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Authors

Farhadian, Mostafa
Bozorg-Haddad, Omid
Pazoki, Maryam
et al.

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Locating and Prioritizing Suitable Places for the Implementation of Artificial Groundwater Recharge Plans

Mostafa Farhadian[1]; Omid Bozorg-Haddad[2]; Maryam Pazoki[3]; and Hugo A. Loáiciga, F.ASCE[4]

Abstract: Artificial groundwater recharge plans (AGRPs) have become central in surface water and groundwater management. This work proposes a two-stage approach for locating and prioritizing suitable sites for AGRP implementation. The two stages consist of (1) determining the effective criteria weights to develop thematic maps with geographic information system (GIS) with which to locate suitable sites for AGRP implementation, and (2) prioritizing the suitable identified sites for artificial groundwater recharge with the Nash conflict resolution method. This paper's approach is applied in the Kerman Province, Iran, and the application results demonstrate that the most suitable sites for AGRPs are located in the western half of the province. **DOI: 10.1061/(ASCE)IR.1943-4774.0001189.** *© 2017 American Society of Civil Engineers.*

Author keywords: Groundwater artificial recharge; Site selection; Geographic information system (GIS); Nash conflict resolution method.

Introduction

The volume of groundwater extraction exceeds the natural recharge in many regions in which groundwater is the main source of water (Kalantari et al. 2010; Loáiciga 2016). It is therefore necessary to resort to artificial groundwater recharge plans (AGRPs) in these regions to protect aquifers from overexploitation.

Chopra and Sharma (1993) conducted a study about groundwater resources in Bist-Doab, India. Satellite observation was used to estimate the volume of groundwater in the case-study region. Their results showed that old channels, lakes, and braided streams have created deep productive aquifers with good-quality groundwater. Floodplains were found to be suitable places for AGRP implementation. Krishnamurthy and Srinivas (1995) showed that geological factors are the most effective in controlling the groundwater recharge. The results of their study on the effects of geological factors on AGRPs demonstrated that alluvial valleys, intensely fractured fault zones, and vast plains are suitable for AGRP implementation. Krishnamurthy et al. (1996) determined suitable places for implementation of AGRPs in a southern region of India by applying geologic criteria, topography, faults, surface water, drainage networks, waterway density, and slope. They classified the developed map into four categories of regions: very good, good, moderate, and poor for groundwater recharge. Their results indicated that quaternary sediments with a slope of less than 5% were most suitable for flood spreading and aquifer recharge. Saraf and Choudhury (1998) in Madhya Pradesh, India, researched AGRPs with land-use maps, vegetation, geology, and ground slope. They combined the thematic layers with a geographic information system (GIS) and identified the appropriate places for the implementation of AGRPs. Zehtabian et al. (2001) researched land-use criteria, vegetation, slope, geology, and soil hydrologic groups in their quest to find suitable places for the implementation of AGRPs in the Togharood Qom River basin, Iran. The weights assigned to each of the preceding criteria were determined by binary Boolean logic and fuzzy logic with which the suitable areas for AGRP implementation were determined. Ramalingam and Santhakumar (2000) evaluated the suitable areas for artificial recharge in India by the use of GIS and remote sensing (RS). They employed geomorphologic information layers, geology, soil, slope, land use, runoff intensity, and depth to groundwater in their study. Mehrvarz and Kalantari Oskouei (2007) implemented five criteria including terrain slope, surface permeability, transmissibility, dried sediment thickness, and the transmissivity of sediments with GIS to find suitable spreading basins for groundwater recharge in the Tassuj plain, Iran. Their results proved that fuzzy logic coupled with GIS was the best method to find suitable places for spreading flood runoff in the case-study region.

Ghayoumian et al. (2005) determined the potential areas for AGRP implementation in the Meimeh basin in Isfahan, Iran, with the use of GIS and a decision support system (DSS) combined with information on slope layers, permeability, the thickness of sediments, water quality, and the aquifer water-pass ratio. Shankar and Mohan (2005) implemented indexes related to geology and water tables in order to locate AGRP regions in Deccan, India. Their maps included the depth to bedrock, the thickness of soil coverage, drainage density, land use, geologic units, terrain slope, and fluctuations in the water table as decision criteria. These maps were combined within a GIS environment aided by the Boolean logic method to locate suitable places for AGRP implementation in the studied region. Shaban et al. (2006) investigated strategies for groundwater preservation in Occidental, Lebanon. Their study showed that areas with fractured rock and karstic limestone are suitable for AGRP implementation, whereas residential areas and flat areas covered with fine-grained soil are the least adept for AGRP

[1]Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 1193653471 Tehran, Iran. E-mail: Farhadian.M@ut.ac.ir

[2]Professor, Dept. of Irrigation and Reclamation Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, Univ. of Tehran, Karaj, 1193653471 Tehran, Iran (corresponding author). E-mail: OBHaddad@ut.ac.ir

[3]Assistant Professor, Faculty of Environment, College of Environmental Engineering, Univ. of Tehran, 1193653471 Tehran, Iran. E-mail: MPazoki@ut.ac.ir

[4]Professor, Dept. of Geography, Univ. of California, Santa Barbara, CA 93106. E-mail: hloaiciga@ucsb.edu

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implementation. Ghayoumian et al. (2005) determined the best areas for artificial recharge of coastal aquifers in southern Iran with the use of GIS and the analysis of slope, permeability, the elevation of the water table, the quality of sediments, and land-use criteria. The thematic layers were processed with Boolean and fuzzy logic. Chenini et al. (2010) analyzed rainfall, runoff intensity, and geology in the Maknassy basin in Tunisia to locate AGRP implementation regions. Information criteria layers were quantified with the weighted cumulative method in the search for groundwater recharge sites. Chowdhury et al. (2010) located suitable areas in West Medinipur, India, with coupled RS, GIS, and multicriteria decision making (MCDM). Sargaonkar et al. (2011) evaluated areas of the Nagpur river basin in Maharashtra province, India, to locate the suitable places for AGRP implementation. They applied GIS with rainfall-runoff modeling and land use, soil, geology of the basin linked to analytical hierarchy process (AHP), and expert judgment to classify and weigh the data layers to find suitable areas for AGRP implementation. Samadder et al. (2011) investigated the strength of old transmission canals for AGRP implementation with the use of RS and collected field data on groundwater, lithology, geology, hydraulic conduction, and rainfall and combined these data with data layers of storage coefficient, the direction of groundwater flow, soil texture, natural recharge rate, and the source of recharge water within a GIS environment.

