

# Recharge Wells Site Selection for Artificial Groundwater Recharge in an Urban Area Using Fuzzy Logic Technique

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**Abstract** In arid and semi-arid area, groundwater is the most important water resources. Surface runoff harvesting is the most important process in the artificial recharge of groundwater that should increase groundwater quality and quantity. Urban impervious area provides an appropriate surface to produce adequate amounts of runoff. Groundwater recharge via recharge wells is one of the successful direct sub-surface methods. As many cities around the world face issues of water scarcity due to a fast and unsustainable urbanization, identify the best locations of groundwater recharge wells is an interesting relevant topic, especially in the arid and semi-arid area. Selection of a suitable area for groundwater recharge could increase efficiency of the recharge wells. In this study, the best location of recharge wells was investigated in Urmia city located in the North-west of Iran using fuzzy logic technique. In this study, locations of the drainage channel junctions with adequate potential of surface runoff were determined using SWMM. Appropriate locations for recharge wells were determined based on different layers including distance to runoff harvesting points, distance to the production water wells and depth of groundwater table. Hydraulic condition (hydraulic conductivity and specific recharge) was also used separately. The input layers were prepared using geostatistical interpolation techniques in ArcGIS 9.3 software. Mamdani fuzzy inference system was applied to incorporate the fuzzified input layers. Finally, in each area, pixels with the highest value were proposed as suitable locations for recharge wells. Based on the results, the number of pixels with “High” priorities increased when the hydraulic conductivity was used to site selection. Comparing hydraulic conductivity layer and selected location of the

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recharge wells shows that the area with low hydraulic conductivity and the area closed to the production water wells has not suitable priority for recharge wells.

**Keywords** Fuzzy logic · Groundwater · Recharge wells · Site selection · Surface runoff

## 1 Introduction

In arid and semi-arid areas, groundwater is the most important water resources. In many areas, quantity and quality of groundwater decrease due to over extraction of groundwater related to population growth and development. In these areas, precipitations are irregular with high intensity and up to 70% of precipitation is loosed via evapotranspiration. Irregular rainfall with high intensity should lead to damage flooding and this is more prevalent in urban areas with large amount of impervious surfaces. However, urban areas can also acts as a water harvesting system that produce a great amounts of runoff (Dietz and Clausen 2008; Schoonover et al. 2006; Wang et al. 2005) that should use for artificial recharge of the aquifers. To transfer surface runoff into the aquifer, various direct and indirect artificial recharge methods are suggested (Todd and Mays 2005; Water 2000). In indirect artificial recharge methods, surface runoff conduct to the ponds and during a natural infiltration process, the harvested water reaches to the aquifer. But in the direct methods, using a bore hole, runoff straightly transferred to the aquifer and minimum runoff losses will occur because surface runoff directly injects to the aquifer. Recharge wells are one of the successful direct sub-surface techniques which are commonly used for shallow water table aquifers. Urban runoff could contain high concentrations of the contaminations and may have significant adverse effects on beneficial uses of receiving water bodies; so runoff management must improve for increasing of the runoff quality before direct injection of the runoff to the aquifers.

Selection of a suitable area for groundwater recharge wells should increase efficiency of recharge wells. Several studies have been performed to recognize the high potential sites for groundwater recharge using Remote Sensing (RS) and Geographic Information Systems (GIS). GIS is a comprehensive computer program that is capable of managing large amount of spatially related information, providing the ability to integrate multiple layers of information for multi-criteria analysis (Chenini et al. 2010; Moody and van Ast 2012). So, it is applied to large number of site selection studies.

Solomon and Quiel (2006), applied GIS for identifying the best location of artificial recharge. The results indicate that structures and landforms are the most important factors to determine the best locations for artificial recharge of groundwater. In one research the best location for artificial groundwater recharge was done via GIS techniques in a coastal aquifer of southern Iran (Ghayoumian et al. 2007). In order to assess the groundwater recharge potential zone, GIS and RS were used to assimilate five contributing factors: lithology, land cover/land use, lineaments, drainage, and slope (Yeh et al. 2009). The results of this study show a significant relationship between locations of the suitable areas for groundwater recharge and soil structure. Overlay weighted model and BOOLEAN logic were used for selection of the best areas for artificial recharge of groundwater (Riad et al. 2011a). Boolean logic method was proposed as an easier and faster method for site selection. Layers slope, distance to urban area, distance from production well, distance from treatment plants, distance from roads, land use, pollution risk and depth to groundwater were overlaid to select the suitable area. In this research all the affecting factors were given an equal weight (10%) except only the distance to treatment plant and the land

use which were given weights equal to 20%. Boolean logic method and fuzzy logic were used for artificial groundwater research site selection in the Sadat City (Semi-Arid Area) in Egypt (Riad et al. 2011a). Fuzzy logic provides the same classification for each zone as the weighed models in GIS. Moreover, fuzzy logic could offer more priority classification for the particular points in each site. GIS and Boolean Logic were used for artificial groundwater recharge site selection in Saudi Arabia (Riad et al. 2011b). Zaidi et al. (2015) presented distance to the usable recharge water (rain water, desalinated sea water and treated waste water) as the most important factors for recharge sites selection. Geospatial techniques were also used for artificial groundwater recharge zoning in Sarabanga sub-basin Cauvery River, Tamil Nadu. Geology, geomorphology, topography, drainage density, land-use and land-cover parameters combined based on the GIS overlay analysis (Prabhu and Venkateswaran 2015). Results of this study showed the efficiency of the artificial recharge system for groundwater recharge even for small flood events.

