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Application of digital techniques to identify aquifer artificial recharge sites in GIS environment

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Because the groundwater is considered as the major source of 99% of all retrievable fresh water, optimization of its usage would be very crucial. Groundwater artificial recharge (GAR) using surface water is the recommended solution because that increases the aquifer storage. Detection of aquifer storage site is the first step in designing GAR projects. The main objective of this research is the identification of suitable GAR sites scattered in the Shahrekord plain, Chaharmahal-va-Bakhtiari province of Iran, using Boolean and Fuzzy logic. Data affecting GAR including ground surface slope, soil infiltration rate, vadoze zone thickness, electrical conductivity of the surface water, land-use, and stream network were collected. After provision of digital maps, they were classified, weighted, and integrated through Boolean and Fuzzy operators. The result revealed almost 4.25% of the whole plain area is appropriate for GAR based on Boolean. Also, 4.79 and 17.94% of the plain area are suitable and rather favorable, respectively, based on Fuzzy. Finally, 34 locations were introduced with priorities A, B, and AB as being potentially suitable for GAR. The relationship between geomorphology and suitable areas for GAR based on Boolean and Fuzzy method indicated that the majority of these areas were located on colluvial fans units.

Keywords: groundwater; artificial recharge; Fuzzy and Boolean logic; geomorphology; Shahrekord plain

1. Introduction

Because of drought problems and occurrence of devastating floods, proper water resources' management is obviously quite essential. Groundwater recharge, optimal utilization of floodwater, and storage of surface water are ideal strategies of water resource management (Mahdavi *et al*. 2004).

Several studies indicate that water resources and groundwater level have been diminishing over the last decade in Iran. As a result, in Chaharmahal-va-Bakhtiari (CHB) province, access to surface fresh water resources has considerably declined and groundwater usage has consequently risen. The annual discharge of groundwater in Shahrekord aquifer is almost 250 million cubic meters. This has caused water table depletion more than 13 meters from 1993 to 2005 and now that is a prohibited aquifer (Lalehzari 2008).

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Groundwater resources can be augmented with the existence of surface water resources such as winter and spring floods. Introducing surface storages in some areas may not be cost effective, because these projects require huge investment and also detected storages will be filled with silt and become unusable after a few years. Nevertheless, saving water in aquifers would protect and improve water quality. Therefore, artificial recharge project is an optimal solution for water crisis in most areas (Morovati *et al.* 2008).

After artificial recharge the water is fed up to a permeable formation. The purpose is to recharge the groundwater aquifer and to reuse that water with a better quality later on. Feeding water is done by providing facilities or sometimes changing the natural conditions of the region (Biz *et al*. 1972).

Detection of an appropriate artificial recharge site of groundwater is a critical step and the main principle of artificial recharge system generation. Thus, selection needs to be done with great care. The success of an artificial recharge project depends very much on design and also maintenance conditions of the system. Following criteria are used to select an artificial recharge location: (1) The ground classes should possess sufficient storage capacity and conductivity. (2) Nonpermeable continuous layers should not exist between the surface and aquifer. (3) The extent of soluble salts must not be notable so it does not decrease the water quality. (4) Use of lands with low price for recharge. (5) If possible, recharge is done across topographical lines to uniform water distribution in the aquifer (Mahdavi *et al.* 2004).

Specifying suitable locations for aquifer artificial recharge based on field studies and traditional methods is difficult and very time consuming. The reason is that there are various sets of relative information and research in the field which necessitate the integration of layers with different models. Geographic information systems are digital programs and can be used in a variety of purposes. This technique prepares digital information layers and combines them with a reasonable accuracy and speed. Furthermore, the use of remote sensing is indispensable due to requirement of updated data (Mahdavi *et al.* 2010).

An overview of artificial recharge was given by Bouwer (1999, 2002), who pointed out major factors to be considered. He also discussed different artificial recharge systems, their design and management. In addition, the application of remote sensing and Geographic information system (GIS) in groundwater resources management and site selection for artificial recharge has been studied by several researchers (Krishnamurthy *et al*. 1996, Saraf & Choudhury 1998, Han 2003, Nouri 2003).

Mahdavi *et al*. (2004) evaluated an artificial recharge project using the GIS system in Iran. That project was manually carried out. Four digital maps including land-use, soil texture, slope, stream network, and climatic data were prepared to estimate the adequacy of rainfall. Each map was converted to a Boolean file and in the end all maps were multiplied. Mohan and Ravi Shankar (2005) considered parameters such as geology and geomorphology, Lineament density, depth of bedrock, depth of soil cover, drainage density, land-use, slope, and water table fluctuation to locate suitable sites for artificial recharge of Deccan Volcanic in India. Finally, these maps in GIS softwares were combined using Boolean method. Alimohammadi (2006) assigned criteria for locating an appropriate site for a park, classified maps, and combined them with the use of Boolean logic, Fuzzy logic, and multi-blower. Finally, he compared the results and concluded that Fuzzy logic gives a more convincing answer, covers wider area, and provides better utility. Hekmatpoor *et al.* (2007) and Ghayoumian *et al.* (2005) in their studies appointed suitable zones for artificial recharge in two different plains in Iran. They considered the following issues as criteria for locating: slope, surface permeability, alluvium thickness, alluvium quality, and transmissivity in alluvium. The layers were overlaid and every situation was decided using Decision Support System (DSS) method. Ataeizadeh and Chitsazan (2008) studied feasibility of artificial recharge in the Mydavand-Dalvan plain using GIS techniques. Layers such as hydraulic gradient, slope, depth to water table, unsaturated section litho-logy, aquifer environment, surface litho-logy (soil infiltration), and electrical conductivity of surface water were all considered, then they were combined with the Weighted Index Overlay method. Finally, suitable areas were introduced for artificial recharge accomplishment. Dadrasi (2008) compared the Fuzzy algorithm with other conceptual models compatible with GIS to locate the flood spread zone. The research was done in six cities of Khorasan-Razavi province, Iran. The results indicate that the Fuzzy logic sum operator (with more than 5.66% conformity with reality) had the highest efficiency.

As previously said, the main objective of this research was site selection for artificial recharge in Shahrekord plain of Iran using Boolean and Fuzzy algorithm. Additionally, a comparison between two methods was made, and the best technique was recognized and introduced.

2. Materials and methods

The position of Shahrekord plain, in the CHB province, is shown in Figure 1. Total area of study was 1235 km^2 of which 551 km^2 was plain and alluvium and the rest was mountainous. The studied area was located between 50°38′–51°10′ E (Longitude) and 32°7′–33°35′ N (Latitude), with an average of 12.2°C annual temperature and an average of 400 mm annual precipitation (Regional water Company of CHB province 2007). The approximate boundary of Shahrekord aquifer is given in Figure 2.

There are many factors affecting groundwater artificial recharge (GAR) such as climatic, morph-metric, floods, soil, and geology, as well as economic and social

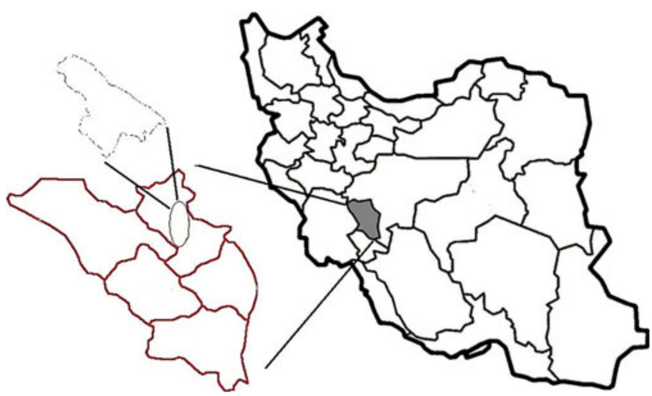

Figure 1. Location of the study area in Iran.

