of recharge (Kalantari et al. 2010). In such areas, managed aquifer recharge (MAR) is an important water-resources management strategy (Mandal and Singh 2004). In arid regions, MAR has been used to: (1) augment the natural recharge by precipitation and surface-water runoff; (2) diminish the rate of fall of the water table of producing aquifers; (3) control the contamination of existing water supplies; (4) recharge water bodies by waste water; and (5) prevent interaction between saline and freshwater in the coastal regions (Abu-Taleb 2003).

Site selection, which has been defined as the evaluation of a variety of needs for the prospective location and the suggestion of an area on the basis of a proper assessment of the land, is the main issue and the prime prerequisite in a MAR scheme (Yi et al. 2010). Its success depends on the collection and analysis of significant geographic data (Kalantari et al. 2010).

Many studies have been done to determine the most suitable areas for MAR schemes; recently, GIS tools have often been used to analyze the geographic data. Elango and Arrikkat (1998) integrated and analyzed seven thematic layers related to groundwater recharge using GIS for the identification of potential recharge sites in parts of Ongur sub-basin in southern India. These layers were ranked, reclassified, and overlaid in GIS tools. They divided the study area into four zones including: very good, good, poor, and very poor, according to their potential for natural recharge. Ghayoumian et al. (2005) made a zoning map of MAR by overlaying layers such as slope, infiltration rate, depth of groundwater, water quality and land use, in a GIS environment.

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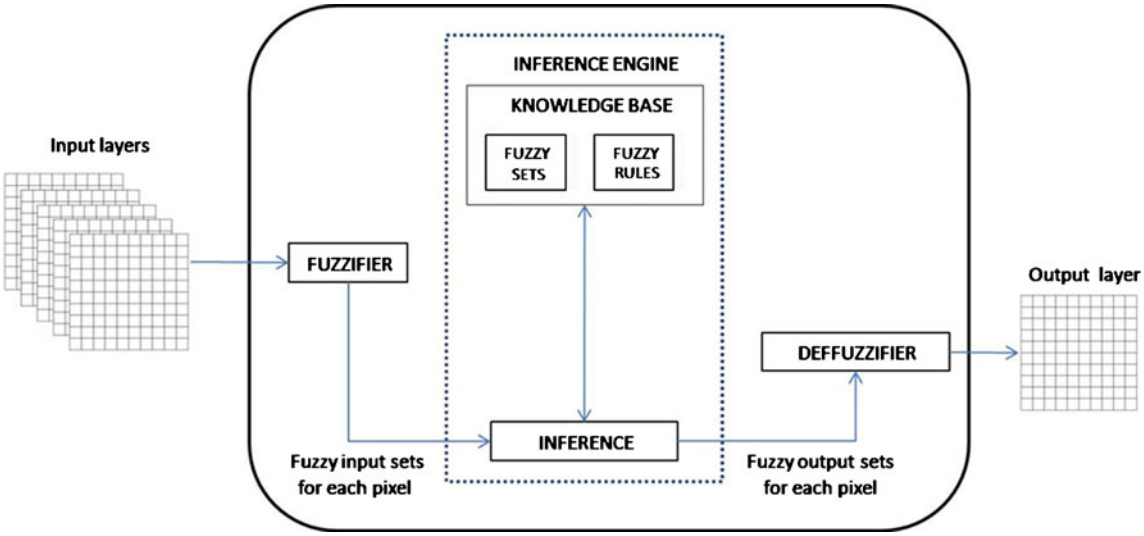


Fig. 1 Structure of the proposed method

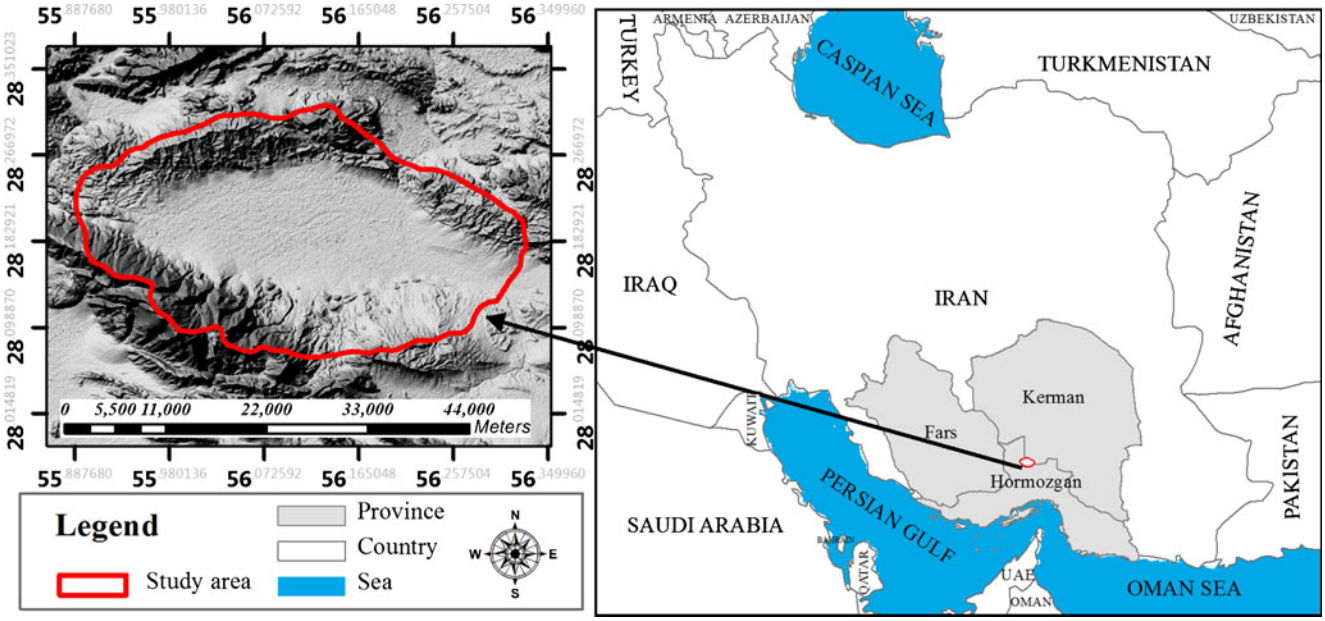


Fig. 2 Location and boundary of the study area in the southern part of Iran

Table 1 Lithology of geological formations in the Shemil-Ashkara plain (FSC Engineers 2010; locations are shown in Fig. 3)

Formation	Lithology	Symbol	Area (% of total)	Area (km^2)	Ranking number for MAR
Hormuz formation	Salt dome	SP	0.5	4	1
Mishan formation	Marl	Mm	4.1	34	2
Quaternary Sediment	Clay and Silt	Qs	0.3	2.9	3
Aghajari formation	Sandstone, Marl	Ma	13.9	114.1	3
Razak formation	Marl	Mr	0.5	3.9	3
Quaternary Sediment	Clay and Silt	Qal2	27.5	226.2	4
Bakhtiari formation	Conglomerate	Pb1	18.1	149.1	5
Pabdeh Gurpi formation	Conglomerate	KEpg	0.9	7.6	5
Bangestan Group	Limestone shale	Kbg	0.8	6.6	5
Gori formation	Limestone	Mg	0.3	2.6	6
Quaternary Sediment	Recent fluvial deposits	Qal1	3.1	26.2	6
Quaternary Sediment	Silt and Gravel	Qt2	21.3	174.9	8
Jahrom formation	Dolomite and dolomitic limestone	Ej	6.8	56.2	9
Asmari formation	Limestone	OMa	1.5	12.5	10

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Chenini et al. (2009) used historic rainfall data, watershed drainage density, surficial geology and aquifer boundary conditions for mapping groundwater recharge zones. These thematic layers were integrated with one another using the weighted aggregation method to derive a groundwater recharge map. The results demonstrated that this GIS methodology has good functionality for mapping groundwater recharge zones.