Also, several methods were used for artificial groundwater recharge site selection (Senanayake et al. 2016; Singh et al. 2017), but rare studies focused on the ability of fuzzy logic technique. Fuzzy logic is a rapid developing methodology in engineering systems (Azadi et al. 2009; Grint 1997). The main aim of this study was to presents a methodology to identify the best locations of the groundwater recharge wells. This research attempts to assess the feasibility of the fuzzy logic technique in site selection for suitable recharge zone. As injection wells used to direct transmittance of surface runoff (Contributors et al. 2013; Ehsan 2013; Narula 2014), this research is a comprehensive attempt to present a method for site selection and parameterization of injection wells using GIS and fuzzy logic technique.

## 2 Methodology

### 2.1 Study Area

Urmia city (37° 32' N and 45° 02' E) located at West of the Urmia Lake in the North-West of Iran (Fig. 1). Urmia Lake is the second largest salt lake in the world and largest salt Lake of Iran. In the recent decade, the quality and quantity of the groundwater was decreased due to the groundwater over extraction and decrease of the lake water input (Ghalibaf and Moussavi 2014).

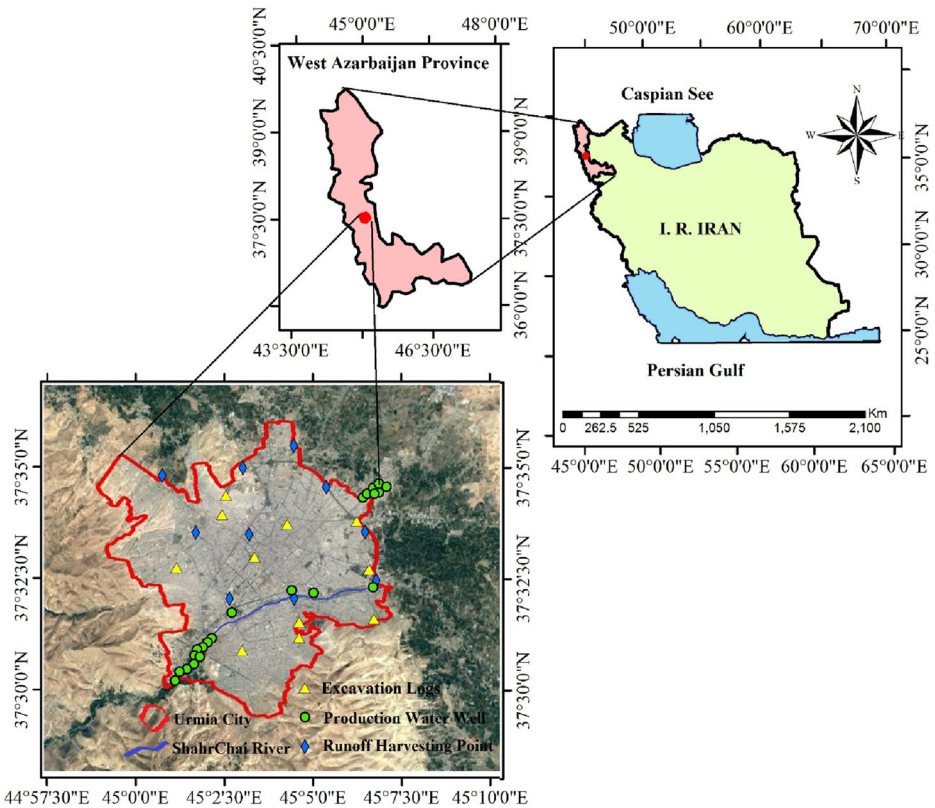
The average annual rainfall of the region is about 375 mm. In the studied area, over than 80% of the surfaces are impermeable, consequently, the precipitation that falls in these areas may be lost to evapotranspiration.

A significant portion of this water can be employed for groundwater artificial recharge.

The geological condition of the studied urban area is also suitable for water harvesting (contains well grained sand with hydraulic conductivity equal to  $15.19 \text{ m.day}^{-1}$  and silty sand with hydraulic conductivity equal to  $0.63 \text{ m.day}^{-1}$  (Todd and Mays 2005). Thickness of the saturated zone in the study area varies from 76 m to 91 m.

