

Research Article

Site selection for artificial groundwater recharge using GIS and Fuzzy logic

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Abstract

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Groundwater is the single water resource in many regions of Iran. In arid and semi-arid regions, special attention has been paid to artificial groundwater recharge in water resource management. Selecting appropriate sites for groundwater recharge is one of the most important factors in this groundwork. To demonstrate the capabilities of Geographical Information System (GIS) techniques and numerical modelling for groundwater resources development in arid areas, specifically to determine the suitable sites for the artificial recharge of groundwater aquifers, a study was carried out in the Batvand Plain which is located in Khuzestan province. In this study, effectual factors that could determine suitable areas for groundwater recharge are: slope, unsaturated zone, electrical conductivity, depth to groundwater, hydraulic conductivity, and drainage density. After making thematic layers, the standardization was done by fuzzy functions: Fuzzy Large, Fuzzy Small, and Fuzzy Linear in ArcGIS environment. Later on, Fuzzy-AHP method used weighting the thematic layers. By completing the matrix and paired comparison with Fuzzy Extent Analysis, the weight of each criterion was determined. Finally, the weighted layers in GIS environment were combined by Fuzzy function SUM to locate suitable areas for artificial recharge.

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1. Introduction

Whether artificial or natural, recharge is the flow of water into aquifers. Artificial recharge of groundwater is the augmentation of the natural infiltration of precipitation or surface water by appropriate methods. These include spreading of water on the ground, pumping to induce recharge from surface water bodies and injection through boreholes, wells, or other suitable access features.

Iran is an arid to semi-arid region receiving an average of only 240 mm of precipitation per year, approximately 30 percent of the world average. Moreover, the timing and location do not coincide with the country's needs [30]. There is unbalanced distribution of precipitation in Iran, both spatially and temporally. In most parts of such regions groundwater is the single water resource and its overuse decrease the ground water level in many aquifers. This is considered to be a major limitation in the social and economic development. Recent studies on water resource development in Iran have shown about 430 billion m³ of the annual precipitation in the country, but 20% is lost during sudden floods which flow into the playas, lakes and seas [12, 26]. Effective management of aquifer recharge is becoming an increasingly important aspect of water resource management strategies [13].

Fuzziness refers to vagueness and uncertainty, in particular to the vagueness related to human language and thinking. Fuzziness provides a way to obtain conclusions from vague, ambiguous or imprecise information. It imitates the human reasoning process of working with non-precise data.

The application of traditional data processing methods in site selection for artificial groundwater recharge is very difficult and time consuming, because the data is massive and usually needs to be integrated. GIS is capable of developing information in different thematic layers and integrating them with sufficient accuracy and within a short period of time.

GIS can be effectively used in the gathering, weighting, analysing, presenting spatial and attribute information to facilitate any location endeavour [1, 24].

Site selection and cost-benefit analysis for artificial recharge in the Baghmalek plain, Khuzestan Province, southwest Iran have been practiced in recent years [19]. Three sites (including basins and check dam) for artificial recharge were suggested in the north and northeast of the area, where the thickness of coarse alluvium is greatest. They concluded that; (1) the rate of recharge that can be achieved at the three sites is approximately 2.2 million m³ per year, (2) the cost-benefit ratio is 1:1.32, and (3) the analysis suggests that the project could recover the investment within 3 years.

The criteria and techniques of detecting site-specific mechanism for artificial-recharge were discussed with a case study from Ayyar basin [29]. An integrated approach was used to identify sites for groundwater recharge in a hard rock terrain through recharge basins or reservoirs [31]. Geographical Information System provides various tools to incorporate new models for any spatial processes [3, 17] and can easily integrate various information layers, such as topography, geology and hydrology to provide a better prediction on the potentials of flood spreading sites [10].