Sargaonkar et al. (2011) determined suitable areas for MAR by using GIS techniques and remote sensing in regards to parameters such as geomorphology, geology, soil, slope, land use, intensity of runoff and the depth to the water table. Kalantari et al. (2010) suggested potential sites for artificial recharge in the southwestern part of Iran by integrated investigation. They used a detailed assessment of surface and sub-surface geology, and hydrogeological surveys, and also evaluated the potential for harvesting storm waters, and their quality and suspended-solids loads.

In those studies, each thematic layer was usually classified into several categories, and for each class, a particular score was assigned. Thematic layers were then weighted, based on their importance to the decision-maker, and finally maps produced for each criterion were overlaid using logical connectives (i.e., Boolean overlay). Thus, the general scope in all of those studies was the

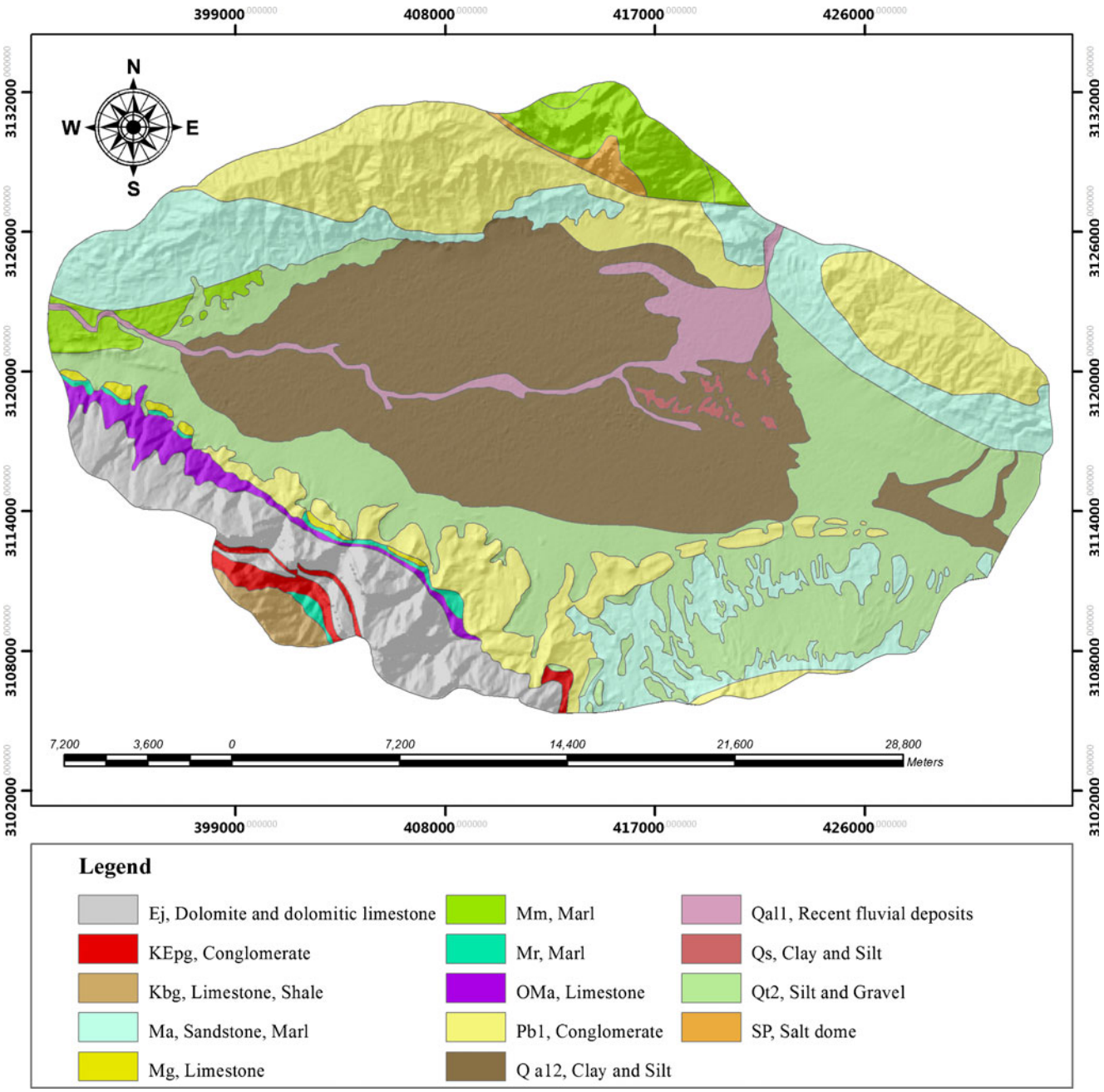


Fig. 3 Geological map of the Shemil-Ashkara plain (lithological information is presented in Table 1)

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data-layer preparation, classification, weighting and integration in a GIS environment.

In the classification of data using GIS, some degree of error is observed. One of the main errors that occurs is due to the finite ranges or intervals resulting from data classification. For example, in MAR site selection, one of the essential factors is groundwater electrical conductivity (EC). In the conventional modeling of this factor in GIS, areas with EC ranging from 0 to 1,000 μS/cm are classified in one category with the same score. In reality, this data range needs to have different scores of suitability for MAR. These kinds of errors in classical set theory increase the uncertainties in the data and result in divergence of GIS simulations and reality.

Fuzzy set theory (FST) encompasses concepts that can be used to overcome some of the uncertainties associated with geographical information (Lodwick 2008). Based on FST, fuzzy logic is being applied in many areas where empirical relationships are not well defined or are impractical to model. The foundations of FST, to deal specifically with non-statistical uncertainties, were first developed by Zadeh (1965). Since that time, other researchers have explored the applicability of fuzzy logic to a variety of problems. Despite the subjectivity of establishing the descriptive variables, fuzzy logic model applications have been widely successful in the field of engineering, particularly in situations where there are many uncertainties in the relationships between the input variables and the output results.

This study integrates fuzzy logic and multi-criteria decision making (MCDM) methods in GIS to enhance the precision of the results in a MAR plan, and to reduce uncertainties associated with data classification. For this purpose, a fuzzy inference system (FIS) has been developed based on the input layers and output layer in GIS. The simple additive weighted (SAW) method, as a technique of MCDM, has been used to determine the rules of the proposed model. To determine the rules of the FIS, MAR site selection has been done by an integrated method of GIS and SAW in a raster environment. Results of this method have been used as a guideline to determine the rules of the FIS model.

Methodology

In the site-selection process, because of the fact that the volume of geographic data is high and the analyses are very complex and time-demanding, using GIS software is inevitable. To reduce the uncertainties that occur due to classification in GIS, fuzzy logic can be

