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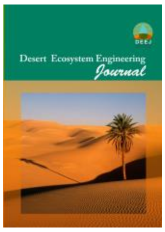

Combination of Fuzzy and Boolean logic and MCDM Methods for Investigating Suitable Areas for Artificial Groundwater Recharge (Case Study: Chenaran Watershed in Razavi Khorasan Province)

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Abstract

More than two-thirds of Iran have been located in arid and semi-arid regions. Overuse of groundwater water resources has decreased the groundwater level in these areas. Artificial recharge plays a pivotal role in the sustainable management of groundwater resources. Investigating suitable areas for optimal use of water floods is one of the most important factors in recharging underground water tables in dry lands where the agricultural and rangelands are vulnerable. Hence, this study proposes a methodology to delineate artificial recharge zones and identify favorable artificial recharge sites using integrated Fuzzy logic, Boolean logic and multi-criteria decision-making (MCDM) methods for augmenting groundwater resources in Chenaran Watershed facing water shortage problems. The thematic layers considered in this study are infiltration rate, slope, geology, geomorphology, land cover, distance to river, distance to road and distance to Qanats and wells, which were prepared using satellite imagery and conventional data. Then, by applying the limiting layer as a combination of four criteria of lithology, land use, slope and geomorphology, the final map of recharge suitable areas was prepared and prioritized from highly suitable to unsuitable. The final obtained map divided the study area into five zones according to their suitability for artificial groundwater recharge. The results were then examined against the existing water spreading site to estimate their accuracy. The artificial recharge suitable zone of the final map was found to be in agreement with the map of water spreading project performed by the Ministry of Agriculture Djehad (accuracy was more than 78%). The results of this study could be used to formulate an efficient groundwater management plan for the study area and other similar areas.

Keywords: Fuzzy & Boolean logic, Artificial Groundwater Recharge, MCDM, Chenaran watershed.

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1. Introduction

Water has become an increasingly scarce commodity, since most parts of Iran are located in semi-arid regions where more than 50 % of precipitations occur in winters, while less than 15 % occur in summers, and most of the rivers are dry from the mid-spring to mid-fall (Rafee et al., 2008). The most important water resource in these regions is groundwater.

Groundwater is considered the preferred source of water to meet domestic, industrial and agricultural requirements, due to its longer residence time in the ground, low level of contamination, wide distribution, and availability within the reach of the end user. Even the existing wells are becoming dried-up due to depletion of ground water table as the natural recharge (Patil & Mohite, 2014). Overuse of groundwater water resources decreases the groundwater level in many aquifers of arid and semi-arid zones (Kheirkhah Zarkesh, 2005), and one of the effective ways to raise the water table is artificial groundwater recharge (AGR) to use water flowing into the salt-lakes or in the sea (Chabok et al., 2010; Hassanzadeh Nafooti et al., 2016).

There are many reasons for AGR, but the main reason for considering artificial recharge is the declining groundwater level in most of the aquifers exploited for irrigation in semi-arid parts of the world (Seckler et al., 1998). A large amount of rainwater is lost through runoff (Murugiah & Venkatraman, 2013); additionally, artificial recharge can also decrease the damage that the episodic flows cause to human life, settlements and agriculture (Ghayoumian et al., 2005).

Replenishing the groundwater through AGR has been carried out in various parts of the world since the last six decades (Babcock & Cusing, 1942; Beeby-Thompson, 1950; Buchen 1955; Todd, 1959; Asano, 1985; Kowsar, 1995). AGR is one idea emerged over the past 20 years as a major water management tool to meet water supply challenges (Eden et al., 2009). In an effort to maintain the water table condition in balance, artificial recharge schemes are implemented in various parts of the world (Das, 2003). AGR is achieved by putting surface water in basins, furrows, ditches, or other facilities where it infiltrates into the soil and moves downward to recharge aquifers (Bouwer, 2002). The basic requirements for recharging the groundwater reservoir are: Availability of noncommittal surplus monsoon run off in space and time and identification of suitable hydrogeological environment and sites to create sub-surface reservoir through cost-effective artificial recharge techniques.

