Identification of groundwater artificial recharge sites using Fuzzy logic: A case study of Shahrekord plain, Iran

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Abstract
In recent decade water resources has decreased and the groundwater level has been falling down in Iran. The best solution is groundwater management and artificial recharge (AR) using surface water. The main objective of this research is to identify the AR sites using Fuzzy logic in the Shahrekord plain, Shahrekord, Iran. Effective factors on AR collected including slope, infiltration rate, thickness of unsaturated zone, surface water EC, landuse and stream network. They classified and weighted in ArcView 3.2a and ArcGIS 9.3 software and were integrated using multiplying operator in Fuzzy model. The results show that 4.79 and 17.94 percent of the plain area is suitable and medium suitability for AR, respectively. The values are 1.87 and 6.89 percent when the landuse restriction considered. Finally, 32 locations identified as having potential for AR.

Introduction
There is the need for recognition and optimal utilization of groundwater: these resources are 99 percent of available fresh water. Proper management of water resources is very important because of problems of droughts and the other hand devastating floods. In this regard, collecting surface water, groundwater recharge and proper regulation of water utilization, are known to be the most important strategies for water resource management (Mahdavi et al., 2004). The use of groundwater is increasing in Iran, thus it should be compensated by using winter and spring floods to compensate the overuse. Introducing surface storages may not be cost-effective in some areas because of the large investment outlay and the fact that they will fill with silt. On the other hand, saving water in the aquifers results in the protection and improvement of water quality. Therefore, artificial recharge is the best solution for water shortage in some areas (Morovati, 2008). Artificial recharge is to feed water to a permeable formation with the aim of recharging the groundwater aquifer and to re-use it and with better quality by providing additional facilities or changing, the natural conditions of the region.
Selection of appropriate artificial recharge locations of groundwater is an inevitable important necessity and is the main principles of creating this system. Thus, it needs to be done with great care. There are several characteristics for locating that should integrated and analyzed together since the quantity of these parameters are constantly changing. In this regard, GIS is a very useful tool (Mahdavi, 2004 and Ghayoumian, 2007). One useful model for combining information concerning artificial recharge is Fuzzy logic. A fuzzy set is a collection of degrees of membership. Membership of a fuzzy set, however, is expressed on a continuous scale from 1 (full membership) to 0 (full non-membership). Using fuzzy functions can be separated maps of a few classes. Then each class is given a membership degree based on their impacting, in the range (0, 1). A variety of operations can be employed to combine the membership values together. There are five operators: namely fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum, and fuzzy gamma.

An overview of artificial recharge is given by Bouwer (1999, 2002), who points out the major factors to be considered. He also discusses about different artificial recharge systems, their design and management. Several studies have been carried out for the determination of areas most suitable for artificial recharge (Krishnamurthy et al., 1996; Saraf and Choudhury, 1998; Han, 2003; Nouri, 2003; Mohan and Shankar, 2005; Ghayoumian et al., 2005).

Khajedin et al. (2006) who in their plan determined the potential habitat of five industrial forestry species: Olive, Pine, Brotesya, Sarvenaz and Lebanon cedar in the Chaharmahal-Va-Bakhtiari (CHB) province. After preparing and classifying the required of layer, they were combined and integrated using Boolean and Fuzzy methods. Alimohammadi (2006) after determining criteria for identification of an appropriate site for a park classified them using the analytic hierarchy process and then combined them with using Boolean logic, Fuzzy logic and multi-blower. Finally, he compared the results and decided that Fuzzy logic gives a wide answer area with more and better utility. Hekmatpoor et al. (2007) identified suitable zones for artificial recharge in Varamin plain, Iran. They considered slope, Surface soil infiltration rate, alluvium thickness, alluvium quality and Ability of water transferring in alluvium as criteria. The layers overlaid and using Decision Support System (DSS) method was decided for every situation. Ghayoumyian et al.(2007) located suitable areas for artificially recharge groundwater of Gavbandy basin, Iran. They consider the factors such as: slope, Surface soil infiltration rate, alluvium thickness and alluvium quality. The maps of the factors combined in GIS’s software with boolean and fuzzy models were classified and combined. Ataeizadeh and Chitsazan (2008) studied feasibility of artificial recharge in the Mydavand-Dalvan plain using GIS techniques with layers such as hydraulic gradient, slope, depth to water table, unsaturated section lithology, aquifer environment, surface lithology (soil infiltration) and surface water electrical conductivity considered. They was combined with the method of Weighted Index Overlay. Finally, a map was produced of suitable areas for the implementation of artificial recharge. Dadrasi (2008) compared the fuzzy logic model to other conceptual models compatible with GIS for locating the flood spread zone. The research was done on 6 cities of
Khorasan-Razavi province, Iran. The results show that the fuzzy logic sum operator with more than 5.66 percent conformity with reality had the highest efficiency.