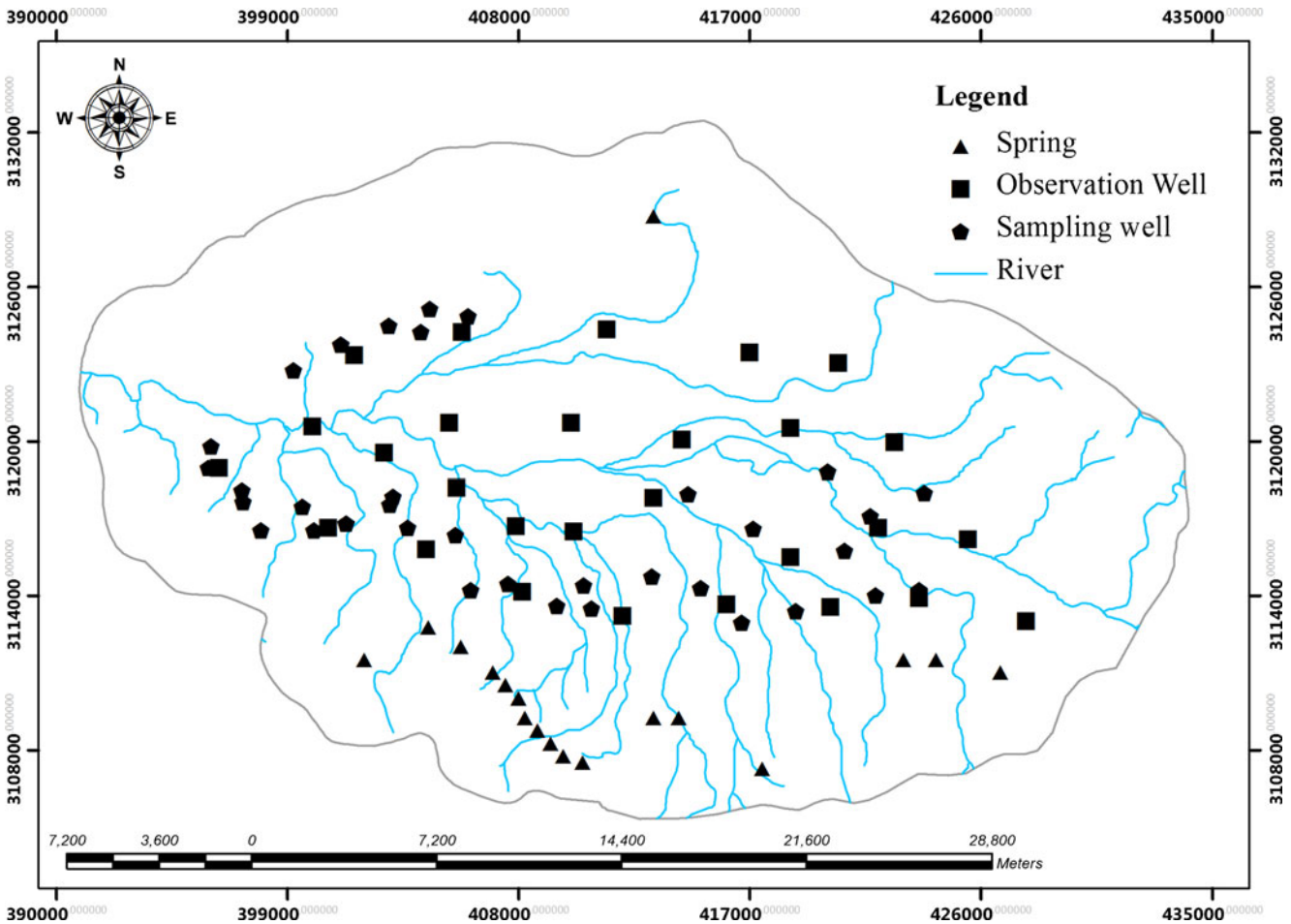


Fig. 4 Locations of wells and springs in the Shemil-Ashkara plain

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incorporated. By using fuzzy logic in GIS, aspects of ambiguity in linguistic variables can be modeled (Benedikt et al. 2002). FIS can be developed in four stages:

- The definition of linguistic variables
- The selection of appropriate membership functions
- The definition of rules based on knowledge of the system
- The selection of a suitable operator to combine fuzzy sets

Fuzzy inference is the process of mapping from a given input set to an output set using membership functions, fuzzy logic operators, and if-then rules. The basic advantage of such a system is its ability to incorporate linguistic data (Elsayed 2009). In this report, the Mamdani fuzzy inference method is adapted to pixel-based site selection for MAR. In this method, as shown in Fig. 1, the output membership functions are fuzzy values that are defuzzified to obtain a crisp output value for each pixel. Raster layers that are prepared in a GIS environment are the inputs and output of the model. In the output layer, each pixel is assigned a value demonstrating its degree of suitability for MAR.

To determine the rules of the proposed model, the SAW method, which is a technique of MCDM, was used. This method is the simplest and most well-known method of MCDM (Hwang and Yoon 1981; Janssen 1992). To determine the rules of the fuzzy model, site selection for MAR was done by an integrated method of GIS and SAW in a raster environment. Thematic raster layers for the parameters were prepared, classified and weighted. The classification and relative weighting of the thematic layers were based on a literature review, engineering judgments, and expert opinions. Then, the result of this method was used as a guideline to determine the rules of the FIS model. The method can be outlined in the following steps:

Step 1: The relative weight of each layer is identified and normalized using the following equation:

$$W'_{\mathrm{j}} = \frac{W_{\mathrm{j}}}{\sum_{\mathrm{j}=1}^{\mathrm{n}} W_{\mathrm{j}}} \tag{1}$$

Where: W'_{j} is the normalized weight and W_{j} is the raw weight for the j^{th} attribute.