One factor that is highly important to successful recharge of groundwater is determining the most suitable areas for AGR. In this regard, a large number of factors play a role in the site selection. These factors pertain to earth science (geology, geomorphology, soils) hydrology (runoff and sediment yield, infiltration and groundwater conditions) and socio-economic aspects (irrigated agriculture, flood damage mitigation, environment, and job creation and so on). Hence, the decision depends on criteria of a diverse nature (Kheirkhah Zarkesh, 2005). To scientifically provide appropriate locations for constructing artificial recharge structures, each hydro-geomorphic unit is evaluated for its recharge potential, and suitably a map showing such groundwater, recharge potential zones for appropriate recharge are prepared (Patil and Mohite, 2014). However, traditional methods of site selections are time-consuming and error prone (Alesheikh et al., 2008). With the advent of powerful personal computers and the advances in space technology, efficient techniques for land and water management have evolved of which RS (remote sensing) and GIS are of highly important. These techniques have fundamentally changed our thoughts and ways to manage natural resources in general and water resources in particular (Jha et al., 2007).

Many methods have been used for locating the most suitable sites for AGR. These methods include Boolean logic, index overlay and fuzzy logics (Alesheikh et al., 2002; Nezam Asghari et al., 2011), AHP [1] (Chabok et al., 2010; Yazdani Moghadam et al., 2012; Malekian et al., 2014), AHP and ANP (Faraji et al., 2011), GCA and FAHP (Faraji et al., 2013) ANP[2] and Fuzzy logic (Zahedi et al., 2016).

In the two past decades, multiple criteria decision-making (MCDM) techniques and approaches have been employed increasingly for suitable artificial recharge zonation. MCDM is considered a complex decision- making (DM) tool involving both quantitative and qualitative factors.

1. Analytical Hierarchical Processing
2. Analytic Network processes

MCDM methods have been designed to designate a preferred alternative, classify alternatives in a small number of categories, and rank alternatives in a subjective preference order. Using MCDM can be regarded as a way of dealing with complex problems by breaking the problems into smaller pieces. After weighing some considerations and making judgments about smaller components, the pieces are reassembled to present an overall picture to the DMs. Most of MCDM methods deal with discrete alternatives described by a set of criteria. Information could be determined exactly or could be fuzzy, determined in intervals. Modern MCDM methods enable decision-makers to deal with all above-mentioned types of information (Mardani et al., 2015). MCDA for identification of AGR suitable sites, has been applied to countries such as Australia (Hostetler, 2007) and Spain (Escalante et al., 2014), as well as in many regions of the world, for example in India (Sukumar & Sankar, 2010; Chowdhury et al., 2010; Singh et al., 2013; Patil & Mohite, 2014), Jordan (Al-Adamat, 2012), Portugal (Rahman et al. 2012, Pedrero et al. 2012) and the United States (Russo et al. 2015).

In recent years, MCDM has been an integration of novel methods applicable for multidimensional problems. This method was ranked as the second method among 393 articles published from 2000 to 2014 in more than 120 paper-reviewed journals (extracted from Web of Science)((Mardani et al., 2015).

Failure to consider economic parameters such as proximity to the river, road and Qanat in identifying suitable artificial recharge areas in many previous studies, as well as the possibility of combining fuzzy model (for standardizing of factors) and Boolean model (for applying the constraints) with the MCDA method, led to use the integration of these three methods. The main purpose of this research is to combine Fuzzy and Boolean logic and MCDM methods to identify suitable areas for artificial groundwater recharge in the Chenaran watershed, which has been affected by drought and excessive groundwater abstraction in recent years due to low level of groundwater.