Several studies have been carried out for the determination of areas most suitable for artificial recharge [5, 14, 15, 16, 21, 22, 28, 31, 38]. Furthermore, the success of artificial groundwater recharge via surface infiltration is discussed [11]. A Decision Support System (DSS) developed for floodwater spreading site selection and the conceptual design of floodwater spreading schemes in the semi-arid regions of Iran [20].

2. Materials and Methods

2.1. Study area

The Batvand plain ($49^{\circ} 04'$ to $49^{\circ}13'$ N and $31^{\circ} 53'$ to $32^{\circ} 01'$ E) is situated approximately 75km northeast of Ahvaz city of Khuzestan province of SW Iran (Fig. 1). Access to the study area is possible via the Ahvaz – Masjed Soleiman main road. Batvand and Golikhoon villages are the most important populated centers in this area. It is located in middle of Karoon watershed with elevation ranging from 195 m in north to 90 m in south. The aerial coverage of Batvand aquifer is about 29.88 km². Geologically speaking Bakhtiari conglomerate, Gachsaran evaporites, Lahbari, Aghajari and Mishan sandstones and marl formations constitutes main outcrop in the area. The most important structural feature in study area is Lahbari thrust fault that extend from northwest to southeast and cause landslides in Lahbari formation. Batvand plain is confined between Gachsaran formation in the east and Lahbari formation in the west. Bakhtiari formation has outcrop in the north and northwest of the plain.

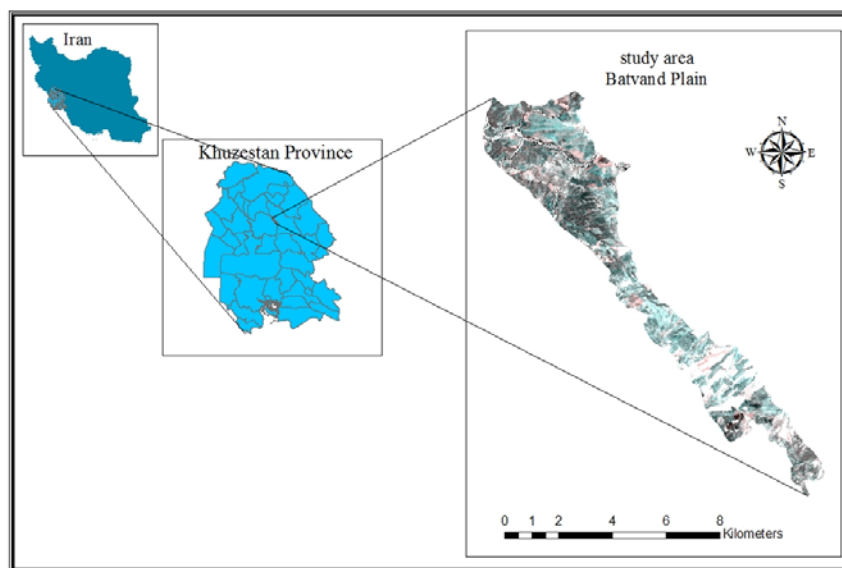


Fig. 1. Study area map

2.2. Criteria

To determine the most suitable locations for artificial groundwater recharge, factors such as slope, unsaturated zone, electrical conductivity, depth to groundwater, hydraulic conductivity and drainage density are used. Thematic layers for these factors were prepared, classified, weighted and integrated in a GIS environment by the means of Fuzzy logic.

Slope is one of the main factors in the selection of groundwater dam areas. Water velocity is directly related to angle of slope and depth. On steep slopes, runoff is more erosive, and can more easily

transport loose sediments down slope. Topographic maps of the Batvand Plain were used to develop a slope map by the means of a Digital Elevation Model (DEM).

Unsaturated zone: Perhaps the lithology of the unsaturated zone is the most important factor after the water in artificial recharge. This layer is effective to supply aquifer and in this section the type of ingredient is considered. To prepare this layer existing well logs in the study area were used.