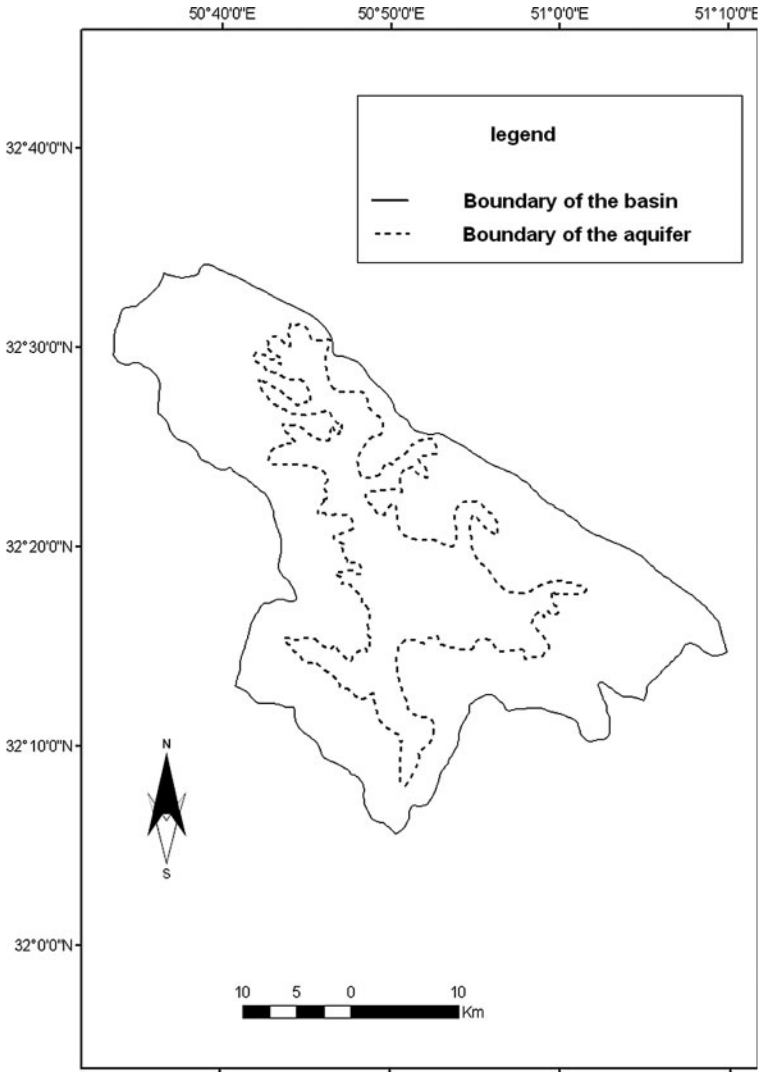

Figure 2. Position of aquifer in Shahrekord plain.

considerations. Taking all effective characteristics into account is obviously not possible. Hence, below issues are considered in factors' selection procedure: the purpose of study, expected scale and factor's accuracy, regional condition, the extent of influence of the factor, and accessibility of information related to the factor.

In the zones where the water table is close to the surface and is not exploited, recharge raises the water table and develops marsh-land. In other words, since natural underground reservoir of water storage is very small, the recharge function is less successful. The factors influencing unsaturated thickness variation are: discharge and recharge points of aquifer, hydraulic gradient, and hydraulic conductivity (Biz *et al*. 1972, Regional water Company of CHB province 2007). The water table was measured in 31 available pizometer wells in 2006. Figure 3 exhibits the location of these wells. Then, using interpolation technique, the map of the unsaturated zone thickness was supplied as it is perceived in Figure 4.

One of the most important factors influencing recharge implementation is the surface permeability. The effect of this phenomenon is revealed in the reduced evapotranspiration; so that, in low slope and small permeability conditions, the water remains on the surface of the soil and its evaporation increases soil salts. The amount of permeability depends on the factors such as soil characteristics, land cover, and slope. To measure this parameter, first in each landform unit (out of eight units), 3 points were selected and 24 samples were collected from the surface of the plain to

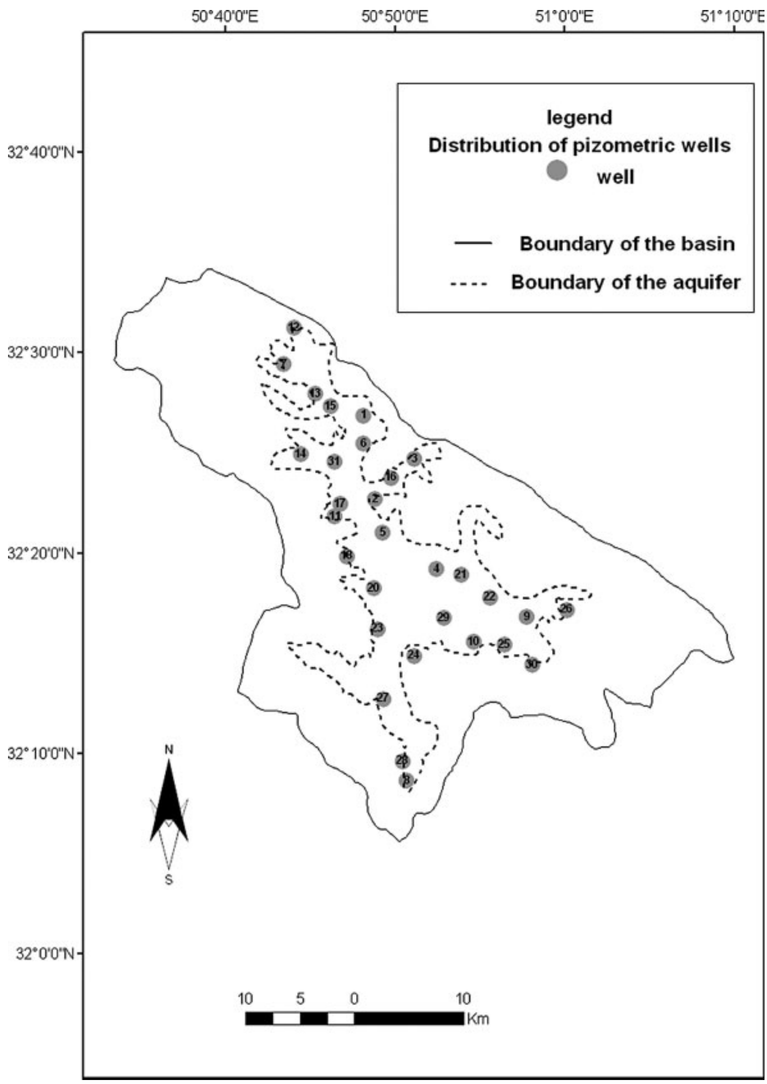

Figure 3. Distribution of pizometric wells in Shahrekord plain.