2. Material and methods

2.1. The study area

The study area of this research is the Chenaran watershed located in the north of Khorasan Razavi Province, near Chenaran city, covering an area of 3364 km^2 that stretches between 36° 19' 59" and 37° 03', 52" latitude and 58° 22', 07" and 59° 16', 44" longitude. This area is located in the plain between the famous mountains of the Hezarmasjed in the east and Binaloud in the west. Figure 1 shows the location of the study area in the country and the province. The maximum altitude of the basin is approximately 2710 m, and the minimum one is 1122 m. The area is located in an arid and semi-arid zone. Observations from the Chenaran Synoptic Station reveal that the annual average precipitation is 203.6 mm during the statistical period. The average annual evaporation is 2197 mm. Average annual temperature is 11.2 °C, and the prevalent wind blows from east and southeast. Due to the recent droughts, there is no permanent river in the region, and the rivers are seasonal. The area is divided into 39 sub-basins. The vegetation of the region includes many species of Artemisia, Astragalus and Agropyron.

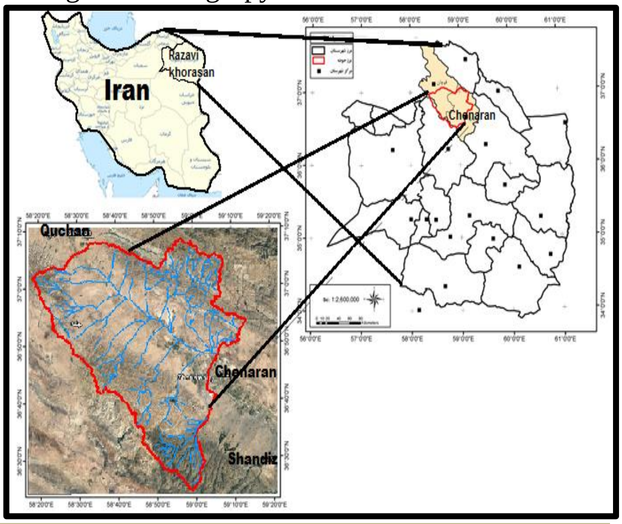

Fig1.The location of the study area in the country and the province

2.2. Creation of a spatial database

Various factors play a role in selecting the most suitable sites for artificial groundwater recharge. These factors pertain to natural conditions (geology, geomorphology, soils, slope), and socio-economic aspects (irrigated agriculture, approximate to river and road and so on). In this research, based on past research and expert opinion, eight criteria (permeability, slope, geology, geomorphology, vegetation density, distance from the well, distance from the road, and distance from the river) were used to identify the areas susceptible to artificial recharge. The procedure for preparation of each layer is described below.

2.2.1. Infiltration

Soil permeability plays an important role in site selection for artificial recharging. If soil Infiltration is low, the discharged water remains on the surface of the soil and not only does not enter the groundwater, but may also increase soil salinity by evaporation (Nezam Asghari, 2011). The permeability map of the area with high, moderate and low levels is based on hydrological groups of the region, which is map (a) in Fig. 3.

2.2.2. Slope

It is highly important to consider the slope of an area for selection of an artificial recharge site and type of artificial recharge structure to be constructed (Winnaar et al., 2007). It plays a key role in the groundwater occurrence as infiltration rate of water into subsurface area is inversely related to slope (Mondal et al., 2009). In gentle slope areas, due to slow surface runoff, rainwater obtains more time to percolate. On the other hand, steep slope areas support high runoff due to less residence time for rainwater, resulting in less infiltration. In other words, break in slope from steep to gentler increases infiltration of rainwater (Todd & Mays, 2005). Slope map of the study area is prepared from the digital elevation model generated from digitized contours from 1:50000 topographic maps (map (b) in Fig. 3).

2.2.3. Geology

The geology map of the study area was digitized from geological maps of Iran Geological Organization and borderlines were checked by field surveys and the necessary corrections were made. The geology of the region consists of 17 lithological units, shown in map (c) in Fig.3.

2.2.4. Geomorphology

Geomorphology is one of the most important features evaluating the groundwater potential and recharge capacity of any area, and controlling the subsurface movement of the groundwater (Kumar & Kumar, 2011). Many of these features are favorable for occurrence and recharge of groundwater, and are classified in terms of groundwater recharge potentiality. Geomorphologic units of the study area delineated from satellite and Google earth images were based on the image characteristics such as tone, texture, shape, slope, color and associations. map (d) in Fig.3 shows the geomorphology map of the study area with eight geomorphological units.