The annual discharge of groundwater in Shahrekord plain is about 250Mm$^3$. This has caused water table reduction that has been more than 13m during 1993 and 2005. The most important reasons include heavy withdrawal, precipitations that are very unevenly distributed, both spatially and temporally and medium high slope (Lalehzari, 2008).

The main objective of this research is site selection for artificial recharge in Shahrekord plain, Iran using fuzzy logic.

Materials and methods

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

As the map's format was vector and for locating operations are used raster format, therefore software used that supports both formats. ArcView 3.2a software employed for opening and weighting input maps. ArcGIS 9.3 software employed for classification and integration of the maps and preparing of output maps.

The use of all the effective characteristics is obviously not possible. Hence, the factors is determined by considering factors such as purpose, expected scale and accuracy for work, regional conditions, influence of each factor, and adequate availability of information. In zones where its water table is close to the surface and not being exploited, recharge will cause the water table to rise and it will become Marsh land. In the other words, the natural underground reservoir for storage of water is small, so recharge does with a lower certainty of success. The water table was measured in 31 pizometer in 2006 (Fig. 3). Then an interpolating the map of the unsaturated zone thickness was produced (Fig. 4).

The soil texture was firstly determined. So in each Landform unit (of which there are eight), three point were selected and twenty-four samples were taken from the surface of the plain in order to analyze the texture. The range of permeability was determined based on texture-infiltration relationships established by the Food and Agriculture Organization (FAO, 1979) at each station (Ghayoumian, 2007). A map of Surface soil infiltration rate obtained using interpolation technique (Fig. 5). For developing the slope map (Fig. 6), digital elevation model (DEM) used.

Groundwater Electrical Conductivity (EC) and Total Dissolved Solids (TDS) variations have similar trends over the area, so the EC factor is used as an indicator of water quality. For this purpose, 40 points across the basin, including 23 wells, 13 flumes and 4 springs selected. Fig. 7 shows the location of the points. Average EC data calculated over a 2-year period (2004-2005) and used to develop the EC map (Fig. 8).
Figure 1. Status of Shahrekord plain

Figure 2. Status of Shahrekord aquifer in plain

Figure 3. Pizometric wells in Shahrekord plain

Figure 4. Thickness of unsaturated zone in Shahrekord plain
Figure 5. Map of soil texture in Shahrekord basin

Figure 6. Map of slope in Shahrekord basin

Figure 7. Distribution of sampling points for EC in Shahrekord basin

Figure 8. Contours of EC in Shahrekord basin
Fig. 9 shows the area covered by each land-use type. This map is applies to the map of suitable areas for recharge, as a filter for deleting areas that have a land-use restriction. According to the different types of land-use, only rangelands are usually appropriate for artificial recharge. After combining layers and finding suitable places for artificial recharge, those limitations evaluated in terms of their distance to water sources. If the region is suitable for recharge, but there is no stream nearby, the project is not be practically implemented at that site. In fact, this characteristic is a sanction for the project. Fig. 10 is stream network.

Fuzzy logic generally bases on two principles: 1- classifying maps compared together and based on importance 2- weighting classes in every map based between 0 and 1(Ghayoumian, 2007). In fuzzy algebraic products, the combined fuzzy membership values tend to be very small with this operator, due to the effect of multiplying several numbers less than 1. The output is always smaller or equal to the smallest contributing membership value and therefore reduced. In this research fuzzy algebraic product operator used because of its high sensitivity in specifying artificial recharge areas (Bonham-Carter, 1996).

Four following maps used as base data: slope, permeability, thickness of dry alluvium and alluvium chemical quality. The landuse and stream network maps employed as a filter map.

Firstly, basic maps ranked based on their importance and effect. If the permeability with the greatest impact on artificial recharge is grade A and the thickness of
unsaturated zone grade B, C is slope and finally the salinity with the grade D. Then, for each of the layers four classes were considered including: unsuitable, moderately suitable, suitable and very suitable. According to expert opinion and previous studies, numerical ranges specified on the classes (Table 1). The four basic factors are quantitatively and classified according to above, but land-use is a qualitative parameter. A land-use case is either appropriate or inappropriate for artificial recharge, thus it weighted using Boolean logic.