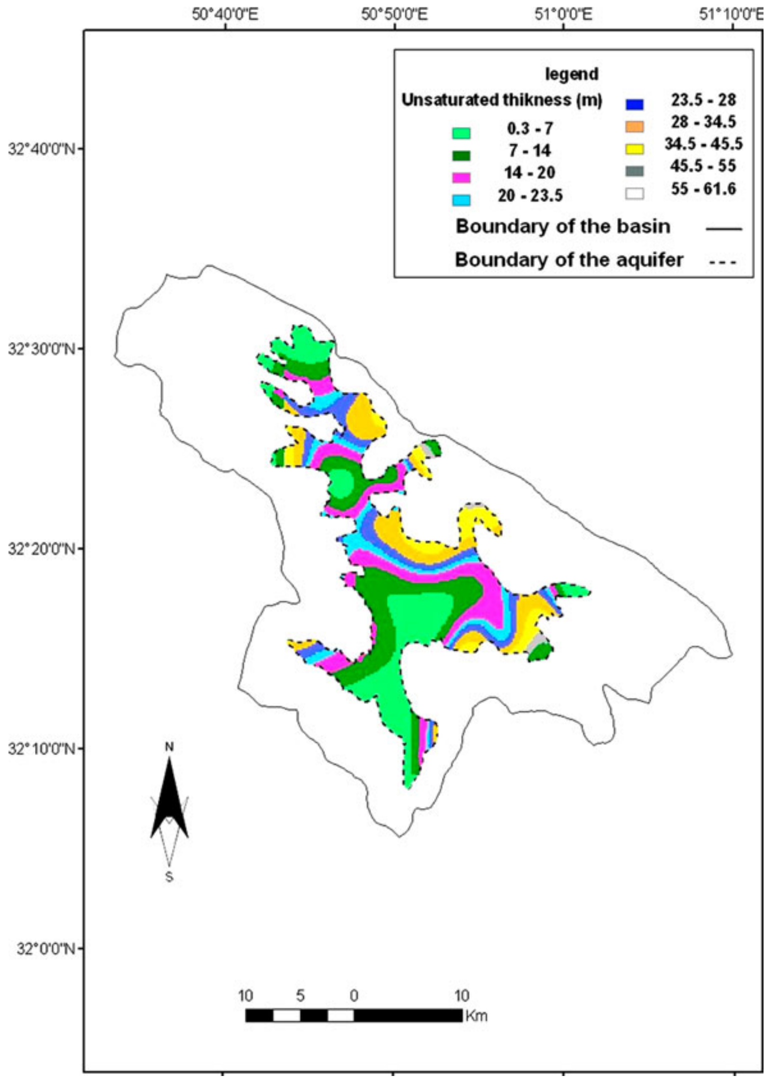

Figure 4. Unsaturated thickness map of various zones in the study area.

analyze the texture. Thereafter, all the soil texture was specified (Figure 5). The range of permeability was defined based on the texture–infiltration relationships established by the Food and Agriculture Organization (FAO 1979) at each station (Ghayoumian *et al.* 2007). The map of surface permeability was then obtained by means of interpolation.

Another extremely important factor for identification of suitable site is slope. This parameter plays an important role to control factors like runoff, erosion, material transportation and permeability. To generate the slope map, a digital elevation model (DEM) was applied (Figure 6).

The main source of groundwater is the water derived from rain and snow-melt that has permeated through the alluvium and usually this water has a good quality.

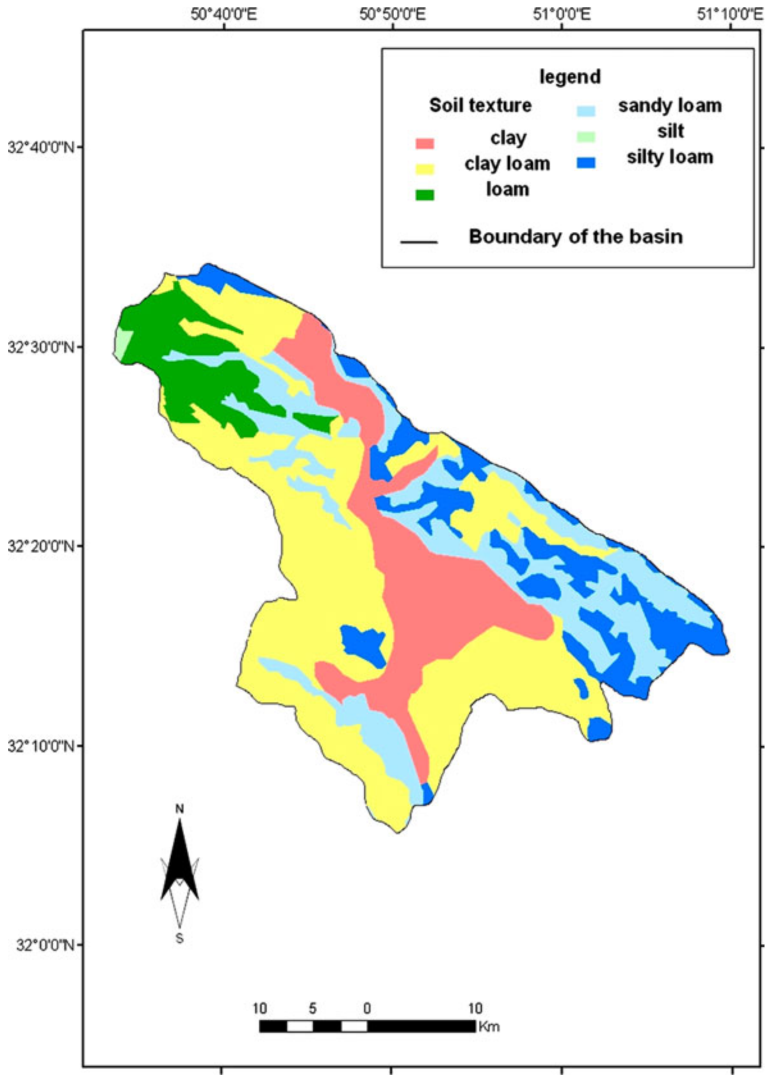

Figure 5. Soil texture map prepared for the study area.

After permeating the soil, rain water quality will change because of the contact with alluvium and dissolving different minerals in it. This qualitative change depends on constituting particles of aquifer, duration of contact with the bedrock, utilization rate of the groundwater, and groundwater level (Regional Water Company of CHB province 2007). Therefore, the quality of groundwater in alluvium as an essential parameter was investigated in the current study. Since electrical conductivity (EC) and total dissolved solids (TDS) variations have similar trends, the EC factor is used as an indicator for water quality. For this purpose, 40 points across the basin, including 23 wells, 13 flumes, and 4 springs were chosen. Figure 7 shows the distribution of these points. The average electrical conductivity data in all stations measured in 2004 and 2005 used to provide the EC map.