### 2.2 Recharge Wells Site Selection

In order to recognize the proper location of recharge wells, fuzzy logic was applied to integrate the primary input layers with fuzzy roles. Locations of the drainage channel junctions with adequate potential of surface runoff were determined using SWMM. Input layers were processed in ArcGIS via geo-statistical analyst extension. Then, output map was achieved by using fuzzy logic toolbox in MATLAB.



**Fig. 1** Locations of Urmia city in the West Azerbaijan province, I.R. Iran

Depth of groundwater table (Information of piezometers such as location, depth and water table) are obtained from Regional Water Company of Urmia city. Municipality presented map of urban drainage system, the type of the sub-layers material and excavation logs information. Location of urban production wells and discharge of production were prepared from Water & Wastewater Company of West Azerbaijan. The presence or absence of the permeable layers, depths of water table and groundwater flow directions, and the sub-surface geology of the study urban area was determined based on the data analysis.

Distance to runoff harvesting points, distance from the production wells and depth of groundwater table were used as the inputs of ArcGIS via geostatistical modeling. Hydraulic coefficients of saturated zone were also applied to consider the potential of sublayers in transferring of the harvested water through the aquifer, the suitable location of recharge wells were obtained via both hydraulic conductivity and specific recharge. The resolution of the GIS layers was 20 m.

Specific Recharge obtained via Eq. (1)

$$\nu = K.H \quad (1)$$

Where  $\nu$  is specific recharge (specific discharge with positive sign),  $K$  is hydraulic conductivity and  $H$  is hydraulic gradient.

Sichardt's formula (Eq. 2) was used to calculate radius of influence and capture zone (the area influenced by a well)

$$R = 3000.S.\sqrt{K} \quad (2)$$

Where R is radius of influence in meters, S is drawdown at well in meters and K is coefficient of permeability in m/s.

### 2.2.1 Fuzzy Sets, Operators and Rules

The arithmetic of fuzzy sets and fuzzy logic is considered in detail in numerous books and papers (Lee 1990; Ruspini et al. 1998; Zadeh 1965; Zadeh 1978; Zimmermann 2010). Here, a general introduction and a minimal information required to realize the construction of fuzzy sets that was presented.

Generalization of classical set theory has created fuzzy collections. (Consider X as a collection of objects, with a discrete or continuous elements represented by x. A is a fuzzy set, so defined by membership function  $f_A(x)$  and each member in X has membership associated with a real value of the range [0, 1] (Zadeh 1965).

If A and B are two fuzzy sets in X with membership functions  $f_A(x)$  and  $f_B(x)$ , respectively, several operations of union, intersection, complement, etc. of these sets are defined via their membership's functions (Zadeh 1965):

**Union:** The union of two fuzzy sets A and B with respective membership functions  $f_A(x)$  and  $f_B(x)$  is a fuzzy set C, presented as  $C = A \cup B$ , which can be defined by  $f_C(x) = \text{Max}[f_A(x), f_B(x)]$ ,  $x \in X$ . In other words, the union of A and B is the smallest fuzzy set holding both A and B. For example if  $A = \{1,3,5\}$  and  $B = \{2,4,6\}$ , Then  $A \cup B = \{1,2,3,4,5,6\}$ . The Union operation in fuzzy sets theory is the equivalent of the "OR" operation in Boolean algebra.

**Intersection:** The intersection of two fuzzy sets A and B with respective membership functions  $f_A(x)$  and  $f_B(x)$  is a fuzzy set C, written as  $C = A \cap B$ , which can be defined by  $c(x) = \text{Min} [f_A(x), f_B(x)]$ ,  $x \in X$ . For example if  $A = \{1,2,3\}$  and  $B = \{2,3,4\}$ , Then  $A \cap B = \{2,3\}$ . The Intersection operation in fuzzy sets theory is the equivalent of the "AND" operation in Boolean algebra.

**Complement:** The complement of a fuzzy set A is denoted by  $A'$  and is defined by  $f_{A'} = 1 - f_A$ . The Complement operation in fuzzy sets theory is the equivalent of the "NOT" operation in Boolean algebra.

**Fuzzy rules:** These rules allow formulation of linguistic rules of a model that can simply be understood when all details of mathematical properties are unknown. A simple form of these rules is given below:

$$[\text{If } A \text{ is } L \text{ AND } B \text{ is } M \text{ THEN } C \text{ is } H]$$

Where A and B are linguistic input variables with linguistic values L (Low) and (Medium) M respectively and where C is the linguistic output variable with linguistic value H (High) (Fig. 2) (see Azadi et al. (2009)). For example, "Depth of Saturated Zone" is a linguistic input, so its linguistic values is one of the term-set  $T(DA) = \{\text{low, medium, high}\}$  where each term in

T(DA) is described by a fuzzy set in the universe of discourse, here, e.g.,  $U = [0, 25]$  (for more details see Azadi et al. (2009)).