One of the important factors to determine most suitable areas for artificial recharge is alluvial thickness. By increasing in thickness of alluvial, the amount of groundwater storage increase, too. Available research shows that few surveys are performed about the effect of alluvial thickness map in groundwater recharge, up to now. But if alluvial thickness be small, it can cause bio-environmental problems such as: waterlogging.

Water quality: The quality of ground water determines chemical and biological characteristics of deposits and has an important role in use of water for specific purposes. In this study, we use EC as an indicator of water quality for evaluation. Thus, we obtain this Component from water quality analysis and prepare its map.

Hydraulic conductivity: it's one of the hydrodynamic coefficients that show transmissivity of water through the entire thickness of the aqueous layer. The formula for calculating transmissivity is $T = K \cdot b$. Whereas K = Hydraulic conductivity and b = Aquifer thickness. The best and most accurate method for determining the hydraulic conductivity is aquifer pumping test [2].

Drainage density is the total length of all the streams and rivers in a drainage basin divided by the total area of the drainage basin and correlated with peak discharge in the basin. It is a measure of the total length of the stream segment of all orders per unit area of drainage area. The drainage density has an inverse relationship with permeability. A rock with lower permeability can infiltrate less runoff which leads to a greater concentration of surface runoff. Drainage density of the study area is calculated using line density analysis tool in ArcGIS software. The suitability of groundwater potential zones is indirectly related to drainage density because of its relation with surface runoff and permeability [27]. In this study, the hydraulic conductivity of the study area has been obtained through aquifer pumping test.

Depth to groundwater: the distance between ground level and groundwater level indicates the depth to water level. It should be noted that depths less than 10 meters because of the high water table is consider dun suitable for artificial groundwater recharge.

Table. 1: Criteria

Criterion	Intervals	Class	Criterion	Intervals	class
Depth to groundwater (m)	>30	Very suitable	Slope %	0-2	Very suitable
	20-30	suitable		2-4	suitable
	10-20	average		4-8	average
Drainage density	<10	unsuitable	Hydraulic conductivity (m/day)	>8	unsuitable
	>0.016	Very suitable		>12	Very suitable
	0.012-0.016	suitable		8-12	suitable
	0.008-0.012	average		4-8	average
	0.004-0.008	unsuitable		<4	unsuitable
Electrical conductivity (EC)	0-500	Very suitable	Unsaturated zone	Sand and gravel	Very suitable
	500-1000	suitable		Sand and gravel with silt and clay	suitable
	1000-1500	average		Silt or clay – shale – sandstone	average
	>2000	unsuitable		Confining layer	unsuitable