Rahman et al. (2012) reported spatial multicriteria decision analysis (SMCDA) to locate AGRP implementation areas. This tool was created by the combination of multicriteria evaluation methods (MCEM) and modern decision analysis techniques embedded in a GIS environment. More specifically, noncompensatory screening, standardization and weighting of criteria, AHP combined with weighted linear combination (WLC), and ordered weighted averaging (OWA) to located regions for AGRP implementation in the Algarve region in Portugal. Kaliraj et al. (2014) applied AHP to locate an AGRP region in the Vaigai basin of Tamil Nadu province, India. They combined data on geologic features, soil type, land use, land coverage, drainage network density, and surface water storage in their analysis. Mahmoud and Alazba (2014) identified suitable areas for AGRP implementation in the Jazan region, Iran, with coupled DSS and GIS applied to rainfall maps, slope, runoff coefficient, land coverage, land use, and soil texture. These maps were weighted by AHP to identify potential areas for AGRPs that were classified into excellent, good, moderate, and poor categories. Zaidi et al. (2015) identified suitable areas for AGRPs in northwestern Saudi Arabia. They considered terrain slope, soil texture, vadose zone thickness, groundwater quality, and the type of water bearing formation criteria in their study. Effective criteria were combined by Boolean logic within a GIS environment.

Loáiciga (2004) presented principles of sustainable use of groundwater considering groundwater recharge processes and aquifer vulnerabilities. Raquel et al. (2007) applied game theory for conflict resolution in Alto Rio Lerma in Guanajuato province, Mexico. Wang et al. (2011) implemented the Nash conflict resolution method to multiperson decision making and multiobjective strategizing to groundwater management in China. Madani and Zarezadeh (2012) introduced bankruptcy game theory to determine solutions for equitable allocation of water in bankrupt water resource systems.

More than 90 percent of Iran's land is located in arid and semiarid regions (Ghayoumian et al. 2005; Mahmoud and Alazba 2014), and most of these regions rely on groundwater resources for their water supply. This study presents a methodology for locating suitable places for AGRP implementation to support agriculture and preserve groundwater reserves. The methodology is applied to the Kerman Province of Iran. The proposed methodology identifies effective criteria for locating artificial recharge areas, and the criteria's relative weights are determined with the AHP method. The maps representing the method's criteria are combined with the *ArcGIS 10.1* software by means of weights, leading to the determination of suitable places for AGRP implementation. Thereafter, social and economic criteria and living conditions in the Kerman Province are coupled with the Nash conflict resolution method in the prioritizing for suitable areas for AGRP implementation.

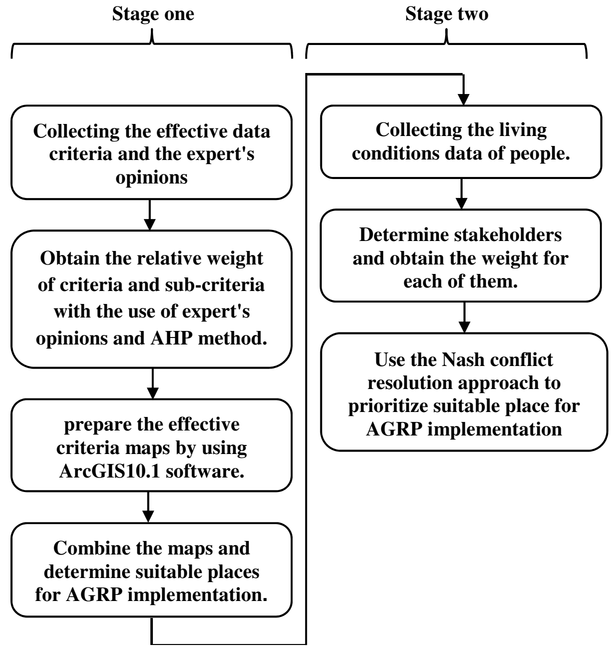

Fig. 1. Method and procedures of study

Research Methodology

This paper's method locates and prioritizes suitable places for AGRP implementation and is applied in the Kerman Province, Iran. The two-stage method's first stage accomplishes AGRP area location, followed by area prioritization in the second stage.

The effective data criteria on AGRPs were identified and experts' opinions about these criteria were collected in the first stage of this study. Thereafter, the relative weight of each criterion and subcriterion was obtained with the use of experts' opinions and the AHP method. Effective criteria maps were prepared with the *ArcGIS 10.1* software. The maps containing all the criteria were combined with the *ArcGIS 10.1* software and final maps with which to locate suitable places for AGRP implementation.

The suitable places identified in the first stage were prioritized according to social and economic data for the region under study in the second stage. This stage involves the preferences of the water-system stakeholders with respect to AGRP implementation. This stage was completed by applying the Nash conflict resolution method to prioritize the suitable places for AGRP implementation identified in Stage 1. This work's proposed two-stage method is depicted graphically in Fig. 1.

Analytical Hierarchy Process

There are several decision-making methods to solve complex conflicts, and these methods are mostly MCDM methods or DSSs (Amirkani et al. 2016).

Table 1. Weighting of Paired Comparisons in the AHP Method (Data from Garcia et al. 2014)

Importance	Definition	Explanation
1	Same importance	Two options are equally weighed.
3	Poor privilege	One option is dominated poorly by the other option.
5	Strong privilege	One option is dominated strongly by the other option.
7	Very strong privilege	One option is privileged relative to the other option.
9	Completely privileged	One option is completely privileged relative to the other option.
2, 4, 6, 8	Moderate values	The importance of the options relative to each other is given by these.
1/2, 1/3, ... ,1/9	Inverse values	They are used for the transposed positions of weighting assignments.