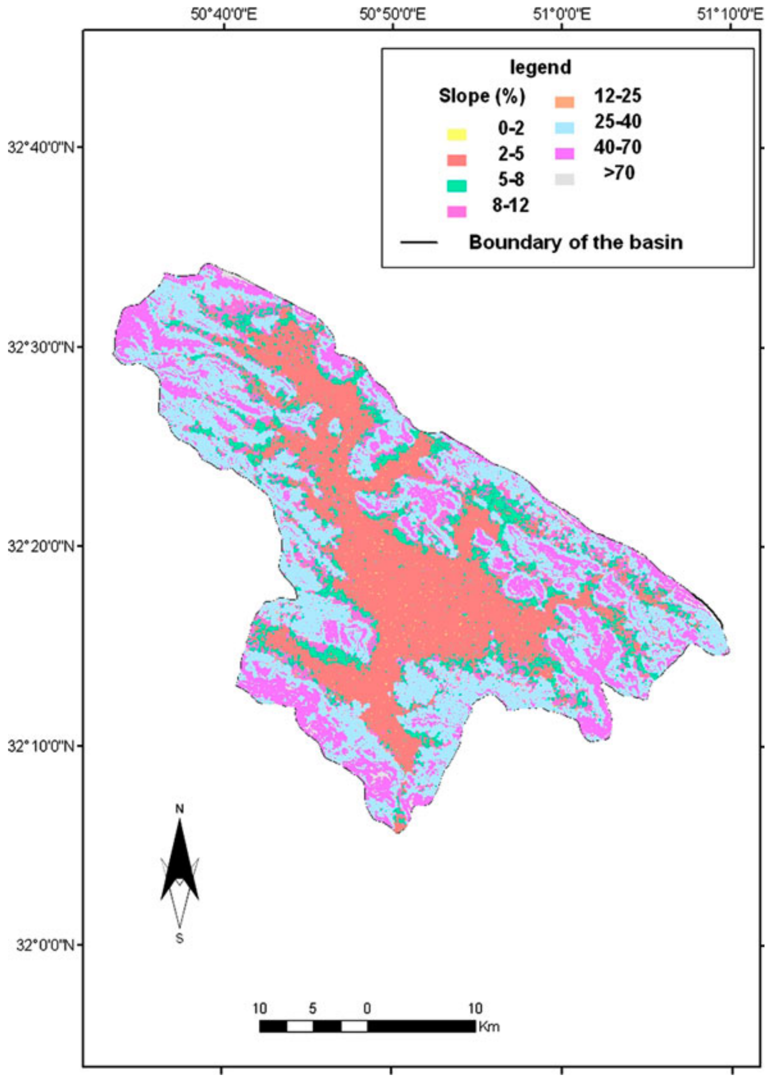

Figure 6. Slope map in Shahrekord plain.

Figure 8 illustrates the area which was covered by each land-use type. This map was helpful to remove areas with land-use restriction. In fact land-use could be presumed as a filter map. It should be underlined that all used layers are naturally constructed except the land-use layer which is created by human intervention. The effect of this characteristic was investigated separately.

After combining the layers and establishing suitable locations for artificial recharge, those locations should be evaluated in terms of proximity to water sources. If a region is suitable for recharge but there is no stream nearby, the project cannot be practically implemented at that site. In fact, this characteristic would result in project cancellation. Figure 9 demonstrates the stream network.

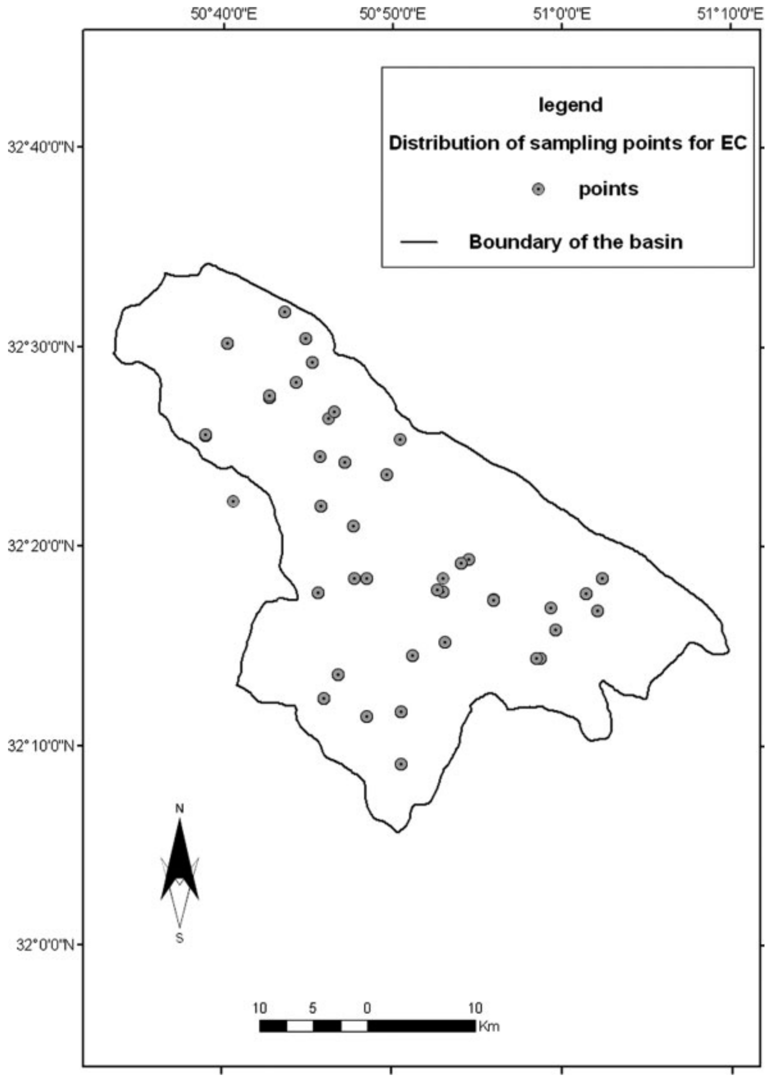

Figure 7. Distribution map of EC sampling points in the study area.

As there is not enough research about the appropriate landform units for artificial recharge, the relationship between geomorphologic units and fitting sites for GAR was investigated. To do so, geomorphology and suitable area map (without land-use filtering) were overlaid. The geomorphology map (Figure 10) shows that there are eight units in study area.

The digital map's format is a vector while locating operation needs raster format. Therefore, softwares which support both formats had to be used. ArcView 3.2a software was employed for opening and weighting input maps. ArcGIS 9.3 software was employed for classification and integration of the maps and preparation of output maps.

3. Classification and Integration of thematic layers

3.1. Boolean logic

One commonly used model to combine information layers is Boolean logic. Mathematical logic Boolean (binary), was introduced by George Boole for the first time in 1854. There are two classification levels in this logic, one is satisfactory and another one is unsatisfactory. In fact, only one or zero value is assigned to each unit area in Boolean logic. There are different operations in Boolean logic including AND, OR, NOT, and XOR. The best conditions for selection are taken into account and all criteria act as a limitation to Boolean method; so, via using this method, the results will be more accurate. Also, this method is more frequently applied in primary studies (Khajedin *et al.* 2006). It could be assumed that the most simple and common type of GIS model is Boolean operations. Robinov (1989) introduced the use of Boolean operations with reasoning for geological maps. Boolean model involves the logical combination of binary maps resulting from the application of conditional operators (Bonham-Carter 1996). This method has also disadvantages such as failure to consider some cases including priority of the factors, internal changes in each parameter, error in defining the conceptual model, and the layers' error (Alimohammadi 2006).

The thematic layers are classified in conformity with Boolean logic in Table 1. The associated area of each class is exposed there. The four following maps that were used as basic data are: slope, permeability, thickness of dry alluvium, and chemical quality of alluvium groundwater. The land-use map is used separately as a filter map.

Based on set theory, the AND operator yields the logical intersection of the two data sets, and the OR operator obtains the logical union of the two data sets. The AND Boolean operator is considered in this study because that is the most sensitive operator. After procuring layers by application of Boolean standard and combining the layers, the final map will be obtained as a binary map.