2.2.5. Vegetation density

Vegetation plays an important role in development of soil and improvement of soil physical conditions for surface water permeability. In addition, one of the goals of flood spreading is to maintain and enhance the conditions of vegetation quality and quantity. Therefore, areas with suitable vegetation density, if other requirements are met, are the priority of artificial recharging. The vegetation density map of the area was determined by satellite imagery and the use of the random plot as shown in map (e) in Fig.3.

2.2.6. Land use

The term 'Land use /Land cover' is often used simultaneously to describe the map providing information about the types of features found on the earth surface (land cover) and the human activity that is associated with them (land use) (Jasrotia et al., 2009). It plays an important role in selecting suitable sites for artificial recharge and evaluating the feasibility whether any structure could be constructed on the selected site (Harbor, 1994). In this research, Landsat satellite imagery was used to prepare land use map. The initial spectral classification of the images was carried out using the Maximum Likelihood method and analyzed with the aid of Google Earth and field surveys. AGR cannot be performed in residential areas, infrastructure and agricultural and horticultural land (due to ownership argument); therefore, these areas should be omitted from the suitability map for artificial groundwater recharging (map (k) in Fig.3).

2.2.7. Distance to river

The distance from the river to implement an artificial recharge project plays a crucial role in project costs If the distance between the project site and the river is long, the cost of constructing water transfer channel increases. Therefore, areas near the water supply river are extremely important. The map of the main rivers of the region was developed to prepare a buffer map from the river from the topographic map of the area (map (f) in Fig.3).

2.2.8. Distance to Qanats and wells

Since the goal of groundwater recharging project is to provide more water to the inhabitants of the area, the proximity of the artificial recharge site to water extraction facilities such as wells and Qanats is preferable. The distribution map of the groundwater recovery facility was developed using data from the location of Qanats and wells of Khorasan Regional Water Company to provide a buffer map (map (g) in Fig.3).

2.2.9. Distance to road

The proximity of the implementation of the artificial recharging project to the road provides easier access and lower cost for transfer of tools and equipment for designing and transporting workers. Therefore, it can play an important role in reducing the cost of implementing the design and the lesser manipulation of nature for construction of a new road to access the site. The main road map of the study area was developed to provide a buffer mapping distance from the road using the topographic map of the area (map (h) in Fig.3).

2.3. Methods

Fig. 3 shows the procedure of the groundwater recharge zoning. As the figure shows, the stages of the research are as follows:

- Creating multi-criteria hierarchy of decision:

At this stage, the effective factors in locating the flood distribution were divided into two main groups 1 – natural group (a, b, c, d, e in Fig.3), including slope, permeability, geology, geomorphology and vegetation density 2 – economical group (f, g, h in Fig.3), including distance from the river, distance from the well and the Qanat and distance from the road. In addition, constraint factors were also identified (j, k, l, m in Fig. 3).

- providing thematic layers and standardizing them
-Weighting the layers and their features using Expert Choice software
- Integrating thematic layers and preparing a composite index map (Primary suitability map)
- Overlaying constraint layers on the map of the combined index and preparing the final map of suitable artificial recharge area (map (n) in Fig.3)
- Validating the accuracy of the final map

2.3.1. Standardization

Since the input maps can have different content and characteristics, and some of them may consist of descriptive characteristics such as distance and proximity (road, river, etc.) or letters (geology, geomorphology, etc.), then maps need to be standardized. One of the methods of standardization is the fuzzy method. A fuzzy set is a collection of membership degrees. Membership of a fuzzy set is expressed on a continuous scale from 0 to 1. The use of 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. However, there are no practical constraints on the choice of fuzzy membership values (Bonham-Carter, 1996).

In addition, in this method, a linear function is used to standardize the phenomena of distance (such as distance from the river) using the minimum and maximum values desired. The values between the minimum and maximum values are between zero and one. In this case, the value is at least one, and the maximum value is zero. For example, the pixels near the river are worth 1 and the distance away from the river, the value of the pixels is close to zero (Hassanzadeh Nafooti et al., 2011). In this research, the fuzzy model was used to standardize the distance maps from the river, the distance from the Qanats and wells and distance from the road to be entered into the MCDM model.