One of the most popular MCDM methods is AHP (Feizizadeh et al. 2014). The AHP method is applied in decision making to choose the weighting criteria and subcriteria. Using the AHP method for weighting reduces the complexity in determining the relative weights. The AHP calculated weights indicate the relative importance of each criterion (Saaty 1977). The AHP method has different levels, in which the highest level is decision making, middle levels involve setting criteria and subcriteria, and the last level is for outlining options. A square matrix of paired comparisons (Matrix A) is composed in the implementation of the AHP method to show the relative weights of the criteria. The number of rows and columns is equal to the number of effective criteria, and each of the matrix's elements indicates the relative weights of the criteria. The values of Table 1 determine the relative weights (Saaty 1980). The elements of Matrix A are normalized with Eq. (1) and are stored in a new matrix (Matrix B) as follows:

$$b_{i,j} = \frac{a_{i,j}}{\sum_{i=1}^{n} a_{i,j}} \tag{1}$$

in which i = row index; j = column index; $b_{i,j}$ = element row i and column j of Matrix B; $a_{i,j}$ = element row i and column j of Matrix A; and n = total number of rows or columns (Feizizadeh et al. 2014). After composing Matrix B, the final weight of each criterion is calculated with Eq. (2) as follows:

$$w_{i,j} = \frac{\sum_{j=1}^{n} b_{i,j}}{\sum_{i=1}^{n}\sum_{j=1}^{n} b_{i,j}} \tag{2}$$

The AHP method defines a consistency ratio (CR) to determine the consistency between the relative weights of the criteria. The CR indicates the accuracy of the expert random judgment made for weighting of the criteria. This ratio is defined by Eq. (3), whose values are equal to or larger than zero (Saaty 1977; Garcia et al. 2014), as follows:

$$CR = \frac{CI}{RCI} \tag{3}$$

in which CI = consistency index; and RCI = random CI. RCI is determined with the recommendation by the Saaty (1977) advice listed in Table 2, and CI is given by Eq. (4) as follows:

Table 2. RCI Values for All Criteria Used (Data from Saaty 1980)

n	RCI
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.46

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

in which $\lambda_{\max}$ = largest special vector (Feizizadeh et al. 2014).

The weights assigned to the criteria are consistent with each other and are accepted when the calculated value of CR is less than 0.1. Otherwise, the weights are inconsistent and unacceptable; thus, their initial weighting criteria must be reassessed.

Geographic Information System

A GIS is a useful computer tool for the analysis and management of spatial data and decision making in many fields of engineering and science. Groundwater management requires comprehensive analysis of aquifer processes' variability in space and time, which is handled satisfactorily with GISs and numerical models (Jha et al. 2010). The application of a GIS is helpful in locating artificial recharge areas because of the large volume of geographic data that must be processed in the analysis (Malekmohammadi et al. 2012). AHP and GIS can be combined successfully in locating recharge areas (Jha et al. 2010; Kaliraj et al. 2014).

Nash Conflict Resolution Method

It is known that the scarcity of water may cause conflicts among stakeholders (Raquel et al. 2007) who may have different priorities and goals. Conflict resolution is called for in this situation. The Nash conflict resolution method has been applied in water resources (Raquel et al. 2007). The Nash method produces resolutions that meet the following conditions: (1) the total allocations to stakeholders cannot exceed the available resources, (2) each stakeholder derives greater benefit from the resources allocated by the Nash resolution than from the stakeholder's minimum admissible allocation, and (3) there is no better allocation for all the stakeholders than the Nash resolution.

The Nash method was introduced to resolve conflicts between two stakeholders and was later extended by Harsanyi and Selten (1972) for conflict resolution among several stakeholders. The Nash function (Raquel et al. 2007) is maximized to find the best solution to a conflict among stakeholders as follows:

$$\text{Max:} \prod_{i=1}^{N} (f_i - d_i)^{h_i}, \quad f_i \geq d_i \tag{5}$$

in which i = stakeholder's index; N = number of stakeholders; f_i is the desire function of stakeholder i; d_i = minimized desire level of stakeholder i; and h_i = relative weight of stakeholder i (Raquel et al. 2007). The Nash function [Eq. (5)] produces the optimal levels d_i for the allocation of scarce resources among competing stakeholders.

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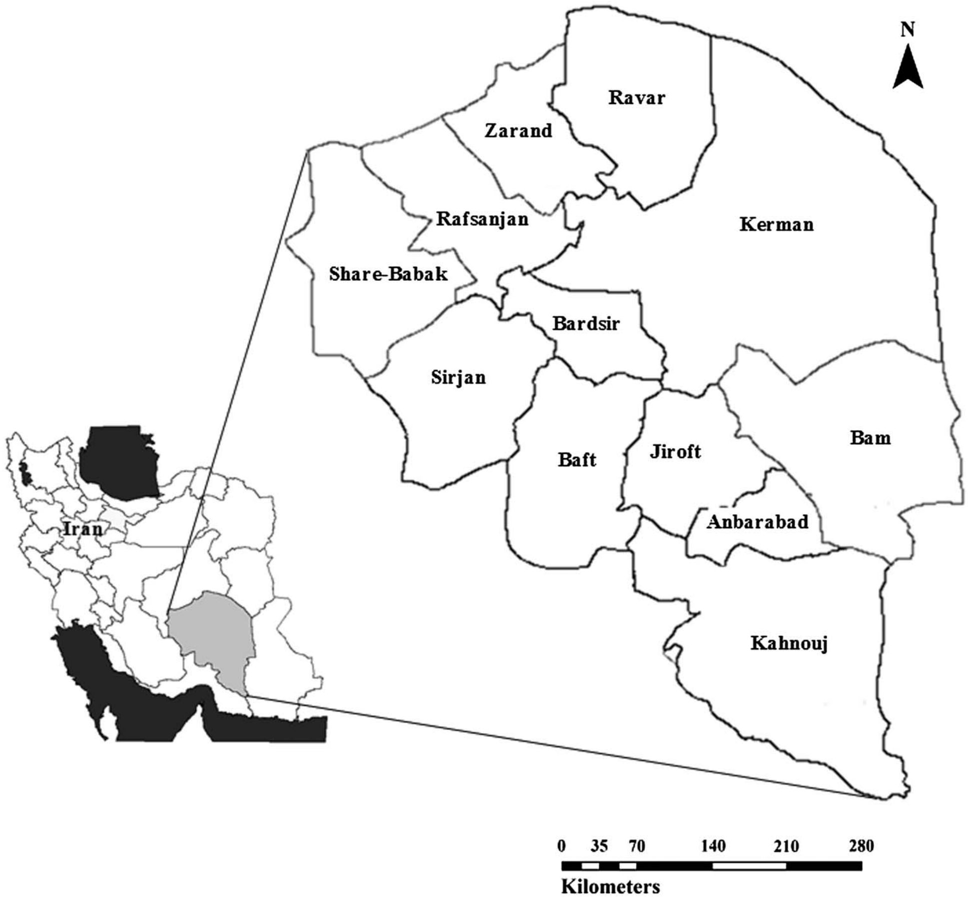