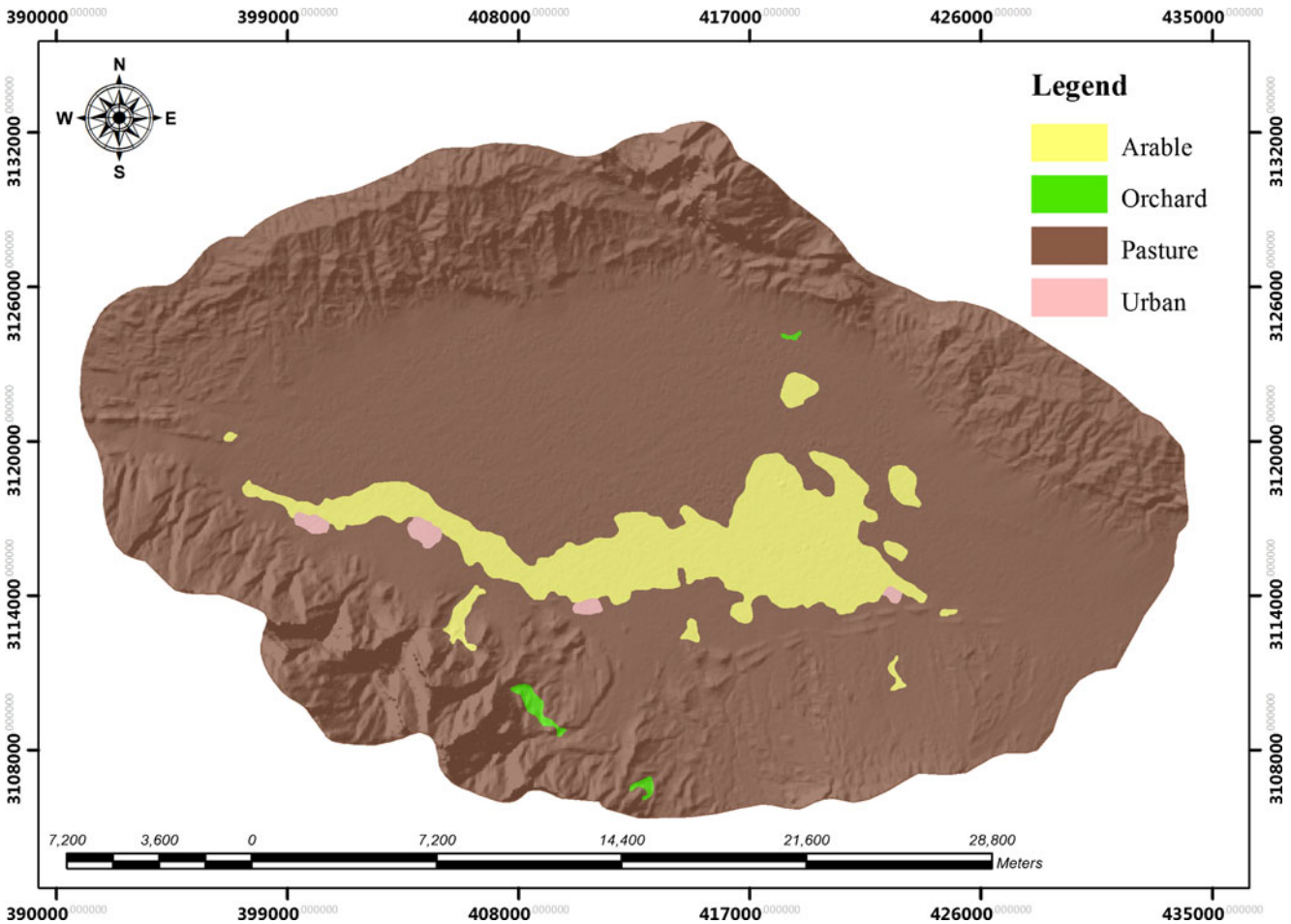


Fig. 5 Land use map of the Shemil-Ashkara plain

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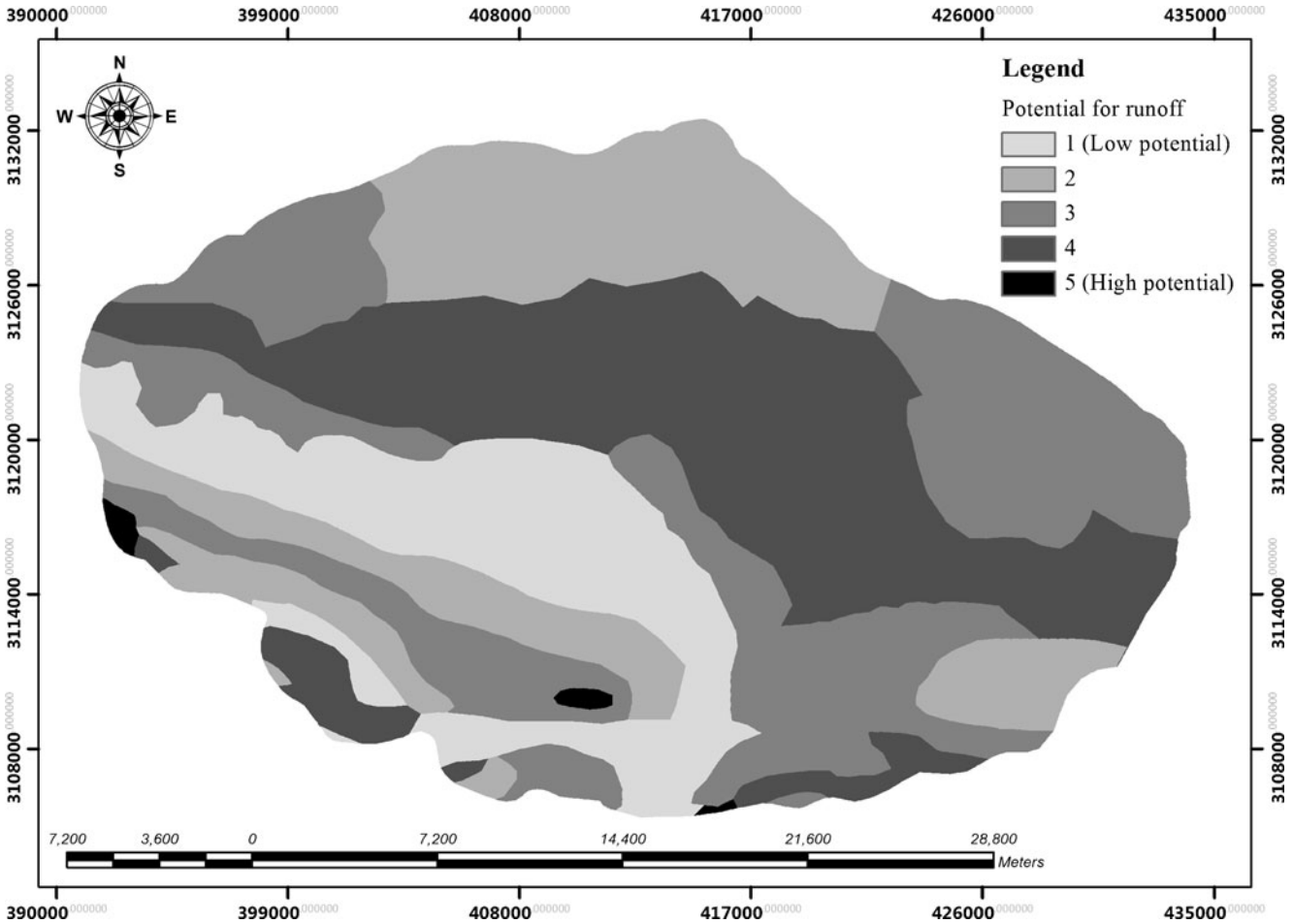


Fig. 6 Categories of potential for runoff in the Shemil-Ashkara plain

Step 2: The input thematic layers are classified and scored in a GIS environment. Because these scores are given in different scales, they should be normalized to a common dimensionless unit (Şener et al. 2006). For this process, the following equation is selected and applied:

$$a'_{ij} = \frac{a_{ij}}{a_j^{max}}, j = 1, \ldots, n \quad i = 1, \ldots, m \tag{2}$$

Where: a'_{ij} is the normalized score and a_{ij} is the raw score for the j^{th} thematic layer (attribute) and i^{th} class (alternative). *n, m*: represent the number of attributes and alternatives, respectively.

Step 3: Integration of the weighted thematic layers is done by using Eq. 3 in the raster environment of the GIS:

$$A_i = \sum_{j=1}^{n} W'_j a'_{ij}, \; i = 1, 2, \ldots, m \tag{3}$$

Where: A_i is the value of suitability for i^{th} alternative (pixel), W'_j is the normalized weight for the j^{th} attribute, and a'_{ij} is the normalized score for the i^{th} alternative and j^{th} attribute.

By using Eq. 3 in the GIS, a raster layer is produced as the result. Each pixel in this layer has a value (from 0 to 1) that indicates its suitability for MAR.

Step 4: The output layer from step 3 is classified into categories such as unsuitable, moderately suitable and suitable.

Step 5: Based on the defined membership functions in the inputs layers, all possible arrangements of the 'if' part (antecedent) of the 'if-then' rules are identified.

Step 6: For each rule, by examining the arrangement of inputs and class of suitability of output from step 4,

Table 2 The criterion weights identified for the SAW method

Layer name	Weight (W_j)	Normalized weight (W'_j)
Suitability of geo-formation	7	0.2593
Slope	6	0.2222
Potential for runoff	5	0.1852
Depth to groundwater	5	0.1852
Electrical conductivity	4	0.1481

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Table 3 Summary of the input layers used in the SAW method

Layer name	Classes of layer	Raw score (a_{ij}) (1–10)	Normalized score (a'_{ij}) (0–1)	Area (%)
Suitability of geo-formation	SP (1[a]), Mm (2), Mr (3) Ma (3), Qs (3)	2	0.28	20
	Qal2 (4), Kbg (5), KEpg (5), Pb1(5), Mg (6), Qal1(6)	4	0.57	51
	Qt2 (8), Ej (9), OMa (10)	7	1	29
Slope	0–<2 %	10	1	11
	2–<4 %	8	0.8	22
	4–<8 %	6	0.6	17
	8–10 %	2	0.2	49
Potential for runoff	Low (1,2[b])	2	0.2	17
	Moderate (3,4)	6	0.6	53
	High (5)	10	1	30
Depth to groundwater	0–<10 (m)	1	0.12	29
	10–<20	3	0.37	44
	20–30	5	0.62	22
	>30	8	1	5
Electrical conductivity (EC)	0–<1,000(μS/cm)	9	1	1
	1,000<2,250	6	0.66	14
	2,250–4,000	2	0.22	81
	>4,000	1	0.11	4

[a] Ranking number for MAR in Table 1

[b] Potential for runoff in Fig. 6

the 'then' part (consequent) of that rule is identified. Some rules can be weighted to have more influence on the result than other rules, if there is physical evidence in the data to support a heavier weighting.