In order to integrate the fuzzified input with the defined rules, Mamdani's fuzzy inference method (Mamdani and Assilian 1975) was used to control the steams by synthesizing a set of linguistic control rules achieved from experienced human operators. He proposed this method based on Zedeh (1973) research on fuzzy algorithms for complex systems and decision processes. Mamdani's method was one of the first controlling systems built using fuzzy set theory. It is one of the most common fuzzy methodologies.

The structure of a fuzzy system is following:

- Fuzzification of crisp inputs into the fuzzy domain
- Definition of fuzzy IF-THEN rules
- An inference engine implementing fuzzy logic by integrating the fuzzified input with the defined rules
- Defuzzification of the fuzzy output of previous step to a crisp value.

Final step in fuzzy systems is defuzzification of fuzzy output. In these systems, the output denoted by a fuzzy set needs to be transformed into a scalar value which is known as the defuzzification process. Various methods have been suggested. Constructing ranking indexes based on centroid (Eq. 3) is one of the common methods (Jang et al. 1997; Saneifard and Saneifard 2011; Wang 2009; Zimmermann 2010).

$$g = \frac{\sum_{i=1}^n x_i \times u(x_i)}{\sum_{i=1}^n u(x_i)} \quad (3)$$

Where,  $x_i, \dots, x_n$  are output crisp values and  $u(x_i), \dots, u(x_n)$  are corresponding fuzzy values. Figure 3 indicate a schematic illustration of input variables, fuzzification and defuzzification process.

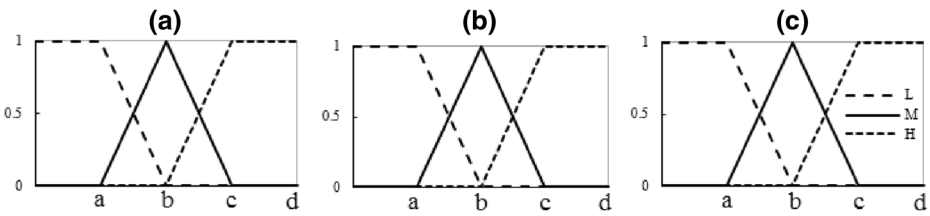
## 3 Results and Discussion

### 3.1 Input Layers

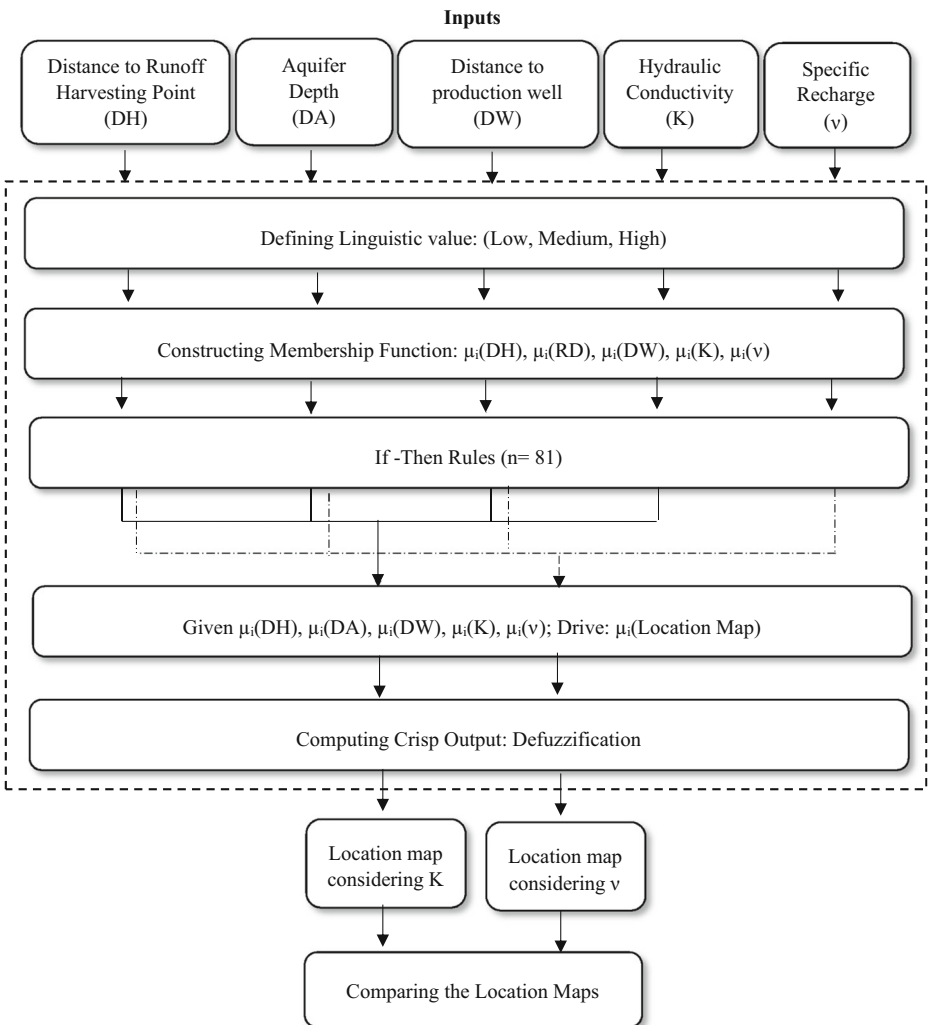
Distance from runoff harvesting point, depth of groundwater, distance from production well and hydraulic condition (hydraulic conductivity and Specific Recharge) of the saturated zone were considered for site selection.