2.3.2. Assignment of weights and integration of thematic layers

As identification of suitable area for artificial groundwater recharge is interdisciplinary in nature; it necessitates the conjunctive and integrated analysis of multidisciplinary data sets, which can be best handled by MCDM approaches as they seek to take an explicit account of more than one criterion in supporting the decision process. In this study, the Analytic Hierarchy Approach (AHP) developed by Saaty (1980) was used as a decision-aiding method to finalize the weights assigned to different themes and their features used in artificial recharge zoning. AHP is a multi-criteria method to weight and order the conflicting qualitative/quantitative criteria hierarchically (based on weight evaluation) and consequently select the best choice (Kheirkhah Zarkesh, 2005). The AHP allows users to assess the relative weight of multiple criteria intuitively. It allows efficient group decision-making, where group members can use their experience, values and knowledge to breakdown a problem into a hierarchy and solve it by AHP steps. It also incorporates systematic checks on the consistency of judgments (must be less than 0.1), being one of the strongest points over other multi attribute value processes. Thus, AHP has been recognized by scientific communities as a useful tool for dealing with complex decision problems (Chowdhury et al., 2010).

In the past studies, the weights of different thematic layers and their features were assigned based only on personal judgments or local experience. However, in this study, to assign weights to different thematic layers and each feature of the individual thematic layers, questionnaires were prepared and filled by specialists (geologists and hydrogeologists) in the country as well as the weights used in related past studies. Higher ranks are assigned to the theme and category having higher potential for groundwater recharge, and lower ranks represents the comparatively lower potential for groundwater recharge. Ranks 9 and 8 are assigned to the themes and categories having higher potential for recharging ground water, 7 and 6 represent moderate to high potential, 5 and 4 stand for moderate potential and 3, 2, 1 symbolize poor potential for groundwater recharge.

After finalizing the suitable weights of the themes and their individual features by considering their importance in AGR in the study area, the layers were divided into two natural (including permeability, slope, geology, geomorphology and vegetation density) and economical (distance to river, distance to Qanat and well and distance to road) groups. The normalized weights of the individual themes and their different features were obtained by Expert Choice software (Fig. 2).

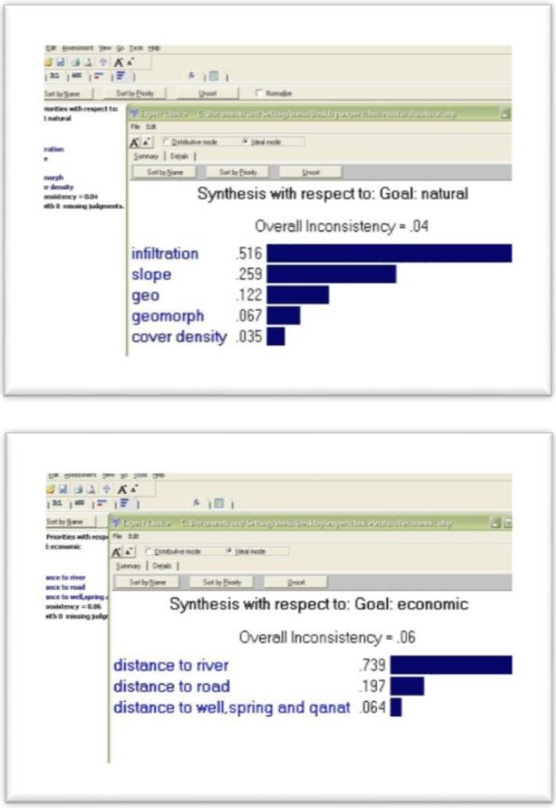

Fig 2. The weight of natural and economic criteria

To demarcate groundwater recharge zones, all thematic layers after assigning weights were integrated (overlaid) step by step using ArcGIS software, and the composite index map was obtained whose pixels value is between zero and one, so that the pixel closer to one is more suitable for AGR.