Case study: Shemil-Ashkara plain, Iran

The Shemil-Ashkara plain is located in the southern part of Iran, in Hormozgan Province, between 55° 53′

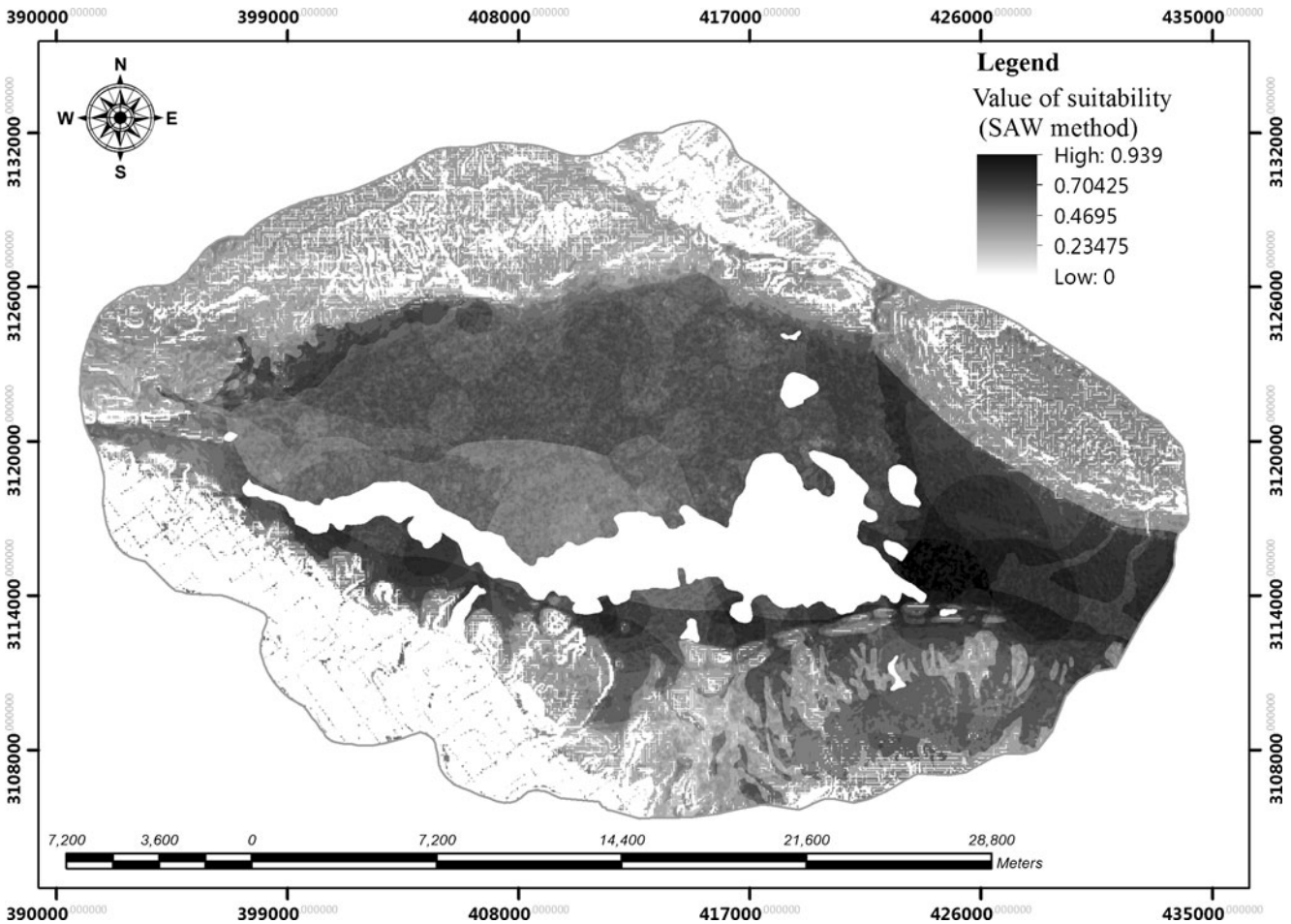


Fig. 7 Map of suitability for MAR using the conventional method of GIS and SAW in the Shemil-Ashkara plain

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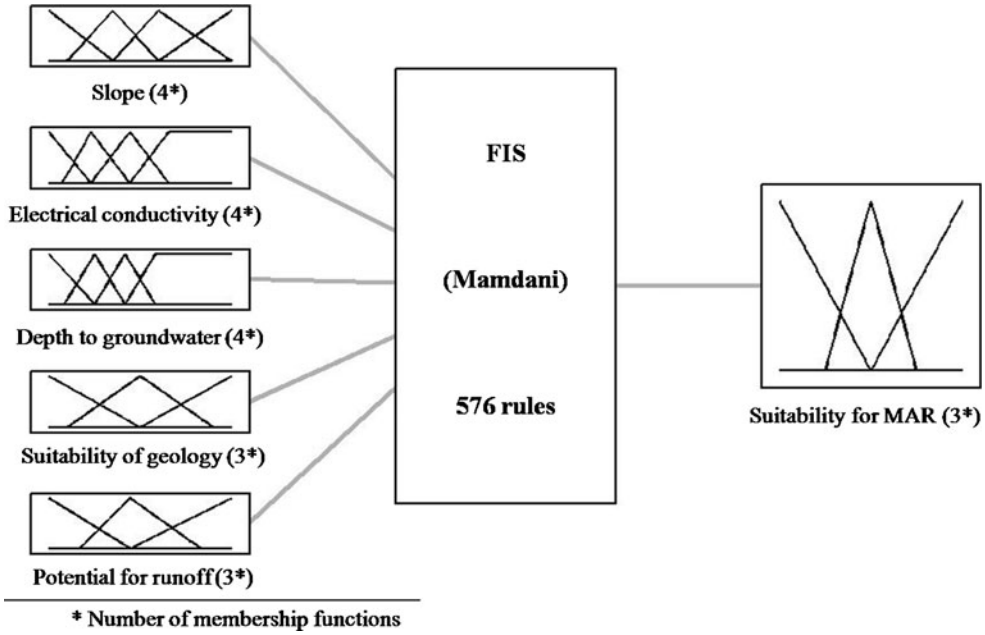


Fig. 8 Specifications of the FIS, showing 5 inputs, 576 rules and 1 output

and 56° 19′ E longitude and 28° 4′ and 28° 18′ N latitude (Fig. 2). The total area of this plain is about 820 km^2, and the average annual rainfall is less than 200 mm. From a geological point of view, the plain is located in the Zagros Fold Belt which has a main W–E trend. The stratigraphy comprises hard formations (such as: Hormuz, Bangestan Group, Razak, Pabdeh Gurpi, Mishan, Jahrom, Bakhtiari, Asmari, Gori, and Aghajari) and soft