#### 3.1.1 Distance from Runoff Harvesting Point

The pixels closed to the output of the sub catchments with maximum runoff production have more priority to construction of the recharge wells. In order to prepare the map of distance from surface runoff harvesting points, 10 sub catchments with maximum runoff production potential were determined via urban drainage systems and potential of storm water production estimated via SWMM model in the Urmia city.



**Fig. 2** Diagrammatic example of two linguistic input variables having linguistic values low, medium, and high defined by corresponding membership functions. a, b, c, and d are the thresholds of each of these linguistic values. C is linguistic output variable with three linguistic mentioned values. Here, nine If-Then rules can be defined, e.g. “If A is L and B is M then C is H”



**Fig. 3** Schematic illustration of input variables, fuzzification and defuzzification process (The dash box notifies the fuzzy parts of the model). In third step of fuzzy parts, location map was provided using hydraulic conductivity and specific recharge separately

In the next step, the final map was developed using surface analysis in ArcGIS (Fig. 4a) To determine the membership function of this variable, the distances less than 500 m were considered as “L” (low), 200 to 1000 m were showed with “M” (Medium) and the distances more than 500 m were introduced by “H” (High) (Fig. 5).

### 3.1.2 Groundwater Depth

Water table in 65 piezometric wells were used to determine the aquifer depth via Ordinary Kriging interpolation method and exponential semivariogram (Major range = 32,768.10, Partial sill = 166.37 and Nugget = 0) using geostatistical technique in ArcGIS (Fig. 4b). Within increasing the depth of the aquifer, depth of recharge well will be increased, and this will enhance the cost of wells construction. So the pixels with linguistic value “M” will selected to construction of recharge well. The depth less than 10 m was determined as linguistic value “L”, depth from 5 to 15 m as “M” and more than 10 m was selected as linguistic value “H” (Fig. 5).

### 3.1.3 Distance from Production Water Well

In the direct recharge of groundwater by surface runoff, there is a high risk of contamination of the aquifer. Therefore, capture zone of the production wells and its influence radius were determined (Eq. 2) the capture zone of wells located in zones with low hydraulic conductivity was defined as the linguistic value “L” and the capture zone of wells in high hydraulic conductivity zones considered as “M”. The pixels placed outside of this radius had linguistic value “H”. To prevent contamination of groundwater, fuzzy rolls were set quite strict. This means that where the linguistic values of this variable were “L” or “M”, the output linguistic value was set “L”. So the pixels within the influence radius, have not priority for the construction of the recharge well.

### 3.1.4 Hydraulic Condition of Saturated Zone

The studied aquifer includes two different hydraulic conditions. To consider this different hydraulic condition, two hydraulic conductivity and Specific Recharge was separately applied to provision of recharge well location map.