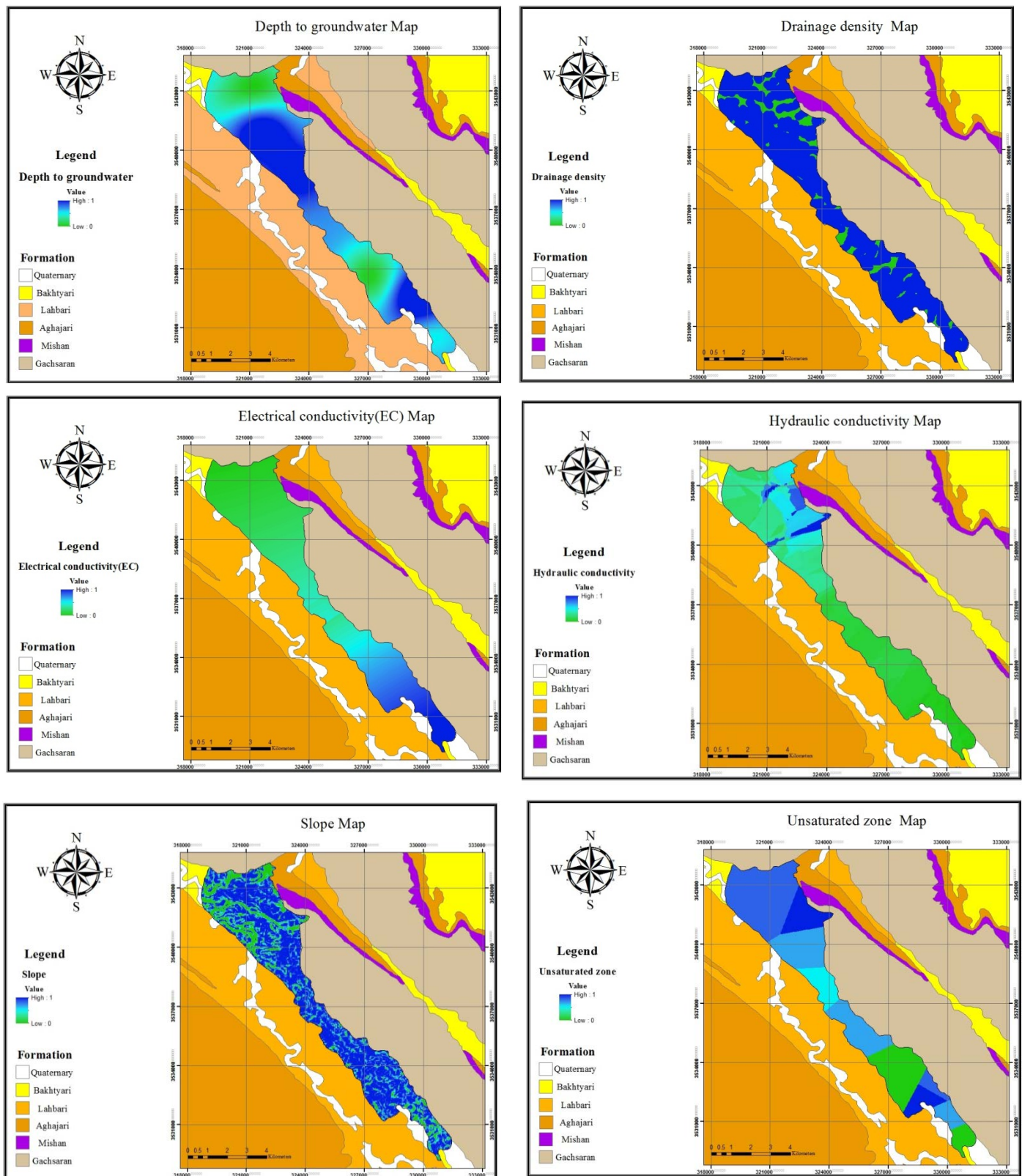


Fig. 2. Standardize maps using fuzzy functions

2.3. Weighting based on Fuzzy AHP

Analytical Hierarchy Process (AHP) to decide is used the most in Crisp conditions and does decision making without the balance. In spite of capabilities of the AHP to prioritize sites, this model does not have the ability to reflect human thought [7]. Therefore, Fuzzy set and in particular the Fuzzy Analytical Hierarchy Process (FAHP) methods are considered suitable for solving this problem [25]. This method is very appropriate tool to decision making in the conditions in which accurate and complete information is not present [8]. Fuzzy theory [37] is a mathematical theory that is used to fuzzy modelling process of the human mind [23]. This method is often used when there is no Crisp boundary between classes [34]. Fuzzy hierarchical analysis (FAHP), using fuzzy numbers does approximate priorities and flexibility. Membership function $M(x)$ of fuzzy theory works on a range of real numbers between 0 and 1. So, Doubtful judgments of an expert can be displayed by fuzzy numbers. Triangular fuzzy numbers (TFNs) is a special type of fuzzy numbers that due to ease of use are highly regarded and its membership function M is defined with three real triangular fuzzy number (l, m, u) . This membership function is explained in Figure 3 [7].