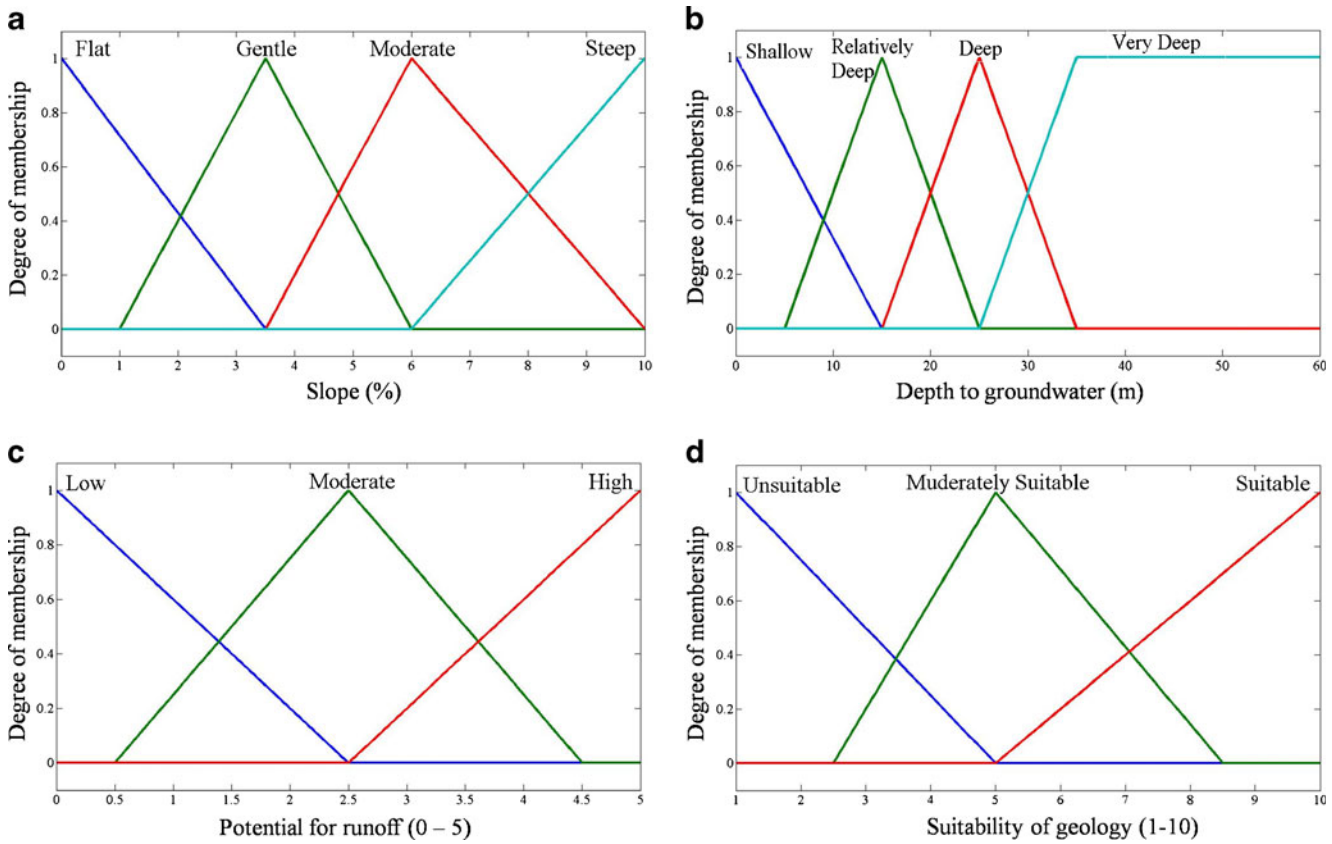


Fig. 9 Input membership functions related to the **a** slope, **b** depth to water table, **c** potential for runoff, and **d** suitability of geology

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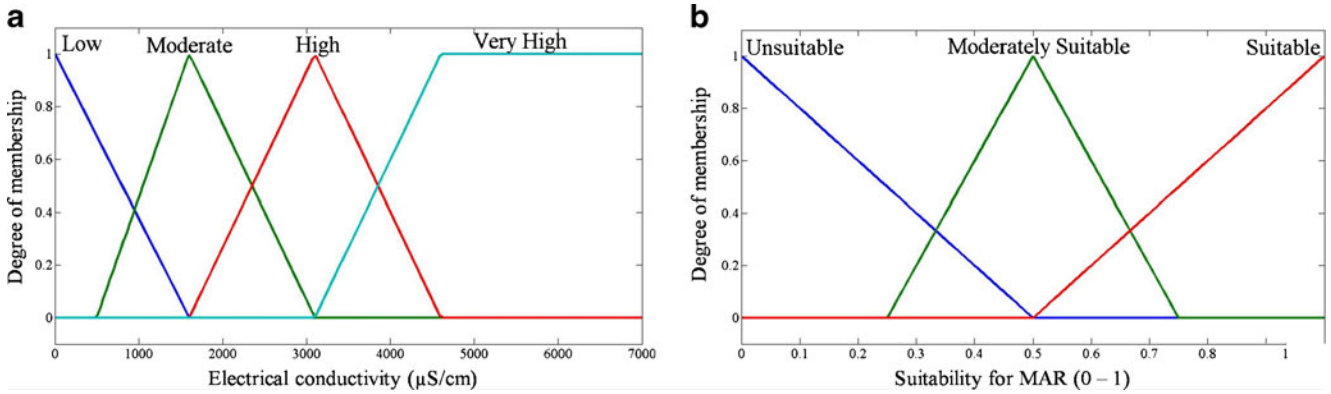


Fig. 10 Input membership function related to the **a** electrical conductivity and **b** output membership function related to suitability of areas for MAR

formations. The lithological features of these formations in the plain are presented in Table 1. In this table, lithology, symbol, area, and ranking number for MAR in each formation have been presented. Ranking number for MAR is defined from 1 to 10 based on the field studies, engineering judgment, and literature review. Formations with higher numbers are considered more suitable for MAR. Figure 3 shows the geological map of the study area, which has been developed based on the information in Table 1, and the figure shows the symbol and lithology for each formation.

In recent years, due to the rapid development of agricultural lands and long-term drought in these areas, the groundwater storage volume has decreased sharply; for example, from 2005 to 2010, about 95 million cubic meters (m^3) of groundwater reserves were

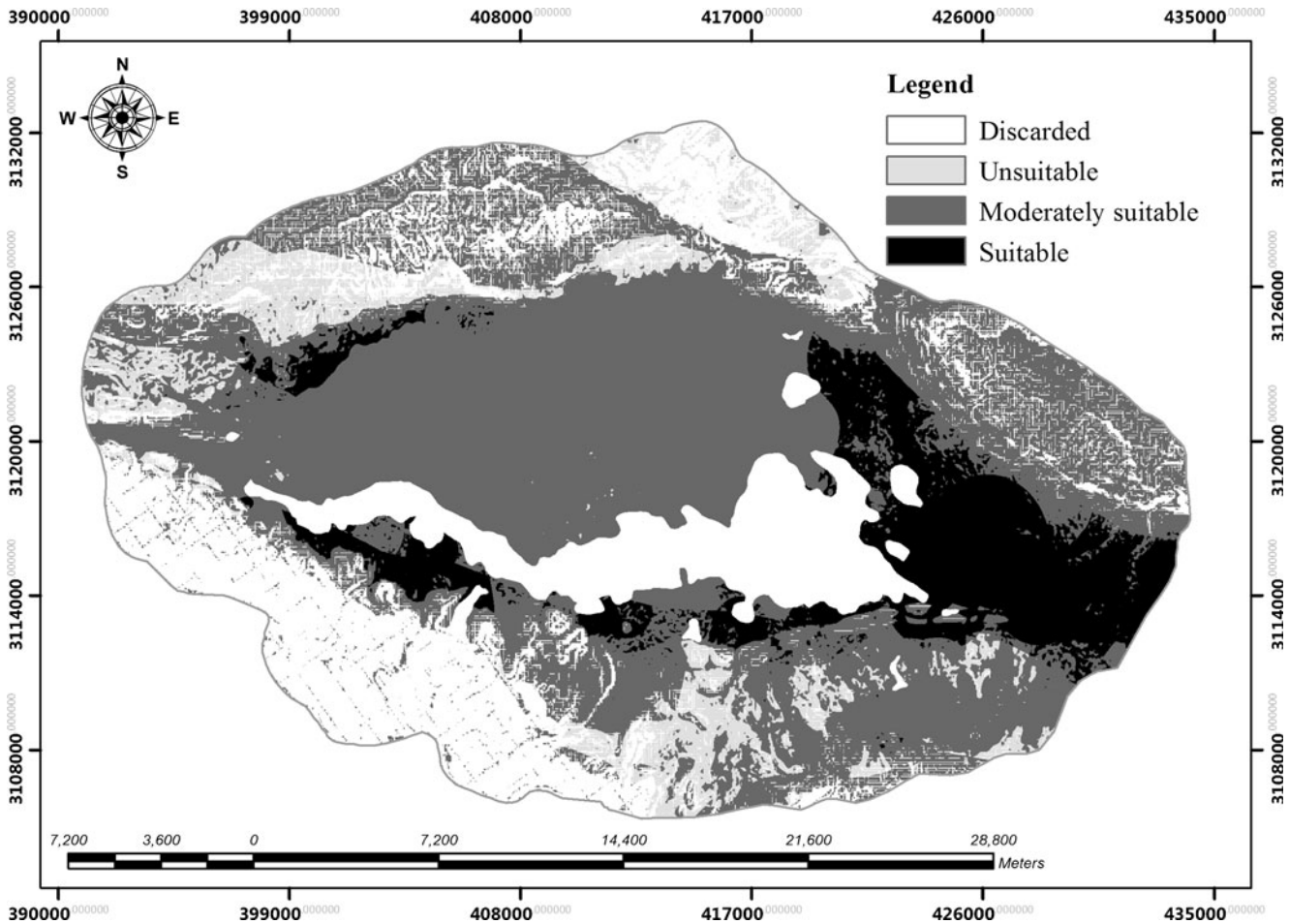


Fig. 11 Map of classifications for suitability for MAR based on the conventional method of GIS and SAW in the Shemil-Ashkara plain