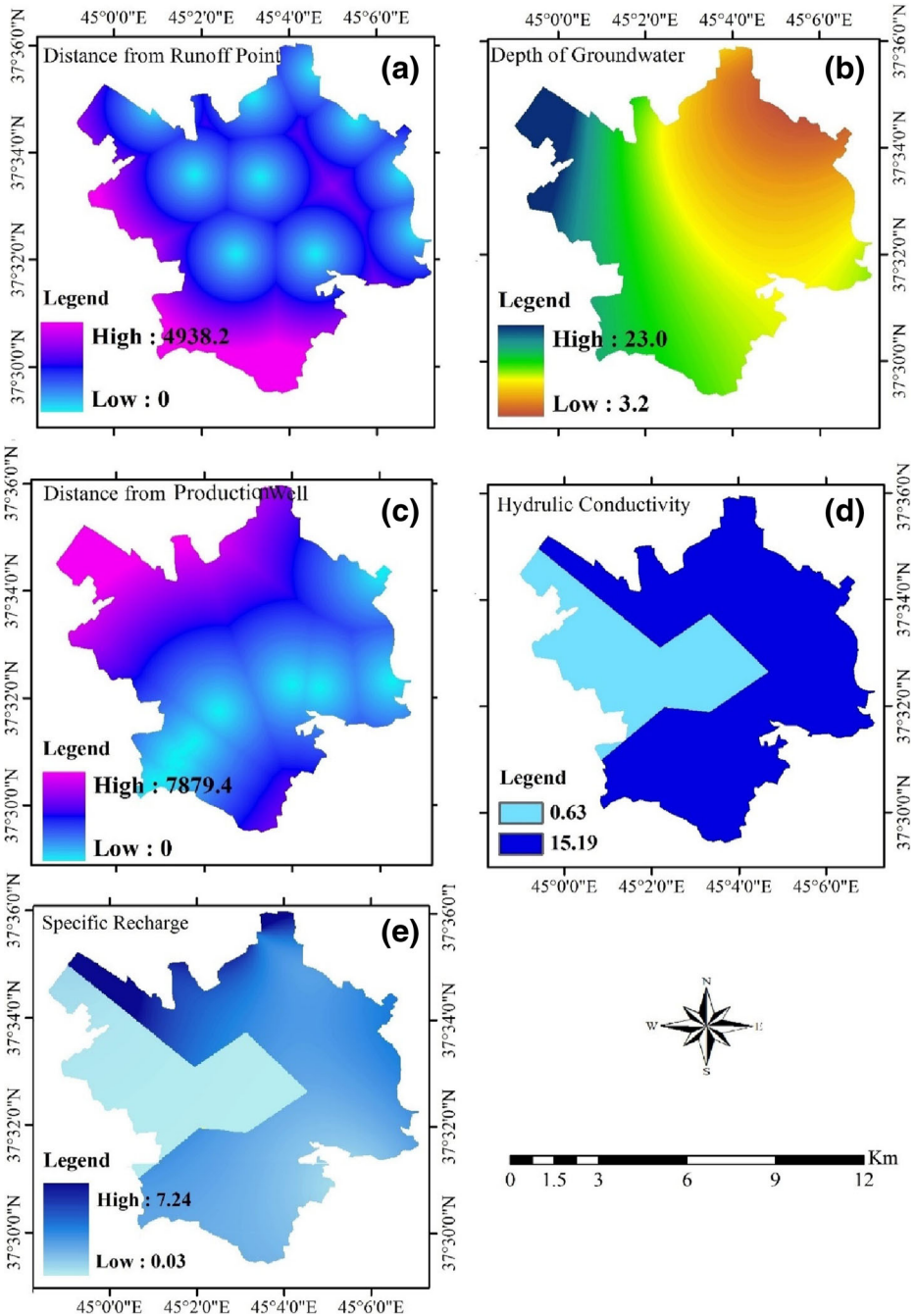
### 3.1.5 Hydraulic Conductivity

Hydraulic conductivity (K) is an important factor that indicates the ability of soil for transferring of the penetrated water. Information of 11 excavation logs were used to prepare hydraulic conductivity layers of the studied aquifer using Thiessen polygons method in ArcGIS (Fig. 4d) (Rahimy 2011). Membership function for this variable includes two linguistic values: “L” for less than  $0.63 \text{ m.day}^{-1}$  and “H” for more than  $15 \text{ m.day}^{-1}$  (Fig. 5). Where K is “H”, considering other input variables (Distance from production water well, Distance from Runoff Harvesting Point, and Groundwater Depth), the output linguistic value will be “M” or “H”.

### 3.1.6 Specific Recharge

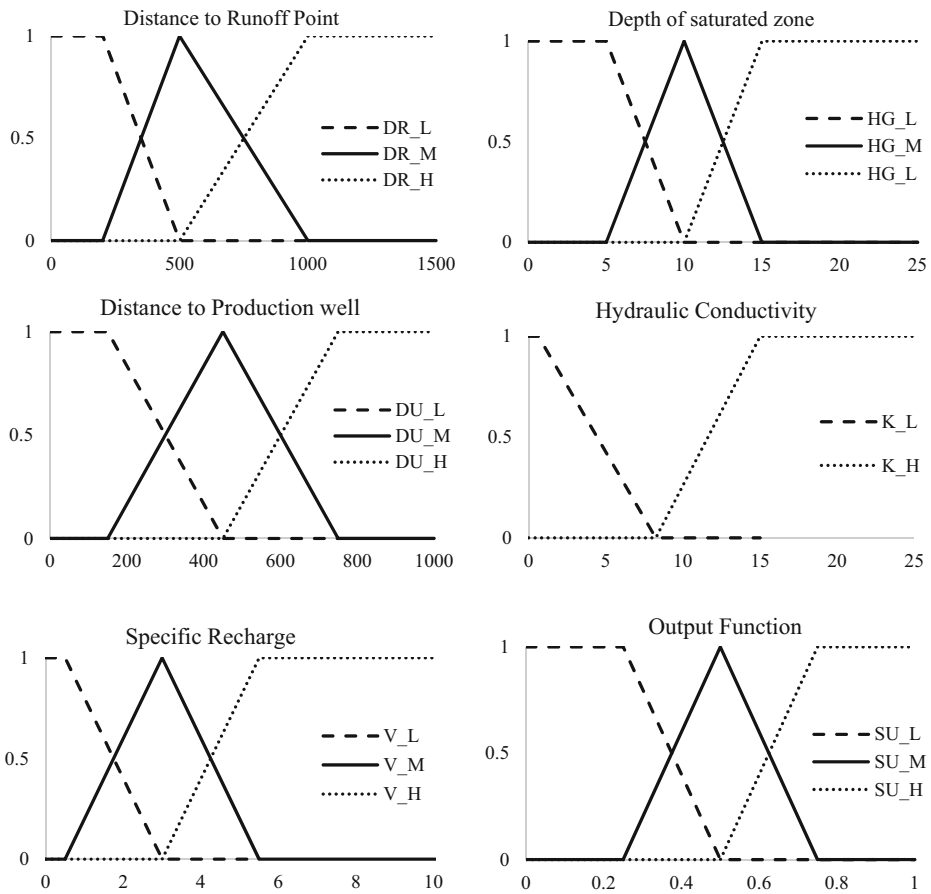
Specific Recharge ( $\nu$ ) is the rate of flow under a unit hydraulic gradient. The specific recharge of an aquifer is related to hydraulic conductivity and hydraulic gradient. This variable was