Fig. 2. Case study area: Kerman Province of Iran and its townships

Case Study

Kerman is the largest province of Iran and is located in the southeastern part of the country within latitudes 26°24′ to 31°57′ north and longitudes 54°30′ to 59°48′ east. The Kerman Province has a range of climates, but overall it has a deficit of water resources given the amount of precipitation. Groundwater is the main source of water supply (about 99% of the water use is from groundwater) of this province. The Kerman Province at present has approximately 32,248 groundwater discharge points (wells, aqueducts, and springs), and the discharge volume is approximately $6{,}764 \times 10^9$ m^3 annually. All the province's regions are faced with a negative balance of water resources. From the beginning of water year 2000–2001 through the end of 2004–2005, the groundwater levels within the Kerman Province's plains dropped approximately 5.44 m (Kerman Regional Water Company 2008). The quality of groundwater in the province is low, and the average electric conductivity of groundwater is approximately 2.860 μS/cm. In some of the province's regions, the quality of groundwater is so low that it is not suitable for drinking or even for agriculture.

The Kerman Province is divided into several townships as shown in Fig. 2. This study relies on the administrative division of the year 2000.

Required Data to Locate Areas Suitable for AGRP Implementation

Consideration of the studies by Jha et al. (2010), Malekmohammadi et al. (2012), Mishra et al. (2015), Kaliraj et al. (2014), and Magesh et al. (2012), experts' viewpoints, and the data available in the Kerman Province led to the creation of eight data groups in this study, which contain the following information:

- Precipitation: Precipitation is the source water for AGRP implementation. Precipitation determines the amount of regional water availability (Adiat et al. 2012).
- Vegetation: AGRP implementation is more effective in lands with suitable vegetation because of the increase of infiltration and enhanced protection against soil erosion.
- Distance from connected roads: The existence of connected roads facilitates AGRP implementation and use. In spite of that, AGRPs encourage agricultural development in regions with adequate networks of connected roads.
- Soil type: Soil type, specially the surface soil type, has a strong effect on filtration and percolation.
- Distance from rivers: AGRP implementation requires surface water resources. One of the best sources for aquifer recharge comprises rivers and streams that carry water during or following precipitation. Conveyance of these surface waters to the intended areas for AGRPs is essential for recharge.
- Geology: Geologic features control many hydrologic characteristics such as transmissivity, storage capacity, and water quality.
- Terrain slope: Slope is one of the effective factors for artificial recharge and plays an important role in the control of flooding (Krishnamurthy et al. 1996). Slope affects overland flow and infiltration into the soil. Mild slopes provide greater residence time of water on the land surface and increase the time available for infiltration (Adiat et al. 2012).

Table 3. Population and Land Area under Irrigation within Kerman Province Townships

Township	Population (person) (×1,000)	Land area (ha) (×1,000)	Population/land area (%)	Normalized values (population/land area) (%)
Baft	145	85	59	100
Bardsir	89	47	53	89
Bam	282	37	13	15
Jiroft	188	43	23	33
Ravar	39	8	21	29
Rafsanjan	295	74	25	37
Zarand	146	23	16	20
Sirjan	246	69	28	43
Shahre-Babak	103	30	29	45
Anbarabad	115	45	39	63
Kerman	678	61	9	7
Kahnouj	327	145	44	73
Entire Kerman Province	2,652	668	25	—

Table 4. Number of Job Openings and Job Applicants in Townships of Kerman Province

Township	Job openings (person)	Job applicants (person)	Job openings/job applicants (%)	Normalized values (job openings/job applicants) (%)
Baft	203	805	25	7
Bardsir	604	2,470	24	6
Bam	1,279	4,284	30	13
Jiroft	348	1,176	30	13
Ravar	192	204	94	100
Rafsanjan	1,353	3,230	42	30
Zarand	943	2,048	46	35
Sirjan	1,201	3,852	31	15
Shahre-Babak	257	930	28	10
Anbarabad	31	143	22	2
Kerman	16,462	22,816	72	70
Kahnouj	312	365	85	88
Entire Kerman Province	23,185	42,323	55	—

- Land use: AGRP implementation is not feasible in all lands, and it is necessary that the suitable lands be identified and classified according to their level of suitability for AGRPs.

Data Required to Prioritize AGRP Implementation

In the Kerman Province, 5 and 94% of the water resources are consumed by the domestic and agriculture users, respectively, and the remaining 1% is devoted to meet other requirements (Kerman Regional Water Company 2008). Scarcity of rainfall and water resources is the limiting factor militating against agricultural development in the Kerman Province. Therefore, an increase of groundwater storage in this region could improve water availability and the living conditions of its people.