Table 1. Acceptable ranges of thematic layers in Boolean logic.

Maps	Classes	Ranges	Area (%)	Weight
Slope (%)	Suitable	0–8	40	1
	Unsuitable	More than 8	59.97	0
Surface permeability (mm/hour)	Suitable	More than 25	19.86	1
	Unsuitable	0–25	80.14	0
Unsaturated zone thickness of alluvium (m)	Suitable	More than 20	56.97	1
	Unsuitable	0–20	43.03	0
Chemical quality of groundwater in alluvium (μmohs/cm)	Suitable	0–2250	100	1
	Unsuitable	More than 2250	0	0
Land-use	Suitable	Range land (poor–moderate)–woodland–bare land	61.68	1
	Unsuitable	Agriculture–urban–water–rock	38.32	0

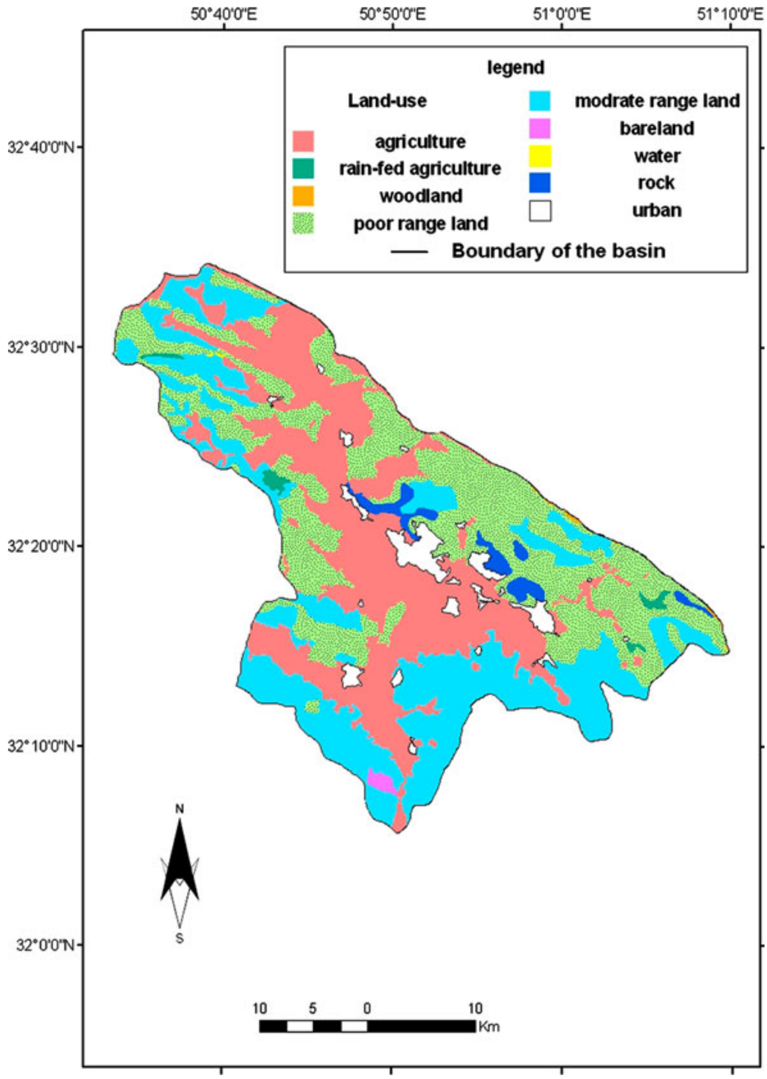

Figure 8. Land-use map in Shahrekord plain.

3.2. Fuzzy logic

One useful model which is used to combine artificial recharge information is Fuzzy logic. A Fuzzy set is a collection of membership degrees. Membership of a Fuzzy set is expressed on a continuous scale from 1 (full membership) to 0 (nonmembership). Using Fuzzy functions can provide separated maps with several classes. The individual classes for each map might be defined according to their degree of membership. Based on their importance, a membership degree is given to each class varied from 0 to 1. But there are no practical constraints on the choice of Fuzzy membership values (Bonham-Carter 1996). A variety of operations can be employed to combine the membership values together. There are totally five operators named:

fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum, and fuzzy gamma (Mahdavi 2010).

First of all, basic maps were ranked based on their impact and effect. The permeability with the greatest impact on artificial recharge was called grade A and the thickness of unsaturated zone was named grade B, the slope was highlighted with the grade C and finally the salinity was shown with the grade D. Then, for each layer four scales were considered including: unsuitable, moderately suitable, suitable, and very suitable. According to experts' opinion, previous studies and experience at artificial recharge stations, numerical ranges were specified on the scales (Table 2).

Four basic factors are quantitative and classified according to the aforementioned explanations, but land-use is a qualitative parameter which could be either appropriate or inappropriate for artificial recharge. Thus, it was weighted by the use of Boolean logic.

In Fuzzy algebraic products, the output is always smaller or equal to the smallest contributing membership value due to the effect of multiplying several numbers smaller than one. In this research Fuzzy algebraic product operator was used because of its high sensitivity in appointing artificial recharge areas (Bonham-Carter 1996).

4. Discussion and conclusion

4.1. Boolean logic results

The result of combining basic maps is given in Figure 11. As it is seen in this figure, 4.25% of the whole area is considered appropriate for artificial recharge.

Table 2. Acceptable ranges of thematic layers in Fuzzy logic.

Maps	Classes	Ranges	Area (%)	Weight
Slope (%)	Very suitable	0–2	2.25	0.7
	Moderately suitable	2–5	23.62	0.5
	Suitable	5–8	14.13	0.3
	Unsuitable	More than 8	59.98	0.01
Soil surface infiltration rate (mm/hour)	Very suitable	More than 45	19.86	0.95
	Moderately suitable	25–45	0	0.74
	Suitable	15–25	8.08	0.34
	Unsuitable	0–15	72.06	0.01
Unsaturated zone thickness of alluvium (m)	Very suitable	More than 30	4.45	0.8
	Moderately suitable	20–30	52.53	0.65
	Suitable	10–20	31.94	0.5
	Unsuitable	0–10	11.08	0.01
Chemical quality of groundwater in alluvium (µmohs/cm)	Very suitable	0–1000	100	0.6
	Moderately suitable	1000–2250	0	0.45
	Suitable	2250–4000	0	0.25
	Unsuitable	More than 4000	0	00.01
Land-use	Suitable	Range land (poor–moderate)–woodland–bare land	61.68	1
	Unsuitable	Agriculture–urban–water–rock	38.32	0