**Fig. 4** Input maps: Surface and subsurface factors that souled influence the location of recharge wells

produced using Eq. 1 (by multiplying hydraulic gradient and conductivity). Within increasing hydraulic gradient of a pixel, the potential of aquifer in transmission of recharge water will be increased. Figure 4e presents specific recharge map of the study area. According to results,



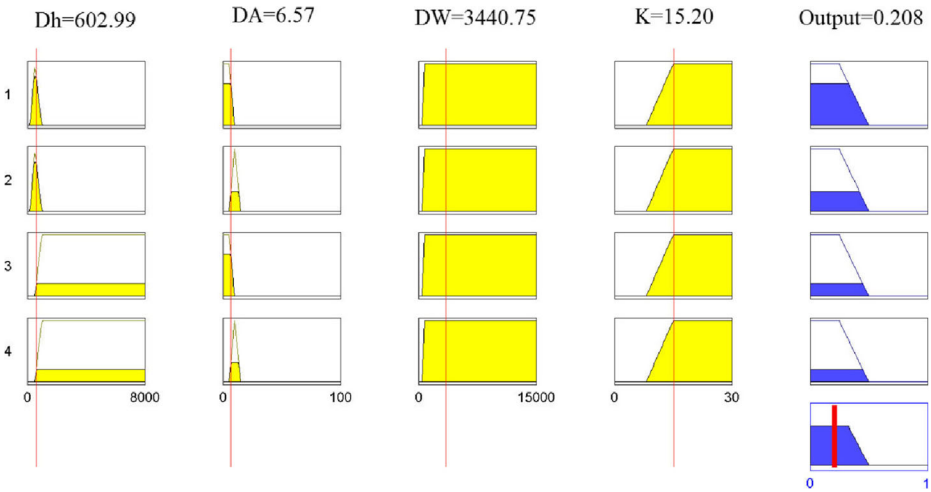
**Fig. 5** Membership function of linguistic variables

specific recharge in the northern part of the city is more than other areas due to higher hydraulic gradient.

Based on the number of the inputs and linguistic values, the basic rules have 54 rules when the hydraulic conductivity was applied for site selection and 81(34) when the specific recharge was applied.

The pixels within the depth of the aquifer is “M”, distance from runoff harvesting point is “L” and hydraulic conductivity or specific recharge is “H” have the highest priority (linguistic value is “H”). So, among these fuzzy rules, when three variables of four inputs have above mentioned linguistic values, the output linguistic value will be “M”. The other rolls have output linguistic value of “L”. By setting such strict conditions, the number of qualified pixels will reduce. Figure 6 illustrate an example of fuzzification and defuzzification process.

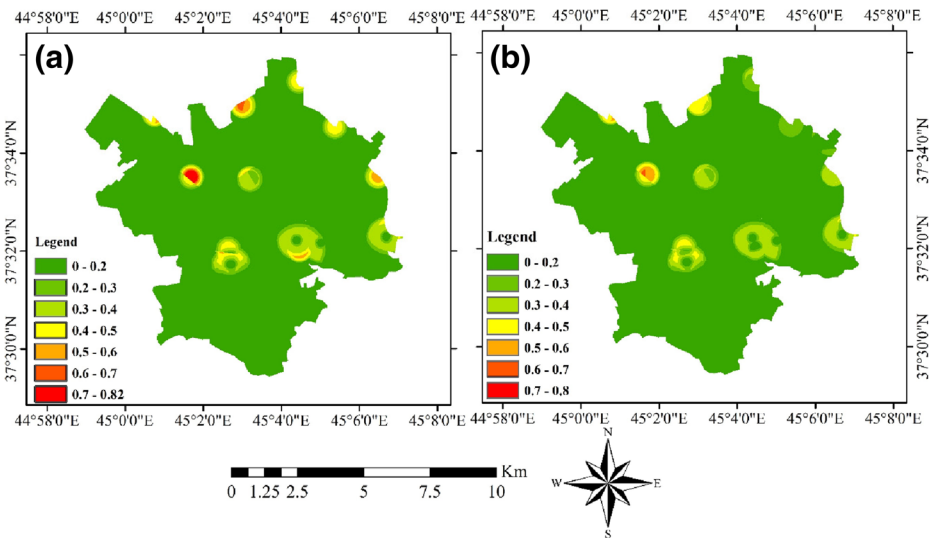
Output map of designed fuzzy system shows the location map of the recharge wells (Fig. 7). In this figure, concentric circles are located where the runoff harvesting points were previously marked. The location map provided via hydraulic conductivity and specific recharge was shown in Fig. 7a and b respectively. Based on the results, the number of pixels with “H” priorities increased when the hydraulic conductivity was used to site selection. When hydraulic conductivity was used for site selection, 6 suitable point with linguistic value more than 0.5