AGRP implementation can increase groundwater storage and improve the living conditions of people in the Kerman Province. This means that the economic and social indices of its regions must be considered for the sake of prioritizing recharge areas. This study relied on data about the lands under irrigation (agriculture and gardening) because of an almost nonexistent dryland cultivation due to low rainfall. Data on population, land area under irrigation, occupational status, and the migration regime for all the townships in the province were collected and analyzed (Iran Census Bureau 2015). Therefore, suitable places for artificial recharge were prioritized by assessing the units composing the provincial townships. The data required to prioritize AGRP implementation is summarized as follows:

- Population and land area under irrigation: Table 3 lists the population and land area under irrigation in the Kerman Province and lists the ratio of the land area under irrigation to the population and their normal values. The ratio of the land area under irrigation to the population represents the average share of land area under irrigation per person in each township. This ratio is one criteria measuring people's living conditions.
- Occupational status: The ratio of irrigated land to the population does not show the land distribution among inhabitants, and it is possible that most of the citizens of a township do not own irrigated lands. It is therefore necessary to resort to other criteria to better measure people's living conditions. The occupational status of people in each township is a criterion measuring their economic and living conditions. Therefore, data were collected about the numbers of jobs available and job applicants in the years 1998–2008 for each township and are listed in Table 4. Table 4 also lists the ratio of job openings to job applicants and their normalized values.
- Migration regime: The townships of the Kerman Province feature different economic, climatic, and social conditions, which are the causes of migration among townships. The migration status of each region is one of the indices of economic and living conditions in the study region. Migration is driven by poor economic and social conditions in one region toward surrounding areas with better conditions. Table 5 lists the total incoming and outgoing migrants for each township from and to any township within the Kerman Province in the past five years (interprovincial migration). The average annual values of the incoming migrants divided by the outgoing migrants are also listed Table 5. The final two columns of Table 5 represent the ratio of the difference in migrants to the total population of each township (migration ratio) and their normalized values, respectively.

Results

The results of selecting the locations and prioritization of AGRP implementation are presented next.

First Stage: Location of Artificial Groundwater Recharge Plans

The location of AGRPs was guided by the effective criteria maps that were introduced in previous sections. The weights of each of these criterion and subcriterion were determined. The maps of criteria were combined according to their weights, and the suitable places for AGRP implementation were determined.

Effective Criteria Maps

For locating GPs, it is necessary to produce effective criteria maps for weighting and overlaying them. Thus, In this section, how to produce maps of each of the eight criteria is described

- Precipitation map: Precipitation mapping was accomplished by analyzing the average annual precipitation at weather forecast stations in the study area and by spatial interpolation with the inverse distance weighting (IDW) method implemented in the *ArcGIS 10.1* software. The IDW method is a common

Table 5. Number of Migrants in Kerman Province

Township	Incoming migrants (person)	Outgoing migrants (person)	Incoming migrants/outgoing migrants (person)	Average annual values (incoming migrants/outgoing migrants)	Population (person) (×1,000)	Average annual values/population (×1,000) (%)	Normalized values (average annual values/population) (%)
Baft	6,147	9,615	−3,468	−694	145	−478	10
Bardsir	2,972	3,493	−521	−104	89	−117	52
Bam	11,650	10,852	798	160	282	57	72
Jiroft	6,478	10,126	−3,648	−730	188	−389	21
Ravar	1,788	1,839	−51	−10	39	−26	62
Rafsanjan	18,666	14,180	4,486	897	295	304	100
Zarand	9,626	10,622	−996	−199	146	−137	50
Sirjan	11,309	10,362	947	189	246	77	74
Shahre-Babak	2,782	3,181	−399	−80	103	−78	56
Anbarabad	1,255	1,899	−644	−129	115	−112	52
Kerman	34,767	29,766	5,001	1,000	678	148	82
Kahnouj	8,766	10,271	−1,505	−301	327	−92	55
Entire Kerman Province	116,206	116,206	0	—	2,652	—	—

method for the interpolation of precipitation and other spatial data (Basistha et al. 2008). The resulting Kerman precipitation map is shown in Fig. 3(a). It is observed in Fig. 3(a) that the highest average annual precipitation occurs in the western and southern regions of the Kerman Province.

- Vegetation map: The vegetation map of the Kerman Province was prepared using Iran's vegetation maps (Department of Soil and Water Ministry of Agriculture 2014). The maps are classified into five categories, from very poor to very good, as shown in Fig. 3(b). It is seen in this map that the southern and western regions of the province have the largest areas of vegetation and match well with the precipitation map insofar as the amount of precipitation is concerned.
- Map of distance from roads: The map of the distance from connected roads is classified into five categories according to the maps of country roads (Department of Soil and Water Ministry of Agriculture 2014) and the distance from roads, depicted in Fig. 3(c). This figure shows the lack of connected roads in the eastern and southern regions of the province. The density of roads in other areas of the province is approximately the same.
- Soil map: A soil map was prepared for the province by using countrywide soil maps (Department of Soil and Water Ministry of Agriculture 2014). The soil maps are classified into four categories, from poor to quite good, based on infiltration, as seen in Fig. 3(d). According to Fig. 3(d), the province exhibits a large variability of infiltration.
- Map of distance from rivers: The map of the distance from rivers is classified into five categories by using Iran's river map (Department of Soil and Water Ministry of Agriculture 2014) and according to the distance from rivers, depicted in Fig. 3(e). It is seen in Fig. 3(e) that the shortest distances from rivers are observed in the eastern region, and other areas of the province are very similar in terms of distances from rivers.
- Geologic map: The geologic map of the Kerman Province is based on the geological map of Iran (Department of Soil and Water Ministry of Agriculture 2014), which was prepared and is classified into four categories, from poor to quite suitable, according to the appropriateness for AGRP implementation, as portrayed in Fig. 3(f). There are four geologic categories within the province, and Fig. 3(f) shows that there are areas with perfectly suitable geology in the eastern portion of the province.
- Slope map: The slope map of the Kerman Province was developed using digital elevation models (DEM) (Department of Soil and Water Ministry of Agriculture 2014) and is shown in Fig. 3(g), where it is observed that terrain slope is classified into four categories from 2% to more than 10%. It is seen in Fig. 3(g) that most lands with steep slope are located in the western half of the province.
- Land-use maps: The land-use map of the Kerman Province was developed from the Iran land-use map (Department of Soil and Water Ministry of Agriculture 2014), which is classified into five categories, from quite unsuitable to quite suitable, according to the level of suitability for AGRP implementation. The map of land use of the Kerman Province is presented in Fig. 3(h), which shows that the lands with unsuitable use for AGRP implementation consist of residential areas, hills, and mountains, which constitute the largest share of the province's area.