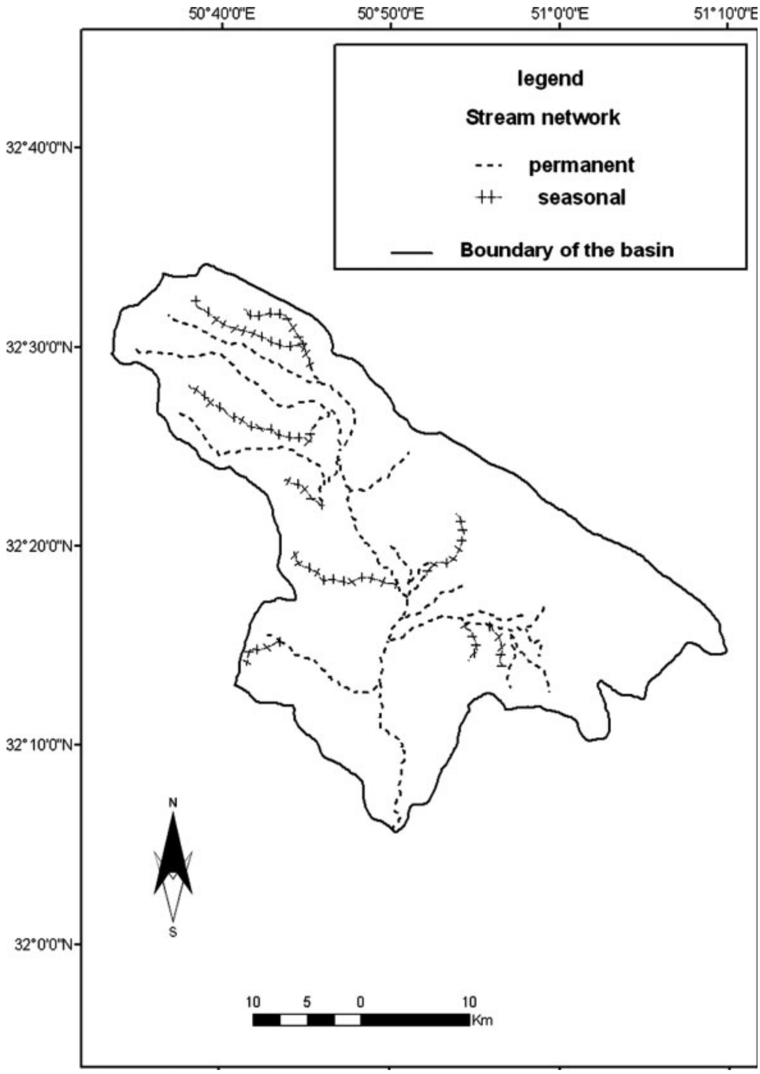

Figure 9. Stream network map in Shahrekord plain.

In the next step, the land-use as a binary map was integrated with resulted map (Figure 11). Filtering the resulted maps indicated that land-use layer decreased the sustainability rate to one-third. Therefore, it is concluded that 4.25% of the total area was suitable for artificial recharge; while 2.62% had land-use limitation; and the rest (1.63%) had no restriction.

The relationship between geomorphologic units and favorable sites for artificial recharge was investigated by combination of suitable zones without land-use and with landform map. The results are exhibited in Figure 12. Suitable areas for artificial recharge were located in the Colluvial Fans and Complex units (Complex unit is a compound of other geomorphologic units which surround one unit).

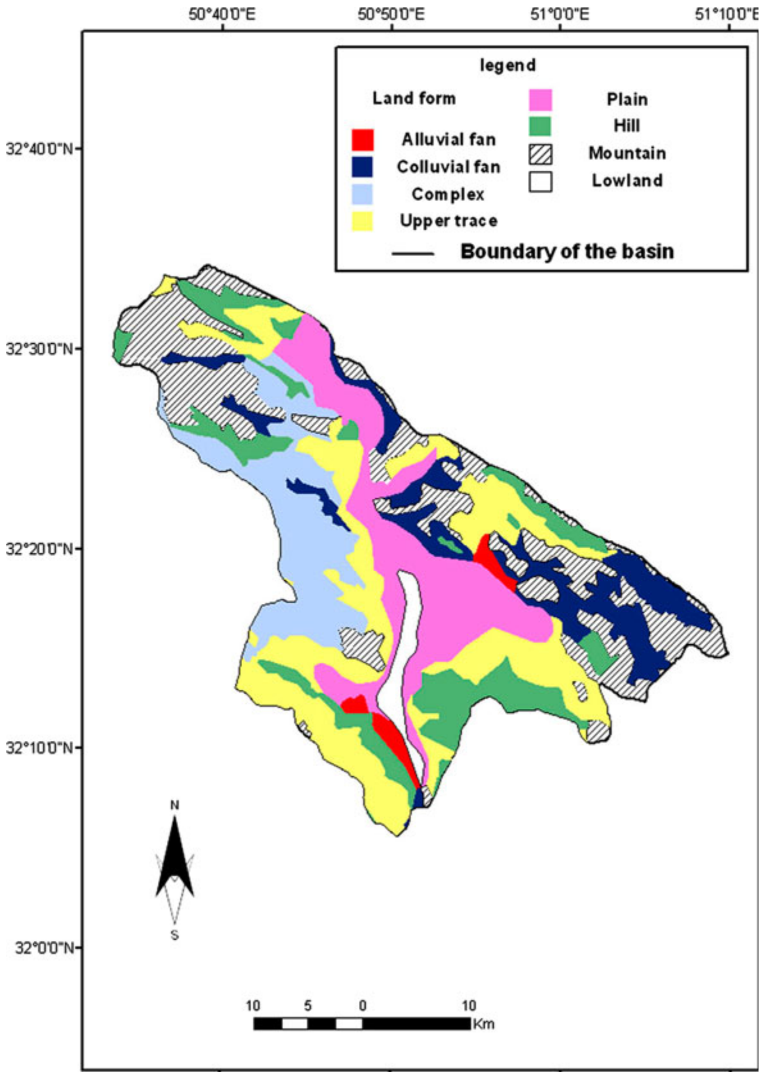

Figure 10. Landform map in Shahrekord plain.

4.2. Fuzzy logic results

The four base maps (slope, surface soil infiltration rate, unsaturated zone thickness and chemical quality of alluvium) were combined via using Fuzzy algebraic product operator. Then, a map was generated with smaller value of weight in each layer that was categorized into three scales named: suitable, moderately suitable, and unsuitable. According to Figure 13, 4.79 and 17.94% of the total area were suitable and moderately suitable, respectively.

The land-use which was a binary map was integrated with the result map. As can be discovered from Figure 13, land suitability for GAR decreased to 1.87%. This point is correct for moderately suitable areas.

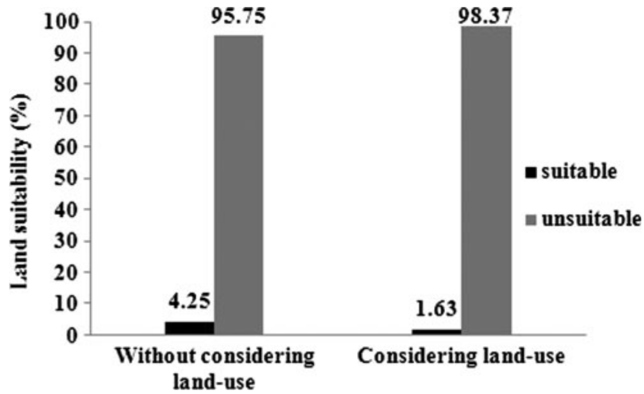

Figure 11. Integrated Result of the basic maps using Boolean logic.

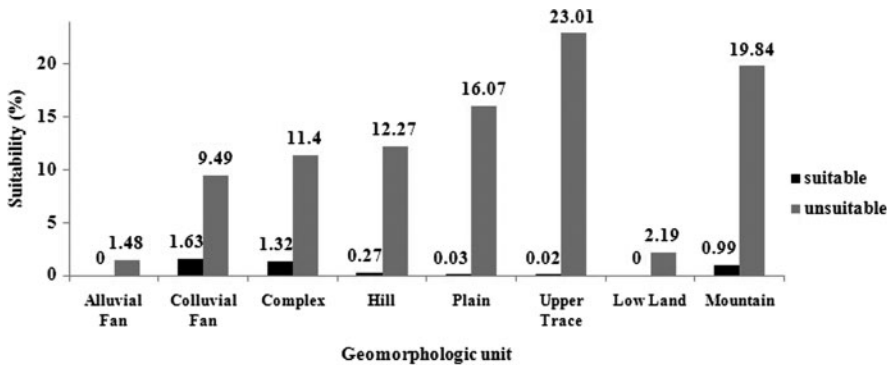

Figure 12. Results of overlaying geomorphology and artificial recharge maps (Boolean).