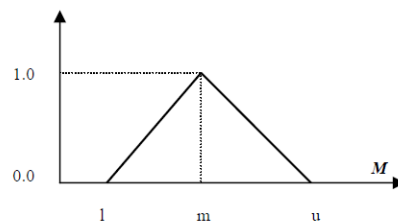


Fig.3. A triangular fuzzy number, \tilde{M}

TFNs are defined by three real numbers, expressed as (l, m, u) . The parameters l , m and u , respectively, indicate the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. Their membership functions are described as;

$$\mu(x \in \tilde{M}) = \begin{cases} 0 & x < l \\ (x-l)/(m-l) & l \leq x \leq m \\ (u-x)/(u-m) & m \leq x \leq u \\ 0 & x > u \end{cases}$$

There are various operations on triangular fuzzy numbers. But here, three important operations used in this study are illustrated. If we define, two positive triangular fuzzy numbers (l_1, m_1, u_1) and (l_2, m_2, u_2) then:

$$(l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$$

$$(l_1, m_1, u_1) \cdot (l_2, m_2, u_2) = (l_1 \cdot l_2, m_1 \cdot m_2, u_1 \cdot u_2)$$

$$(l_1, m_1, u_1)^{-1} \approx (\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1})$$

2.4. Analysis method of the Fuzzy AHP: Modified extent

Chang's extent analysis method is one of the most popular and preferred methods in the FAHP field since the steps involved in this approach are relatively easier than those in the other FAHP approaches and similar to those in the conventional AHP. Fuzzy extent analysis is dependent on the degree of the probability of each criterion. According to The expert judgments, for all relevant variables triangular fuzzy numbers are determined and their pairwise comparison matrix is formed.

Step 1: The value of fuzzy synthetic extent with respect to the i th object is defined as follows:

$$S_i = \sum_{j=1}^m M_{gi}^j * [\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j]^{-1}$$

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

$$\sum_{j=1}^m M_{gi}^j = (\sum_{j=1}^m L_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j)$$

And to obtain

$[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j]^{-1}$, perform the fuzzy addition operation of $M_{gi}^j (j = 1, 2, \dots, m)$ value such that

$$\sum_{i=1}^n \sum_{j=1}^m M_{gi}^j = (\sum_{i=1}^n L_i, \sum_{i=1}^n m_i, \sum_{i=1}^n u_i)$$

And then compute the inverse of the vector above, such that:

$$[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j]^{-1} = (1/\sum_{i=1}^n u_i, 1/\sum_{i=1}^n m_i, 1/\sum_{i=1}^n l_i)$$

The normalization formula on the synthetic extent is defined as follows [35]:

$$S_i = (\frac{\sum l_{ij}}{\sum l_{ij} + \sum \sum u_{kj}}, \frac{\sum m_{ij}}{\sum \sum m_{kj}}, \frac{\sum u_{ij}}{\sum u_{ij} + \sum \sum l_{kj}})$$

Step 2: 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

$$V(M_2 \geq M_1) = \sup_{y \geq x} [\min(\mu_{M_1}(x), \mu_{M_2}(y))]$$

And can be equivalently expressed as follows:

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

$$(M_2 \geq M_1) = \begin{cases} 1 & \text{if } m_i \geq m_j \\ 0 & \text{if } l_j \geq u_i \\ \frac{l_j - u_i}{(m_i - u_i) - (m_j - u_j)} & \text{otherwise} \end{cases}$$

Where d is the ordinate of highest intersection point D between μ_{M_1} and μ_{M_2} (see Figure 4).

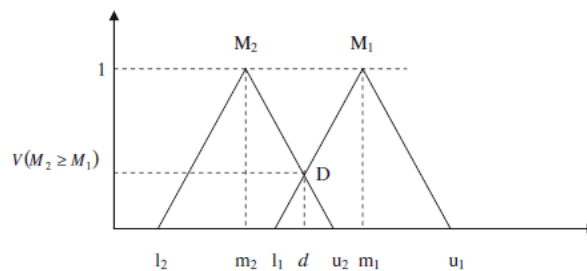


Fig. 4. The intersection between M_1 and M_2 [39]

to compare M_1 and M_2 , we need both the value of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$.