Weights Assigned to Maps

Because of the different impact of the eight criteria used for AGRP locations, it is necessary to appropriately weigh them. To do so, previous studies (Malekmohammadi et al. 2012; Mishra et al. 2015; Kaliraj et al. 2014; Magesh et al. 2012), experts' viewpoints, and the AHP method were relied on.

Table 6 lists the AHP paired comparison matrix and final weights of each criterion. The last column of Table 6 lists the weights calculated with Eqs. (1) and (2). The *CR* was calculated to be 0.098 with the use of Eqs. (3) and (4) to assess the compatibility between criteria weights. Therefore, the final weights of the criteria are compatible with each other given that this value is less than 1.

To locate an AGRP area, one must weigh the criteria, which means that the appropriate weights for subcriteria must be determined. This was performed similarly to the manner in which the criteria were weighed. Because of the large number of criteria, the paired comparison (Table 7) lists only the final weights for each of the eight criteria. It is seen in Table 7 that the classification and paired comparisons between the categories of precipitation, vegetation, the distance from connected roads, and the distance from rivers were accomplished based on previous studies and that the same final weights were obtained for these four criteria.

Combining Maps and AGRP Locations

After the weight of each criterion and subcriterion was determined, their maps were combined according to weights determined with *ArcGIS 10.1*. The map of appropriate areas for AGRPs was obtained according to the total points assigned to each area. The obtained map is classified into five categories, from quite unsuitable

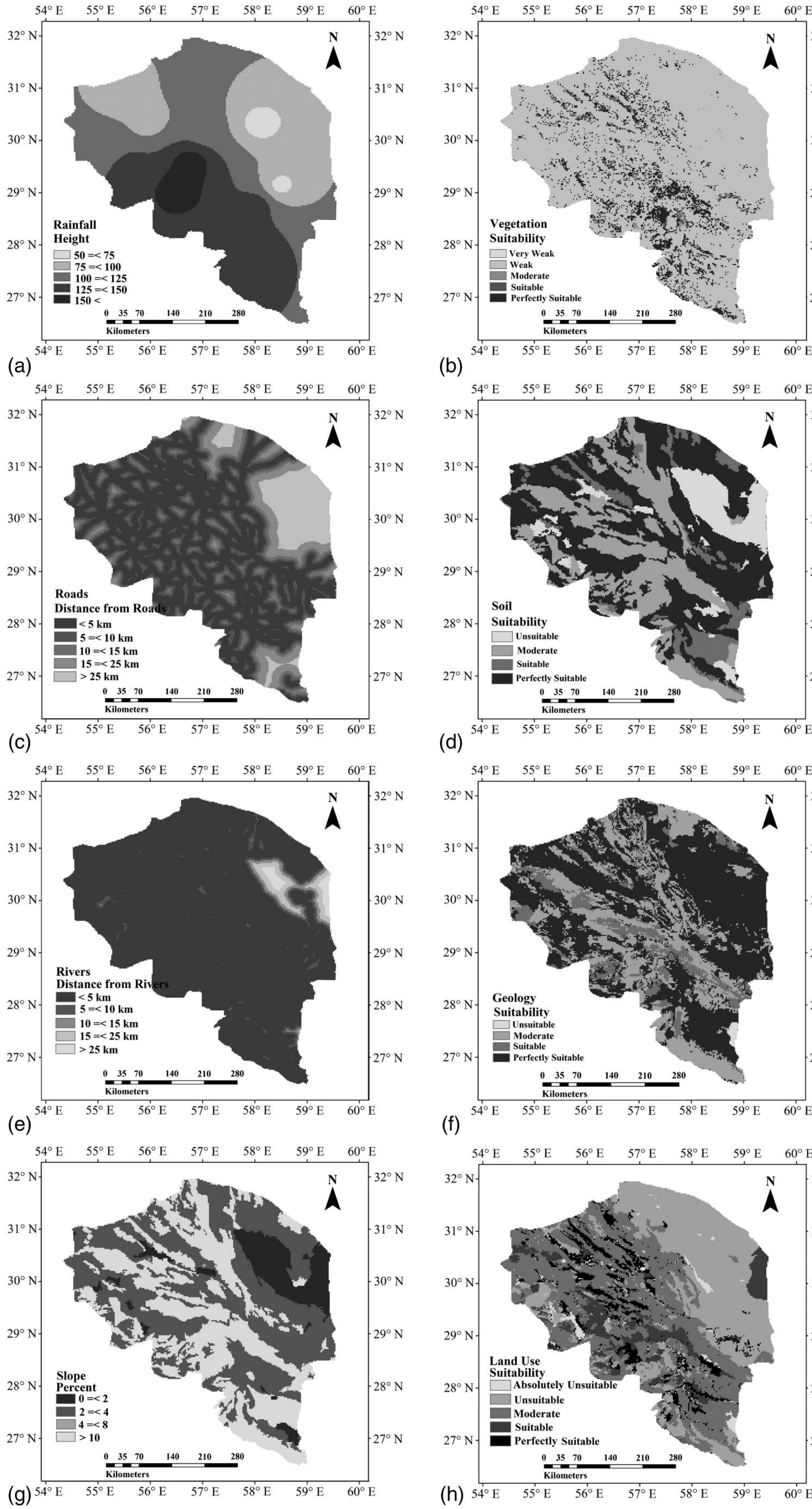

Fig. 3. Effective criteria maps for AGRPs: (a) precipitation; (b) vegetation; (c) distance from connected roads; (d) soil; (e) distance from rivers; (f) geology; (g) slope; (h) land use