Table 1. Acceptable ranges of thematic layers in Fuzzy logic

<table>
<thead>
<tr>
<th>Maps</th>
<th>Classes</th>
<th>Ranges</th>
<th>Area (%)</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (%)</td>
<td>very suitable</td>
<td>0 to 2</td>
<td>2.25</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>moderately suitable</td>
<td>2 to 5</td>
<td>3.62</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>suitable</td>
<td>5 to 8</td>
<td>14.13</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>unsuitable</td>
<td>More than 8</td>
<td>59.98</td>
<td>0.01</td>
</tr>
<tr>
<td>Surface soil infiltration rate (mm/hr)</td>
<td>very suitable</td>
<td>More than 45</td>
<td>19.86</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>moderately suitable</td>
<td>25 to 45</td>
<td>0</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>suitable</td>
<td>25 to 15</td>
<td>8.08</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>unsuitable</td>
<td>0 to 15</td>
<td>72.06</td>
<td>0.01</td>
</tr>
<tr>
<td>Unsaturated zone thickness of alluvium (m)</td>
<td>very suitable</td>
<td>More than 30</td>
<td>4.45</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>moderately suitable</td>
<td>20 to 30</td>
<td>52.53</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>suitable</td>
<td>10 to 20</td>
<td>31.94</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>unsuitable</td>
<td>0 to 10</td>
<td>11.08</td>
<td>0.01</td>
</tr>
<tr>
<td>Chemical quality of alluvium (μmohs/cm)</td>
<td>very suitable</td>
<td>0 to 1000</td>
<td>100</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>moderately suitable</td>
<td>1000 to 2250</td>
<td>0</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>suitable</td>
<td>2250 to 4000</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>unsuitable</td>
<td>More than 4000</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>Land-use</td>
<td>suitable</td>
<td>Range land(poor-moderate)-woodland-bare land</td>
<td>48.52</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>unsuitable</td>
<td>Agriculture-urban-water-rock</td>
<td>51.48</td>
<td>0</td>
</tr>
</tbody>
</table>

Results and Discussion
The four base (slope, surface soil infiltration rate, unsaturated zone thickness and chemical quality of alluvium) maps combined using fuzzy multiplying method. A map generated with smaller value of weight in each layer that it classified to three classes including: suitable, moderately suitable and unsuitable (Fig. 11). According to this table 2 there is 4.79, 17.94 and 77.26 percent of the total area suitable, moderately suitable and unsuitable, respectively.

Table 2. Result of integrating of basic maps

<table>
<thead>
<tr>
<th>class</th>
<th>Without considering landuse</th>
<th>Considering landuse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (m²)</td>
<td>Area (%)</td>
</tr>
<tr>
<td>suitable</td>
<td>59141977</td>
<td>4.79</td>
</tr>
<tr>
<td>moderately suitable</td>
<td>222465406</td>
<td>17.94</td>
</tr>
<tr>
<td>unsuitable</td>
<td>953404225</td>
<td>77.26</td>
</tr>
</tbody>
</table>
Figure 11. Map of integrating without landuse
Figure 12. Map of integrating with land-use
The landuse, that is a binary map, integrated with the result (Fig. 11) and Fig. 12 generated considering landuse. Table 2 shows that suitability area for AR decreases to 1.87 percent. The result shows that 2.66 out of 4.79 percent of the total area has no limitation for AR in case that the landuse does not considered but the area (2.66 %) mark limitation for AR when the landuse considered. This point is correct about moderately suitable areas.

After obtaining suitable zones (with landuse), these factors should be investigated about being near the water resources. With overlaying the stream network and map of suitable zones (Fig. 12), Fig. 13 generated.