Step 3: The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i ($i = 1, 2, \dots, k$) can be defined by the following:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and } \dots \text{ and } (M \geq M_k)] = \min V(M \geq M_i),$$

$$i = 1, 2, \dots, k$$

Assume that: $d'(M_i) = \min V(S_i \geq S_k)$ for $k = 1, 2, \dots, n; k \neq i$. Then the weight vector is given by

$$w' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T$$

where A_i ($i = 1, 2, \dots, n$) are n elements.

Step 4: Via normalization, the normalized weight vectors are as follows:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T$$

Where W is a non-fuzzy number.

In this paper, identification of suitable areas for artificial groundwater recharge using the methods of FAHP and fuzzy TOPSIS (FTOPSIS) was done in GIS environment. Based on fuzzy logic, based maps were standardized according to their nature and importance. To do this, at first, fuzzy functions

were defined for each layer. These functions show how the values of a layer changes. In this paper, Fuzzy Large, Fuzzy Small and Fuzzy Linear were used. Thus the data using fuzzy membership functions as described above, were standardized (Fig.2).

After standardization of the layers, the FAHP was used to weight the layers. To this purpose, according to the table below fuzzy numbers and fuzzy scales used to define pairwise comparison matrix. The layers were pairwise compared and according to expert's opinion, fuzzy numbers were assigned to each of them.

Table 2: Triangular fuzzy number

Linguistic Scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1,1,1)	(1,1,1)
Equally important	(1/2,1,3/2)	(2/3,1,2)
Weakly important	(1,3/2,2)	(1/2,2/3,1)
Strongly more important	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strong more important	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more important	(5/2,3,7/2)	(2/7,1/3,2/5)

After the pairwise comparison matrix and fill it using Fuzzy Hierarchy Integral Analytic, the weight of each criterion was found. To this purpose, the program that was written in the MATLAB software is used. Thus, the weight of each criterion is determined.

Criterion	weight
Slope	0.1098
Land use	0.1546
Drainage density	0.1318
Unsaturated zone	0.2021
Electrical conductivity(EC)	0.0975
Depth to groundwater	0.1284
Hydraulic conductivity	0.1758

2.5. Layers overlaying

Overlap is one of the spatial functions that can combine spatial data layers that obtained from different sources using hybrid models. New layer generation (output) is a function of two or more layers of the input. Hybrid models are divided into several groups according to the procedures. For example, functions such as the Boolean operators, Arithmetic operators, Fuzzy operators, Probabilistic methods, Overlap index, Genetic algorithm and etc. specifically can be used for network data.

In this article, fuzzy operators were used to measure classes and units with a degree of membership between zeros to one. Then criterion maps using fuzzy operators (SUM, PRODUCTION, GAMMA,

AND, OR) can be combined. Considering that effective criterions have different weights and all of them should participate in the overlap. So each layer was multiplied by its corresponding weight. This work was performed for all criterions and then the new obtained layers were combined using a fuzzy operator SUM and the best options for artificial recharge obtained (Fig.5).