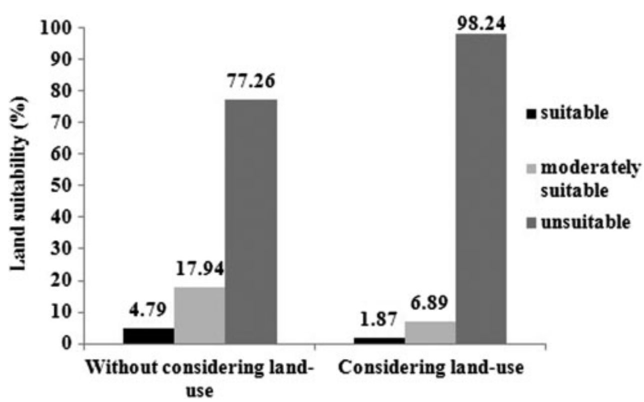

Figure 13. Results of integrating basic maps using Fuzzy logic.

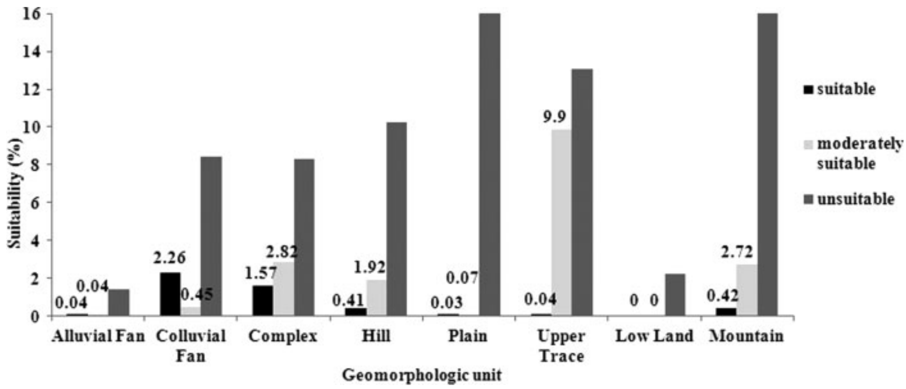

Figure 14. Results of overlaying geomorphology and artificial recharge map (Fuzzy).

The result of integration of the geomorphology map and suitable areas for artificial groundwater recharge via application of Fuzzy logic is shown in Figure 14. The figure expresses that Colluvial Fan and then Complex units have the highest percentages for suitable mode. Upper Trace and Complex units are moderately suitable.

4.3. Discussion

According to Fuzzy investigation, 4.79% of the study area was absolutely suitable and 17.94% was moderately suitable. Also in Boolean technique, 4.25% of the lands were measured to be suitable (Figure 15).

Percentages of favorable areas in both algorithms were approximately equal. Fuzzy logic operated similar to Boolean logic in terms of calculating 100% appropriate and risk-free areas. Furthermore, Fuzzy method had superiority over Boolean logic; because of introducing the moderately suitable mode in addition to suitable mode. Although, medium mode has less reliability, the project sometimes can be practically implemented at those sites. Therefore, Boolean technique is

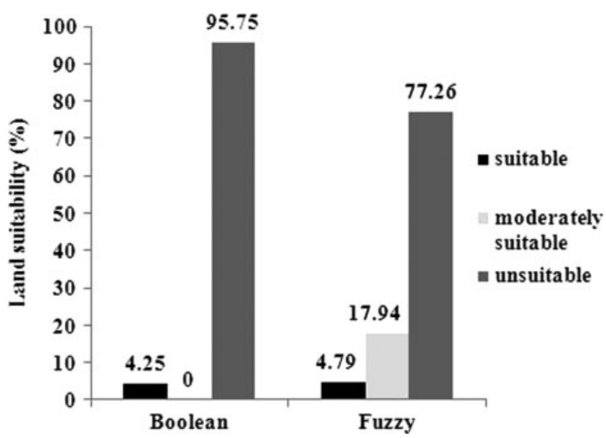

Figure 15. Comparison between the result of Boolean and Fuzzy techniques.

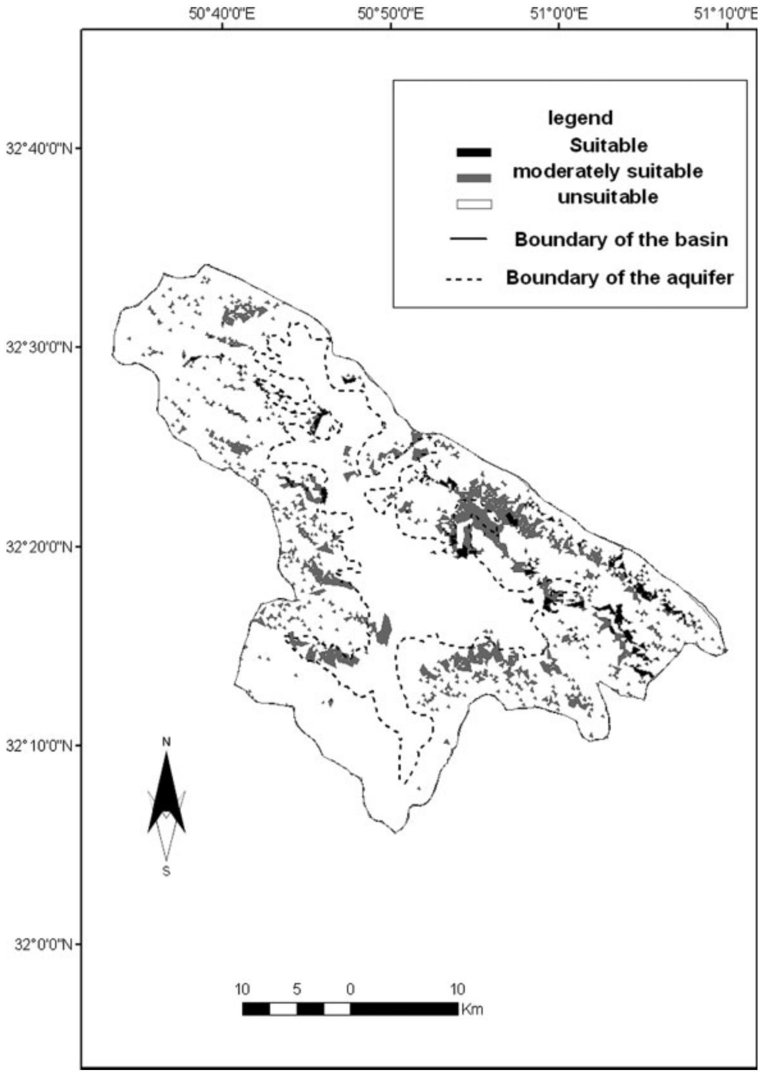

Figure 16. Final map of suitable sites based on Fuzzy logic.

preferred for primary studies and Fuzzy method is strongly proposed to identify groundwater artificial recharge projects.