Based on fuzzy logic suitable, moderately suitable and combined (suitable-moderately suitable) locations that have access to water distinguished. They marked with $A_{\text{index}}$, $B_{\text{index}}$ and $AB_{\text{index}}$, respectively (Fig. 14). It is described in tables 4, 5 and 6 the detail of the locations such as: geographic coordinates, distance from water sources (distance to source), the type of water resource, slope, soil texture, land form and the area of proposed unit.
Table 3. Characteristics of the most suitable zones for artificial recharge

<table>
<thead>
<tr>
<th>Points</th>
<th>UTM x(m)</th>
<th>UTM y(m)</th>
<th>Distance from water sources(m)</th>
<th>Kind of water source</th>
<th>Slope (%)</th>
<th>Soil texture</th>
<th>Landform</th>
<th>Area(m×m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>47240</td>
<td>8</td>
<td>0</td>
<td>permanent</td>
<td>2 to 5</td>
<td>sandy loam</td>
<td>complex</td>
<td>1400×380</td>
</tr>
<tr>
<td>A2</td>
<td>47417</td>
<td>1</td>
<td>438</td>
<td>permanent</td>
<td>0 to 5</td>
<td>sandy loam</td>
<td>complex</td>
<td>980×900</td>
</tr>
<tr>
<td>A3</td>
<td>47789</td>
<td>6</td>
<td>0</td>
<td>permanent</td>
<td>2 to 8</td>
<td>sandy loam</td>
<td>complex</td>
<td>1000×370</td>
</tr>
<tr>
<td>A4</td>
<td>47755</td>
<td>8</td>
<td>0</td>
<td>permanent</td>
<td>2 to 8</td>
<td>loam</td>
<td>mountain</td>
<td>1600×550</td>
</tr>
<tr>
<td>A5</td>
<td>48045</td>
<td>5</td>
<td>954</td>
<td>permanent</td>
<td>2 to 12</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>900×380</td>
</tr>
<tr>
<td>A6</td>
<td>47823</td>
<td>3</td>
<td>128</td>
<td>permanent</td>
<td>2 to 8</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>1020×450</td>
</tr>
<tr>
<td>A7</td>
<td>49018</td>
<td>5</td>
<td>2221</td>
<td>seasonal</td>
<td>2 to 40</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>1000×400</td>
</tr>
<tr>
<td>A8</td>
<td>49011</td>
<td>0</td>
<td>315</td>
<td>seasonal</td>
<td>0 to 8</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>715×415</td>
</tr>
<tr>
<td>A9</td>
<td>49106</td>
<td>2</td>
<td>112</td>
<td>seasonal</td>
<td>0 to 8</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>900×650</td>
</tr>
<tr>
<td>A10</td>
<td>49704</td>
<td>6</td>
<td>1000</td>
<td>permanent</td>
<td>2 to 12</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>840×240</td>
</tr>
<tr>
<td>A11</td>
<td>49878</td>
<td>9</td>
<td>0</td>
<td>permanent</td>
<td>2 to 8</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>1000×400</td>
</tr>
<tr>
<td>A12</td>
<td>50149</td>
<td>5</td>
<td>1700</td>
<td>permanent</td>
<td>0 to 8</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>1400×270</td>
</tr>
<tr>
<td>A13</td>
<td>48929</td>
<td>1</td>
<td>3855</td>
<td>permanent</td>
<td>2 to 25</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>1000×350</td>
</tr>
<tr>
<td>A14</td>
<td>48753</td>
<td>5</td>
<td>2249</td>
<td>permanent</td>
<td>2 to 25</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>900×650</td>
</tr>
<tr>
<td>A15</td>
<td>48689</td>
<td>4</td>
<td>0</td>
<td>permanent</td>
<td>2 to 12</td>
<td>sandy loam</td>
<td>collovial fan</td>
<td>600×600</td>
</tr>
</tbody>
</table>
Table 4. Characteristics of the moderately suitable zones for artificial recharge