2.3.2. Apply Constraints

Implementation of AGR is subject to a number of constraints such as slopes of more than 6%, fine-grained and erodible formations such as Eocene formations, rock massive areas and residential lands, crops, and gardens (due to ownership issues). Therefore, these areas should be eliminated from the artificial recharging suitability map (Jamali et al., 2010; Khabak et al., 2010; Karimi et al., 2012; Yazdani Moghadam et al., 2013; Zahedi et al., 2016). To remove such areas, the constraint thematic layers should be used. These layers were created using the Boolean logic in the GIS setting. The weight of any feature in thematic layers in this method is based on one and zero logic i.e., any unit of thematic layer is considered either good or bad (one or zero). Then, the boundary layers were applied on the composite index map, and the final map of the suitable areas for AGR was obtained.

3. Results and Discussion

The final map of the suitable areas for AGR by applying constraint layers on the map of the composite index map was obtained (map (n) in Fig. 3). In this map, inappropriate areas are eliminated by limiting layers, and other areas are classified into four classes of low proportion to very high proportionality. The results of the research showed that approximately 11% of the area had a high and very high proportion of artificial recharging located in the central parts of the study area. These areas are mainly consisted of rangeland lands located on sedimentary plains and young Quaternary sediments (Qal-Q) with slopes less than 4%. More than 80% of the studied area is inappropriate in terms of groundwater recharging due to various restrictions such as land use, slope, lithology and geomorphology. Moreover, the rest of the region has a moderate to low suitability.