After obtaining suitable zones having land-use restriction with both logics (Figures 16 and 17), by overlaying the stream network and suitable zones' map, these points should be investigated due to the proximity of the water resources. And then, areas with access to water will be found.

Finally, according to overlaid maps (stream network layer and final map) corresponding to Boolean logic, suitable sites were obtained with A_i sign. Also, based on Fuzzy logic, suitable, moderately suitable, and combined locations (suitable–moderately suitable) were distinguished. They are marked in Figure 18 as

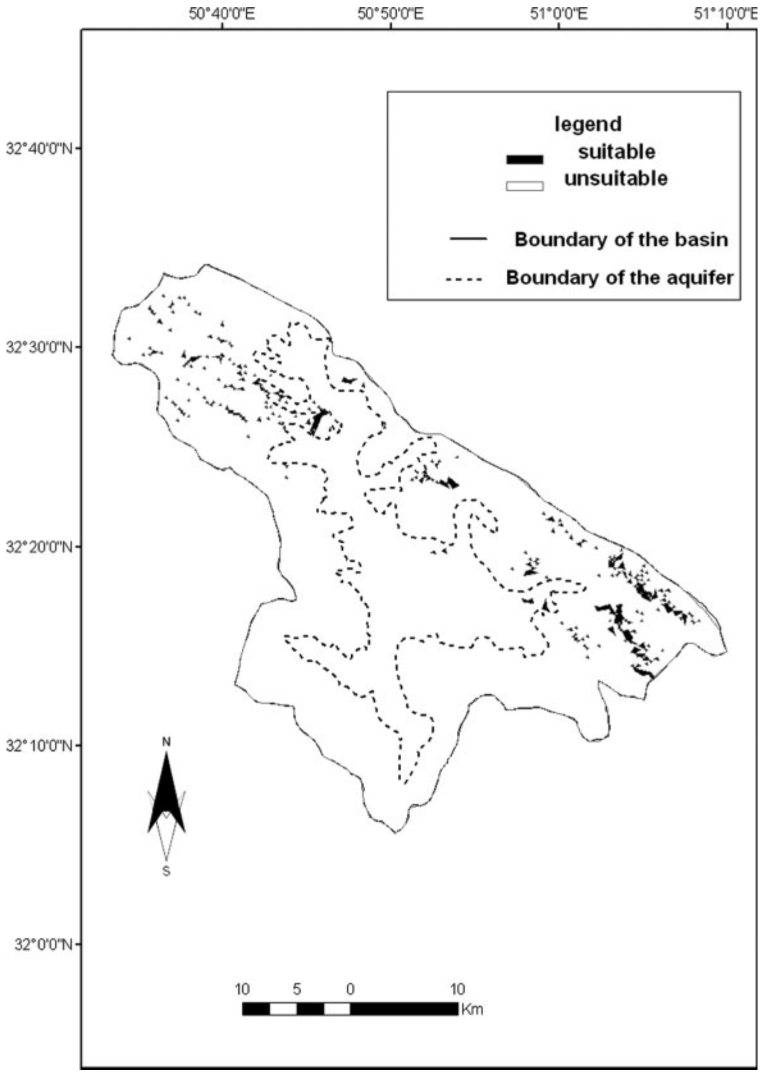

Figure 17. Final map of suitable sites based on Boolean logic.

A_i, B_i, and AB_i, respectively. Suitable points corresponding both methods were measured the same.

4.4. Conclusion

The following results were achieved from this research:

According to Fuzzy technique there were 4.79, 17.94% of the study areas suitable and moderately suitable for artificial recharge, respectively; while, according to Boolean technique, 4.25% of the lands were suitable.

Appropriate points were almost the same in both Fuzzy and Boolean logic.

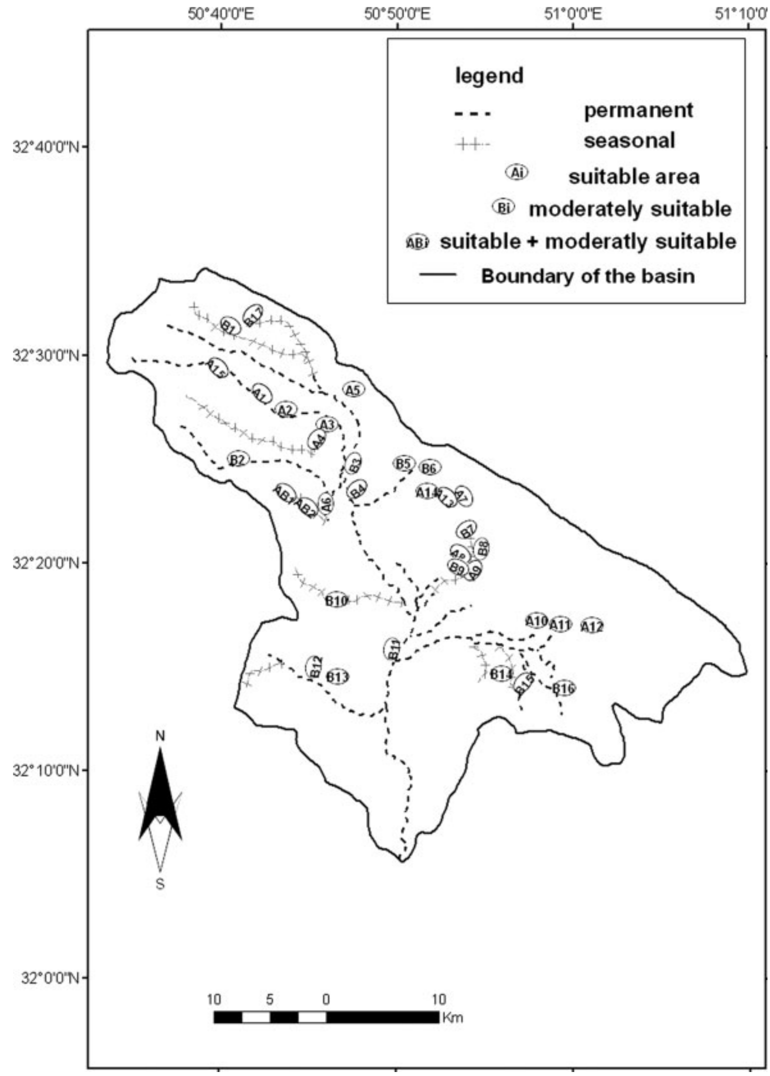

Figure 18. The suitable zones for GAR in Boolean and Fuzzy logic.

Fuzzy technique had superiority over Boolean. It introduced another group with less reliability which is named ‘medium mode’.

The mountainous parts of the study area were mostly inappropriate for artificial recharge in the light of factors like slope and the infiltration rate.

In Boolean method, Suitable areas for artificial recharge were located in the Colluvial Fan and Complex units.

In Fuzzy method, Colluvial Fan and then Complex units had the highest percentage as the most suitable cases. In addition, Upper Trace and then Complex units were moderately suitable cases for artificial recharge. Thus, it could be interpreted that the Colluvial fan units were favorable geomorphologic units for artificial recharge.

After obtaining suitable zones (with land-use), the state of being sited near the water resources with overlaying the stream network and suitable zones' map, should be investigated.

According to Fuzzy logic, 15 suitable, 17 moderately suitable, and 2 combined (suitable–moderately suitable) locations with access to water were distinguished. These locations are demonstrated in Figure 18.

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