Table 6. Paired Comparison Matrix and Effective Weight Criteria for Locations

Criteria	Precipitation	Vegetation	Distance from connected roads	Soil type	Distance from rivers	Geology	Slope	Land use	Final weights
Precipitation	1.00	3.00	7.00	5.00	7.00	2.00	3.00	3.00	3.27
Vegetation	0.33	1.00	3.03	1.00	3.03	0.50	1.00	1.00	1.05
Distance from connected roads	0.14	0.33	1.00	0.25	1.00	0.50	0.17	0.20	0.34
Soil type	0.20	1.00	4.00	1.00	4.00	3.03	0.25	1.00	1.12
Distance from rivers	0.14	0.33	1.00	0.25	1.00	0.20	0.20	0.20	0.31
Geology	0.50	2.00	2.00	0.33	5.00	1.00	4.00	1.40	1.44
Slope	0.33	1.00	6.00	4.00	5.00	0.25	1.00	1.00	1.33
Land use	0.33	1.00	5.00	1.00	5.00	0.71	1.00	1.00	1.25

Table 7. Categories and Final Weight Values of Each Effective Criteria

Category	Final weight
Precipitation	
≥ 150 and ≤ 175 mm	3.9
≥ 125 and <150 mm	2
≥ 100 and <125 mm	1
≥ 75 and <100 mm	0.5
≥ 50 and <75 mm	0.3
Vegetation	
Perfectly suitable	3.9
Suitable	2
Moderate	1
Weak	0.5
Very weak	0.3
Distance from connected roads	
<5 km	3.9
≥ 5 and <10 km	2
≥ 10 and <15 km	1
≥ 15 and <25 km	0.5
≥ 25 km	0.3
Soil type	
Perfectly suitable	1.6
Suitable	1.3
Moderate	0.9
Unsuitable	0.5
Distance from rivers	
<5 km	3.9
≥ 5 and <10 km	2
≥ 10 and <15 km	1
≥ 15 and <25 km	0.5
≥ 25 km	0.3
Geology	
Perfectly suitable	1.6
Suitable	1.3
Moderate	0.9
Unsuitable	0.5
Slope	
0 =< 2%	1.8
2 =< 4%	1.2
4 =< 8%	1
8 =< 10%	0.5
Land use	
Farms	1.9
Woodland	1.4
Cultivation of dry and arid lands	0.9
Residential and hills	0.4

to quite suitable, based on classification method. This map is presented in Fig. 4.

The percentage of areas corresponding to each category of suitability for AGRP locations in each township was determined with *ArcGIS 10.1* after determining the proper locations for AGRP implementation. The percentages of the areas assigned to each category of the AGRP implementation locating map are listed in Table 8, which shows that the largest percentage of suitable and quite suitable areas for AGRP implementation are found in the Baft, Bardsir, and Ravar townships.

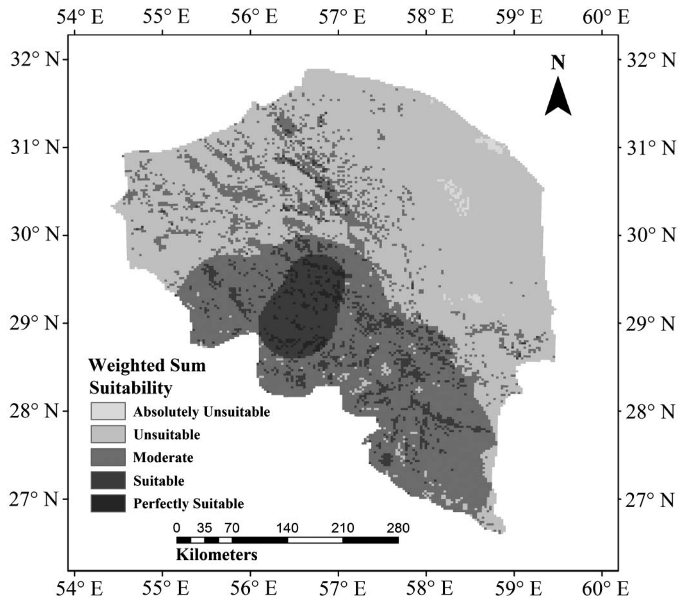

Fig. 4. Final map of AGRP implementation

Second Stage: Prioritizing Suitable Locations for Artificial Groundwater Recharge Plans

It is necessary to prioritize the development of recharge areas identified in the first stage because of the scarcity of available funding and required infrastructure. Therefore, the second stage of this paper's method assesses the living conditions of people in all of the townships of the Kerman Province using social and economic data. The order of AGRP implementation is determined for townships following the results of the assessments. The Nash conflict resolution method provides a mechanism for resolving conflicts that arise in the allocation of scarce resources among competing stakeholders. Application of the Nash conflict resolution method for prioritizing townships for AGRP implementation requires as input the evaluation criteria and the existing stakeholders, minimized desires of stakeholders, and relative weights of the evaluation criteria with which to calculate the Nash function. The prioritization of townships based on the Nash conflict resolution follows.

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Table 8. Percentage of Each Location Categories in Townships of Kerman Province

Township	Absolutely unsuitable	Unsuitable	Moderate	Suitable	Perfectly suitable	Total
Baft	0.0	0.7	37.2	53.6	8.5	100
Bardsir	0.0	21.0	39.5	33.4	6.1	100
Bam	0.7	88.3	9.9	1.1	0.0	100
Jiroft	0.0	5.8	75.4	18.8	0.0	100
Ravar	0.0	33.3	33.3	33.3	0.0	100
Rafsanjan	0.0	37.1	61.2	1.8	0.0	100
Zarand	0.0	69.8	26.3	3.9	0.0	100
Sirjan	0.0	15.0	76.9	8.2	0.0	100
Shahre-Babak	0.0	87.5	12.2	0.4	0.0	100
Anbarabad	0.0	4.5	77.7	17.8	0.0	100
Kerman	1.4	87.1	10.5	0.9	0.0	100
Kahnouj	0.0	13.1	79.0	7.9	0.0	100
Entire Kerman Province	0.5	50.9	37.0	10.7	0.9	100

Assessment Criteria and Present Stakeholders

The assessment of the people's living conditions requires data about (1) the fraction of land area under irrigation, (2) occupation status, and (3) the migration regime, which are listed in Tables 3–5, respectively. These criteria are improved by supplying water needs for agriculture in the water-scarce Kerman Province. Each township in the Kerman Province is a stakeholder in prioritizing for AGRP implementation to supply water for agriculture. The living conditions of people in each township are improved by such supply. Therefore, the province townships have conflicts over AGRP implementation. A conflict resolution method can be used to assess the evaluation criteria for each township. Thereafter, the order of AGRP implementation for townships is determined.