**Fig. 6** Graphical illustration of fuzzification and defuzzification process. A pixel with  $DH = 602.99$ ,  $DA = 6.57$ ,  $DW = 3440.75$  and  $K = 15.20$  had linguistic value of “M, H”, “L, M”, “H” and “H” respectively. According to Fig. 3, there are 4 rules with these linguistic values. Finally, the center of gravity method (centroid) divides the curve area into two equal subareas. Here, output value of defuzzification process is 0.208

was determined (M and H output linguistic value). whereas, only two site with more than 0.5 linguistic value were determined when specific recharge was applied. As the Northwest region of the study area has a higher hydraulic gradient, a greater number of pixels have a suitable conditions for recharge wells, whereas the areas with low hydraulic conductivity and the areas close to the production water wells have not suitable priority for recharge wells.

It is accepted that recharge wells should increase the contamination risk of the groundwater. Vicinity to the production water wells should increase hydraulic gradient, consequently pollution risk of the injected water should increase. In this study, to decrease pollution risk,



**Fig. 7** Location maps of recharge wells. **a** location map using hydraulic conductivity and **b** location map using specific recharge

**Table 1** Area of each priority class in Km<sup>2</sup>

No.	Priority range	Location map with K (Km <sup>2</sup> )	Location map with $\nu$ (Km <sup>2</sup> )
1	0.00–0.20	70.45	70.39
2	0.20–0.30	2.23	3.07
3	0.30–0.40	3.49	3.61
4	0.40–0.50	1.30	0.82
5	0.50–0.60	0.40	0.21
6	0.60–0.70	0.12	0.03
7	0.70–0.82	0.15	0.00

high membership function was only selected for the areas located at the acceptable distance of the production water wells.

Table 1 shows the number of pixels placed to each class using hydraulic gradient and specific recharge. These classes were defined in ArcGIS (using equal interval Re-classify tool). Comparing these classes indicates variation of the pixel priority when two site selection methods was applied. According to results, the same results were obtained for the area with the priority less than 0.4. Results show more than 70% of the study area is not suitable for developing recharge wells. Based on the results, suitable areas for recharge wells is only 0.7 and 0.2 Km<sup>2</sup> when hydraulic gradient and specific recharge were applied for site selection respectively.

## 4 Conclusion

Recharge well is a suitable artificial recharge method in urban areas that minimize losses of infiltrated water, which increase groundwater recharge and decrease flood damages. Also, several methods were used for artificial groundwater recharge site selection, rare studies focused on direct recharge of groundwater via injection wells. A suitable site selection should increase the efficiency of the recharge wells. In this study, fuzzy logic was used for recharge wells site selection. Membership function of linguistic variables and fuzzy rules were defined based on the distance to runoff harvesting points, distance to the production wells, depth of groundwater table and hydraulic coefficients (hydraulic conductivity and specific recharge) of saturated zone.

Location of recharge wells extracted using both hydraulic conductivity and specific recharge separately. The results show that the number of suitable sites with high priority will increase when the hydraulic gradient was applied for site selection, whereas the efficiency and confidence of the site selection process should increase when specific recharge was applied (because both hydraulic gradient and hydraulic conductivity were considered in the calculation of the specific recharge). Based on the results, we can conclude that site selection via specific recharge should increase the competence of the site selection.

Direct injection of surface runoff into aquifers becomes a contentious issue, particularly in arid and semi- arid region with high evapotranspiration. In this study, appropriate locations for recharge wells were determined based on different layers include distance from runoff harvesting points, distance to the production water wells and depth of groundwater table, hydraulic conductivity and specific recharge. Initiating more comprehensive monitoring and research programs on the effects of injection process in the groundwater quality and quantity could provide investigation of the environmental problems related to the injection wells. As the

recharge wells should increase the contamination risk of the groundwater, possible contamination sites should be included as a layer of the site selection for the area within high risk of pollution.

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### Compliance with Ethical Standards

**Conflict of Interest** None.

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