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abstracted (FSC Engineers 2010). This matter has led to the encouragement of studies on groundwater restoration. One of the most suitable methods for improvement of the groundwater resources in the aquifer of this plain is MAR using winter flood waters.

Results and discussion

In this study, a wide plain with an area of about 820 km^2 has been investigated for initial MAR site selection. Based on the literature review and available data for this plain, important criteria have been selected for primary site selection. To determine the most suitable areas for MAR in the Shemil-Ashkara plain, EC of groundwater, depth to water table, geology, potential for runoff, land use, and slope have been considered. For each parameter, the raster thematic layer with pixel size of 20×20 m was prepared in a GIS environment.

Land use and slope factors have been used for preparing the constraint layer. Since areas with pasture as the land use and with a slope of less than 10% have potential for MAR, the constraint map was prepared using the slope and land use layers. In the constraint map, the pixels have values of 0 or 1. Zero is for pixels with a slope of more than 10% or any other land use except pasture.

Wells and springs of the Shemil-Ashkara plain have been sampled to determine groundwater EC and the water-table depth. Then, thematic layers of EC values and water-table depths have been developed. Figure 4 shows the locations of the wells and springs of Shemil-Ashkara plain. A digital elevation model (DEM) of the Shemil-Ashkara plain has been used to develop a slope map.

Figures 5 and 6 show land use and the potential runoff layers respectively, based on information from the Forests and Pastures Organization of Iran (Zaki zadeh 2006). As can be seen from Fig. 5, pasture land use, which includes barren areas or land covered with grass, has the largest area in this plain. Among the different land uses shown in Fig. 5, only pasture land use is practicable for MAR. In Fig. 6, based on the variation of physiographic and climatic characteristics in the basin, potential for runoff is classified from 1 to 5 (low potential to high potential). The potential for runoff layer shows the classification of the areas based on the ability of surface water to flow in the basin.

In this report, SAW has been used in two ways. Firstly, the degrees of suitability for MAR have been driven directly from SAW using a conventional GIS method. Secondly, based on the steps described previously (see section Methodology), SAW has been used for defining FIS rules in the proposed method. The two approaches have been compared, in order to evaluate the accuracy of the FIS method. SAW is a well-known method which has the ability to rank alternatives by simple calculation, based on simple information. When GIS and SAW are integrated as a method for MAR site selection, some uncertainty is introduced, so the results of this method have been compared with the proposed method.

The weights, scores, and classification of data in the SAW method have been derived from literature review, engineering judgments and information gathered from brain-storming sessions with engineering experts. In this study, national experts were selected from different organizations in the chosen region. Four geologists, four water-resources experts, three environmentalists, and three agricultural experts were used in the brain-storming session using a questionnaire.

In the questionnaire, the experts were invited to assign a number from 1 to 7 for the weights of each criterion. The chosen weights for each criterion are shown in Table 2. As can be seen from this table, for this region, the suitability of geo-formation was identified as far more important than the other criteria. The normalized weights in this table were calculated using Eq. 1. In Table 3, the criteria are classified based on the range of the data, literature review and engineering judgment. The slope, depth to groundwater, and EC were classified based on the possible values of these criteria in the plain. The suitability of geo-formation and potential for runoff were classified based on the ranking number for MAR and runoff potential in Fig. 6, respectively. Raw scores in Table 3 (from 1 to 10) were assigned by the experts, via the questionnaires. Classes with higher numbers are considered more suitable for MAR. In this table, the normalized score of classes in different layers were determined using Eq. 2.

Table 4 A selection of the rules used as the knowledge base in the FIS

Number of rule	Rule	Weight
1	If (slope is Steep) and (EC is Very High) and (depth is Shallow) and (potential for runoff is Low) and (geology is Unsuitable) then (suitability is Unsuitable)	1
2	If (slope is Steep) and (EC is High) and (depth is Shallow) and (potential for runoff is Low) and (geology is Unsuitable) then (suitability is Unsuitable)	1
3	If (slope is Steep) and (EC is Very High) and (depth is Relatively Deep) and (potential for runoff is Low) and (geology is Unsuitable) then (suitability is Unsuitable)	1
25	If (slope is Moderate) and (EC is High) and (depth is Relatively Deep) and (potential for runoff is Low) and (geology is Unsuitable) then (suitability is Moderately Suitable)	1
26	If (slope is Steep) and (EC is Moderate) and (depth is Shallow) and (potential for runoff is Moderate) and (geology is Unsuitable) then (suitability is Moderately Suitable)	1
27	If (slope is Steep) and (EC is Very High) and (depth is Very Deep) and (potential for runoff is Low) and (geology is Unsuitable) then (suitability is Moderately Suitable)	1
562	If (slope is Flat) and (EC is Very High) and (depth is Very Deep) and (potential for runoff is High) and (geology is Suitable) then (suitability is Suitable)	1
563	If (slope is Flat) and (EC is Moderate) and (depth is Very Deep) and (potential for runoff is Moderate) and (geology is Suitable) then (suitability is Suitable)	1

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Data sets in Tables 2 and 3 were used for integrating GIS layers in the SAW method. Figure 7 shows the resulting map of suitability for MAR using the conventional method of SAW and GIS. As can be seen from this figure, based on Eq. 3, the values of suitability range from 0 to 0.939. A value of 0 is assigned to areas that have a slope of more than 10% or where the land use is anything else except pasture.

An FIS was developed, using five input layers that are entered into the inference engine to generate the output layer, which is the spatial suitability for MAR. The five chosen input layers are slope, depth to groundwater, potential for runoff, suitability of geology, and EC of groundwater. Figure 8 shows the specifications of the developed FIS. As shown in this figure, slope, depth to water table, potential for runoff, suitability of geology and EC of groundwater are the input layers, and suitability for MAR is the output layer. Figures 9 and 10 illustrate the membership functions related to the input and output layers. In these figures, based on the classes of layer in Table 3 and engineering judgment, numbers and intervals of membership functions for linguistic terms are defined.

By defining fuzzy rules between input and output membership functions (based on the aforementioned steps), the FIS model has been developed. For defining these rules, Fig. 7 was re-classified into four zones: discarded, unsuitable, moderately suitable, and suitable. This classification is related to the membership functions for suitability for MAR in Fig. 10b. Figure 11 shows the results of this revised classification, which is used as a guide for developing fuzzy rules.

Based on the input membership functions in Fig. 9, all possible arrangements of inputs or 'if' part of the rules have been determined. The number of possible rules for the defined membership functions is 576 ($4\times4\times4\times3\times3=576$). By examining the class of suitability of each arrangement in the zoned map (Fig. 11), the then-part of the rules was determined. Some of the rules that were determined using the results of the SAW method are listed in Table 4. The components of the rules are based on the intervals of the membership functions in Figs. 9 and 10. As can be seen from this table, the weights of all of the rules are the same, meaning that they are considered to be of equal importance.