The total percentage of the areas pertaining to the suitable and perfectly suitable categories, which were identified in the first stage, was considered as the fourth evaluation criteria for prioritizing townships. This is in addition to the three criteria that measure the living conditions of people in the provincial townships. This was done because the possibility of AGRP implementation in townships increases with the increasing percentage of suitable or perfectly suitable areas for recharge. Therefore, four evaluation criteria were applied for the prioritizing of the order of townships (stakeholders) to implement AGRPs.

Minimized Desires of Stakeholders

One of the inputs to the Nash conflict resolution method is the minimized desire for a scarce resource in question (e.g., groundwater from artificial recharge) by stakeholders. It is therefore necessary to determine the minimized desires of all stakeholders (all 12 townships) with respect to each of the four criteria separately. This would require the determination of 48 ($= 4 \times 12$) minimized desires according to the economic and social expectations of people living in each township. This determination is not possible because of a lack of sufficient data. Alternatively, the values of minimized desires can be determined for each of the four evaluation criteria and their values applied to all of the stakeholders (the 12 townships).

The living conditions of people in deprived townships, which do not have sufficient water for agriculture and have few job openings and numerous migrants, can be improved by prioritizing these townships for AGRP implementation. To do so, the evaluation criteria data used in the Nash method must prioritize deprived townships. This is accomplished in the Nash method by increasing the difference between the desire function [f_i in Eq. (5)] and the minimized desires [d_i in Eq. (5)] in deprived townships. Therefore, the difference between the desire function and the minimized desire for each of the four adopted criteria for deprived townships was increased relative to more affluent townships after defining the minimized desire of each evaluation criterion. This procedure assures that deprived townships have a larger Nash function value. Their more acute deprivation according to the evaluation criteria induces a larger difference, and these townships are assigned a higher priority for AGRP implementation.

Table 9. Relative Weights of Each Criterion

Criteria	Scenarios A	B	C	D	E
Percentage of location area	1	2	1	1	1
Ratio of irrigated lands to population	1	1	2	1	1
Occupation status	1	1	1	2	1
Migration regime	1	1	1	1	2

Relative Weights of the Evaluation Criteria

The Nash method requires the determination of the relative weights for each evaluation criteria. This is achieved for the four criteria chosen by the opinions of experts on the matter of AGRP implementation. Five scenarios of relative weights (A, B, C, D, and E) for criteria were considered to investigate a range of possible results. The differences between these criteria are the relative weights assigned to them. The relative weights of each criterion for the five scenarios are listed in Table 9.

Calculation of the Nash Function and Prioritization of Townships for AGRP Implementation

The calculation of the Nash function [Eq. (5)] involves the differences between the desire function of each criterion and the minimized desire for each township (stakeholder). Thereafter, these obtained values are multiplied, and the Nash function values for each township are calculated. This procedure is carried out for all the townships, and the largest and smallest values of the Nash function are assigned the first and last priority for AGRP implementation, respectively. The Nash function for all five scenarios is calculated for all the townships, and its values are normalized

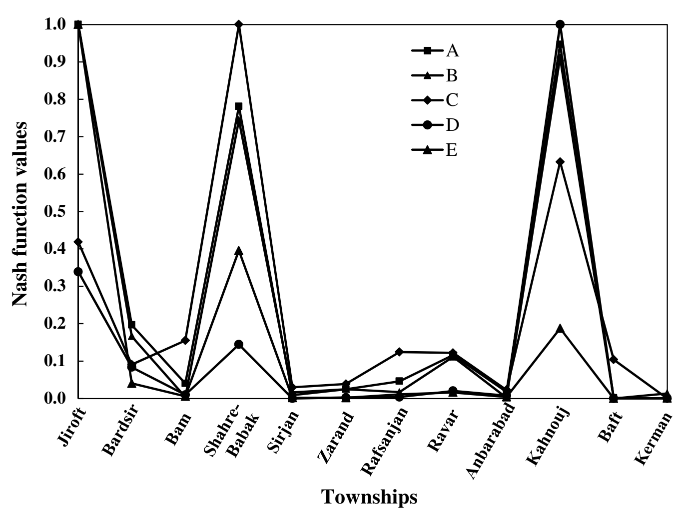

Fig. 5. Township priorities in each of the scenarios according to the Nash function values

for each township to yield the numerical values of each of five scenarios depicted in Fig. 5. It is seen in Fig. 5 that in each scenario, the township with Nash function value 1 has the highest priority, and townships with Nash function value 0 have the lowest priority for recharge implementation. Fig. 5 shows that the Jiroft, Shahre-Babak, and Kahnouj townships have priorities from first to third in all scenarios, and only their rankings differ in each scenario.

Concluding Remarks

AGRP implementation increases water storage in aquifers. It is infeasible to implement AGRPs in all regions at the same time. The suitable places for AGRP areas are first located. Thereafter, the identified suitable places for AGRPs are prioritized because of the scarcity of resources for AGRPs. In this work, locating and prioritizing of AGRPs was accomplished with a two-stage method. In the first stage, effective criteria data on AGRPs were collected, and their maps were prepared with *ArcGIS 10.1*. The weights of each effective criterion and subcriterion were determined using experts' viewpoints and the AHP method. Criteria maps were combined in *ArcGIS 10.1*, and suitable places for AGRP implementation were determined. In the second stage, criteria on agricultural land, occupation status, and migration regime in townships were collected and normalized. These three criteria and the percentage of location area were considered as evaluation criteria of the conflict resolution model. The Nash conflict resolution method was then implemented for prioritization of the AGRP implementation order for townships. This paper's method was implemented in the Kerman Province, Iran. The results of this study showed that Jiroft, Shahre-Babak, and Kahnouj townships have the highest priorities among the townships of the province for implementation of artificial groundwater recharge plans.

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