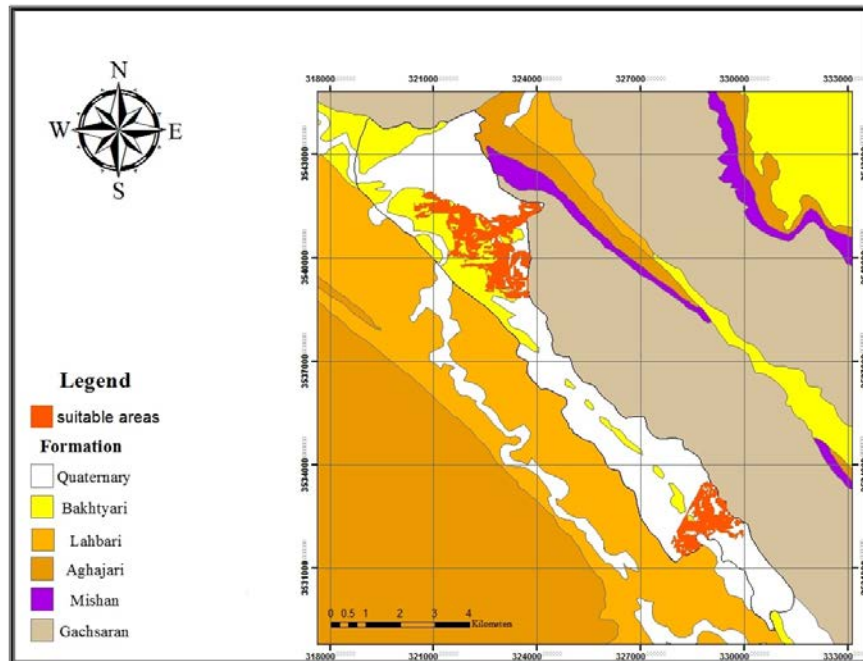


Fig. 5. Overlay map shows suitable sites for artificial recharge.

2.6. Prioritizing using Fuzzy TOPSIS method

TOPSIS is proposed [18]. According to the theory, the best alternative should have two features: one is nearest to positive-ideal solution; the other is farthest from the negative-ideal solution [8]. The positive-ideal solution minimizes the cost criteria and maximizes the benefit criteria. It is consisted of all best values attainable from the criteria. At the same time, the negative-ideal solution is a solution that maximizes the cost criteria and minimizes the benefit criteria, which has all worst values attainable from the criteria [35]. TOPSIS is widely used to solve MCDM problems [6, 33, 35, 36]. TOPSIS consists of the following steps [32].

Step 1: Construct a decision matrix.

If the count of criteria is n and the number of alternative is m , decision matrix with m rows and n columns will obtain as following:

Table 4. A typical multiple attribute decision problem.

	Criterion 1	Criterion 2	...	Criterion j	...	Criterion n
Alternative 1	f_{11}	f_{12}	...	f_{1j}	...	f_{1n}
Alternative 2	f_{21}	f_{22}	...	f_{2j}	...	f_{2n}
...
Alternative i	f_{i1}	f_{i2}	...	f_{ij}	...	f_{in}
...
Alternative m	f_{m1}	f_{m2}	...	f_{mj}	...	f_{mn}

In the table 4, f_{ij} ($i = 1, 2 \dots m$; $j = 1, 2 \dots n$) is a value indicating the performance rating of each alternative i th with respect to each criterion j th.

Step 2: Calculate the normalized decision matrix. The normalized value f_{ij} is calculated as:

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{j=1}^n f_{ij}^2}} \quad i = 1, 2 \dots m; \quad j = 1, 2 \dots n.$$

Step 3: Calculate the weighted normalized decision matrix. The matrix is from multiplying the normalized decision matrix by its associated weights as:

$$v_{ij} = w_j * r_{ij} \quad i = 1, 2 \dots m; \quad j = 1, 2 \dots n,$$

Where w_j is the weight of the j th attribute or criterion, and w_j

$$\sum_{j=1}^n w_j = 1$$

Step 4: Determine the positive-ideal and negative-ideal solutions.

$$A^+ = \{v_1^*, v_2^*, \dots, v_n^*\} = \{(max_j v_{ij} | i \in I'), (min_j v_{ij} | i \in I'')\} \quad i = 1, 2 \dots m; \quad j = 1, 2 \dots n,$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \{(min_j v_{ij} | i \in I'), (max_j v_{ij} | i \in I'')\} \quad i = 1, 2 \dots m; \quad j = 1, 2 \dots n,$$

Where I_0 is associated with benefit criteria, and I_{00} is associated with cost criteria.