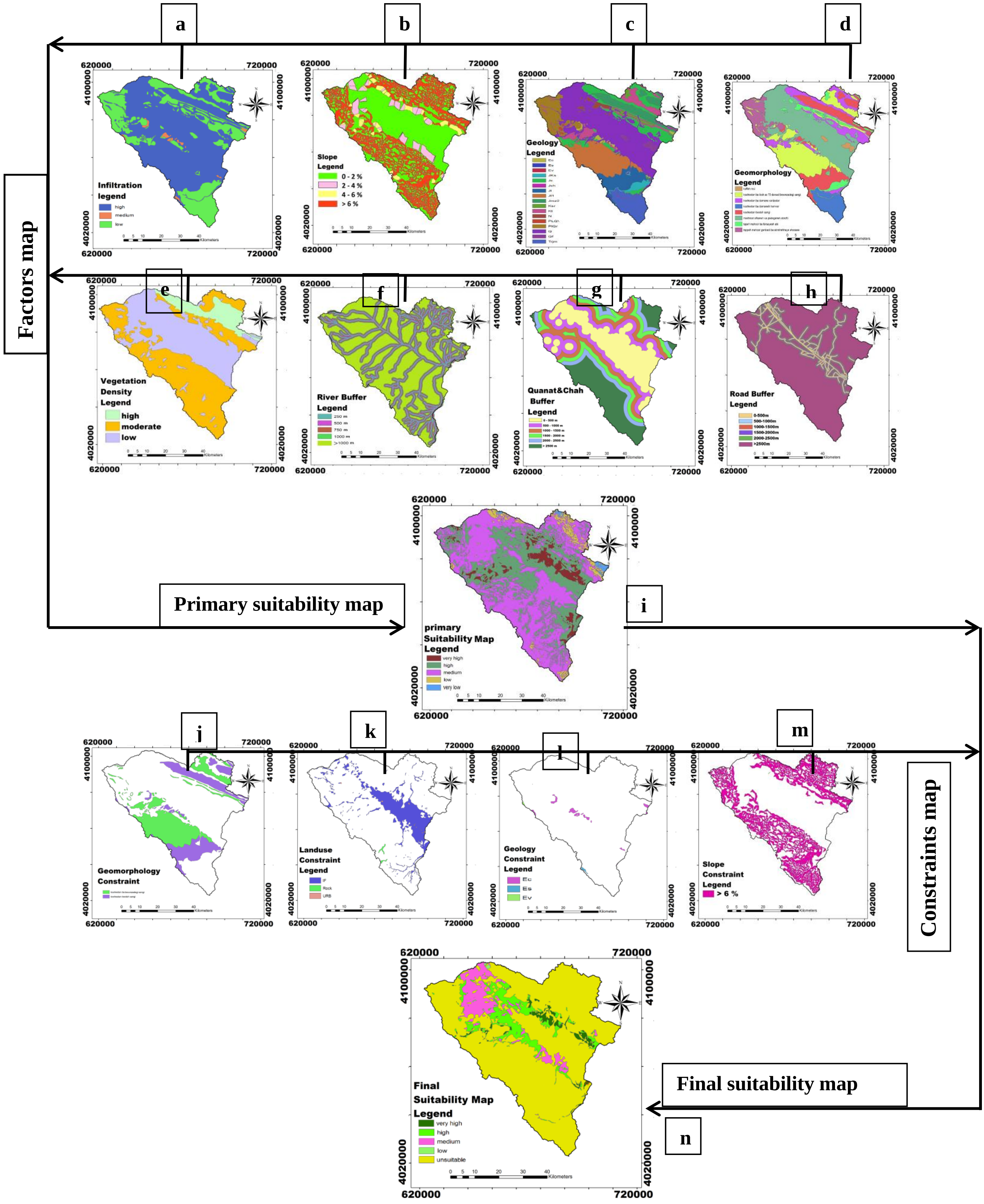

Fig 3. Steps to prepare the artificial groundwater recharging suitability map

To assess accuracy of the models, the final maps of site selection were overlaid on the map of the existing groundwater recharge site (control area). The flood spreading project was built in 1995 by the Ministry of Djahad e Agriculture and dozens of flood was spreaded in it and has been successful in evaluating the project and fed more than 12 million cubic meters of water to the groundwater (Aazamirad & Memari, 2012). For this purpose, final suitability map was overlaid with the map of control areas. The ratio of the total number of pixels in the very high suitability areas to the number of pixels in the flood spreading area (control areas) was calculated. In fact, their overlap percentage was considered the model's evaluation criterion (Sabokbar et al., 2011).

A = (sum of pixels with high and very high suitability/ sum of pixels in control areas) * 100

The value of A is the accuracy of the model. The results of overlaying showed an amount of approximately 78 percent. In other words, approximately 78 percent of very high suitability areas fit with the control areas where the flood spreading operation is successfully implemented, indicating the acceptable accuracy of the method used.

4. Conclusions

The interdisciplinary nature of groundwater necessitates the integrated and conjunctive analysis of a large volume of multidisciplinary data, the decisions regarding groundwater recharge zones and suitable recharge sites require considerable time, labor and cost. The multi criteria decision-making approach can considerably minimize the time, labor and cost, thereby enabling quick decision-making for efficient water resources management. It is a valuable practical tool for the regions (especially developing countries) where data scarcity (in terms of quantity and quality) is often an obstacle to solve real-world water problems. This study was conducted to propose a methodology for identifying AGR zones using a combination of Fuzzy & and Boolean logic and MCDM methods. MCDM methods have been designed to designate a preferred alternative, classify alternatives in a small number of categories, and/or rank alternatives in a subjective preference order. Fuzzy logic was used to standardize thematic layers, and Boolean logic was used to apply the constraint layers. Remote sensing data, topographic maps and conventional data were used to prepare the thematic layers of infiltration, slope, geology, geomorphology, vegetation density and land use. Considering the relative importance of different themes from the recharge viewpoint, these thematic layers and their corresponding features were assigned weights on a 1 to 9 scale, and their normalized weights were obtained by the AHP as a MCDM technique. The thematic layers were then integrated in the GIS setting to prepare an initial suitability map of the study area. Finally, favorable sites for artificial recharge were identified by overlaying the composite index map and the constraint layer maps. Then, the flood spreading project implemented in the area was used to investigate accuracy of the suitability of the map. The results showed that there was more than 78 % of adaptation between the proposed areas for AGR and flood spreading areas (control area). Thus, it can be inferred that the artificial recharge zones delineated by Fuzzy and Boolean logic and MCDM techniques are reliable. It was also showed that combination of Fuzzy and Boolean logic and MCDM methods could be a good approach to model the site selection for artificial groundwater recharge. The results of the present study can serve as guidelines for planning future artificial recharge projects in the study area and other similar areas to ensure dependable water supply and sustainable groundwater utilization in the long term.

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