<table>
<thead>
<tr>
<th>Points</th>
<th>UTM x(m)</th>
<th>UTM y (m)</th>
<th>Distance from water sources(m)</th>
<th>Kind of water source</th>
<th>Slope (%)</th>
<th>Soil texture</th>
<th>Land form</th>
<th>Area(m×m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₁</td>
<td>469234</td>
<td>3598489</td>
<td>300</td>
<td>seasonal</td>
<td>2 to 12</td>
<td>C-L</td>
<td>hill-upper trace</td>
<td>1200×500</td>
</tr>
<tr>
<td>B₂</td>
<td>470417</td>
<td>3586615</td>
<td>0</td>
<td>permanent</td>
<td>2 to 12</td>
<td>C-L</td>
<td>hill</td>
<td>1500×600</td>
</tr>
<tr>
<td>B₃</td>
<td>480251</td>
<td>3586493</td>
<td>100</td>
<td>permanent</td>
<td>0 to 12</td>
<td>C-L</td>
<td>upper trace</td>
<td>760×360</td>
</tr>
<tr>
<td>B₄</td>
<td>480505</td>
<td>3584208</td>
<td>133</td>
<td>permanent</td>
<td>0 to 12</td>
<td>C-L</td>
<td>upper trace</td>
<td>960×400</td>
</tr>
<tr>
<td>B₅</td>
<td>484874</td>
<td>3586130</td>
<td>454</td>
<td>permanent</td>
<td>2 to 25</td>
<td>C-LtoSi-L</td>
<td>upper trace</td>
<td>900×450</td>
</tr>
<tr>
<td>B₆</td>
<td>486924</td>
<td>3586131</td>
<td>358</td>
<td>permanent</td>
<td>0 to 40</td>
<td>C-L</td>
<td>upper trace</td>
<td>1350×700</td>
</tr>
<tr>
<td>B₇</td>
<td>490742</td>
<td>3580170</td>
<td>0</td>
<td>seasonal</td>
<td>0 to 25</td>
<td>C-L</td>
<td>upper trace</td>
<td>2000×840</td>
</tr>
<tr>
<td>B₈</td>
<td>491476</td>
<td>3578419</td>
<td>170</td>
<td>seasonal</td>
<td>0 to 25</td>
<td>C-L</td>
<td>upper trace</td>
<td>1900×560</td>
</tr>
<tr>
<td>B₉</td>
<td>490250</td>
<td>3577421</td>
<td>290</td>
<td>seasonal</td>
<td>0 to 25</td>
<td>S-L</td>
<td>hill</td>
<td>660×320</td>
</tr>
<tr>
<td>B₁₀</td>
<td>479200</td>
<td>3574282</td>
<td>0</td>
<td>seasonal</td>
<td>0 to 25</td>
<td>C-L</td>
<td>complex-upper trace</td>
<td>3060×600</td>
</tr>
<tr>
<td>B₁₁</td>
<td>483808</td>
<td>3569500</td>
<td>0</td>
<td>permanent</td>
<td>0 to 5</td>
<td>C-L</td>
<td>upper trace</td>
<td>2500×800</td>
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<tr>
<td>B₁₂</td>
<td>476967</td>
<td>3567386</td>
<td>0</td>
<td>permanent</td>
<td>0 to 12</td>
<td>C-L</td>
<td>upper trace</td>
<td>1200×640</td>
</tr>
<tr>
<td>B₁₃</td>
<td>479580</td>
<td>3567239</td>
<td>580</td>
<td>permanent</td>
<td>0 to 40</td>
<td>C-L</td>
<td>upper trace</td>
<td>3140×850</td>
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<tr>
<td>B₁₄</td>
<td>492298</td>
<td>3567603</td>
<td>0</td>
<td>seasonal</td>
<td>2 to 40</td>
<td>C-L</td>
<td>upper trace</td>
<td>4360×1100</td>
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<tr>
<td>B₁₅</td>
<td>495336</td>
<td>3567236</td>
<td>0</td>
<td>permanent</td>
<td>2 to 40</td>
<td>C-L</td>
<td>upper trace</td>
<td>1000×650</td>
</tr>
<tr>
<td>B₁₆</td>
<td>499195</td>
<td>3566165</td>
<td>0</td>
<td>permanent</td>
<td>0 to 25</td>
<td>C-L</td>
<td>upper trace</td>
<td>1300×500</td>
</tr>
<tr>
<td>B₁₇</td>
<td>470703</td>
<td>3598774</td>
<td>220</td>
<td>seasonal</td>
<td>2 to 12</td>
<td>C-L</td>
<td>upper trace</td>
<td>1300×600</td>
</tr>
</tbody>
</table>

Table 5. Characteristics of the combined points A and B zones for artificial recharge

<table>
<thead>
<tr>
<th>Points</th>
<th>UTM x(m)</th>
<th>UTM y (m)</th>
<th>Distance from water sources(m)</th>
<th>Kind of water source</th>
<th>Slope (%)</th>
<th>Soil texture</th>
<th>Land form</th>
<th>Area(m×m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB₁</td>
<td>475145</td>
<td>3583382</td>
<td>0</td>
<td>seasonal</td>
<td>0 to 25</td>
<td>S-L</td>
<td>collovin fan-complex</td>
<td>1500×550</td>
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<td>AB₂</td>
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<td>C-LtoSi-L</td>
<td>collovin fan-complex</td>
<td>1700×350</td>
</tr>
</tbody>
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