Step 5: Using the n -dimensional Euclidean distance to calculate the separation measures. The separation of each alternative from the ideal solution is given as:

$$D_i^+ = \sum_{j=1}^n d(v_{ij}, v_j^*) \quad i = 1, 2 \dots m,$$

Similarly, the separation from the negative-ideal solution is given as:

$$D_i^- = \sum_{j=1}^n d(v_{ij}, v_j^-) \quad i = 1, 2 \dots m,$$

Step 6: Calculate the relative closeness to the ideal solution. The relative closeness of the alternative i is defined as:

$$CC_i = \frac{D_i^-}{D_i^* + D_i^-}$$

Step 7: Rank the preference order. The CC_i is between 0 and 1. The larger CC_i is, the better alternative A_i is.

Finally FTOPSIS was used to prioritize the options. Then by constructing the fuzzy decision matrix and computing the fuzzy positive ideal solution and fuzzy negative ideal solution, the fuzzy positive ideal solution and fuzzy negative ideal solution matrixes was performed. And by combining these layers, the final layer, obtained (Fig.6).

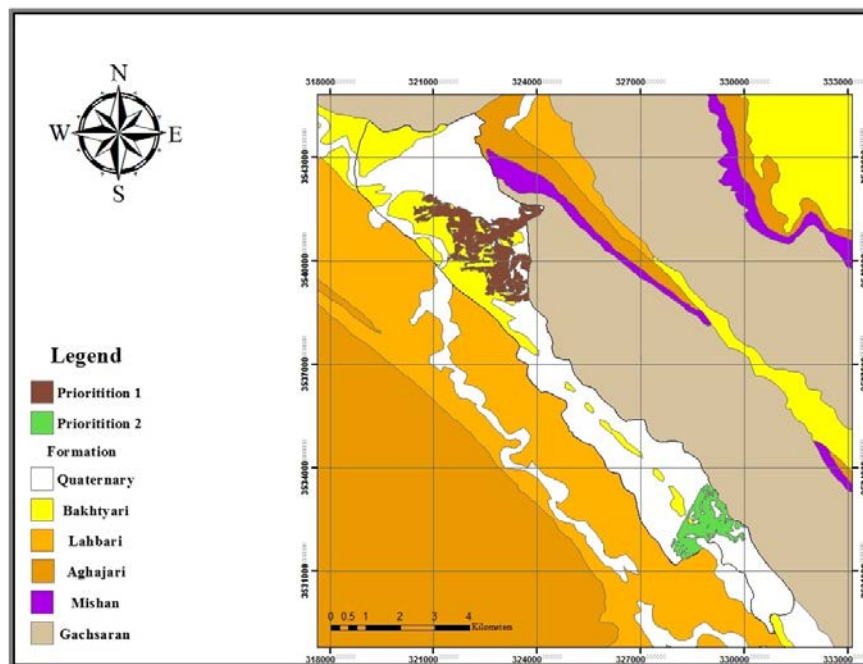


Fig. 6. Final map shows the priority of selected sites for artificial recharge.

3. Results and discussion

Geological formations of the study area from groundwater point of view have different situations. This difference refers to their lithological characteristics and structural behaviour. Since, site selection for artificial groundwater recharge is sometimes difficult and time consuming, in the present study GIS technique along with fuzzy logics is used. Generally, many factors influence artificial recharge. In this paper the thematic layers such as slope, unsaturated zone, electrical conductivity,

depth to groundwater, hydraulic conductivity and drainage density are used and weighted with fuzzy logics. Furthermore, by combining these thematic layers, suitable sites for artificial recharge obtained. Then, FTOPSIS used to prioritize the artificial recharge sites that generated. As can be seen (fig.6) in the northern part of Batvand plain, due to better soil and hydraulic conductivity, potential for artificial recharge are better. This is because the sediments in this part are mainly coarse conglomerate which have desirable discharge. Thus, the prediction of groundwater recharge sites can be used for the augmentation of groundwater. The final output map also shows that the method of assigning weights to different factors according to their importance in groundwater recharge and combining various factors by fuzzy logics may be more accurate for the demarcation of groundwater recharge sites than any other conventional methods.

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