Using the defined rules, FIS has been developed and the value of suitability for each pixel has been calculated in a GIS raster environment. For developing the FIS, Fuzzy Cell Software was used to support raster input and output layers. Fuzzy Cell Software was designed and

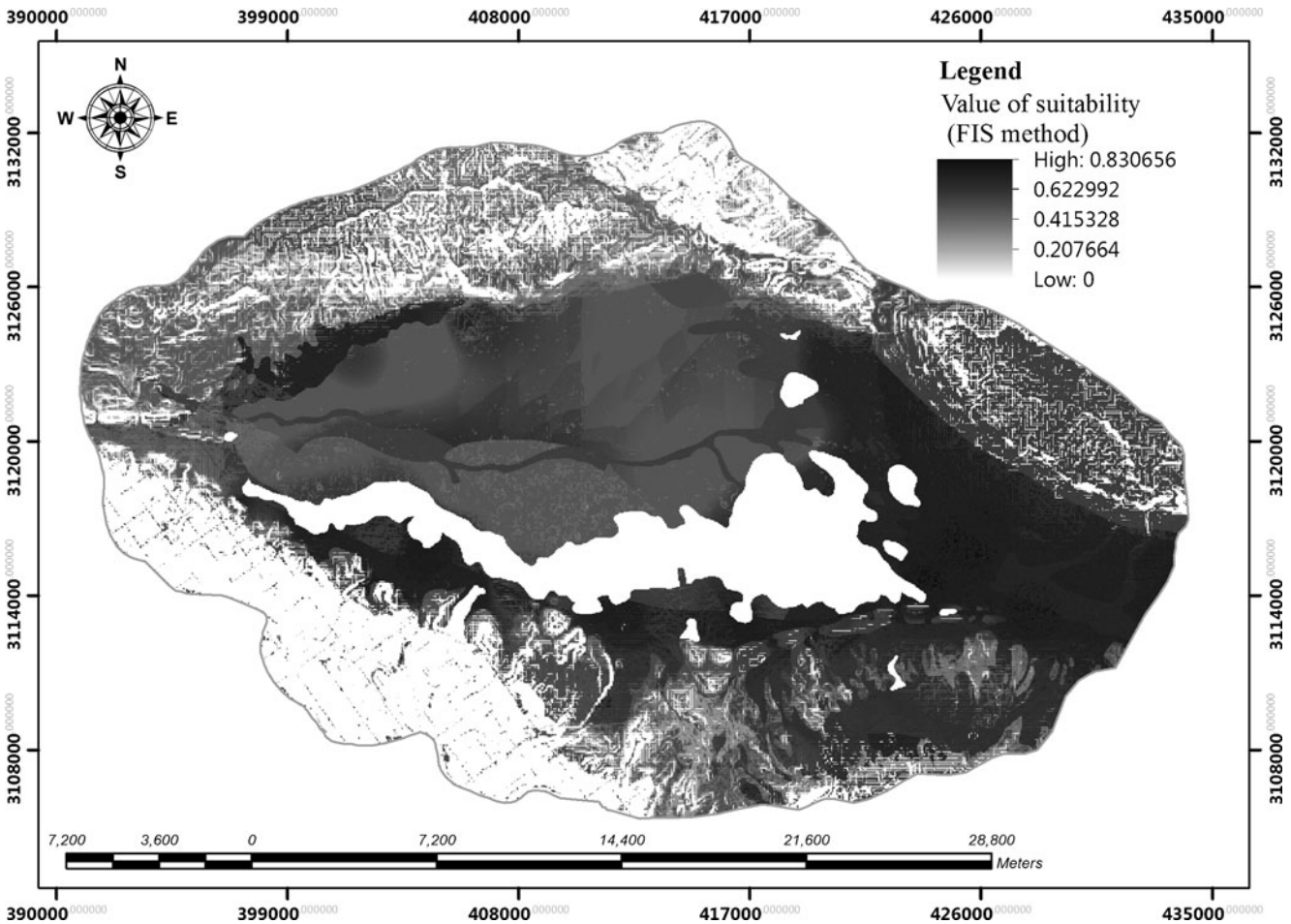


Fig. 12 Final map of suitability for MAR using the proposed FIS method

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Table 5 Comparison of site-selection results between SAW and proposed method

Samples	Inputs					Output (value of suitability)	
	Slope (%)	EC (μS/cm)	Depth (m)	Potential for runoff	Geology	(SAW)	(FIS)
1	3	2000	15	3	5	0.60	0.60
2	2.1	2000	15	3	5	0.60	0.61
3	2.1	1200	15	3	5	0.60	0.63
4	2.1	1010	15	3	5	0.60	0.64
5	2.1	1010	20	3	5	0.60	0.65
6	2.1	1010	20	4	5	0.60	0.66
7	2.1	1010	20	4	6	0.60	0.67

implemented to enhance commercial GIS software with fuzzy set theory (Yanar and Akyürek 2006).

The output layer obtained from FIS has been multiplied by the constraint layer. Thus, the pixels that do not have obvious potential for MAR were assigned a value of 0. Figure 12 illustrates the final result of the proposed method. In this raster map, the pixels have values ranging from 0 to 0.831; pixels with higher values are more suitable for MAR.

Table 5 presents a comparison of the results obtained from the two methods (SAW and the integrated proposed method) in some pixels. As can be seen from this table, the output values for selected pixels (with different inputs) are the same using the SAW method, but are different in the proposed method. The final score for each pixel in the proposed method changes with even small differences in the input characteristics. For example, in sample 2, compared to sample 1, the slope has decreased but other factors are the same. Due to the decrease in slope, sample 2 would be expected to have better suitability for MAR, but it is constant in the SAW method and different in the proposed method.

Similarly, comparing samples 3 and 4 with sample 2, the EC of groundwater has been decreased but other factors are the same. Due to the decrease in EC, samples 3 and 4 would be expected to have better suitability for MAR, but the values are constant in the SAW method and different in the proposed method. For the other samples in Table 5, these precise and sensitive responses to inputs for the proposed method can be observed. Comparison of the result maps of the two methods (Figs. 7 and 12) shows that there are smooth changes in the degree of suitability for MAR in the proposed method as opposed to the SAW method. It can therefore be stated that the results of the proposed method are more precise and sensitive to the inputs.

Conclusions

In the initial site selection for MAR using GIS, due to the finite ranges or intervals resulting from data classification, some degree of error is incurred. In this study, to deal with this kind of error, FIS has been combined with GIS to enhance the precision of the results. Fuzzy logic provides a framework for processing linguistic knowledge and its corresponding data through membership functions for MAR site selection. In the proposed method, linguistic terms are used for modeling the uncertainty that exists in geographic data classification.

Comparison of the results obtained from the integrated proposed method and the conventional SAW method shows that the output values for selected pixels, with different input values, have the same values of suitability when using SAW and different values when using the proposed method. The final score for each pixel using the proposed method changes even with only small differences in the input characteristics. This comparison demonstrates that the results of the proposed method are more precise and sensitive to inputs. As a result, integration of FIS and GIS is recognized as an effective method for modeling the uncertainties and reducing the errors that are associated with data classification in GIS.

In previous studies, SAW has been used for site selection, but in the proposed method, it has been used as a guide for determining the rules of the FIS. Due to there being numerous cells in the existing raster input layers and the output layer, Fuzzy Cell Software was utilized for developing FIS in MAR site selection.

The method proposed in this study can open new frontiers in the application of GIS to initial site selection for MAR. Further development of the proposed methodology can focus on using the method to model other uncertainties such as assigning the values for weighting the criteria and dealing with the spatial quality of the data. In addition to the criteria used in this study, other factors such as permeability of vadose zone and aquifers, and the location in relation to regional groundwater flow, may need to be considered in MAR site selection.

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